Greenhouse Operation and Management

Paul V. Nelson

Seventh Edition

PEARSON NEW INTERNATIONAL EDITION

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Edinburgh Gate
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glossary

Abortion The partial or complete arrest of a developing tissue, as in embryos, buds, and so forth.

Abscission The separation of leaves, flowers, fruits, or other plant parts from the plant, generally following the formation of a separation layer of cells.

Actinomycetes An order of bacteria that usually grows in filamentous form.

Aerated steam pasteurization Using a mixture of air and steam that is adjusted to a temperature below that of steam for pasteurizing root media.

Aeroponics A system for growing plants with their roots suspended in air. Water and nutrients are misted onto the roots.

Ambiphotoperiodic plants Dual day-length plants that require short days and long days in a sequence for their photoperiodic response to occur.

Apical dominance The suppression of lateral shoot development by the apical bud (shoot tip).

Asset Any resource or item of value. Assets of a business include cash, amounts owed to the business by its customers for goods and services sold to them on credit, merchandise held for sale by the business, supplies, equipment, buildings, and land.

Auxin A group of hormones that induces growth through cell elongation.

Azalea pot A pot with an inside rim diameter equivalent to that of a standard pot, but only three-quarters the depth of a standard pot.

Bactericide An agent or preparation used for killing bacteria.

Bacterium (plural, *bacteria*) A unicellular plant that lacks chlorophyll and multiplies by fission.

Bedding plants A wide range of plants that are propagated and cultured through the initial stages of growth by commercial growers and then sold for use in outdoor flower and vegetable gardens.

Blindness The condition of a plant stem evidenced when the bud stops developing. It is a frequent problem of roses during low-light periods.

Blown head A bloom that is excessively open.

Bluing The objectionable development of a blue pigment in flower petals, usually after harvest.

Boiler horsepower A quantity of heat equal to 33,475 Btu.

Bract A more or less modified leaf subtending a flower or belonging to an inflorescence.

Bracteole A secondary bract, as upon the pedicel of a flower.

Btu (British thermal unit) The amount of heat required to raise the temperature of 1 pound of water 1°F at or near its point of maximum density.

Bulk density The mass per unit bulk volume. For example, the bulk density of a soil-based medium in a dry state might be 70 pounds per cubic foot.

Bullhead A flower whose short petals, particularly at the center, give it a blunt, broad appearance. Also, a flower whose excess number of petals gives it a blunt, broad appearance.

Calyx A term referring to the sepals collectively. It is the first of the series of floral parts and is usually green and leaflike but may be colored like the petals.

Cambium A zone or cylinder of meristematic (dividing) cells located between xylem and phloem tissues in plants. The cambium cells divide to form new xylem and phloem cells.

Cation exchange capacity (CEC) A measure of the ability of an absorbing material such as a root medium to hold exchangeable cations—for example, various fertilizer nutrients, including ammonium nitrogen, potassium, calcium, magnesium, iron, manganese, zinc, and copper. CEC is generally measured in milliequivalents per 100 cubic centimeters (me/100 cc) of dry absorbing material, and a value of 6 to 15 me/100 cc is considered ample for greenhouse root media. A root medium with low CEC does not retain nutrients well and consequently must be fertilized often.

CEC *See* Cation exchange capacity.

Central heat system A system in which the heat used for heating one or several greenhouses is generated in a single location in one or more boilers.

Chelate A chemical complex that will hold or bind a metal. Metals that are commonly chelated for agricultural use are less subject to tie up in adverse root-media environments. These metals include iron, manganese, zinc, and copper.

Chloropicrin Tear gas. A chemical used for pasteurizing greenhouse root media. It is not as popular as methyl bromide but can be used in carnation root media.

Chloroplast A specialized body (organelle) in the cytoplasm of some plant cells that contains chlorophyll.

Chlorosis The state in which normally foliage plant tissue is lighter green and possibly yellow due to the loss of chlorophyll or the failure of chlorophyll to form.

Chord A support member of the greenhouse frame that is under tension.

Clay A mineral component of soils consisting of particles less than 0.002 millimeter in diameter.

Closed cultural system Any method for growing plants in which the nutrient solution is recirculated. Nutrients are not allowed to leach from the pot or bench to the ground.

CO_2 The chemical formula for the gas carbon dioxide.

Cold-sensitive crops Crops that develop unacceptably slow at average day–night temperatures below 60° to 65°F (16° to 18°C) and not at all below 50° to 55°F (10° to 13°C).

Cold-tolerant crops Crops that successfully develop at cooler average day–night temperatures than generally recommended, that is, 40° to 60°F (4° to 16°C) versus 70°F (21°C) and above.

Conduction heat loss Heat loss by transmission through a barrier such as the covering of a greenhouse.

Conidiophore A specialized hypha on which one or more conidia are produced.

Conidium (plural, *conidia*) An asexual fungus spore formed from the end of a conidiophore.

Container capacity The maximum amount of water a root medium can hold against the force of gravity when this root medium is in a container that has open drainage holes in its base.

Convection heat loss Loss of heat from the greenhouse as it moves in air convection currents to the greenhouse covering, then through the covering by conduction, and finally away from the outside of the covering.

Convection heater A heater that does not contain a heat exchanger. Heat leaves the heater in the smoke. The smoke is carried the length of the greenhouse in a pipe that serves as an exchanger as heat passes through its walls to the greenhouse air.

Corporation A legal entity, separate and distinct from the persons (stockholders or shareholders) who own it. The corporation has all the rights and responsibilities of a person and may buy, own, and sell property; sue and be sued; and enter into contracts with both outsiders and its own shareholders. The most important advantage of the corporate form is its responsibility for its own acts and debts and the freedom of its owners from liability for either.

Cost accounting The use of the cost data of producing a given product for the purpose of assessing and controlling those costs. Since a knowledge of costs and controlling costs is vital to good management, a large greenhouse firm often engages the services of a cost accountant.

Critical night length The length of darkness less than which a short-night plant or more than which a long-night plant will undergo a photoperiodic response. The critical night length varies with plant species and even sometimes with cultivars within a species.

Cross-fluted cellulose pad An evaporative cooling pad composed of laminated sheets of fluted (corrugated) cellulose impregnated with insoluble antirot salts, rigidifying saturants, and wetting agents. Pores are oriented diagonally through the pad in two directions, crossing each other.

Crown bud A flower bud whose development has ceased. It sometimes develops the appearance of a crown. Generally, this cessation of development breaks apical dominance, resulting in the development of side shoots. Crown buds may be caused by excessively low or high temperatures or in long-night plants by a series of short nights while the flower bud is developing.

Cultivar A cultivated variety. A cultivar usually has less variation within it than does a botanical variety.

Curtain wall The nontransparent lower portion of the side walls of a greenhouse.

Cut flowers (also known as *fresh flowers*) Flowers marketed after being cut from commercial crops.

Cuticle A nonliving waxy layer covering all plant cells that are in contact with air. Although this layer protects plant cells from drying, water and nutrients can slowly penetrate it, as in the case of foliar fertilization.

Cutting The portion of a plant removed for the purpose of asexual propagation. It may be part of a stem, a leaf, or part of a root, depending on the species of plant to be propagated. Commercial cultivars of chrysanthemums, for example, are propagated by removing terminal stem pieces and placing the lower inch of them in a rooting medium in a moist environment to induce new root formation.

Cyclic lighting An alternative method of applying light during the night to achieve the photoperiodic effect of long days. The customary lighting period is divided into a number of subperiods, each comprised of a duration of light followed by darkness. The total duration of light can be reduced by as much as 80 percent. Where three hours of light are customarily applied, six consecutive cycles of 5 minutes of light and 25 minutes of darkness can be substituted, thereby reducing electrical consumption greatly.

Damping-off A disease caused by a number of fungi, mainly *Pythium, Rhizoctonia,* and *Phytophthora*. The symptoms include decay of seeds prior to germination; rot of seedlings before emergence from the root medium; and development of stem rot at the soil line after emergence, causing seedlings to topple.

Day-neutral plant A plant that does not respond to the relative lengths of light and darkness in the daily cycle.

Depreciation Decline in value of an asset due to factors such as wear or obsolescence.

Desiccation The process of drying. Desiccation of plants results from a lack of water. High levels of soluble salts in the root medium cause desiccation of roots by preventing water from entering the roots.

Detergent *See* Surfactant.

DIF The difference between day and night temperatures computed by subtracting the night temperature from the day temperature. By controlling DIF, the length of stem internodes (overall plant height) can be controlled. For many crops, the lower the DIF value is, the shorter the plant will be.

Disbudding The process of removing flower buds from a plant stem, generally to improve the size of the remaining bud or buds. In most cases, the terminal flower bud is retained and all of the lateral (side) flower buds are removed.

Disease A plant is said to be diseased when it develops a different appearance or changes physiologically from the normally accepted state. These differences are called *symptoms*. Disease can be caused by unfavorable environmental conditions such as temperature extremes or insects, or by pathogenic organisms such as nematodes, fungi, bacteria, or viruses.

Distribution tube A clear plastic tube with holes along either side that is installed along the length of a greenhouse to provide uniform distribution of air within the greenhouse.

Dry matter That portion of the plant remaining after water has been driven off. For purposes of foliar analysis, leaves are generally dried for one day at a temperature of 158°F (70°C).

Eave A component of the greenhouse frame to which the side wall and roof are connected.

Ebb-and-flow system A cultural system in which containerized plants are grown in a watertight bench top. When watering is required, nutrient solution is pumped into the bench to a depth of 0.5 to 0.75 inch (13 to 19 mm). The solution is drawn into the root medium by capillarity. When the pot is thoroughly wet, after about 10 to 15 minutes, the nutrient solution is drained from the bench to a holding tank where it is stored until needed by the crop again. This is a closed cultural system.

Eco-label Within the floral industry, this is a label that can be imprinted on plants and cut-flower packaging and/or sales-related correspondence including packing slips, invoices, and advertisements that indicates compliance with worker social justice and/or environmental protection standards of one of four or more independent labeling organizations.

Employee One who works for wages or salary in the service of an employer.

Employer One who employs another individual.

Emulsifiable concentrate (EC) A liquid pesticide preparation containing the pesticide dissolved in oil and an emulsifying agent to render the oil miscible in water.

Emulsifying agent A chemical that, when added to two immiscible liquids, renders them miscible.

Epinasty State in which the more vigorous growth of the upper surface of an organ (as in an unfolding leaf) causes a downward curvature.

Equinox The two times of the year when day and night are of equal length everywhere on the earth. The sun is closest to the equator. The vernal equinox occurs about March 21; the autumnal equinox, about September 23.

Even-span greenhouse A greenhouse whose roof slopes are of equal length and angle.

Excelsior pad A pad composed of curled shreds of wood, generally aspen, that is used for evaporative cooling of greenhouses.

Facultative irradiance plants Facultative irradiance plants respond to increasing light by flowering earlier, developmentally. In these plants, the number of leaves formed before the first flower is reduced. The maximum reduction in flowering time generally occurs when the daily light integral reaches 12 to 14 moles per square meter per day.

Facultative short- and long-day plants Plants that do not require a night length longer or shorter than a given critical length for a response to occur, but will respond faster if the dark period is longer or shorter respectively than a critical length.

Fan-and-pad cooling A system for cooling greenhouses used during the warm months of the year. Warm air expelled through exhaust fans in one wall is replaced by air entering through wet pads on the opposite wall. The entering air is cooled by the evaporation of water in the pad.

Fan–tube cooling A system for cooling greenhouses used during the cool months of the year. Cold air entering through a louver high in the gable of the greenhouse is directed along the length of the greenhouse through a clear plastic distribution tube. Pairs of holes spaced equidistant along the length of the tube's opposite vertical walls permit uniform air distribution throughout the greenhouse.

Fasciation A malformation in plant stems resulting in an enlarged and flattened stem, as if several stems were fused.

Fertigation The combined application of watering and fertilizer such that fertilizer solution is applied every time the plants require water.

Fertilizer proportioner (also known as a *fertilizer injector*) Equipment used to inject concentrated fertilizer solution into a water line to result in a desired dilution prior to plant application.

Fixation The process or processes in a soil by which certain chemical elements essential for plant growth are converted from a soluble or an exchangeable form to a much less soluble or nonexchangeable form.

Fixed costs Costs of conducting business that are not directly related to the number or type of items produced. Interest on a greenhouse mortgage, for example, is fixed because it remains unchanged if poinsettias are grown rather than azaleas, or even if no crop is grown.

Flat A container used in greenhouses and nurseries for purposes such as germinating seeds or holding several small plant containers. Flats are commonly constructed from wood or plastic. They are variable in size but commonly approximately 21 inches (53 cm) long by 11 inches (28 cm) wide by 2.5 inches (6 cm) deep.

Floor heating Application of heat in or near the floor of a greenhouse.

Floriculture The art and science of growing and utilizing plants valued for their aesthetic characteristics other than woody plants used in outdoor landscape.

Flowering plants Greenhouse crop plants grown in a pot and sold in the flowering state.

Fog cooling A system for cooling greenhouses in which fog is generated inside the greenhouse. As the fog droplets evaporate, heat is absorbed, thus cooling the air.

Foliage plants (also known as *green plants*) Commercial crop plants grown in a pot and sold primarily for the aesthetic value of their foliage.

Foot candle (fc) A unit of illumination equal to the direct illumination on a surface everywhere 1 foot from a uniform point source of 1 international candle. It is equivalent to 10.76 lux.

Forced-air heater A heater containing a heat source, a heat exchanger, and a fan for expelling the heated air.

Fritted nutrients Nutrients, usually potassium or micronutrients, contained in a solid, finely ground glass powder. The glass slowly dissolves in the root medium, releasing nutrients over an extended period of time.

FRP (fiberglass-reinforced plastic) A type of panel used as the transparent covering on some greenhouses.

Fungicide An agent or preparation used for killing fungi.

Fungus A eukaryotic, multicellular, filamentous, branched microorganism.

Gibberellins A category of hormones that stimulate growth through cell division or elongation or both.

Glasshouse A term used in Europe to designate a structure for growing plants that has a transparent cover and an artificial heat source. The equivalent American term is *greenhouse*.

Gravelculture A system for growing plants in a root substrate consisting exclusively of gravel.

Gravitational force In reference to soil water, the force of the earth's gravitational pull on water in the soil that causes water to move downward in the soil profile.

Greenhouse A structure used for growing plants that has a transparent covering and an artificial heat source.

Greenhouse range A term referring collectively to two or more greenhouses at a single location that belong to the same business entity.

Headhouse A work-building in close proximity to or attached to a greenhouse. This facility might be used for a workshop, storage area, pesticide room, potting area, or eating area. This building may also be referred to as a *service building*.

Herbicide A chemical used for killing weeds.

Hormone An organic substance produced in one part of the plant and translocated to another part where in small concentrations it regulates growth and development.

Horticulture The art and science of growing fruits, vegetables, flowers, and woody ornamentals as well as spice, medicinal, and beverage plants.

Host plant A plant that is invaded by a parasite and from which the parasite obtains its nutrients.

Humus The relatively stable fraction of the soil organic matter remaining after the major portion of added plant and animal residues have decomposed.

Hydroponics The culture of plants in a root substrate consisting exclusively of water and dissolved nutrients.

Hypha (plural, *hyphae*) A single branch of the mycelium that makes up the body of a fungus.

IAA (indole-3-acetic acid) A naturally occurring auxin produced in apical meristems of both roots and shoots.

IBA (indole-3-butyric acid) A synthetically produced auxin.

Infiltration heat loss Loss of heated air from the greenhouse through cracks.

Inoculum The pathogen or its parts that can cause disease; that portion of individual pathogens that are brought into contact with the host.

Insecticide An agent or preparation used for killing insects.

Intermediate-day plants These are plants that will flower only when the night length is intermediate, not too long nor too short.

Internode The portion of a plant stem between two nodes. The node is the portion of the stem where one or more leaves are attached.

Interveinal Pertaining to the space between the vascular tissues (veins) on a leaf.

Intumescence A swollen or enlarged part of a plant or animal.

IPM (integrated pest management) A holistic approach for managing pests, including insects and related animals, pathogenic diseases, and weeds. Components of the program can include restriction of pest entry into the cultural area, establishment of environmental conditions unfavorable to the pest at hand, biological control, and, only when necessary, the use of chemical pesticides.

Irradiance indifferent plants Plants in which time to first flowering is not shifted developmentally by increasing light. The required number of leaves before initial flowering does not change with increasing daily light integral.

Lap sealant A clear sealing material forced into the space formed between two overlapping panes of glass.

Larva The immature, wingless, and often wormlike form in which some insects hatch from the egg and in which they remain through increase in size and other minor changes until they assume the pupa or chrysalis stage.

Leaching percentage The percentage of water or nutrient solution applied to a pot or bench of root substrate that drains from the bottom of that container.

Lean-to greenhouse A greenhouse built against the side of another structure such that it has only one sloping roof.

LED (light-emitting diode) A semiconductor diode that emits light from its junction when electricity passes through it. The wavelength (color) of the light emitted depends on the type of material and impurities used to make the junction. The emitted wavelength of light can be set between 250 (UV-C) and 1,000 nanometers (infrared).

Loam A textural class name for soils having reasonably balanced amounts of sand, silt, and clay. Loam soils can contain 7 to 28 percent clay, 28 to 50 percent silt, and less than 52 percent sand.

Lodging The condition of a crop when it has been lain over horizontally from a force such as wind or heavy rain.

Long-day plant A plant that undergoes a photoperiodic response, such as flowering, only when the night length is less than a critical length.

Lumen The unit of light equal to the light emitted in a unit solid angle by a uniform point source of 1 international candle.

Lux The international unit of illumination, being the direct illumination on a surface that is everywhere 1 meter from a uniform point source of 1 international candle. It is equal to 1 lumen per square meter, or 0.0929 foot candles.

Management The making of decisions that affect the profitability of a business.

Mark-on The percentage of the wholesale price added on to the wholesale price to cover overhead and profit and arrive at a retail price.

Markup The percentage of the retail price added on to the wholesale price to cover overhead and profit. An item purchased for $1 and sold for $2 has a markup of 50 percent and a mark-on of 100 percent.

Mass marketing In the field of floriculture, the sale of floral products through high-traffic outlets such as supermarkets, discount stores, department stores, sidewalk stands, and shops in shopping malls.

Matrix force The attraction of the soil (matrix) for water. This force is responsible for the adsorption and capillarity of water in soil.

Meristem A tissue composed of embryonic, unspecialized cells actively or potentially involved in cell division. An apical meristem is a meristem located at the apex (tip) of a shoot or root.

Methyl bromide A chemical commonly used for pasteurizing greenhouse root media. It should not be used in carnation root media.

Miticide An agent or preparation used for killing mites.

Mycelium The hypha or hyphae that make up the body of a fungus. Mycelia are the microscopic threadlike strands that make up the body of a fungus.

NAA (naphthalene acetic acid) A synthetically produced auxin.

Necrosis The state of being dead and discolored.

Nematicide An agent or preparation used for killing nematodes.

NFT (nutrient film technique) The culture of plants in a system where a thin film (a few millimeters deep) of nutrient solution is circulated through a trough that also contains the plant roots. It is a specialized form of hydroponics.

Open cultural system Any system for growing plants in which nutrient solution is allowed to pass through the root zone and out into the environment.

Opportunity cost The value of other opportunities (alternatives) given up in order to produce or consume any good; that which must be forfeited when alternative *A* is abandoned in order to pursue alternative *B*.

Organelle One of several types of small structures within plant or animal cells that is bounded by a membrane. The chloroplast is an organelle in which photosynthesis occurs.

Ovipositor A prominent structure projecting from the posterior end of females of some insect species that is used to deposit eggs.

PAR (photosynthetically active radiation) Light of wavelengths between 400 and 700 nanometers that corresponds to the wave band absorbed by photosynthetic pigments.

Parthenogenesis Reproduction by development of an unfertilized female gamete (egg) that occurs especially among lower plants and invertebrate animals.

Pasteurization The selective destruction of some, but not all, living microorganisms. Root media are pasteurized to eliminate harmful disease organisms and to retain the beneficial microorganisms.

Pathogen An entity (fungus, bacterium, nematode, virus) that can incite disease.

Peat The organic remains of plants that have accumulated in places where decay has been retarded by excessively wet conditions. There are many types of peat, some desirable and others not, used for greenhouse root media.

Peat humus Peat that is at an advanced stage of decomposition so that the original plant remains are not identifiable. It is not generally a desirable form of peat for greenhouse root media because of its rapid rate of decomposition and its occasionally high rate of ammonium nitrogen release.

Peat moss Peat consisting predominantly of slightly humified (decomposed) *Sphagnum* moss species. Horticultural peat moss contains over 75 percent sphagnum moss.

Pedicel Stem of one flower in a cluster.

Perimeter heating system A row of heating pipe or pipes just inside the perimeter walls of a greenhouse.

Perlite A siliceous volcanic rock that is crushed and heated to 1,800°F to cause it to expand into lightweight (about 6 pounds per cubic foot) particles with closed air-filled cells. Perlite is used as a substitute for sand when a lightweight root medium is desired.

Pesticide An agent or preparation used for killing living organisms that are a nuisance or are harmful to crops.

Petiole The stalk or stemlike portion of a leaf.

Photomorphogenesis The formation and differentiation of tissue and organs controlled by light.

Photoperiodism The response of a plant or animal to the relative length of day and night. The response in plants can take on many forms, including flowering, changes in leaf shape or internode length, and bulb or tuber formation.

Photosynthesis The manufacture of carbohydrate from carbon dioxide and water in the presence of chlorophyll, using light energy and releasing oxygen.

Phototropism The alteration of plant growth patterns in response to the direction of incident radiation.

Phytotoxic Toxic to plants.

Pinching Removal of the top of a vegetative plant stem in order to cause it to form several branches.

Plug seedlings Seedlings produced and contained in a small cohesive volume of root medium. This unit of root medium is known as a *plug*.

Polyethylene A plastic material used in the greenhouse industry in the form of thin films for covering greenhouses. It is an inexpensive substitute for glass. Generally, two layers are used—an outer layer 6 mils (6 one-thousandths of an inch) thick and an inner layer either 4 mils (0.10 mm) or 6 mils (0.15 mm) thick.

Pompon chrysanthemums A term used in this book to denote the chrysanthemum cultivars grown with several flowers on each stem. The term *spray chrysanthemum* is more commonly used.

Potable Drinkable.

PPE (personal protective equipment) This is the clothing and protective equipment a person must wear when applying a pesticide, as specified on the pesticide label.

Precipitation The process whereby a dissolved substance comes out of solution to form a solid. The solid substance is a *precipitate*.

Pressuring fan A fan in the end of the clear plastic greenhouse distribution tube that forces heater air, exterior cold air, or interior warm air through the tube, depending on whether the system is being used for heating, cooling, or air circulation, respectively.

Proprietorship A business owned by a single individual.

Pupa The intermediate, usually quiescent, stage assumed by many insects after the larval stage and maintained until the adult stage.

Purlin A component of the greenhouse frame running the length of the greenhouse just below the roof covering that connects the trusses together.

PVC (polyvinyl chloride) A plastic material available in corrugated sheets. This material was used for covering greenhouses during the 1960s, but because of its rapid deterioration from ultraviolet light, it has virtually disappeared from the greenhouse industry.

Radiant heat loss The radiation of heat from a warm body, such as plants in a greenhouse, to a cooler body, such as the covering on the greenhouse or the sky and earth outside.

Rafter A frame component spanning the space between the eave and the ridge. Unlike a sash bar, glass is not attached to it.

Reactive limestone The portion of limestone that reacts (dissolves) rapidly after initial application to bring the root substrate pH to the target level.

Reglaze To replace the glass or the glazing compound that seals the glass on a greenhouse.

REI (restricted-entry interval) This is the period of time (generally 0 to 72 hours) when only suitable trained and equipped pesticide handlers are allowed in the pesticide treated area.

Residual limestone The portion of limestone that remains unreacted (undissolved) after the reactive limestone portion has dissolved.

Respiration Biochemical processes in the plant or animal that result in the consumption of oxygen and carbohydrate, the evolution of carbon dioxide, and the release of energy. Respiration has the reverse effect of photosynthesis.

Revenue Income; return from investment.

Ridge A component of the greenhouse frame to which the upper portion of the two roof slopes are connected.

Ridge-and-furrow greenhouses Two or more greenhouses connected to each other along their length at the eave. In this case, the eave becomes a gutter, or furrow. The common side wall is eliminated in each greenhouse. Such greenhouses are less expensive to heat and easier to automate than an equivalent area of separate greenhouses.

Rock wool A fibrous material used for thermal and acoustical insulation as well as a root medium for plants. It is made from melted rock that can be basalt or limestone, sometimes in combination with iron slag. The hot liquid is spun and cooled into long fibers. The fibers may be formed into granules for use in potting media, blocks for plant propagation, or large slabs for growing finished crops of vegetables and cut flowers.

Root medium *See* Root substrate.

Root substrate (also called *root medium*) A suitable substrate in which plant roots can grow. It consists of one or more mineral and/or organic components mixed together. This term is most commonly used in the greenhouse and nursery circles of agriculture.

Sand A soil mineral particle measuring 0.05 to 2.0 millimeters in diameter.

Sandculture The culture of plants in a root substrate consisting exclusively of sand.

Sash bar The bar to which glass is attached in a greenhouse.

Saturated paste extract (also known as *saturated media extract*) A procedure for water extraction of nutrients from soilless root substrate. Deionized water is stirred into a sample of substrate in a watertight container until the surface glistens (reflects light). After water comes into equilibrium with the substrate nutrients, about one hour, the solution is removed for subsequent analysis. Some labs will include the chelating agent DTPA in the extracting water when they intend to use the extract for micronutrient analysis.

Senescence The process of growing old; aging.

Sepal One of the components of the calyx.

Shatter When used to describe a floral condition, this term refers to the dropping or abscission of petals.

Short-day plant A plant that undergoes photoperiodic response, such as flowering, only when the night length is greater than a critical length.

Sill The portion of the greenhouse that rests on the curtain wall and to which the side wall sash bars are attached.

Silt A mineral component of soils consisting of particles measuring 0.002 to 0.05 millimeter in diameter.

Slab-side (also known as *cling-side*) A flower that has failed to open symmetrically. The petals on part of the circumference are still straight up, while the remaining petals have opened in a normal fashion.

Sleepiness A condition in flowers in which petals curve upward, giving the appearance of a wilted condition. It is commonly caused by ethylene gas after harvest.

SME (saturated media extract) *See* Saturated paste extract.

Soil The upper, heavily weathered layer of the earth's crust that supports plant life. It is a mixture of mineral and organic materials.

Soil structure The combination of primary soil particles into secondary aggregate particles.

Solenoid valve An electrically activated valve that controls the flow of gases or liquids. Such valves can be activated by a timeclock to control the flow of water in automated greenhouse watering systems.

Solstice The two times of the year when the sun is farthest from the equator (closest to the poles). In the Northern Hemisphere, the summer solstice occurs about June 22 and the winter solstice about December 22.

Split A flower having a split calyx, in which the petals protrude from the split. It is a common problem of carnations.

Spore The reproductive unit of fungi consisting of one or more cells; analogous to the seed of foliage plants.

Sporophore A hypha or fruiting structure bearing spores.

Spreader-sticker *See* Surfactant.

Standard chrysanthemums Cultivars of chrysanthemum customarily grown with one large flower on each stem.

Sterilization The destruction of all living organisms. Greenhouse tools and growing containers are periodically sterilized to eliminate harmful organisms, including pathogenic diseases, insects, nematodes, and weeds.

Strap leaves Leaves whose margins are partially or completely missing such that the leaf is narrower than normal, often resembling a strap.

Strut A support member of the greenhouse frame that is under a compression force.

Surfactant A chemical used to alter the surface properties of liquids. Surfactants are added to pesticide sprays to reduce the surface tension over the plant leaf surface. Without a surfactant, complete coverage of the leaf surface often is not achieved. Surfactants used for this purpose include *spreader-stickers, wetting agents*, and *detergents*. Surfactants are also used to enhance the initial wetting of root media containing relatively dry peat moss, which tends to be waxy and water-repellant.

Symphillid A small, translucent to white, many-legged arthropod that ranges up to ¼ inch (6 mm) in length and feeds on the roots of plants.

Systemic Spreading internally throughout the plant body. Some pesticides are systemic, as are some pathogens.

Texture The relative proportion of various sizes of mineral particles in a given soil or root medium.

Transpiration The loss of water from plant tissue in the form of vapor.

Tropism A growth response or bending toward or away from a stimulus. Geotropism is in response to gravity; roots grow toward, and shoots away from, the center of the earth's gravity. Phototropism is in response to light; shoots tend to grow toward light.

Trough culture A closed system for growing potted plants in which a single row of pots is placed in a watertight trough arranged on a slight incline. Nutrient solution is pumped to the high end of the trough. It flows by gravity around the bases of the pots to the low end, where it is channeled to a holding tank. Solution is drawn into the root medium by capillarity. The solution is reused each time the crop requires watering.

Truss A compound component of the greenhouse frame spanning the width of the greenhouse and consisting of rafters, chords, and struts that are welded or bolted together.

Ultralow volume When used to describe pesticide application to plants, this term refers to the application of a very low volume of liquid pesticide formulation per unit area. When less than 5 gallons is used per acre (47 L/ha), the application is referred to as *low volume*; below 1 gallon per acre (9.5 L/ha), it is referred to as *ultralow volume*.

Uneven-span greenhouse A greenhouse with one roof slope longer than the other, generally an adaptation to a hillside.

Unit heater A forced-air heater. Unit heaters are usually mounted overhead in a greenhouse. They may contain a firebox or receive heat in the form of steam or hot water from a boiler elsewhere.

Variable cost A cost that increases proportionately with each additional unit produced and ceases if no units are produced. The costs of pots, root media, and plants are variable costs; the mortgage on the greenhouse range is not a variable cost, but a *fixed cost* because it continues even if no plants are produced.

Vascular tissue Tissue in the root, stem, leaf, or flower stem, including phloem for conducting organic substances throughout the plant, xylem for conducting water and nutrients primarily from the roots to the shoot, and supporting fiber cells. Vascular tissue in leaves is often called *veins*.

Vase life The length of time that a cut flower retains its aesthetic value after it has been placed on display.

Vector An organism, such as an insect, that transmits a pathogen. To vector is to transmit a pathogen.

Veinal Pertaining to the vascular tissue (veins) or the tissue immediately above the vascular tissue in a leaf.

Ventilator A glazed panel attached to the greenhouse with hinges that permit opening for ventilation purposes.

Vermiculaponics The culture of plants in a root substrate consisting exclusively of vermiculite.

Vermiculite A micaceous mineral that exfoliates (expands by separation of the many layers composing it) when heated. It is used in the expanded state as a lightweight component of greenhouse root media. Its desirable properties include a light bulk density of 7 to 10 pounds per cubic foot, a relatively high CEC of 19 to 23 me/100 g, and a high water-holding capacity.

Vernalization The process of hastening the flowering of plants by treating seeds, bulbs, or seedlings to low temperature.

Wettable powder In floriculture, an agricultural chemical formulated generally in talc or dry clay. It is suspended in water by continual mixing and is applied as a spray or root-media drench.

Wetting agent *See* Surfactant.

Whole-firm recirculation A closed-circuit system encompassing an entire firm. Effluent from all benches or beds is channeled to a treatment pond. There it is often treated for pathogens, analyzed, and nutritionally altered prior to being recirculated through the crops.

Witch's broom A symptom of boron deficiency in a plant. A witch's broom consists of a large number of shortened plant stems situated parallel and close to one another to give the appearance of the straws in a broom.

Xylem A tissue in the plant that transports water and nutrients upward from the roots to the foliage. Cells connected from end to end form xylem tubes. Vessels are the predominant xylem cells in flowering plants and have open ends. Tracheids predominate in the conifer (pines, etc.) xylem; rather than having open ends, they have pits along their sides connecting to adjacent tracheid cells. Vessel and tracheid cells are nonliving at the time they carry out the function of water and nutrient transport.

Floriculture—A Global Industry

The leading retail markets for floral products in the world coincide with the more economically developed societies. In such societies, people have sufficient discretionary money to support the floral industry. The largest markets today are Western Europe, the United States and Canada, and Japan. The Chinese, Indian, and Russian markets are developing rapidly. The retail value of flower and plant sales in the United States in 2005 was estimated to be approximately $6 billion.

Until the middle of the 20th century, most floral production was dispersed throughout the world in close proximity to the more affluent population centers. Economic development after World War II brought with it interstate and intercountry highway systems as well as improved refrigerated trucking. This fostered consolidation of much cut-flower production from scattered population centers to warm regions during the 1950s and 1960s. In the United States, these regions included Florida, Texas, and California where flowers could be produced outdoors with less energy input and cheaper labor. Floral production change continued to escalate in the 1970s with the development of intercontinental floral trade. Production areas for cut flowers opened up in South America and Africa, which supplied flowers to North America and Europe. The new production areas enjoy low labor and energy costs and, in the case of counties such as Colombia, higher quality due to better climatic conditions.

Production changes have brought with them equally great changes in floral packaging, handling, and transportation, as well as wholesale and retail marketing. These changes will be discussed in this chapter. Firms that have been aware of these impending changes have been able to make the necessary shifts in crops grown and markets serviced. Consequently, they have been able to grow and profit from the changes. Firms that learned of the changes after the fact suffered or went out of business. Change in the greenhouse industry is advancing at an ever-increasing rate. This points out the need for continuing education and networking throughout one's career in this industry.

ORIGIN OF THE GREENHOUSE INDUSTRY

The greenhouse industry in the western world appears to have originated in Holland during its "Golden Age," the 1600s. The stage was set during the first half of the 17th century when The Netherlands became the world's foremost sea power. Its merchant fleet tripled during this period to the point where The Netherlands provided half the world's shipping, and Amsterdam became the world's leading commercial city. The Dutch standard of living was the highest in the world. Milestones during this period occurred in 1602, when the Dutch East India Company was founded, and in 1621, when the Dutch West India Company was founded. Both expanded trade throughout a vast colonial empire. However, The Netherlands was under the proclaimed rule of Spain during this time, a situation that diverted considerable naval strength. Although The Netherlands declared its independence from Spain in 1581, it was not until the end of the Thirty Years' War (1618–1648) that The Netherlands won its cause to become an independent nation and realized its full potential commercial naval strength.

The royal courts of Europe at this time had a taste for elegance and the means to afford it. Spring flowers in the winter and fruit out of season were very enticing. The productive capacity of the large middle class, unique to The Netherlands, and the trade channels of the merchant segment soon gave birth in The Netherlands to what is today one of the largest greenhouse industries in the world. Grapes were grown along rock walls in western Holland under glass enclosures constructed in a lean-to fashion. These greenhouses conserved the energy of the sun during the winter and permitted early crops of grapes. Today, a vast greenhouse vegetable and cut-flower industry exists, with its center in the Westland area, as a direct descendant of this initial business.

In the region near Amsterdam, field-grown lilac bushes were dug in late fall, prior to the freezing of the ground, and were stored outside. Periodically during the winter, bushes were moved into greenhouses where they broke dormancy and flowered (Figure 1). The cut blooms graced the palaces of 17th-century royalty in Great Britain, France, Germany, and other countries. Even today, this industry persists, although much of this region, near Aalsmeer, is involved in potted-plant culture in general. Today, The Netherlands is the largest producer of floral products in the world, producing over 18 percent of the total world value (Table 1).

Development of the greenhouse industry in North America followed much later because of its dependence on the economic growth of this new land. Greenhouse technology brought in by immigrants from Europe was used to establish an industry that began to flourish during the 19th century. The first reported greenhouse in the United States was that of James Beckman in 1764, located in New York City (Kaplan, 1976).

(a) (b)

Figure 1
Lilacs were one of the first floral crops grown in The Netherlands, and they are still grown there. (a) Dormant bushes are dug in the late fall and stored. (b) Periodically during the winter, bushes are brought into the greenhouse for forcing.

Table 1
Wholesale Value of Cut Flower Plus Containerized Floral Plant Production (euros and dollars in millions), Number of Firms, and Year of Data Collection in Countries of the World for Which Statistics Are Available[1]

Country	Production Value (million)	Production Value $ (million)	Number of Firms	Data Collection Year[2] Value	Data Collection Year[2] Firms
Europe					
Austria	240	299	855	2004	
Belgium	263	243	2,953	2002	1999
Czech Republic	43	59	1,150	2007	
Denmark	349	434	489	2003	2007
Finland	97	143	739	2008	
France	956	1,250	7,663	1998	
Germany	1,289	1,604	9,561	2005	2004
Greece	172	214		2004	
Guernsey	45	56	64	2005	
Hungary	95	119	850	2006	
Ireland	19	25		1998	
Italy	1,627	2,024		2005	
Netherlands	4,005	5,891	5,787	2008	
Norway	145	182	402	2006	
Poland	186	243		1995	
Portugal	457	569	704	2005	1994
Russia	150	187		2003	
Spain	412	517	5,454	2006	2003
Sweden	128	159	685	2005	
Switzerland	228	286	549	2006	2003
United Kingdom	431	591	9,400	2007	1998
Total	**11,337**	**15,095**	**47,305**		
Middle East					
Israel	205	255	1,100	2005	
Turkey	15	20	5,000	1996	
Total	**220**	**275**	**6,100**		
Africa					
Ethiopia	90	113	80	2006	
Kenya	389	572	140	2008	2002
Morocco	11	14		1995	
South Africa	69	64	900	2000	
Uganda	8	10	20	1996	2002
Zambia			40	1998	
Zimbabwe	27	35	240	1997	
Total	**594**	**808**	**1,420**		
Asia/Pacific					
Australia	335	438	3,046	1996	1997
China	2,903	3,979		2007	
Chinese Taipei	360	493		2007	
Hong Kong	7	9		1995	
Japan	2,606	3,242	77,980	2005	
Korea (Republic)	558	515	10,383	2000	
Malaysia	20	25		2005	
Singapore	10	13		1995	
Sri Lanka	5	7		1995	
Thailand	61	80		1995	
Total	**6,865**	**8,801**	**91,409**		

(*continued*)

Table 1

Wholesale Value of Cut Flower Plus Containerized Floral Plant Production (euros and dollars in millions), Number of Firms, and Year of Data Collection in Countries of the World for Which Statistics Are Available[1] (continued)

Country	Production Value € (million)	Production Value $ (million)	Number of Firms	Data Collection Year[2] Value	Data Collection Year[2] Firms
North America					
Canada	1,006	1,379	3,578	2007	2006
United States	2,992	4,101	6,140	2007	
Total	**3,998**	**5,480**	**9,718**		
Central/South America					
Brazil	350	323	3,600	2000	1995
Colombia	745	1,096	541	2008	2007
Costa Rica	80	105		1994	
Ecuador	190	175		1999	
Guatemala	17	22		1995	
Total	**1,382**	**1,721**	**4,141**		
World	24,396	32,180	160,128		

[1]Data derived from AIPH (2009).
[2]Year of data collection for firms same as for value unless otherwise stated.

Floriculture first started around the population centers of Boston, New York, Philadelphia, and later, Chicago. In those days, prevailing modes of transportation necessitated production in close proximity to the markets. As the population spread west across the continent, floral production followed and became established in each urban area.

UNITED STATES PRODUCTION

The Netherlands is the largest floral producer in the world at $5.9 billion (18.3 percent). The United States is the second largest. Of the estimated total world wholesale production value of $32.18 billion, the United States produced $4.10 billion (12.7 percent) in 2007 (see Table 1). The next two top producers were China with $3.98 billion (12.4 percent) and Japan with $3.24 billion (10.1 percent). Together, the top four countries produced approximately 54 percent of the world's floral products.

U.S. production fits into six categories (Figure 2). These categories and the percentage of the total production of each in 2009 were 9.7 percent cut (fresh) flowers,

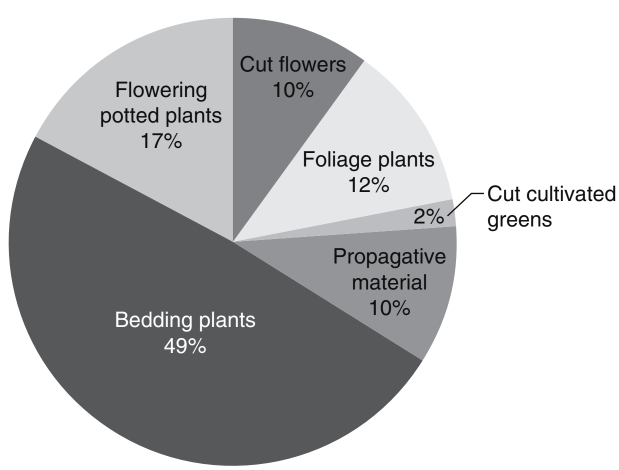


Figure 2
Greenhouse crop categories produced in the United States in 2009 and their value and percentage of the total.
(From Agricultural Statistics Board, USDA [2010]).

12.3 percent foliage (green) plants for indoor and patio use, 17.2 percent flowering potted plants, 49.1 percent bedding plants, 2.0 percent cut cultivated greens for use in floral arrangements, and 9.7 percent propagative material. Bedding plants can be further divided into annual bedding/garden plants in flats, pots, and hanging baskets (73 percent of bedding plants) and potted herbaceous perennial plants (27 percent of bedding plants). Propagative material includes production of young plants from seed or cuttings for bedding plants, flowering potted plants, cut flowers, foliage plants, or cut cultivated greens. Over the past decade, propagative materials have gained in proportion while the other categories have remained constant or declined. Most notable in the decline were foliage plants and cut cultivated greens. These statistics are gathered annually by the USDA Agricultural Statistics Board (Agr. Statistics Board, 2010). Prior to 2006, data were gathered from the top 36 production states, while after 2005 they were gathered from the top 15 production states. Before entering into floral production, it is important to understand the history of changes and the forces now shaping future potential in each category. One could be doomed to quick failure by entering the wrong commodity area.

Floral production is not uniformly distributed across the United States (Table 2). California produces 25 percent and Florida 18.3 percent of the total produced by the top 15 states. The top 15 production states had a combined wholesale production level of $3.69 billion in 2009. California, Florida, and Texas have the most favorable climates for producing foliage plants and cut cultivated greens, while California has the best climate for cut flowers. Thus, the majority of these three commodities are produced in those three states. The remaining states in the top 15 list are situated in close proximity to major markets, giving them the opportunity to supply large quantities of bedding plants and flowering potted plants, the two largest commodities in the floral mix. The 35 states not included in the top 15 list are also heavily committed to bedding-plant and flowering potted-plant production. Their production levels tend to be proportionate to the size of their urban areas.

Table 2
Value of Wholesale Floral Production in the Top 15 Production States in the United States During 2009[1]

State	Value ($ million)	% of Top 15 States
California	935.2	24.4
Florida	696.0	18.2
Michigan	397.4	10.4
North Carolina	252.6	6.6
Texas	245.3	6.4
Ohio	206.5	5.4
New York	170.5	4.5
New Jersey	165.5	4.3
Pennsylvania	155.3	4.1
Washington	138.4	3.6
Illinois	130.9	3.4
Oregon	127.6	3.3
Maryland	92.9	2.4
South Carolina	68.2	1.8
Hawaii	46.5	1.2
Total	**3,828.8**	

[1]Agricultural Statistics Board, USDA (2010).

Cut Flowers

Through the end of the 19th century, floral products were transported by horse-drawn wagons. Because these lacked refrigeration and were rough on the product, transportation was limited to local areas. The development of truck transportation in the early 20th century changed that. Paved roads and faster speeds made it possible to transport greater distances without undue damage to the product. *Cut flowers*, otherwise known as fresh flowers, could be packed in ice. For the first time, it was possible to produce a floral commodity in a remote area that lent itself better to profitability than the area around the local market. Before looking at the production area shifts that occurred as a result of changing transportation, it is important to understand the three factors that govern the suitability of a given production area: production cost, quality, and transportation cost (Figure 3).

Eastern Centers Cut flowers were the first floral commodity to undergo centralization of production. As trucks became commonplace in the early 20th century, transportation posed less of a problem. The populated areas of eastern Massachusetts, Connecticut, and New York City, particularly Long Island, became major centers for carnation production. Rose production became especially important in these same areas, as well as around Philadelphia and Chicago. From these centers, cut flowers were transported considerable distances to smaller towns. This early centralization was probably driven by an information infrastructure. These areas had a state agricultural university with heavy involvement in floriculture, a critical mass of growers, and the allied supply industry to share technical information, to foster new innovations of efficiency, and to create the wholesale distribution channels needed. All of these factors led to lower grower costs.

Southern Outdoor Production The movement toward centralization suddenly escalated during the 1950s. An interstate system of highways was emerging and air and refrigerated-truck transportation had developed to the extent that shipping cut flowers to any point was economically feasible. The growing of cut flowers outdoors in warm climates for shipment to distant markets became a possibility. Production of cut chrysanthemums expanded at a startling rate in Florida, southern California, and to a lesser extent, Texas. Crops were grown year-round under shade fabric supported on inexpensive frames (Figure 4). No heating or cooling was required. The increased cost of transportation was more than offset by lower production costs—cheaper growing facilities, no heating expenses, and less expensive labor.

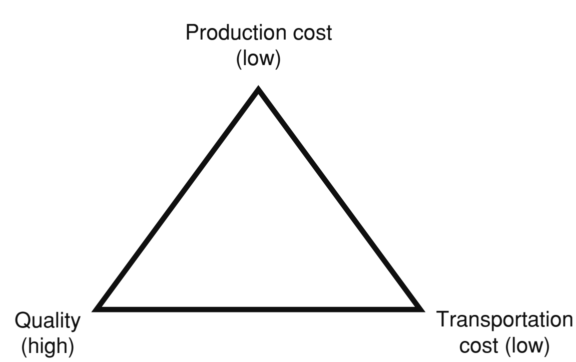


Figure 3
Crop production areas often can be evaluated on the basis of three factors: production cost, quality, and transportation cost. If all three factors are ideal, then the area is safe from competition. If conditions are less than ideal, as is usually the case, weakness of any one factor must be offset by strengthening one or both of the others in order for the production area to meet outside competition.

Figure 4
Large areas of crops, particularly cut flowers such as this chrysanthemum crop in Florida, were grown outdoors under shade fabric in Florida and California.

Consequently, the production of stock (*Matthiola*), a cut-flower crop of secondary importance, essentially came to a halt in northern greenhouses since nearly all the demand was met by southern California growers (Figure 5). Northern chrysanthemum growers feared that they too would soon become a relic of the past. Interestingly, chrysanthemum production in the field reached a plateau during the 1960s and came into balance with the rest of the country. The attainment of this position caused many greenhouse growers to turn away from the production of this crop.

Those northern growers who foresaw the trends improved the quality of their product to give themselves a competitive edge over poorer-quality flowers grown during periods of harsh weather in the fields. Particularly in the northern areas, near the ends of the distribution lines from the southern fields, chrysanthemum growers established year-round production schedules to guarantee a steady, 52-week supply of flowers. Where it was not possible to meet the competition of southern spray-type chrysanthemums during the winter months, astute growers switched to greenhouse-grown standard chrysanthemums, which at that time did not grow well in the fields.

The equilibrium between field- and greenhouse-grown chrysanthemums was further supported by the lack of control over natural factors in the weather-dependent field environment. Frosts, tropical storms, winds, periods of excessive moisture, and sudden infestations of insects were (and are) all very difficult and sometimes impossible to control in the field. When these forces came into play, the market demands for

Figure 5
*Relatively inexpensive field culture, such as this crop of field-grown stock (*Matthiola*) in California, replaced greenhouse crops in the northern states.*

(Photo courtesy of R. A. Larson, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.)

quantity and quality were not met, and the door was opened for controlled-environment (greenhouse) crops. Roses are a good example of this point. They are particularly prone to powdery mildew disease and spider mites as well as to any adversity in handling. Because of the quality factor, open-field production of roses as a cut flower has not developed.

Colorado Greenhouse Production Carnation production did not shift to the southern outdoor fields because those climates were too hot to achieve required quality. During the late 1950s, a shift did occur. Through the efforts of forward-thinking individuals like Professor W. D. Holley of Colorado State University, more satisfactory environments were identified that came closer to fitting the requirements of this crop, which calls for 52°F (11°C) night and 75°F (24°C) day temperatures, high light intensity, and a 12-hour day length. The Denver, Colorado, region offered more temperate summer temperatures and a high light intensity because of its high elevation. From an essentially nonexistent floral industry in 1950, an impressive greenhouse carnation industry grew in Colorado, which accounted in 1965 for 22 percent and in 1975 for 27 percent of the number of blooms produced in the leading 27 states. This production-area shift was supported by the higher product quality that could be achieved in the Denver area. Along with carnations, a large greenhouse rose industry also developed in the Denver area.

California Greenhouse Production However, in spite of higher quality, production costs, particularly those of fuel, were also high. As a consequence, a shift to greenhouse production rapidly occurred in the San Francisco Bay area during the early 1960s. Although light intensity was lower in the Bay area, the shift in quality was more than offset by lower production costs stemming from more temperate winter and summer temperatures and a greater availability of inexpensive labor. Of the total number of U.S. carnation blooms produced, 45 percent were grown in California in 1965, 66 percent in 1975, and 79 percent in 1985. Development of the California industry (Figure 6) had its repercussions in that carnation production in Colorado dropped back to 21 percent of U.S. production by 1980. The phenomenal expansion in Colorado and later in California had a devastating effect upon the eastern carnation production areas.

Besides carnations, massive shifts in the production of other cut flowers into several areas in California also occurred. The percentages of the total value of cut-flower

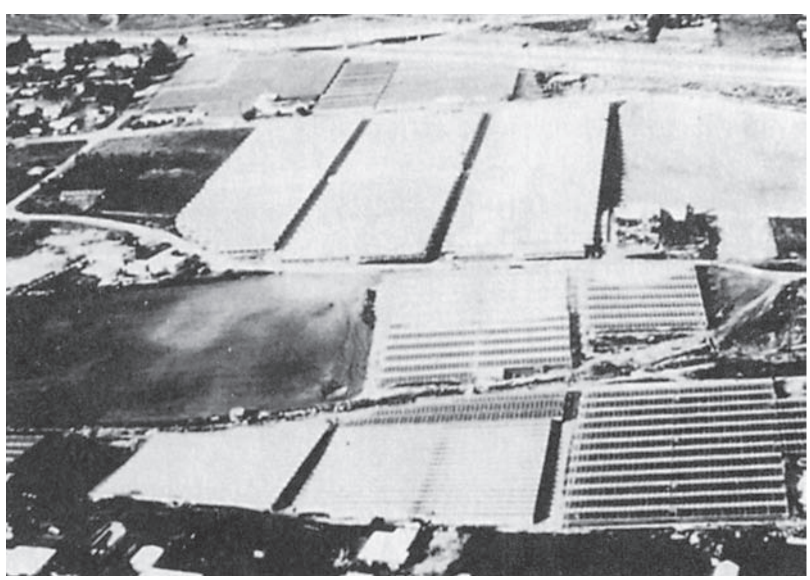


Figure 6
The past three decades have seen a dynamic expansion in greenhouse-grown cut flowers in California.
(Photo courtesy of Hall-Manatee Greenhouses, Encinitas, CA.)

production in the United States that were produced in California in 1965, 1975, 1985, 1995, and 2005 were 27, 36, 56, 62, and 73, respectively. In 2005, 15 percent of the value of all remaining U.S. floral production, other than cut flowers, occurred in California. Throughout this period of an initial southward and later westward shift of cut-flower production, growers in the remainder of the continental United States and Canada were either closing their businesses or shifting to other crops, mainly bedding plants and flowering potted plants.

The shift of cut-flower production to California was partly in response to the large market developing in the western coastal states. But that alone could not justify the volume of cut-flower production. Lower production costs due to a milder climate and less expensive labor compared to Colorado and the eastern United States further explained the shift. The final reason was lower transportation costs. The predominant movement of air cargo in 1950 was westward, resulting in partially empty planes returning eastward. To fill these planes, lower rates were offered for eastward transport. This effectively opened the eastern markets to western growers and at the same time protected the western markets against competition from eastern growers. The air freight rate for 1,000 cut carnations (1.67 boxes) from San Francisco to Chicago was $21.47 in 1950 (Table 3). This rate fell to a low point of $12.65 in 1965, a strong motivation for air shipment of flowers. Rates then gradually rose. But even in 1980, the rate of $20.75 was still lower than it had been 30 years earlier.

In 1975, more than 90 percent of cut flowers were shipped via air from California. Then, as air fares rose and developments in precooling, packaging technology, and truck cooling systems progressed, truck transportation became competitive. By 1980, the percentage of flowers shipped by air fell to about 25 percent, with the remainder shipped by truck. Through the 1980s, shipping costs played a major role in selection of the mode of transportation. By 1990, airlines shipped about 60 percent of cut flowers from California. Since then, the airline proportion has slipped. In 2000, the breakdown of transportation channels was 60 percent truck, 20 percent airline, and 20 percent Federal Express (FedEx), with most of the latter being via air. Today, most flowers continue to move by truck because trucks remain the cheapest mode of transport. The proportion of truck transport increases on Fridays. The wholesale markets are mostly closed on the weekend and truck delivery can be completed in three days, bringing the flowers to the markets on Monday.

FedEx is used when a short delivery time is important. The most common service used for flowers is "Standard Overnight" whereby the package is delivered by 3:30 P.M. the next day. Shipping rates are about 45 percent more than the

Table 3
AIR FREIGHT RATES FROM SAN FRANCISCO TO CHICAGO[1]

Year	Rate ($)
1950	21.47
1957	13.03
1965	12.65
1969	13.40
1972	15.15
1980	20.75
1990	25.00
1996	30.00
2000	31.75

[1]Per 1,000 cut carnation flowers, 600 flowers per box.

passenger airline rate. Passenger airlines are used more often than freight airlines because the minimum shipment required by freight airlines to receive competitive rates is too large for most shipments. Passenger airlines are used when the flowers need to reach market faster than the truck delivery time. The minimum lot for low airline rates equates to about three to four boxes and for FedEx one box. The minimum load for trucks is about 10 to 15 boxes, depending on the destination and time of year. Shippers try to avoid connecting flights because considerable flower quality can be lost when the shipment has to be transferred between planes at an airline hub. Flowers are cooled at the airport while waiting for delivery and again at the destination airport when not picked up immediately. They are not cooled in the cargo hold of planes because pets and other sensitive materials are shipped in these holds. However, a shipping temperature of 60°F (16°C) is common in the hold. Truck transport has reached its prominence because it is cheaper and trucks can access more destinations than airlines. Also, while flowers are shipped dry via air, they can be shipped upright in containers with their stems in preservative solution in trucks. These containers can then be used for displaying them in the retail shop. An important advantage of truck shipping is temperature. Flowers shipped by truck are cooled at the truck terminal prior to loading and then are transported all the way to their destination in refrigerated trucks. Even though the trip may take three to five days, quality protection is generally high.

In summary, FedEx, air, and truck transport each serves its own niche. It is not likely that one will completely replace another, although their proportions will shift over time. Together, the three make up the overall system of floral transport required by the industry.

Foreign Imports In 1969, an intercontinental shift became apparent. Actually, the story began in 1966, when two carnation ranges in Bogotá, Colombia, began producing quality carnations at an incredibly low price. They were joined in 1969 by a U.S. firm, and others quickly followed. Today, the majority of cut flowers consumed in the United States come from Colombia. Greenhouses are primarily covered with polyethylene. Bogotá, at an altitude of 8,660 feet (2,640 m), enjoys a day length close to 12 hours year-round because of its location near the equator. Evening temperatures are in the 40–50°F (4–10°C) range, and daytime temperatures are in the 60–70°F (16–21°C) range in all seasons. The area offers high light intensity because of its high altitude. These factors are ideal for high-quality carnation production. Additionally, the cost of labor is low, and in the past there was no expense for heating because flowers were produced in unheated plastic houses in Colombia (Figure 7). Today, the trend is toward a simple heating system to ward off dips in night temperature.

Colombian carnations constituted a modest 0.5 percent of all carnations sold in the U.S. market in 1970, but by the end of 1974, the figure was a stunning 25 percent. In 1978, 1981, 1988, 1995, 2000, and 2009, imported carnations from all sources constituted about 40, 60, 76, 87, 95, and 99 percent, respectively, of total sales in the United States (Figure 8a).

A chrysanthemum production industry developed simultaneously in Colombia. At first, it was located on the savanna around Bogotá, but later it expanded to the area around Medellín. Medellín is located at a lower altitude of 4,880 feet (1,490 m) in the Andes Mountains northwest of Bogotá. At this lower altitude, the average temperatures are about 10°F (6°C) higher, which favors chrysanthemum production. Imported pompon chrysanthemums made up 91 percent of those sold in the United States in 2009 (Figure 8b). Rose imports became significant during the late 1970s. The level of imports has grown continuously since

(a)

(b)

Figure 7
Greenhouses in the Bogotá area of Colombia, South America. (a) A metal frame gutter-connected polyethylene greenhouse and (b) a wood frame, tropical saw-tooth-style polyethylene greenhouse.
(Picture (b) courtesy of John Dole, Dept Hort. Science, North Carolina State Univ., Raleigh, NC 27695-7609.)

then, and in 2009 constituted 97 percent of roses sold in the United States (Figure 8c). Rose imports lagged behind carnation and chrysanthemum imports because roses originally had a short shelf life and are more susceptible to mishandling. Roses require more sophisticated production and marketing. The Latin American industry, in the early stage of development, found it difficult to address these needs. However, this was a temporary obstacle. Rose breeders focused on developing cultivars better adapted to growing conditions in the exporting countries and have achieved much longer vase life. Sizable quantities of roses began to be imported from Colombia, followed more recently by Ecuador, Guatemala, and Mexico. Roses from Ecuador have become the standard of the world due to their exceptional size and quality. This quality factor relates to the excellent climatic conditions in Ecuador.

The value of cut flowers and cut foliage imported into the United States in 2008 (Table 4) was $928 million. This made up 65 percent of the wholesale value of cut flowers and cut foliage consumed in the United States that year. The majority of these imports came from Latin America, primarily Colombia and Ecuador. However, in total perspective, cut-flower imports constituted only 18.7 percent of the total U.S. combined production of cut flowers, flowering potted plants, foliage plants, bedding plants, and cut greens plus imported cut flowers in 2008.

Figure 8
Number of stems, or bunches in the case of pompons, of three types of cut flowers produced in and imported into the United States per year from 1971 through 2009.

(Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695. U.S. production data from Agricultural Statistics Board, USDA, 1972 through 2010; import data from USDA, Agr. Mkt. Ser. [2002] and Foreign Agr. Service [2010].)

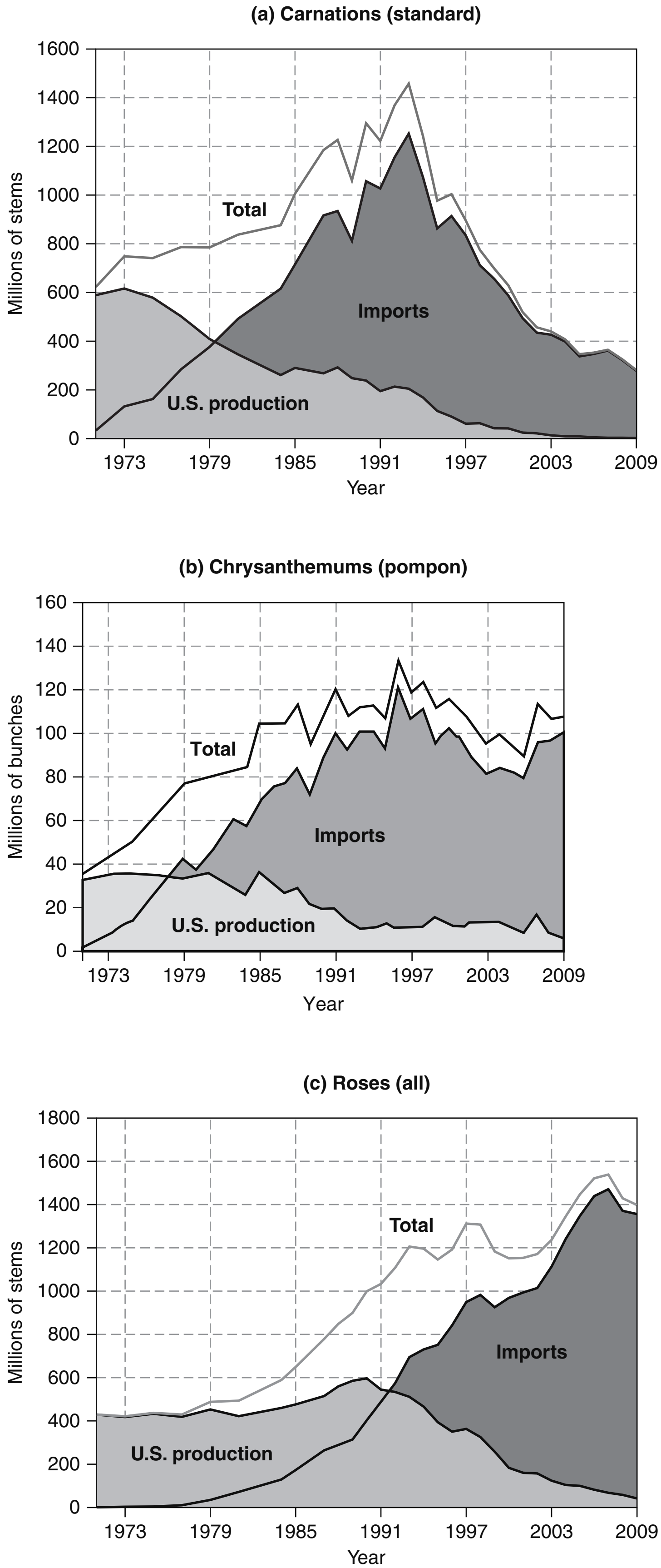


Table 4
VALUE ($1,000) OF CUT FLOWERS AND CUT FOLIAGE IMPORTED INTO THE UNITED STATES IN 2008 BY COUNTRIES OF ORIGIN THAT EXPORTED OVER $140,000[1]

	Value ($1,000)		Value ($1,000)
Latin America		**Asia/Pacific**	
Colombia	513,490	China	13,953
Ecuador	134,237	India	9,423
Costa Rica	33,107	Thailand	8,667
Mexico	32,050	New Zealand	5,431
Guatemala	4,928	Philippines	4,800
Dominican Republic	4,119	Australia	3,219
Peru	2,613	Indonesia	862
Chile	2,306	Chinese Taipei	772
Brazil	540	Malaysia	707
Bolivia	404	Sri Lanka	528
Europe		**Middle East**	
Netherlands	60,841	Israel	6,925
Italy	10,271	Turkey	640
France	559	**Africa**	
Spain	555	South Africa	1,606
United Kingdom	361	Kenya	1,276
Ireland	296	Madagascar	215
North America		**Others**	**1,460**
Canada	65,113	**World Total**	**926,274**

[1]From AIPH (2009).

During the 1970s and first half of the 1980s, the first 15 years of cut-flower importing, the U.S. cut-flower production industry compensated in part for the decline in domestic production of standard carnations and chrysanthemums by increasing production of miniature carnations and miniature gladioli. During this period, demand increased in the retail market for smaller sizes of these flowers in arrangements. Due to increased production of these miniature crops and to rising prices of flowers, the total value of U.S. production of cut flowers continued to increase modestly throughout that period (Figure 9). But averages do not tell every-

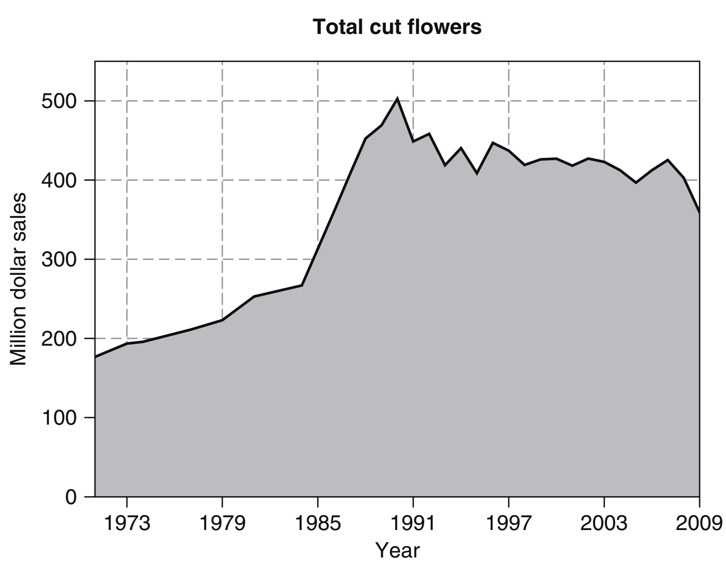


Figure 9
Wholesale value of cut flowers produced in the United States from 1971 through 2009.
(From Agricultural Statistics Board, USDA, 1977 through 2010. Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695.)

Table 5
Total Number of Growers Producing Specified Floral Crops in the Leading 36 States in the United States from 1971 Through 2005[1]

Crop	Number of Growers 1971	1979	1989	1995	2000	2005
Chrysanthemum, pompon	2,168	999	477	92	87	48
Chrysanthemum, standard	2,134	829	397	113	79	—
Carnation, standard	1,525	418	254	131	50	24
Rose, hybrid tea	323	238	285	175	114	59
Pot chrysanthemum	1,394	1,424	1,090	710	557	432
Foliage plants	835	1,687	2,094	1,186	1,554	1,472
Bedding plants	—	2,819	4,458	2,384	3,225	3,040
Poinsettia	—	1,977	3,069	2,044	1,821	1,510

[1]From Agricultural Statistics Board, USDA (1972, 1980, 1990, 1996, 2001, and 2006).

one's story. Some growers, particularly those operating at a low level of efficiency, went out of business, while others switched to containerized crops, mainly foliage plants (Table 5). Greenhouse cut-flower production in states other than Colorado and California and outdoor production of chrysanthemums in Florida and Texas almost ceased.

During the decade of the 1980s, a very fortuitous event occurred. The retail floral industry fostered a shift in floral arrangement style. The trend called for freer forms containing new floral materials. A good part of the trend can be credited to the Dutch floral industry, which undertook an ambitious program to export cut flowers to the U.S. market during the 1980s and met with considerable success. Interestingly, many of the flowers that they exported were new or minor crops in the U.S. market at that time. Such crops included alstroemeria, freesia, cut hybrid lilies, ranunculus, gerbera, and liatris. Introduction of those crops to the consuming public not only met with success but cultivated a demand for more of the same and for new flower types. What started as a perceived disaster for the domestic floral production industry turned out to have a silver lining.

This demand for new flowers came at a very opportune time. During the 1980s, production of gladioli and pompon chrysanthemums took a downturn. If not for the shift on the part of domestic growers to the new minor cut-flower crops, total cut-flower production might have declined during that decade. As it turned out, total production rose (Figure 10). Again, not all growers were successful in this shift. Some went out of business, and others shifted to containerized crops, mainly flowering potted plants and foliage plants (Table 5).

The value of cut-flower production in the United States reached its peak in 1990 and then declined during the early years of that decade. This was caused in part by a decline in rose production after 1991 (Figure 8c). Rose quality improved dramatically in developing countries around the world. This was due in great part to successful breeding of cultivars suited to the climates of those regions. The decline in domestic cut-flower production during this period was also a result of adoption of many of the minor crop introductions of the previous two decades by the newly developing floral production areas of the world. As demand was established in the developed markets of the world, these new crops were adopted in the new production areas (see Table 6 for

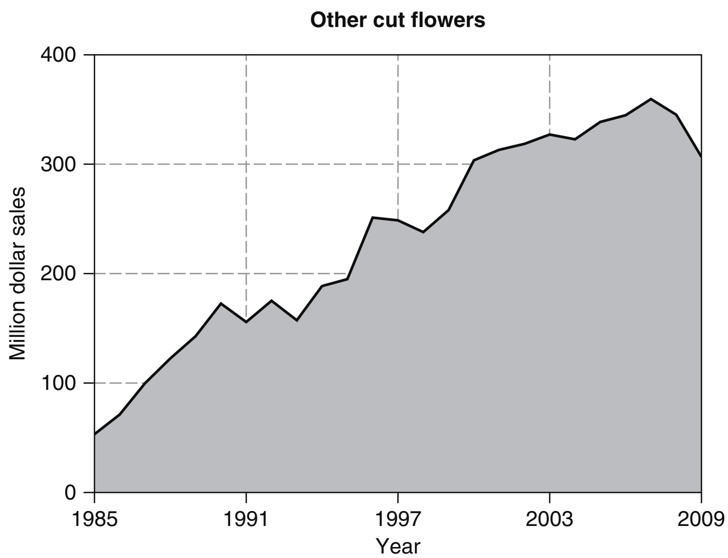


Figure 10
Wholesale value of "other" cut flowers (all cut flowers except carnation, chrysanthemum, gladiolus, and rose) produced in the United States from 1985 through 2009.
(From Agricultural Statistics Board, USDA, 1986 through 2010. Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695.)

a list of cut-flower crops imported into the United States). Thus, crops that served to prevent a downtrend in production during the 1980s now faced strong competition during the early 1990s.

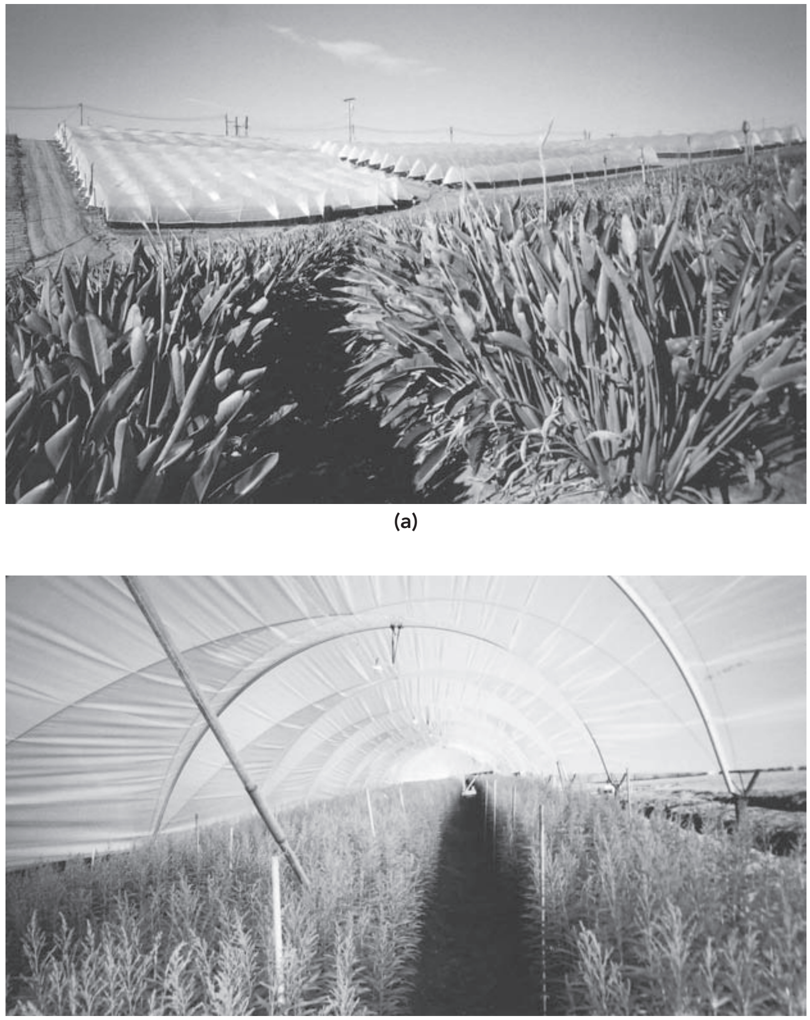
From 1993 through 2007, production of cut flowers was relatively constant. This was not due to the mainline flowers such as carnation, chrysanthemum, and rose since they continued to decline in domestic production. The offsetting factor was the rapid rise in "other" cut flowers (Figure 10). The major contributing factor within this group during the 1990s was the adoption of specialty cut-flower crops to meet the continually changing acceptance of new flowers in arrangements. Many of these crops are being grown outdoors, especially in warmer climates (Figure 11). These cut products represent annuals and perennials, herbaceous and woody forms, wild and cultivated plants, and bare as well as foliated stems. They include plants

Table 6
Value ($1,000) and Percent of Total of Individual Cut-Flower Crops Imported into the United States in 2009 from All Countries Combined[1]

Crop	Value ($ million)	% of Total
Roses	316,804	41.3
Chrysanthemum, pompon	34,077	4.4
Chrysanthemum, standard	21,858	2.8
Carnation, standard	63,061	8.2
Carnation, miniature	12,727	1.7
Alstroemeria	49,047	6.4
Lilies	28,748	3.7
Gypsophila	18,031	2.4
Orchid, dendrobium	5,988	0.8
Orchid, other	5,336	0.7
Snapdragon	1,813	0.2
Anthurium	132	0.0
Other cut flower and buds	210,104	27.4
Total	**767,726**	

[1]From Foreign Agr. Service (2010).

Figure 11
A few of the more than 45 specialty cut-flower crops grown outdoors and in polyethylene hoop greenhouses at Mellano & Company, San Luis Rey, California. (a) Bird-of-paradise flowers in the foreground and blocks of hoop greenhouses in the background. (b) Solidago flowers growing in an unheated hoop greenhouse.



(a)

(b)

such as *Achillea,* ageratum, aster, *Aquilegia,* banksia, calendula, carnations from the garden cultivars, *Carthamus, Celosia,* cosmos, *Craspedia,* delphinium, dill, *Echinacea, Eryngium,* fruit branches, godetia, *Gomphrena,* heather, hypericum, kalanchoe, larkspur, leucadendron, *Lisianthus, Lupinus,* ranunculus, rudbeckia, sedum, star of Bethlehem, smilax, statice, strawflower, sunflower, sweet William, tuberose, verbena, veronica, waxflower, wheat, and yarrow. This list is not nearly complete since more than 100 plant taxa are extensively grown for cut production. The optimism in such a list lies in the large number of potential plants not yet commercialized and in the wide range of climatic conditions required for growth. In the future, growers in all regions should be able to find crops well adapted to their conditions. Success for a given cut-flower grower located within the major market regions of the world depends on adopting crops that are efficiently grown in that area and are expensive to ship from distant sources due to factors such as weight. Gladiolus is a good example of this latter point. Evidence that there are cut flowers that offer an advantage to growers in the United States is seen in the figures for exported cut flowers and greens from the United States to other countries (Table 7). In 2008, the total value of cut flower and greens exports was $225 million. Major recipient countries were Canada (52.5 percent), The Netherlands (14.2 percent), Belgium (8.2 percent), Mexico (5.6 percent), Germany (2.4 percent), and Japan (1.7 percent). Market destinations were located on most continents.

Table 7
VALUE ($1,000) OF CUT FLOWERS EXPORTED FROM THE UNITED STATES IN 2008 TO RECIPIENT COUNTRIES[1]

Recipient Region/Country	Value ($1,000)	Recipient Region/Country	Value ($1,000)
North America		**Asia/Pacific**	
Canada	107,335	Japan	5,773
Europe		Australia	546
Netherlands	47,003	China	423
Belgium	27,553	Hong Kong	364
Germany	7,773	New Zealand	322
United Kingdom	987	Korea, South	245
France	327	Singapore	234
Latin America		**Middle East**	
Mexico	18,455	Saudi Arabia	2,170
Brazil	288	United Arab Emirates	1,780
Venezuela	272	Kuwait	937
Columbia	181	Qatar	527
		Others	**1,393**
		World Total	**224,888**

[1]Agricultural Statistics Board, USDA (2010).

The decline in the graphs after 2006 for total and other cut flowers in Figures 10 and 11 was due in great part to the switch from 36 states surveyed to 15 states by the Agricultural Statistics Board and to a lesser degree to the faltering world economy.

The import competition felt in the cut-flower arena in the United States has had its counterparts in Europe and Japan. Within Europe, a large increase occurred in the production of cut flowers in the warmer southern countries of Spain, France, and Italy. Also, flowers are now being imported from Africa, the Middle East, Asia, and South America. Listed in Table 8 are the countries exporting flowers to the European Union (EU) countries and in Table 9 the countries exporting to Japan. These changes are similar to the shifts in the United States, first to southern fields, then to greenhouses in Colorado and California, and finally to foreign imports.

Flower imports originate primarily from parts of the world along established trade routes. Africa, the Middle East, and Asia are the likely origins of floral imports into Western Europe because of the established trade between these parts of the world. Similarly, North America and South America are logical trade partners. Trading partners for Japan are mainly the countries of Asia and the Pacific. Well-established means of transportation exist along each of these routes. The cost of shipping in these channels is inexpensive relative to shipping between parts of the world in different channels. While there are well-established trade channels between Japan and the United States, as well as Europe and the United States, the United States receives almost no imports from Japan and only 7.9 percent of its cut-flower imports from Europe (see Table 4). One important reason is that production and marketing costs do not vary enough between these areas to offset the shipping costs. Labor is expensive in both areas, and energy inputs are high.

This does not mean that no imports will travel along these channels. There are always niche markets. For instance, the United States imports proteas from South Africa,

Table 8
COUNTRIES EXPORTING TO THE EUROPEAN UNION COUNTRIES AND THE VALUE ($1,000) OF CUT FLOWERS AND PLANTS THEY EXPORTED IN 2008[1]

Exporting Region/Country	Value ($1,000)	Exporting Region/Country	Value ($1,000)
Africa	**783,281**	Peru	3,390
Kenya	516,817	Chile	2,386
Ethiopia	97,841	Brazil	1,793
Uganda	63,542	Mexico	1,006
Zimbabwe	27,626	**Middle East Asia**	**105,471**
Zambia	25,034	Israel	92,140
South Africa	20,831	Turkey	13,331
Tanzania	16,717	**Asia**	**41,193**
Morocco	4,843	Thailand	31,718
Ivory Coast	4,380	India	3,796
Egypt	2,895	Taiwan	3,470
Cameroon	1,446	Malaysia	2,209
Mauritius	1,309		
Latin America	**371,582**	**Others**	**3,410**
Ecuador	184,325	Australia	1,483
Colombia	174,462	New Zealand	1,927
Costa Rico	4,220		
		World Total	**1,304,937**

[1]From AIPH (2009).

cut bulb crops from The Netherlands, and orchids from Thailand and Taiwan because each of these countries has production advantages not yet found in the Latin American countries that are our trading partners. Likewise, Japan imports roses from Ecuador because of their exceptional quality.

Table 9
VALUE OF CUT FLOWERS AND FLOWER BUDS ($1,000) IMPORTED INTO JAPAN IN 2001 FROM COUNTRIES EXPORTING $300,000 OR MORE[1]

Exporting Region/Country	Value ($1,000)	Exporting Region/Country	Value ($1,000)
Asia/Pacific		**South America**	
Thailand	24,063	Colombia	14,262
Korea, South	19,416	Ecuador	1,810
New Zealand	17,556	**Africa**	
Taipei, Chinese	9,671	Mauritius	1,955
Malaysia	9,030	South Africa	1,880
Australia	6,121	Kenya	1,780
Singapore	5,588	Zimbabwe	706
India	2,386	**North America**	
Vietnam	2,135	United States	2,484
China	1,006	**Middle East**	
Sri Lanka	560	Turkey	821
Europe		Israel	541
Netherlands	24,863		
Italy	861	**World Total**	**149,495**

[1]From AIPH (2009).

Foliage Plants

Foliage plants, also commonly referred to as green plants, are plants sold in a pot and valued more for their foliage than for their flowers. Foliage plants made up 10.9 percent of U.S. floral production in 2009. They include philodendrons, dracena, ficus, croton, ferns, a wide range of hanging-basket plants, and many others. The size of this crop was very stable through 1970, with a wholesale value of about $25 million. After that, it exploded to a value of $282 million in 1978 (Figure 12). The area in production expanded 308 percent from 1968 through 1978, while the wholesale value increased 968 percent! In 1978, the market began to saturate, prices leveled off, and many marginally efficient producers perished. This stress fostered change through the surviving innovative growers. Attention to quality, acclimatization of plants to better guarantee their survival in the consumer environment, and sensitivity to the changing desires of the consuming public for smaller as well as larger pot sizes and new crops all led to increases in demand for the years 1980 through 1985. The wholesale value climbed to $508 million in 1985. In 1986, the foliage-plant industry entered another period of adjustment. One contributing factor was the large number of growers who were attracted to this commodity by the former boom period (see Table 5). As marginal growers dropped out over the next decade, the larger, more efficient growers survived. They brought about a new wave of innovation resulting in an increase in production through 2005. The decline after that is related in great measure to the world recession. The decrease in number of states surveyed from 36 to 15 after 2005 played a lesser role since the main production states, Florida and California, were included in both surveys.

Of the U.S. production value of foliage plants in the top 15 states, 68.5 percent were grown in Florida, 19.0 percent in California, and 2.6 percent in North Carolina, in 2009. These are the three leading states in production. Many of the foliage plants are of tropical origin and can be produced more economically in subtropical areas.

Northern areas, where heated greenhouses are required, have found a future in foliage plants, although it is more modest than that of the subtropical regions. Premium hanging-basket plants, being large in volume and cumbersome to handle, are expensive to ship. They are best grown close to their terminal markets. The production costs of hanging-basket plants are low, since many of the fixed costs such as greenhouse depreciation and heat are shared with another crop on the benches or the ground below. Hanging baskets offer a means for utilizing nearly 100 percent of the equivalent floor space of a greenhouse (Figure 13).

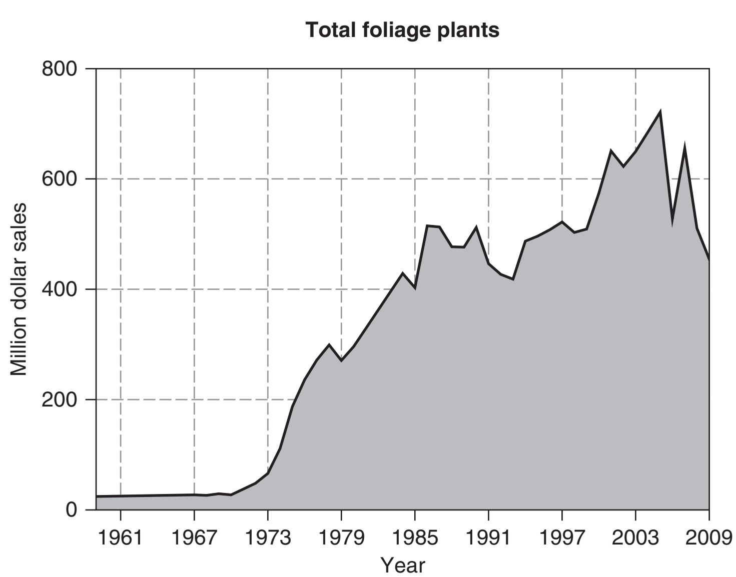


Figure 12
Wholesale value of foliage plants produced in the United States from 1959 through 2009.
(From Agricultural Statistics Board, USDA, 1960 through 2010. Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695.)

Figure 13
The expense involved in producing hanging-basket plants is shared with other crops, since the baskets occupy space over the walks not formerly used. It is possible to achieve 100 percent utilization of the equivalent floor area of a greenhouse with such a production program.

Many greenhouse enterprises in temperate regions purchase foliage plants in the final stage of development from the subtropical regions and hold them in their greenhouses until they can sell them to the network of retail outlets they service. Other foliage-plant crops are purchased in various intermediate stages of development and are grown to the finished market stage in the temperate-region greenhouses.

The rapid rise in foliage-plant sales began in 1972, one year after cut-flower imports began their rapid ascent. Further, one of the two major cut-flower production scenarios initially stressed by imports was field production in Florida, California, and Texas. The demise of one production segment within the same geographic area in which the rise of a second segment took place presented an opportunity for some growers. These were growers who realized what was happening and had the fortitude to change.

Flowering Potted Plants

The principal flowering potted plants grown in the United States are listed in Table 10. The production value of this group of crops increased at a rapid pace until 1990 and at a slower pace until 2005 (Figure 14a). Flowering potted plants made up 24.3

Table 10
Flowering Potted-Plant Crops Grown in the Top 15 States in the United States in 2009 Along with Their Wholesale Value and Percentage of the Total[1]

Crop	Value ($ million)	% of Total
Orchid	159.6	25.2
Poinsettia	145.1	22.9
Spring flowering bulbs	46.7	7.4
Florists' azalea	32.2	5.1
Easter lily	27.3	4.3
Chrysanthemum	25.0	4.0
Rose	25.2	4.0
African violet	3.6	0.6
All others	167.7	26.5
Total	**632.4**	**100.0**

[1]From Agricultural Statistics Board, USDA (2010).

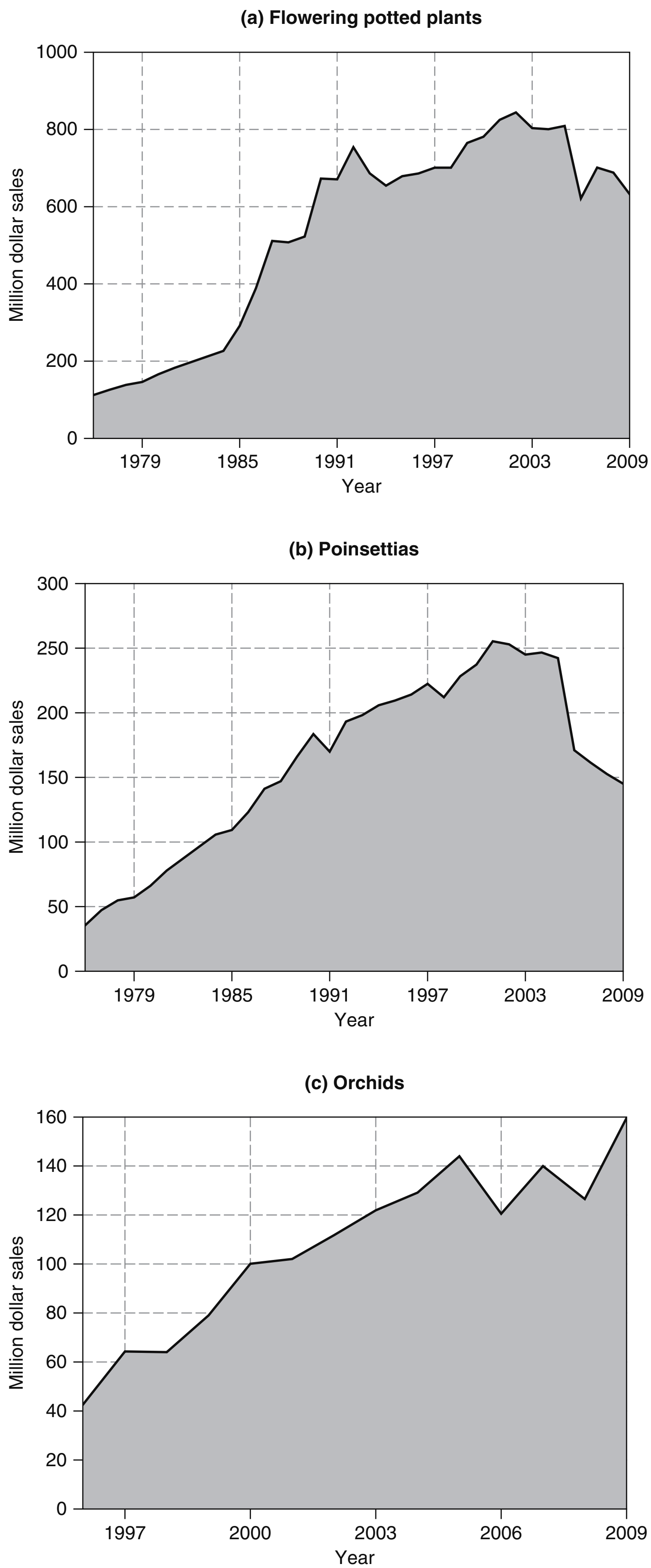


Figure 14
Wholesale production of (a) all flowering pot crops, (b) poinsettias from 1976 through 2009, and (c) pot orchids from 1996 through 2009 in the United States.

(From Agricultural Statistics Board, USDA, 1977 through 2010. Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695.)

percent of the value of U.S. floral production in 1990 and 15.9 percent in 2005. Although the percentage of total floral production in the United States represented by flowering potted plants declined through 2005, the actual value of this group increased. The decline in rank of flowering potted plants was due to the disproportionately high increase in bedding-plant production.

The long, steady increase in production up to 1990 was due to several factors: an increase in consumer demand for the traditional plants; a renewed interest in crops that had waned during the middle of the 20th century, including calceolaria, cineraria, cyclamen, and kalanchoe; and acceptance of new crops such as *Clerodendron,* exacum, gerbera, and Rieger begonia. Many of these crops were not new to Europe, where a much wider variety of plants are grown commercially.

The lower rate of growth of the flowering potted-plant group since 1990 is due in large part to consumer tastes and also to importation of flowering potted plants. The number of pot mums and poinsettias imported in 2009 were 5.5 and 1.8 million, respectively. This was equivalent to 73 and 5 percent of the number of these two crops produced in the 15 top production states. Most of these came from Canada. Production of the second most valuable crop, poinsettia, has kept pace with the total value of the group (Figure 14b). The most striking shift within this group of plants has been the phenomenal rise in value of pot orchids (Figure 14c). Statistics have been collected only since 1996. From 1996 through 2005, wholesale value increased by nearly 335 percent, from $43 to $144 million. Today, the pot orchid is the largest crop within this group.

The future still looks optimistic for flowering potted-plant production. However, one must look carefully at the trends of individual crops. The decline in pot chrysanthemum production and increase in orchid production are two good examples. Another concern is that of tariffs and quarantines. The North American Free Trade Agreement (NAFTA) of 1994 is in effect today. It allows shipment of ornamental plant products duty-free to the United States from Canada and Mexico. Since it is a reciprocal agreement, it also allows the United States to ship duty-free to these countries. Quarantine 37, which takes its name from section 7 CFR 319.37 of the Code of Federal Regulations governing import of "plants for planting," is aimed at preventing the influx of disease and insect problems. However, it has inadvertently been an impediment to the import of potted plants. Quarantine 37 specifies crops, countries of origin, and root substrate that are not allowed to be imported into the United States. Soil and sand are among the components that cannot be imported. The list of crops that can be imported from Canada is extensive. But, from other countries, it is very restrictive. Additional exemptions are being sought by European, Latin American, and Japanese producers. If granted, Mexico's geographic position will permit effective truck transport of potted plants to markets in the southern portions of the United States. An amendment of Quarantine 37 is currently under consideration that would make it more restrictive.

It was possible for cut-flower growers to shift to foliage plants, flowering potted plants, and bedding plants when import competition increased. There are no remaining areas of floral production for the potted-plant producers to shift into. It becomes ever more important for domestic growers to increase their production and marketing efficiency. In short, we are moving steadily toward a single international floriculture industry in which production of each commodity category will go to the group of growers that can best manage costs.

Bedding Plants

Bedding plants are a unique group of plants (Figure 15). Over 100 plant species are grown. The bedding-plant group includes annual and perennial floral plants as well as vegetable plants in flats and small pots for planting in the garden, hanging bas-

Figure 15
A bedding-plant crop at Rockwell Farms, Rockwell, North Carolina.

kets and bowls of single or mixed species flowering plants, geraniums from seeds or cuttings in flats and pots, and hardy garden chrysanthemums. The wholesale value of bedding-plant production in the United States in 1990, 2000, and 2005 was \$1.0, 2.2, and 2.6 billion, respectively. This represented 35, 50, and 51 percent of total floral production (Figure 16). During that period, it was the largest and fastest-growing segment of floral production. Since 2005, bedding plants have held the same share of total production. Bedding plants have provided an opportunity for growers forced out of cut-flower and foliage-plant production in the United States, Europe, and Japan. The future looks excellent for bedding plants.

A significant change in greenhouse technology during the past 20 years has been the production of seedlings as *plugs*. While this method of production is used extensively in the bedding-plant industry, it is not restricted to it. Within the floral industry, a number of cut-flower, foliage-plant, flowering potted-plant, cut greens, and field vegetable crops are also established this way. In this system, seeds are mechanically sown in trays containing from less than 100 to more than 800 small cells. One plant is produced in each cell, as opposed to broadcasting seed in an open flat and later digging the seedlings out for transplanting. Customarily, plug seedlings

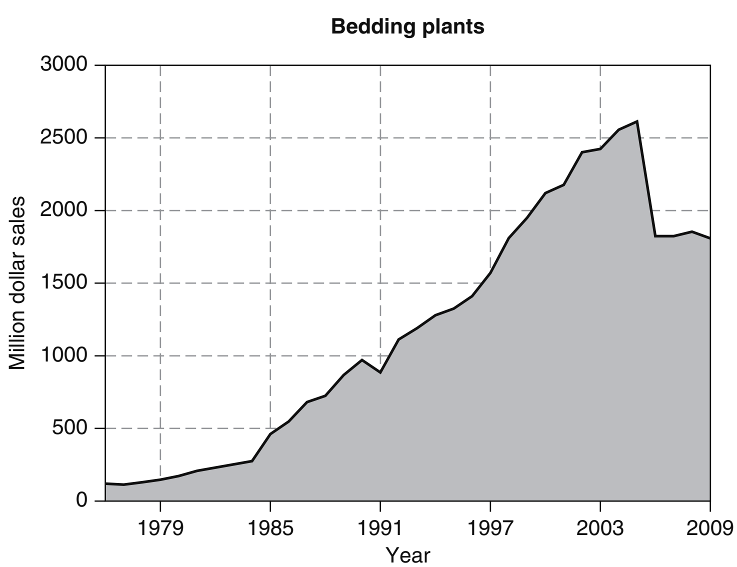


Figure 16
Wholesale value of bedding plants produced in the United States from 1976 through 2009.

(From Agricultural Statistics Board, USDA, 1977 through 2010. Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695.)

are germinated in ideally controlled growth rooms. From there, the plug trays are moved to the greenhouse, where they remain at a high density for several more weeks, depending upon the plant species. Automatic spray booms deliver water and fertilizer, and again conditions are idealized for this second stage of growth. Such plug seedlings may be used by their propagator or sold to smaller firms that cannot justify the cost of equipment and facilities for producing plugs. The highest labor input into bedding-plant production is the transplanting of seedlings. Mechanical transplanters are available that will remove plug seedlings from trays and plant them into flats that have been automatically filled with root substrate.

Plug technology is equally well suited to cutting propagation. Trays with larger cells, 50, 100, or more cells per tray, are used. Cuttings are rooted in the cells and carried forward under similar conditions to those used for seedling propagation.

Plug technology is revolutionizing the bedding-plant industry and greatly aiding growers of cut-flower as well as flowering and foliage potted-plant crops that are propagated from seed or cutting. The advantages include lower overhead costs (because the young plants can be held at high densities for a considerable time); a better chance to establish ideal cultural conditions during the early stages of growth for the purpose of reducing crop time; less transplanting shock, which leads to faster finish-plant production; and reduction in sowing and transplanting labor. An equally great advantage that plug technology has brought to the floral industry is the door that has been opened to other plant industries. Most tobacco seedlings, many forest-tree seedlings, and numerous vegetable seedlings for commercial outdoor production are now produced by plug technology.

As with most technological advancement, the firms that first adopt it are able to translate the advantage into large profits. As the technology is more widely adopted, the savings are passed on to the consumer in terms of lower prices. This stems from those producers who are trying to gain a greater local market share by lowering their prices below those of their competitors. After this point is reached, the remaining producers must adopt the technology simply to maintain their current profitability. Individuals entering the bedding-plant field should study the currently changing plug technology in order to assimilate it into their businesses.

WORLD PRODUCTION

Floral markets grow with the economic development of a nation, its population, and its trend toward urbanization. Throughout the 19th and much of the 20th centuries, production of containerized floral plants and cut flowers grew to meet market demand in the developed nations of the world. Then, in the latter part of the 20th century, a major production shift took place. In the early 1970s, Israel began to produce cut flowers for export to Europe, particularly The Netherlands. This expansion in production was fostered by governmental support for a marketing and shipping system. It was further aided by duty-free import concessions from some European nations, including The Netherlands and Germany, until 1985 and thereafter by duties only charged for excess shipment above a threshold or on flowers selling for below-average prices. During the early 1970s, Colombia and Costa Rica in South and Central America began to develop cut-flower production industries for exporting to the United States, while Ivory Coast and Kenya developed production for export to Western Europe. With time, the list of countries with sizeable exports grew to include Brazil, Colombia, Ecuador, Costa Rica, Guatemala, and Mexico in Latin America; Ethiopia, Kenya, Zimbabwe, South Africa, Zambia, Uganda, and Morocco in Africa; Israel and Turkey in the Middle East; and China, Thailand, and Taiwan in Asia. These countries export primarily cut flowers and cut foliage. Although the

Latin American countries export most heavily to the United States and Canada, some of their product also goes to Europe (see Tables 4, 8, and 9). The African and Middle Eastern nations send most of their floral products to Europe. Thailand and Taiwan are major sources of cut and pot orchids for the entire world. Newly emerging floral exporting nations in Southeast Asia direct most of their exports to Japan. See Table 1 for the value of floral production and number of production firms in 47 important floral-producing countries.

These exporting countries have been able to penetrate the Western European, U.S., and Japanese floral markets through reduced costs of production compared to producers in the market countries and, in some cases, through higher floral quality. Their higher shipping costs are more than offset by lower production labor and/or energy costs. Crops in these countries are mostly grown in unheated shade or polyethylene greenhouses or in minimally heated greenhouses. Natural cooling is typically used.

One would think that every developing nation with favorable conditions for floral production would soon enter this industry. However, that is not the case. To support such an industry, a country must have a suitable infrastructure that includes the following. Climatic factors, including temperature, humidity, light intensity, and day length, must be suitable for the crops to be grown. Unless quality can equal or exceed that expected in the market, it will be very difficult to succeed. Lower quality commands a lower price. This must be compensated by lower production costs, since transportation cost is already high for most developing nations. High temperatures, particularly at night, and high humidity in Uganda preclude the production of carnations and are currently challenging its hybrid tea rose industry. Tropical crops would make more sense in that setting.

There needs to be social stability. Land redistribution occurring in parts of Africa today discourages long-term investment in production. Credit must be available locally for financing businesses. The terms must be sufficiently long to cover a reasonable return on investment to meet the obligation. An international airport needs to be in close proximity to the production area. This airport must have cooling facilities and personnel with flower handling expertise. Frequent flights need to be available to market destinations such as Frankfurt and Amsterdam in Europe or Miami, Los Angeles, New York, and Chicago in the United States. There must be adequate cargo space on these flights. Finally, air freight rates must be competitive with those in competing export nations. Roads to the airport play an important role. In countries where roads are unpaved or poorly maintained, flower quality can be lost due to bruising and excessive delivery time.

Utilities play an integral role in profitability. An interrupted electrical supply reduces the feasibility of automation and wreaks havoc with cooling of the product after harvest. Continuous telecommunications are imperative for procurement of supplies and marketing. Reduced irrigation water quality, due to the presence of pathogens, alkalinity, or salts, requires expensive corrective procedures or else takes its toll on yield and quality. The availability and price of material inputs are important. The best situation is one in which materials such as fertilizers, pesticides, and polyethylene are domestically produced. This is rarely the case. Many nations will place high import tariffs on these goods in an attempt to control outflow of currency from the nation.

Low labor cost and plentiful supply is important because in many developing nations this offsets a lack of automation and shipping costs. In some African nations, AIDS has decimated the labor force, making it difficult to procure sufficient workers. The length of the official work week can create problems. The 44-hour work week in Colombia is an advantage over the 40-hour week in Ecuador or the 35-hour week in France. With a shorter week, more workers are required, and with that factor comes a greater difficulty to find them and a higher management cost. Technical support undergirds the development of a floral production industry. It can be a source of political, production, and marketing information crucial to the system. Technical support has several faces, including a university to generate trained management and locally focused technical information, grower and marketing associations, and a critical mass of production and marketing materials suppliers with the capability to serve as a conduit of information from the rest of the world.

International policies, in addition to the previously mentioned infrastructural factors, have also played a role in the emergence of flower exporting nations. As mentioned earlier, Israel enjoyed a trade concession with Europe. In 1991, the United States set up the Andean Trade Preference Act, which exempted cut flowers from U.S. import tariffs for countries located along the Andes Mountains in South America, including Colombia, Ecuador, Bolivia, and Peru. This act was later amended as it became the Andean Trade Preference and Drug Eradication Act (ATPDEA). It currently allows flowers to come into the United States from Colombia, Ecuador, and Peru duty-free. The former 71 African, Caribbean, and Pacific colonies of European countries were formerly covered by the Lome Agreement, which provided them with duty-free access to the EU countries. Other countries paid a tariff of 12 percent during the summer and 7.5 percent during the winter. Countries exporting to Russia paid a year-round 25 percent tariff, with the exception of developing nations, which paid only 12 percent. The Lome Agreement has been replaced by the Cotonou Agreement, which continues the tariff concessions for shipment to the EU nations from 79 countries in Africa, the Caribbean, and the Pacific.

The global shift in floral production still continues. The next nations that will expand rapidly in floral exports appear to be Chile, Guatemala, and Mexico in Latin America and China and India in Asia. Chile, located along the west coast of South America, extends about 2,700 miles (4,300 km) north from the southern tip of the continent. This encompasses a wide range of climates suitable for many crops. An additional asset is its location in the Southern Hemisphere, which permits Chile to produce crops such as spring flowering bulbs and flowers during off seasons in the Northern Hemisphere. Even more important is the infrastructure that has been developed in Chile for handling and exporting fruits and vegetables to North America. This and available cargo space on airliners bound for the United States make floral export very feasible. Recent relaxation of the trucking rules from Mexico to the United States opens up an opportunity for truck transport of cut flowers and potted plants to the United States. Before this can be fully realized, however, improvements must be made in the floral handling infrastructure in Mexico. U.S. and European firms have invested heavily in young plant propagation facilities in Guatemala. Supported by low production costs and high quality, this business has grown rapidly. A sizeable flower production industry already exists in China. In 1997, it encompassed about 22,000 acres (8,800 ha). The center of the production industry is in the southern province of Yunnan. The Yunnan government cooperated with the Yunnan Flower Association in the construction of a major flower wholesale market in Kunming. At this point in time, most of China's floral production is consumed within the country. In 1999, only 10 percent was exported. With China's economic growth and consumer demand, this figure is still a good estimate. Korea has invested heavily in its governmental and academic horticulture programs. These support an industry that includes over 10,000 growers producing floral crops on 12,500 acres (5,000 ha). With a wholesale value of $515 million in 2000, Korea is the third largest producer in Asia.

FLORAL MARKETING

We have just seen that changes in flower production have been phenomenal during recent times. Within developed market countries, cut-flower production of the old standard crops has either ceased or become exceptionally efficient. Where the traditional cut-flower crops have ceased, new crops never imagined possible in earlier times, such as wild flowers, garden annuals and perennials, woody stems, grains, and vegetables, have taken their place. Numerous new potted crops have appeared. Many developing nations have entered into floral production and are currently producing a significant proportion of the world's cut flowers. All of these changes have been driven by changes in marketing both nationally and internationally. To understand the production changes, we must first understand the marketing changes.

Until 1960, virtually all floral products moved through full-service flower shops. These shops provided floral arranging, delivery, and credit. Price markup was fairly significant. Studies showed that 85 percent of sales were for weddings, funerals, and major holiday purchases of flowers such as Easter lilies and poinsettias. Other than for these purposes, only about 25 percent of the public purchased flowers on a routine basis. Then, during the mid- to late 1960s, floral mass-market channels in supermarkets, discount stores, and street corners (Figure 17) began to develop. It was a painful process that involved boycotts of some growers who sold to the new market. But the change was inevitable. In the end, the mass market achieved a number of positive changes for floral marketing. A significant portion of the 75 percent of the public who did not purchase routinely from full-service florists were now purchasing flowers on an impulse basis. The new customers were not nearly as tradition bound and were open to new potted plant and cut-flower types, new floral arrangement styles, and a wider range of colors. This opened up new possibilities for growers. It came at a very fortuitous time, when imported flowers were forcing many growers to shut down or change. With time, the boundary between full-service florists and mass-market outlets blurred to a degree. The former offered simpler floral bouquets in addition to arrangements, sold individual flowers by the stem, included smaller plants in the line of potted plants, relocated to higher pedestrian traffic areas, and embraced a higher degree of self-service.

During this transition in the early 1970s, imported cut flowers appeared on the scene. This force was even more painful and brought about a package of changes for the grower. Large numbers of cut-flower growers had to shift to growing flowering

Figure 17
This street-side outlet for cut flowers in San Francisco is one of the forms mass marketing has taken. Others include no-service cash-and-carry shops in supermarkets, airports, and shopping malls.

(Photo courtesy of J. C. Raulston, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.)

potted plants, foliage plants, and bedding plants. Fortunately, development of the mass market as well as the green movement of the 1970s increased the demand for these container plants. Among the flowers exported to the United States were a number of flower species that were new to florists, including liatris, alstroemeria, and colored lilies. The new customers of the mass market were not tradition steeped and rapidly accepted these. The new flowers brought with them new colors and shapes that translated into new floral arrangement forms. This synergy supported increased demand. While it was not economically feasible for most cut-flower growers to grow the traditional cut flowers due to declining prices, it was possible to grow some of the new crops. From this point on, it became a chase for the cut-flower growers. As the market accepted new species, domestic growers incorporated them into their production schemes. Then exporting nations saw the potential and likewise adopted these crops. With increased supply, prices declined and domestic growers shifted from these new crops to yet newer crops as the market continued to accept more new crops.

The changes in marketing and production in North America had their counterparts in Europe and Japan. In addition to the major trade patterns of Africa and the Middle East supplying Europe, and Southeast Asia, New Zealand, and Australia supplying Japan, some crossing over between these trade partners has developed. South Africa supplies proteas and Thailand and Taiwan supply orchids to the world. Dutch cut flowers are likewise shipped worldwide. South America ships cut flowers to Europe, although far fewer than are shipped to the United States. To expedite this worldwide movement of flowers, a central system has emerged. The crossroad for this market system is the Dutch auctions and wholesalers. During 2008, the value of flowers and plants exported from The Netherlands was $6.4 billion. This was 40 percent of the total $16 billion value of flowers and plants exported by every country in the world. To understand how the system works, let's trace an order for cut flowers placed by a retail florist in Omaha, Nebraska. Wholesaler A in Omaha takes the order and transmits part of it to wholesaler B in The Netherlands. Wholesaler B purchases miniature gladiolus and lisianthus from a Dutch auction. The gladioli originated in Israel, and the lisianthus were locally grown in The Netherlands. Wholesaler B also places orders through its branch or affiliate wholesalers in South Africa for proteas and in Thailand for orchids. Wholesaler A sends a second portion of the original order to an importer in Miami, requesting carnations and roses that originate in Colombia and Ecuador, respectively. A third part of the original order is sent to a wholesaler in Vancouver, Canada, for cut gerberas. The final part of the original order is placed with a local grower for cut Asiatic lilies. Flowers are then shipped from either the auction or their originating countries to wholesaler A in Omaha, who gathers them together and delivers them to the retail florist. This single order represents flowers produced in eight countries located on five continents and has engaged the services of four wholesalers, a Miami importer, exporters in each originating country, and additional importers in The Netherlands and the United States. Unless this florist thinks about it, he or she could easily assume that all of these flowers came from a domestic source. In order to guarantee the satisfaction of the final consumer, these transactions need to occur within 48 hours, or if longer, the flowers need to be under refrigeration throughout their journey.

In recent years, there has been a feeling that the world market for flowers was nearing saturation. This has come to pass with the world recession. It is therefore imperative that new demand be stimulated. A number of strong possibilities exist for accomplishing this.

Several countries in recent years have experienced changes that are stimulating attractive market growth. The former communist countries of eastern Europe and Russia currently have the fastest-growing floral markets in the world. Korea, China, and India are each experiencing moderate growth in their floral markets that is not being met by domestic production. Within Latin America, Brazil and Mexico are both enjoying expanding floral markets. With proper attention to local civic and religious celebration traditions as well as color and plant preferences, these markets can be nurtured. This would help offset the waning markets in the developed market countries.

More can also be done to stimulate additional growth in the developed markets of North America, Western Europe, and Japan. Too little support goes into generic promotion of floral products by the floral industry. Although exact figures are not available, estimates place this investment at well below 1 percent of retail sales. Recent promotional investments have returned phenomenal dividends. If all components of the floral industry could come together and support a reasonable level of promotion, impressive increases in the demand for floral products would ensue. Only 55 percent of households in the United States purchased floral products in 2005. There are still many more consumers to be reached.

Equally important to funding promotional programs is the vision of where potential markets exist. The U.S. Federal Reserve Board indicates that the over-50 age group constitutes 35 percent of the population, controls 77 percent of the nation's financial holdings, and accounts for 42 percent of the after-tax income. This segment has considerable resources to purchase floral products. But these purchases will reflect the age of the group. A situation that baby boomers and younger people share is lack of time. Outlets must be quickly accessible, near the workplace or in established shopping areas. The population is much more individualistic in its choice of products and places less value on product or company loyalty than in the past. This opens up the door for continual change in types of plants or arrangements, sizes, colors, and end uses of the purchases. In recent years, there has been a rapid acceptance by consumers for arrangements of plants rather than individual species of plants in hanging baskets, patio pots, color bowls, etc. Many new potted-plant and cut-flower types have been introduced in recent years. This trend needs to continue.

PRODUCTION OPPORTUNITIES IN DEVELOPED MARKET COUNTRIES

Small Growers

Small growers will always have a place in the floral industry. Niches that can best be handled by these growers include superior quality, new crop introductions, low-volume specialty crops, integration of production and retailing, and education. It is imperative to provide the level of quality sought in a given market. But the level of quality sought varies in different markets. Most people purchasing standard chrysanthemums for an arrangement in their home would be satisfied with 5-inch (13-cm)-diameter blooms. While they would accept larger blooms for the same price, they probably would not pay extra for them. The 5-inch bloom meets their perceived need, given the dimensions of the room in which they will display these flowers. On the other hand, a five-star hotel ordering flowers for its lobby perceives a need for larger flowers and expects to pay more. Beyond a given point, increases in quality are met with diminishing demand. It is difficult for large production firms to offer ultra-high-quality levels. Chrysanthemums, for example, require a longer growing time and greater space allocation. A small grower is better positioned to meet the smaller demands for high quality.

A period of time is required to develop the full market potential after a new crop is introduced. The demand during this developmental stage is too small to lend itself to the high level of automated production required by larger firms. This window of time offers an advantage for small growers because it is often possible to command higher prices than will be possible later when the market is saturated. Within the cut-flower category, numerous new introductions are possible if one simply looks at the availability of annual and perennial flowers, vegetables, and wild plants. Examples of container plant innovations that have come along recently include orchids, herbs for production in the kitchen, and container gardens. Given time, plants with large market potential will be adopted by the larger domestic growers and then will probably shift to the developing floral export countries.

A number of specialty crops have a small demand even after the market potential has been met. Since it is difficult for a large grower to produce large numbers of low-volume crops, these crops are best left to the small growers. Such crops could include bonsai plants, terrarium plants, aquatic plants for fish tanks, plants with unusual fragrances, rare plants for plant collectors, and collections of a given category of plant such as begonia, geranium, or carnivorous plants.

Integration of production and retailing is another vehicle that small growers can use to carve out a niche for themselves. Value can be added to greenhouse products in several ways that would support higher sales prices. Many people have never been in a production greenhouse and would enjoy the experience enough to consider it an outing. Pick-your-own cut flowers would afford customers an opportunity to put their own bouquets together. To foster such a cut-flower program, a point might be given for each dollar spent. A given number of points would entitle the customer to a class in floral design. Classes in houseplant care as well as outdoor gardening and design would stimulate potted-plant and bedding-plant purchases. Other enticements sometimes found in production/retail greenhouses include free consultation, root substrate, fertilizer solutions, or repotting. Each of these services can translate into higher sales prices above the retail market average.

Large Growers

Large production firms will continue to gain a greater proportion of the market for main crops, at the expense of midsize growers. These crops include flowering potted plants such as Easter lilies, geraniums, gloxinia, poinsettias, pot mums, the principal bedding-plant annual and perennial species, and major foliage-plant crops. These firms will continue to become larger to justify more automation to lower production costs and to become more efficient in marketing.

Midsize Growers

Midsize growers are in the most difficult situation. Their production level of the main crops does not lend itself to the levels of automation possible for the large growers, and many small niche items enjoyed by the small growers may not provide the required revenue for their business scale.

However, midsize growers should be in a good position to service traditional florists. The sizes of orders delivered to each florist are small compared to deliveries to discount stores. Large trailer trucks often cannot be accommodated at florist shops, yet these trucks are mandatory for the level of marketing economy required of large producers. The cost of marketing is higher to traditional florists than to the mass market, and the selling price is generally higher. The economics of this situation do not suit the large grower very well.

Cooperative arrangements among several midsize growers are another option. In such arrangements, each grower could specialize in a given crop or category of crops. The larger quantity of each crop grown would foster automation and lower production costs. Marketing could be carried out more efficiently by a single department representing all growers in the cooperative.

Midsize growers marketing to the mass market will have to be extremely efficient. Analysis of production and marketing costs will be essential. Crops that return a profit should be increased, and those that do not could be purchased in the finished stage for satisfying customer demand. Another option to consider is the purchase of prefinished plants from other larger growers. These plants are grown to an intermediate stage by one grower and then sold to a second *finish grower*, who carries them through their final stage of production. An example would be pot mums that have received supplemental long-day treatment, have been pinched, have been treated with a chemical height retardant, and are ready for the final stage of production at a cooler temperature. Another example would be bedding plants already transplanted into flats. In this case, the finish grower does not need to purchase seeds, root substrate, and flats, or provide the labor of transplanting, which is the greatest labor input into the production of this crop. These items are provided by a larger grower who can purchase at a much lower discounted price and can afford expensive transplanting equipment.

CAREERS IN THE GREENHOUSE INDUSTRY

The greenhouse industry offers a wide variety of career opportunities. The range of employers traverses greenhouse firms, wholesalers and retailers, floral transport lines, allied supply and facilities companies, seed and plant propagators, private and governmental associations, private and governmental extension services, high schools and universities, industrial and governmental research labs, publishers, and others. A wide mix of career interests can supplement a horticultural background, such as business, statistics, journalism, education, computer science, basic biology, and plant breeding. The world greenhouse industry has a bright future that will continue to expand as a function of economic development of countries and population growth.

Individuals interested in plant production can set their goals on conservatory management or commercial greenhouse production. Those interested in conservatory management should supplement their training in the areas of plant identification and ecology. Anyone planning a career associated with a horticultural business or an agency offering advice relative to crop production should seek additional training in business. This is very important, whether one plans to own his or her own business or to assume a management position within a firm. In either event, it is imperative that the person be capable of assisting the firm in generating profits that more than offset his or her own salary.

There are many careers in the wholesale marketing of greenhouse products. These may be found in auctions, wholesale houses, or brokerage firms around the world. Likewise, many opportunities exist in the retail channel, including florist shops, garden centers, plant departments in the various mass-market channels, or wire/web service companies. Numerous companies supply the greenhouse industry with production supplies, agricultural chemicals, seeds, plant material, computer controls, equipment, and greenhouse facilities. Many positions within these companies require knowledge of greenhouse management.

Private plant consultant firms and governmental extension services also employ people with greenhouse training. A B.S. degree is generally required for county-level extension positions, an M.S. degree for directorship of county offices, and a Ph.D. degree for statewide positions. Along these same lines of education, the teaching profession is open to individuals trained in greenhouse management. Those with a B.S. degree can teach horticulture courses in high schools. An M.S. degree is usually sufficient for teaching in technical and junior colleges, and a Ph.D. degree is the norm for teaching in universities.

The field of research offers careers as well. Graduates with B.S. degrees are often employed as research technicians for companies and governmental institutions. Research project leaders generally hold M.S. degrees in smaller companies and Ph.D. degrees in larger companies. These companies may be producers of seeds, plant material, pesticides, organisms for biological pest control, or a wide variety of other products.

Other less obvious careers include a wide array of possibilities, including plant quarantine, horticultural statistics, writing for vocational or professional magazines, and management of growers' and marketing associations.

A student should begin the process of landing a career position the day he or she begins college. The mechanism for doing this is in the fabric of a resume. Each step of the college education presents opportunities for adding lines into the resume. Join the horticulture or related club where you can network with students and faculty for a wealth of information beyond the classroom. Many of these people will become your network after college. Get active in projects in the club such as plant sales and community gardening. Pursue scholarships. Even if your grades are limited, there are scholarships based on other criteria. Seek employment during the summer in your field of interest. This can lead to a good future job reference, particularly because you will gain experience in the field you seek to enter. Attend grower field days and conferences presented at your institution or attended elsewhere by members of your faculty. Ask to travel to grower firms or conferences with the extension person at your college. If you lean toward teaching as a career, volunteer as a teaching assistant. If your institution offers a teaching certificate curriculum, sign up for it. Many students miss a big opportunity by not participating in an internship in their field. An excellent example of this is the Vic and Margaret Ball internship where the student is partnered with a nationally renowned firm for a three- to six-month apprenticeship. At the end, the student, in addition to receiving pay, is presented with up to $6,000. Most internships lead to a position with the same firm after graduation and at a salary $2,000 to $4,000 higher than would have been attained without the introduction afforded by the internship. All of above activities build the resume and speak volumes to your potential employer. Equally important, they expand your education beyond the classroom, giving you a greater chance to succeed in your profession.

Greenhouse technology and the associated business climate are changing rapidly. Unless one continues to be a student throughout his or her life, he or she will not succeed in this or any profession. This can be accomplished through reading trade literature, attending trade shows and educational seminars, visiting other greenhouses and related businesses, and building a network of colleagues. It is important that this process extends beyond greenhouse production to all fields that support it. Technical knowledge and intellect alone will not ensure success. A plan for what you want to achieve, belief in yourself, and the persistent effort you are willing to put forth are integral to achieving your goal.

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SUGGESTED READINGS

An excellent method for maintaining a perspective of the greenhouse industry is to read international and domestic trade magazines. Some key magazines are listed here.

FloraCulture International. Published monthly. Vondelstraat 162, 1054 GV Amsterdam, The Netherlands, *www.floracultureinternational.com*

Flower Tech. Published eight times per year. Reed Business bv, P.O. Box 4, 7000 BA Doetinchem, The Netherlands. E-mail: *int@reedbusiness.nl*

Greenhouse Grower. Published monthly plus two additional issues. Meister Media Worldwide, 37733 Euclid Ave., Willoughby, OH 44094, *www.greenhousegrower.com/magazine*

Greenhouse Management & Production (GMPro). Published monthly. G.I.E. Media, Inc., 4020 Kinross Lakes Parkway, Richfield, OH 44286, *www.GMProMagazine.com*

Greenhouse Product News. Published monthly. Scranton Gillette Communications, 3030 W. Salt Creek Ln., Suite 201, Arlington Heights, IL 60005-5025, *www.gpnmag.com*

GrowerTalks. Published monthly. Ball Publishing, P.O. Box 1660, W. Chicago, IL 60186, *www.growertalks.com*

Greenhouse Construction

In the United States, the term *greenhouse* refers to a structure covered with a transparent material for the purpose of admitting natural light for plant growth. The structure is usually heated artificially and differs from other growing structures, such as cold frames and hotbeds, in that it is sufficiently high to permit a person to work from within. The European definition of a greenhouse differs in that it refers to a structure that receives little or no artificial heat; the term *glasshouse* is used in Europe to refer to an artificially heated structure. Quite frequently, two or more greenhouses in one location are referred to as a *greenhouse range*. A building associated with the greenhouses that is used for storage or for operations in support of growing of plants, but is not itself used for growing plants, is referred to as a *headhouse* or *service building*. Greenhouses are to be found in many designs, including the conventional A-shaped, Quonset, and gutter-connected types. The transparent coverings are as varied as the designs. Originally, glass was used, but now film plastics, fiberglass-reinforced plastic (FRP), acrylic panels, and polycarbonate panels and sheets are used as well. The future holds promise for new covering materials that will reduce the burden of heating and cooling and also for new frame designs that will be more economical.

LOCATION

The first consideration in establishing a greenhouse range is location. Several factors to consider follow.

Room for Expansion

A parcel of land larger than the grower's immediate needs should be acquired. The ultimate size of the range should be predicted. Area should then be added to this predicted figure to accommodate service buildings, storage, access drives, and a parking lot. Additionally, extra space should be allotted to cover unforeseen needs. To meet the environmental codes of some municipalities, it is necessary to use holding ponds for water effluent from the range in order to reduce nutrient release into streams. Doubling the area covered by greenhouses would constitute a bare minimum land requirement.

The floor area of service buildings required for small firms equals about 13 percent of the greenhouse floor area. This requirement diminishes with increasing firm size, to 7.5 percent of the growing area for large firms with 400,000 square feet (37,000 m^2) of greenhouse area. On the average, service buildings occupy 10 percent of the growing area (Brumfield et al., 1981).

Topography

The service building and greenhouses should be on the same level to permit easy movement of personnel and materials and maximum automation. Thus, the building site should be as level as possible to reduce the cost of grading. The site should be well drained. Because of the extensive use of water in greenhouse operations, providing a drainage system is always advisable. Where drainage is a problem, it is wise to install drainage tile below the surface prior to constructing the greenhouses. It is also advisable to select a site with a natural windbreak, such as a treeline or hill, on the north and windward sides. In regions where snow is expected, trees should be 100 feet (30.5 m) away in order to keep drifts back from the greenhouses. To prevent shadows on the crop, trees located on the east, south, or west sides should be set back a distance of 2.5 times their height.

Land-Use Prediction

Local zoning and tax laws are subject to changes brought on by development pressures. Such changes have brought about the termination of many greenhouse businesses. The past development of the location in question should be carefully studied in order to assess its future direction. Some local governments classify greenhouses as agricultural businesses to protect them from prohibitive property taxation due to zoning shifts. Others, in order to change the occupants within a zone, have denied expansion permits to floral production businesses.

Climate

Climatic conditions have dictated worldwide geographical shifts in horticulture. Such forces are also at work within local regions. The primary limiting factor to crop production in greenhouses is low light intensity during the winter. Areas having frequent fog, inclement weather, or shadows from the north slope of tall mountains are poor for crops in general. The better light intensity of higher altitudes is advantageous for crops in general and particularly for high-light-requiring crops such as carnation and rose. The advantage is much lower for crops with a requirement for low light intensity, such as African violet, begonia, gloxinia, and most foliage plants.

Labor Supply

Present and future labor needs should be assessed and should be in accord with the labor supply in the area. Procurement of a labor supply has been a perennial problem in the horticulture industry. While the solution has appeared to rest on locating close to an urban area, this brings on a problem of wage level. Traditionally, greenhouse wages have been low, which has given the labor-recruitment advantage to the more technologically advanced industries. The solution appears to lie in meeting the competition directly through higher wages. Higher wages can be offset by automation, which reduces the number of employees but increases the productivity of each.

Accessibility

A site should be selected where shipping routes are easily accessible. Marketing of floral crops costs approximately one-quarter of the gross wholesale return, with shipping being a significant portion of this cost (Brumfield et al., 1981). Minimization of shipping costs by close proximity to the target markets will go a long way toward alleviating this burden. At the same time, local carrier costs for goods received will be reduced.

Site location is often the deciding factor in the type of fuel used. In some regions, natural gas is a cheaper source of energy than other fuels. Some greenhouse ranges are not able to take advantage of this factor because their location is at a prohibitive distance from the gas line, while the competition located near the line can enjoy this advantage. In one situation where a greenhouse range was built at a high altitude to take advantage of light conditions, the remoteness of the location necessitated the transfer of oil from large tank trucks to smaller trucks during delivery, thus raising the cost of the oil.

Water

Water is one of the most frequently overlooked resources in the establishment of a greenhouse business. Before a site is purchased, the available water source should be tested for quality and quantity. There have been several cases in which businesses located in coastal and riverbed regions were compelled to move to new locations to obtain water of suitable quality. The cost of removing ions such as sodium, chloride, and bicarbonate can reduce profitability, but failure to do so results in plant injury. Water quantity is equally important, since as much as 2 quarts of water can be applied to 1 square foot (20 L/m^2) of growing area in a single application. Well water is the desired source, since municipal water is often too costly and may contain harmful fluoride. Pond or river water is subject to disease organisms and may require expensive pasteurization.

Orientation

Shadows are cast by the greenhouse structure. The magnitude of the shadows depends on the angle of the sun and thus on the season of the year. The effect can be most detrimental to growth in the winter, when the sun remains closer to the horizon and shadows are longer.

Single greenhouses located above 40°N latitude in the Northern Hemisphere should be built with the ridge running east to west so that low-angle light of the winter sun can enter along a side rather than from an end where it would be blocked by the frame trusses. Below 40°N latitude, the ridge of single greenhouses should be oriented from north to south, since the angle of the sun is much higher. Ridge-and-furrow and gutter-connected greenhouses (greenhouses connected to one another along their length) at all latitudes should be oriented north to south. This north–south arrangement avoids the shadow in a greenhouse that would occur from the greenhouse lying immediately south of it in an east–west arrangement. Although the north–south orientation has a shadow from the frame trusses, it is much smaller than the shadow that would be cast from a whole greenhouse located to the south.

L. G. Morris made the calculations presented in Table 1 in England at a latitude of about 50°N. They leave little doubt that the ridge of a single greenhouse at higher latitudes should run from east to west. The difference in light intensity due to orientation is not great during the summer, when the angle of the sun is high. A difference shows up in the winter, when light is an important issue.

Table 1
Effect of Greenhouse Orientation on Light Transmission in Midsummer and Midwinter at a Latitude of Approximately 50°N

	Percent Transmission	
Orientation	Midsummer	Midwinter
North–south	64	48
East–west	66	71

FLOOR PLAN

It is important to develop a greenhouse floor plan that allows for more future expansion than will likely occur. This consideration best ensures that an efficient operation will always be possible. If there is a slope to the land, construction should begin at the midpoint (average elevation). In this way, the soil excavated will provide the fill needed during each expansion. In the end, there will be one final elevation for the entire greenhouse range. A plan as pictured in Figure 1 allows for additions to the service building and greenhouses without the removal of previous buildings or the accumulation of multiple service buildings. The service building is centrally located in a nearly square design of the firm, which minimizes distances that plants and materials need to be moved. The whole firm is on one elevation and is internally connected so that an internal transport system can be used (Figure 2).

Doors between the service building and the greenhouse should be wide enough to facilitate full use of the corridor width. Doors at least 10 feet (3.1 m) wide by 9 feet (2.7 m) high are common. The drive through the corridor and greenhouse should be at least 8 feet (2.4 m) wide in larger greenhouse ranges to allow two trains to pass each other. Today, the minimum height of greenhouse gutters off the ground is 12 feet (3.7 m), with 14 and 16 feet (4.3 and 4.9 m) being common. This height is needed to accommodate thermal blankets, supplemental lighting, and hanging

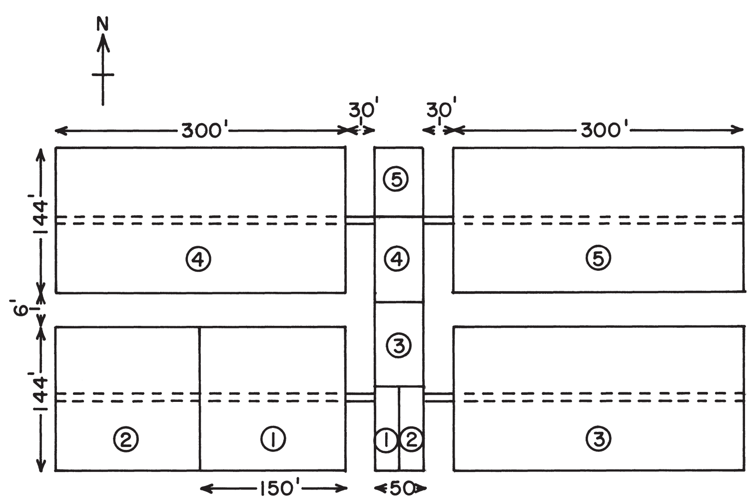


Figure 1
This floor plan for a greenhouse firm allows for construction in five phases. The design employs a single, central service building. Building phases are numbered consecutively. The adjacent greenhouse or service building walls between each building phase are removed. Greenhouses are separated from the service building by transparent corridors 30 feet (9 m) long to prevent shadows in the growing area.

Figure 2
An internal transport system at Rockwell Farms in Rockwell, North Carolina, consisting of a train of shelved, self-tracking trailers and an electric cart for pulling the train. Main aisles in each greenhouse block need to be wide enough to accommodate two trains passing each other.

baskets and still leave room for future innovation. Many greenhouses are being built with 14- and 16-foot (4.3- and 4.9-m)-high gutters to accommodate hanging-basket plants in addition to the previously mentioned features. The greenhouse gutters need to be oriented north to south. A greenhouse gutter length of 144 feet (44 m) coincides well with the greenhouse brands using 12- and 24-foot (3.7- and 7.3-m) gutter modules, while a 140- or 150-foot (43- or 46-m) gutter length works well for brands with 10-foot (3.1-m) gutter modules. All of these gutter lengths are within the maximum effective summer cooling distance of approximately 150 feet (46 m). The service building should have at least 16-foot (4.9-m) eaves to allow for doors 12 feet (3.7 m) wide by 14 feet (4.3 m) high, which are needed to accommodate trailer trucks for both receipt of goods and shipping of plants. Eighteen-foot (5.5-m) eaves are better where two levels are desired within the service building, which is the situation when a storage area is located above the office area. All plant loading should be carried out from a central point inside the service building.

Service buildings are constructed from a variety of materials, steel being the most common. Economics generally dictate the type. Some growers use a few bays of the greenhouse itself for the service building because of the 25 to 50 percent lower cost. In this case, the service area may be covered with the same transparent material as the growing area or with standard building materials, such as board and shingle or corrugated metal. Facilities within the service building include offices, restrooms, a lunch/break area, a fertilizer room, a workshop, storage, a truck-loading dock, a staging area for market-bound plants and flowers, possibly a central boiler area, and extra space for staging various jobs. A pesticide storage and handling room is sometimes included in the headhouse. However, for safety purposes it is better when the pesticide facility is in a separate building.

GLASS GREENHOUSES

Only glass greenhouses existed prior to 1950. Glass greenhouses have an advantage of greater interior light intensity over plastic panel and film-plastic-covered greenhouses. The greater light intensity is due to the single glass covering during the day compared to the double plastic covering that remains on all the time. The heat requirement can be the same in a glass greenhouse as in a double-layer film plastic greenhouse if a thermal screen is installed in the glass greenhouse for use during the night and the glass greenhouse is located in a mild climate where little daytime heating is needed. Glass greenhouses tend to have a higher air infiltration rate, which leads to lower interior humidity. This is advantageous for disease prevention. On the other hand, glass greenhouses have a higher initial cost than double-layer film plastic greenhouses. Recently, the prices of glass greenhouses, particularly the low-profile type, have come much closer to film plastic greenhouse prices. When comparing the price of a glass greenhouse to that of a film plastic greenhouse, one needs to take into account the initial purchase price of each as well as the cost of re-covering the film plastic greenhouse every four years. The typically higher long-term cost of the glass greenhouse is justified by some growers by the higher crop yield. In 2009, the proportion of greenhouse covering types in use in the United States was 13 percent glass, 16 percent FRP and rigid plastic panels, and 71 percent film plastic (Agricultural Statistics Board, USDA, 2010). Floricultural crops were also grown in additional areas under shade screen and out in the open in areas equal to 72 and 15 percent of the covered greenhouse area.

Several styles of glass greenhouses are designed to meet specific needs. A *lean-to* design is used when a greenhouse is placed against the side of an existing building (Figure 3a). This design makes the best use of sunlight and minimizes the requirements for roof supports. It is found mostly in the retail industry. An *even-span* greenhouse is one in which the two roof slopes are of equal pitch and width (Figure 3b). By comparison, an *uneven-span* greenhouse has roofs of unequal width, which make the structure adaptable to the side of a hill (Figure 3c). This style is seldom used today because such greenhouses are not adaptable to automation.

Finally, a *ridge-and-furrow* design uses two or more A-frame greenhouses connected to one another along the length of the eave (Figure 3d). The eave serves as a furrow or gutter to carry rain and melted snow away. The side wall is eliminated between greenhouses, which results in a structure with a single large interior. Consolidation of interior space reduces labor, lowers the cost of automation, improves personnel management, and reduces fuel consumption because there is less exposed wall area through which heat can escape. The snow load must be taken into account in the frame specifications of these greenhouses. Snow cannot slide off the roofs, as in the case of individual freestanding greenhouses, but must melt away. Heating pipes are generally located beneath the gutters for this purpose. In spite of snow loads, ridge-and-furrow greenhouses are effectively used in the countries of northern Europe and in Canada.

Basically, three frame types have been used in greenhouses. *Wood frames* were used in the past for greenhouses under 20 feet (6.1 m) in width. Side posts and

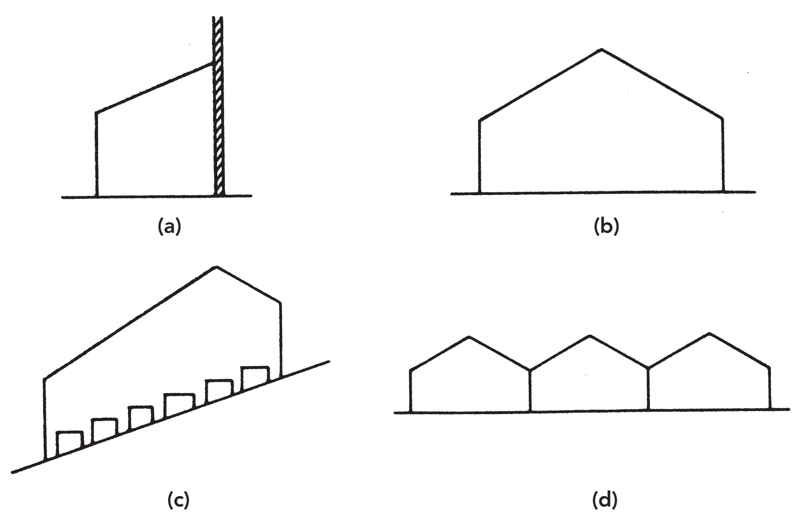


Figure 3
Four basic greenhouse styles: (a) lean-to, (b) even-span, (c) uneven-span, and (d) ridge-and-furrow.

columns were constructed of wood without the use of a truss. Wider houses required sturdier frames. *Pipe frames* served well for greenhouses up to a width of about 40 feet (12.2 m) (Figure 4a). The side posts, columns, cross ties, and purlins were constructed from pipe. Again, a truss was not used. The pipe components did not all interconnect but depended on attachment to the sash bars for support. Pipe-frame greenhouses are not constructed today. In the past, some greenhouses under 50 feet (15.2 m) in width and most over this width were built on *truss frames* (Figure 4b). Today, only truss-frame glass greenhouses are built. Truss-frame greenhouses are best suited to prefabrication, which has made the construction of greenhouses more economical. Flat steel, tubular steel, or angle iron is welded together to form a truss encompassing the rafters, chords, and struts. Steel is typically galvanized to prevent rusting. Aluminum frames, although more expensive, are also used due to complete freedom from rust. Struts are support members under compression, while chords are support members under tension. Angle-iron purlins running

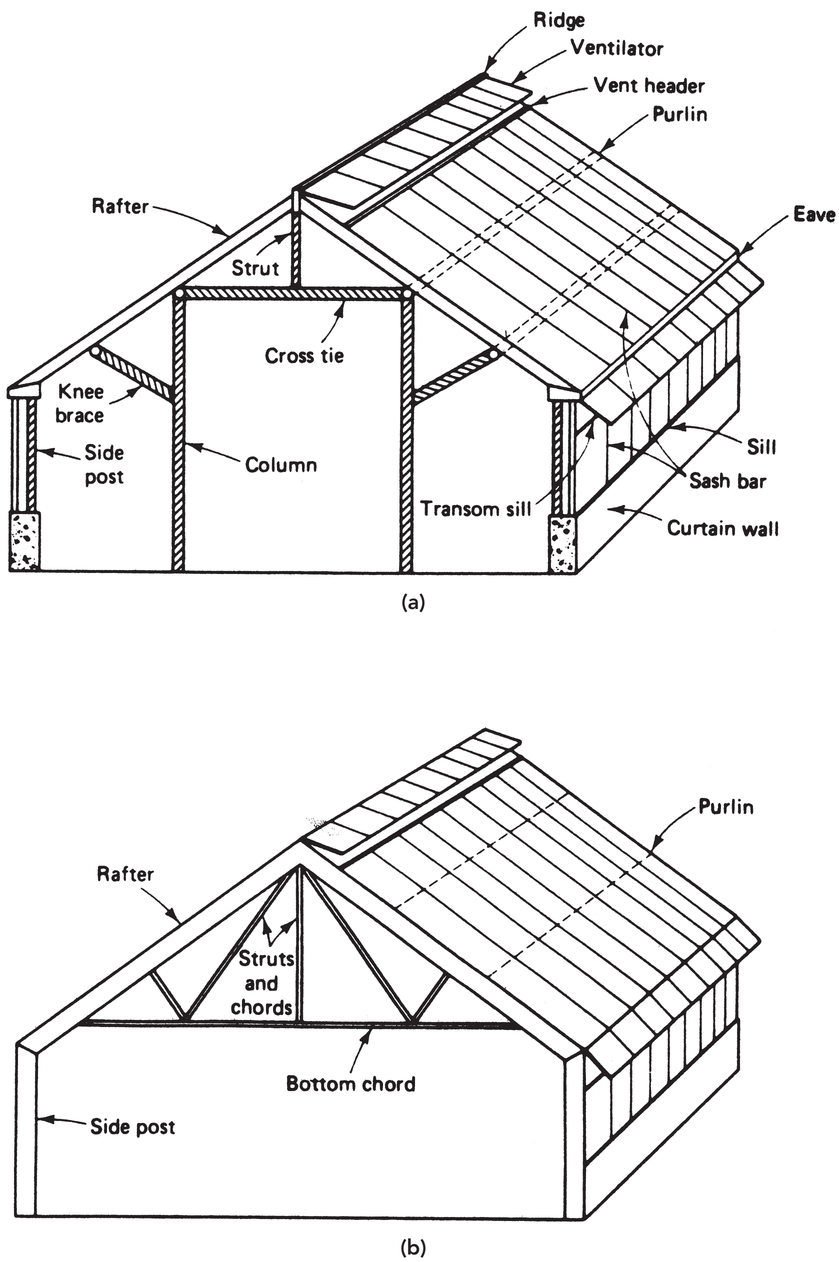


Figure 4
Structural components of (a) a pipe-frame greenhouse and (b) a truss-frame greenhouse. In the house in (b), the side posts, rafter, chords, and struts are one unit known as a truss.

the length of the greenhouse are bolted to each truss. A frame thus constructed can stand without support of sash bars. Columns are used only in very wide truss-frame houses of about 70 feet (21.3 m) and wider. Gutters can be galvanized iron or aluminum. Since gutters are more prone to rust than trusses, aluminum gutters are definitely preferred.

The glass on the greenhouse is attached to sash bars. In earlier days, sash bars were made exclusively of wood, primarily cypress and redwood. The wood required periodic painting to protect it against rot. Ideally, exteriors were painted every two years and interiors every five to seven years. This practice was costly. Aluminum sash bars and ventilators were introduced in the early 1950s. The resultant all-metal greenhouses were very expensive at the outset but quickly became competitive with houses having wooden sash bars. All-metal greenhouses proved cheaper to maintain since they required no painting. Today, all glass-greenhouse construction is of the metal type.

The structural members of the greenhouse cast shadows that reduce plant growth during the dark months of the year. Aluminum sash bars are stronger than wooden bars; thus, wider panes of glass can be used with aluminum bars. The reduction in structural material plus the reflectance of aluminum have given these metal greenhouses a great advantage over wooden greenhouses in terms of higher interior light intensity.

Today's glass-greenhouse construction can be categorized as high profile (Figure 5a) or low profile (Figure 5b). The low-profile greenhouse originated in The Netherlands and is known as the Venlo greenhouse. Eaves are 10.5 feet (3.2 m) apart, and single panes of glass extend from eave to ridge. The lower profile slightly reduces exposed surface area, thereby reducing the heating cost. It is suggested, however, that these greenhouses are more expensive to cool in warm climates where fans are required. Ventilator cooling during intermediate seasons is not as effective due to the lower height from ground to ventilator; however, this difference is becoming negligible due to the higher gutter heights used today. There is a movement in The Netherlands toward wider greenhouses based on increments of 10.5 feet (3.2 m), including 21-foot (6.4-m) and 31.5-foot (9.6-m) widths. In North America, both low- and high-profile greenhouses are currently popular. Since heating and cooling differences are very small, price appears to be the dominant factor in the relative popularity of these greenhouse types. The price advantage has shifted back and forth in the United States and is currently with the low-profile greenhouses.

Throughout recent history, the Venlo greenhouses have been available with and without ventilators on the roof and sides. In cool climates, ventilators have been adequate for passive cooling of these greenhouses. However, in warm climates, active fan-and-pad or fog cooling has been necessary, which precludes the use of ventilators. More recently, new concepts of passive cooling are effectively used to cool greenhouses in warm climates. For this purpose, there is a need to open the entire greenhouse roof. Various systems are available. In one, the two roof slopes of each greenhouse are hinged at the ridge. The base of one roof slope is permanently attached to the gutter by hinges, while the other roof slope is attached at its base to a rack-and-pinion mechanism that draws the base of this roof horizontally to the base of the other roof. When fully open, the two roofs are positioned vertically against each other next to a gutter. A second design for opening the entire roof of a glass greenhouse is seen in Figure 6. In this situation, the two roof slopes of a given greenhouse are hinged to the gutters and detached at the ridge.

High-profile greenhouses are available with special sash bars that hold two or even three layers of glass. This layering produces one or two dead-air spaces to cut

(a)

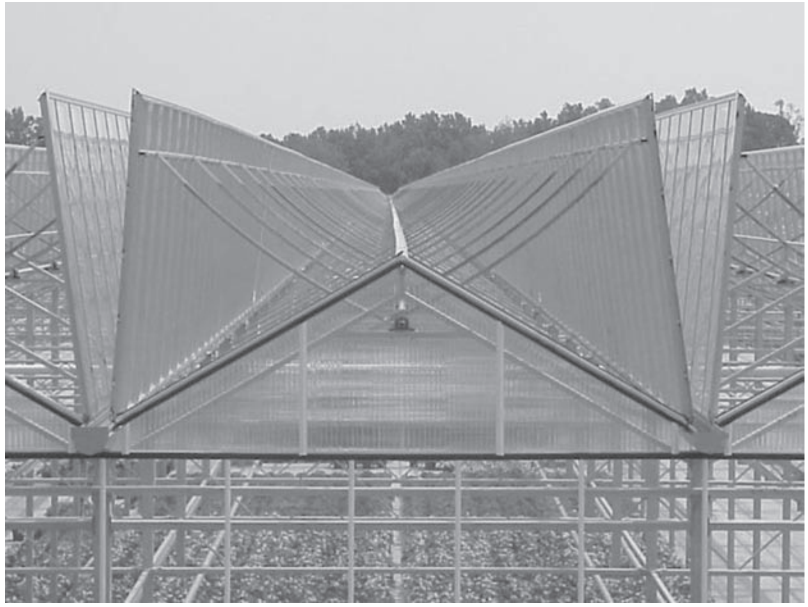
(b)

Figure 5
(a) A high-profile, ridge-and-furrow greenhouse. (b) A low-profile, ridge-and-furrow greenhouse.

heat loss. A problem with this design is the unsealed junction between pieces of glass in the inner layer. Moisture and dust can get between the layers and reduce light transmission. It is expensive to remove and clean the glass. For these reasons, few of these greenhouses were ever built.

The size of glass panes has evolved to become larger over the years to minimize the number of sash bars for light and the number of laps between panes for installation labor economy and air infiltration reduction. The original width of 16 inches (41 cm) is typically 30 or 36 inches (76 or 91 cm) in the United States and 39 inches (1 m) in The Netherlands. The length of panes has increased from the original 18 inches (46 cm) to the length necessary to fill the space from eave to ridge with a single pane, as long as 7 or 8 feet (2.1 or 2.4 m) in low-profile greenhouses. For the Dutch Venlo greenhouse, a 65-inch (1.65-m) pane is used. In high-profile

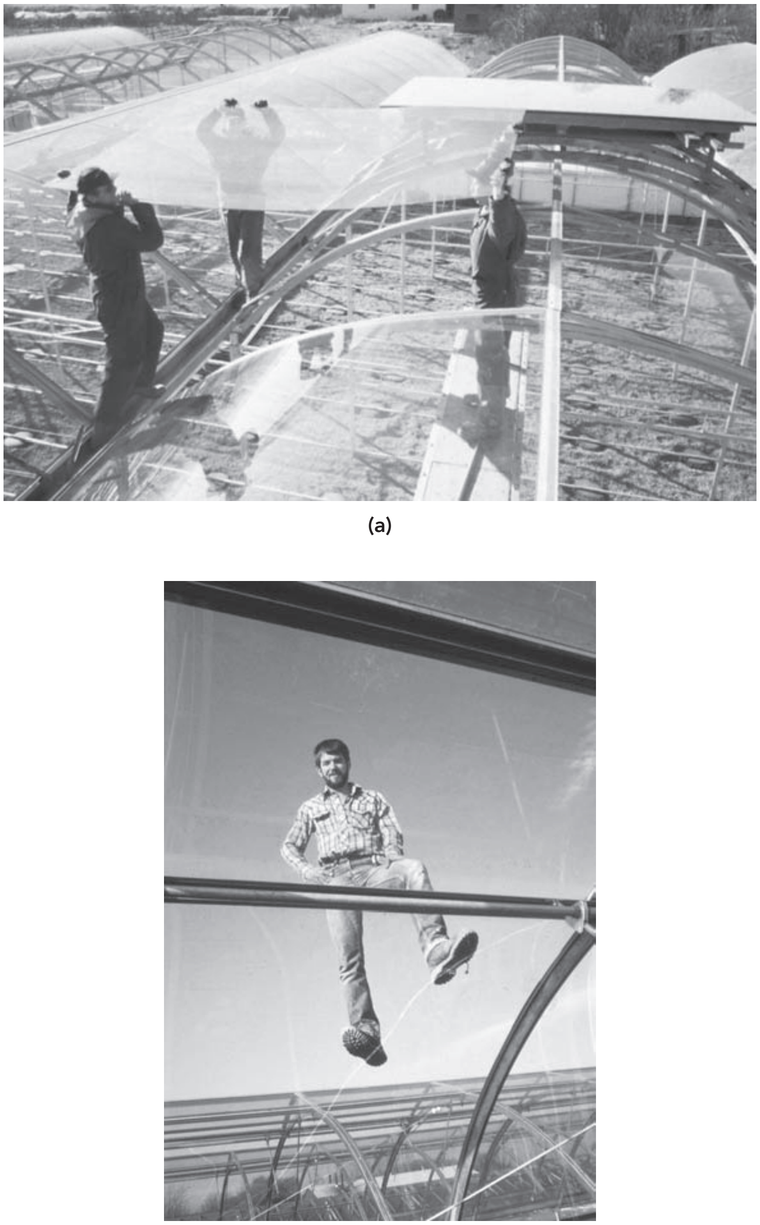
Figure 6
The MX ridge-and-furrow glass greenhouse pictured with roofs open. Each roof is hinged to its gutter and detached at the ridge. A rack-and-pinion mechanism just below the ridge is used to open and close the roofs.
(Photo courtesy of Van Wingerden Greenhouse Co., 4078 Haywood Rd., Horse Shoe, NC 28742, Web: van-wingerden.com.)



greenhouses, multiple panes are required. Even larger panes of 5/32-inch (4-mm) thick tempered glass up to 6 feet by 13 feet (1.8 m × 3.9 m) have been used since 1985. These panes cover the roof from gutter to ridge. Being tempered, they can be and are bent to fit a curved roof for extra strength (Figure 7).

Due to building code requirements in America, most glass is 4 millimeters (5/32 in.) thick, whereas in The Netherlands it is 3 millimeters (1/8 in.) thick. It is generally necessary to use tempered glass overhead for safety reasons. When impacted, tempered glass breaks into numerous small, granular pieces that do not cut a person when struck by them. Most production greenhouses today are covered with tempered glass. Float glass, on the other hand, breaks into long, sharp-edged pieces that can severely cut a person. Tempered glass is much more resistant to hail damage than float glass. Float glass is permitted on side and end walls up to a given height, depending on the local building code. Float glass works out well on end and interior partition walls since it can be cut on-site. Tempered glass cannot be cut on-site. Building codes generally require laminated glass overhead in public greenhouses, such as retail greenhouses and conservatories. Nonlaminated glass can be used if a screen is installed below to catch it should it break. Laminated glass consists of two layers of glass, with an inner layer of plastic to hold the glass together if it is broken. Hammered glass (glass with a rough, uneven surface) has been used to a moderate degree in Dutch-design greenhouses. This glass scatters the light so that intensity is more uniform across the inside of the greenhouse, which leads to more uniform crop growth. Hammered glass is seldom used today outside of The Netherlands because of its high rate of breakage during shipping and handling. In The Netherlands, it is used on side and end walls. Low-iron-content glass has a higher light transmission, of 90 to 92 percent versus 88 percent for float glass. Due to its cost, only a modest amount of low-iron-content glass has been used and only for high-light-requiring crops such as roses.

The price of glass varies with the quantity purchased and to a lesser degree with the size of the panes. Reasonable prices for the quantity of glass required for 1 acre (0.4 ha) of greenhouse are as follows: 4-millimeter float glass, \$0.80/ft^2 (\$8.61/m^2); 4-millimeter tempered glass, \$0.95/ft^2 (\$10.23/m^2); and laminated glass (0.25 in., 6.4 mm thick; this is the thinnest available), \$3.00 to \$4.00/ft^2 (\$32.28 to \$43.00/m^2).



(a)

(b)

Figure 7
(a) A range of gutter-connected greenhouses with roofs covered with tempered glass panes 6 feet wide by 10 feet long (1.8 m × 3.0 m), each extending from gutter to ridge and bent to fit the arched roof shape. (b) The resulting covering is exceedingly strong, due in part to the curvature of the glass, and has very high light transmission.

(Photo courtesy of Westbrook Greenhouse Systems Ltd., P.O. Box 99, Grimsby, Ontario, L3M 4G1, Canada.)

FILM PLASTIC GREENHOUSES

Role

Flexible plastic films, including polyethylene, polyester, and polyvinyl chloride (PVC), have been used for greenhouse coverings. Polyethylene is principally used today throughout the world, although considerable PVC is used in Japan. Film plastic is currently the leading greenhouse covering for two reasons. First, film plastic greenhouses with permanent metal frames cost less than glass greenhouses. Even greater savings can be realized when film plastic is applied to less permanent frames, such as the cheaper Quonset greenhouses. Second, film plastic greenhouses are popular because the cost of heating them is approximately 40 percent lower compared to single-layer glass or FRP greenhouses. Granted, a thermal screen can be installed inside a glass greenhouse that will lower the heat requirement to approximately that of a double-layer film plastic greenhouse, but this further increases the cost of the glass greenhouse.

Polyethylene film was developed in the late 1930s in England, and its use as a greenhouse covering was pioneered around the middle of the 20th century. The use of polyethylene for greenhouses has increased rapidly and continues to do so. Film plastic greenhouses constitute the largest portion (71 percent) of greenhouses in the United States today. While they are popular in southern Europe, their popularity is not as great in northern Europe, where glass remains popular.

Along with the advantages of film plastic are some disadvantages. The two coverings are permanently on the roof, cutting light transmission to a level lower than that for a single layer of glass. These covering materials are short-lived compared to glass and plastic panels. The highest-quality, ultraviolet (UV) light–resistant, 6-mil-thick (0.006 in., 0.15 mm) polyethylene films last up to four years. UV light from the sun causes the plastic to darken, thereby lowering light transmission, and to become brittle, which subjects it to breakage in the wind. While the time required to cover a 30-foot-by-100-foot (9.1 m × 30 m) Quonset-design greenhouse is minimal (about 8 labor hours), the task is never-ending and carries implicit costs of management and the use of equipment. However, with proper management, the savings in fuel as well as the lower initial purchase price give the film plastic greenhouse a lower cost than a glass greenhouse.

Types of Film Plastic

Polyethylene Polyethylene has always been and still is the principal choice of film plastic for greenhouses in most of the world. Nearly all current heated greenhouses have two layers. The outer layer is customarily 6 mil (0.15 mm) thick, while the inner layer needs to be only 4 mil (0.1 mm) thick. All polyethylene used for covering year-round production greenhouses has a UV protection additive in it; otherwise, it would last for only one heating season rather than up to four years. UV-grade polyethylene is available in widths up to 64 feet (19.5 m) in sheets and up to 32 feet (9.8 m) in tubes. Some standard lengths include, among others, 100, 110, 150, 200, and 220 feet (30.5, 33.5, 45.7, 61.0, and 67.0 m). Custom interim and longer lengths are available.

A polyethylene covering is colder in the winter than the air inside the greenhouse. When warm, moist greenhouse air contacts the cold polyethylene, it cools. As a result, water vapor condenses on the inner polyethylene surface. The surface is repellent to water; thus, the water forms into beads. With time, the water beads increase in size to a point where they drop off to the plants below. The wet foliage fosters disease development, while the constantly wetted soil becomes waterlogged and oxygen deficient. If the plastic surface were not as repellent to water, the condensing water would spread out better over the surface of the plastic, without forming droplets large enough to drop off. Ultimately, this water would flow down along the surface of the plastic to the gutter, where it would be collected. A liquid surfactant, Sun Clear, is available that can be sprayed on the inner surface of film plastic and rigid-panel greenhouses to give the benefit of lower surface tension. The materials cost for this treatment is $\$0.0071/ft^2$ ($\$0.077/m^2$) of surface treated. The treatment lasts a year or more. Today, polyethylene film as well as rigid FRP, acrylic, and polycarbonate panels are available with an anti-condensate surfactant built into the film or panel. It is advisable to use an anti-condensate product because, in addition to the water-dripping problems, this condensation also reduces light intensity within the greenhouse. Condensation is particularly problematic in the morning when, due to a cold greenhouse covering and humid air inside, a thick layer of droplets often forms. This cuts light transmission into the greenhouse at a time of the day when light is most effective for growth. Also, in the early hours after sunrise, greenhouse temperatures are generally in a more optimal range for growth than later when they often warm up to more adverse temperatures over 82°F (18°C). Most greenhouse coverings used today have the anti-condensate additive. The anti-condensate additive lasts about three years.

During the day, objects such as plants, the greenhouse frame and covering, and soil warm by absorbing light, particularly in the infrared (IR) range. When it becomes colder outside, such as at night, the warm objects re-radiate thermal energy to cold objects outside, such as the ground and the sky. This radiant energy is transmitted mainly as IR radiation in wavelengths around 1,000 nanometers. Polyethylene is a poor barrier to radiant energy. However, thermal polyethylene, sometimes referred to by manufacturers as IR film, is available, which contains an additive that reduces re-radiation of this IR energy. IR film reduces re-radiation by about 50 percent. Thus, on cold clear nights, as much as 25 percent of the total heat loss of a greenhouse can be prevented in this way. On cloudy nights, only about 15 percent is saved because cloud cover blocks some of the transmission.

Light that is utilized in photosynthesis is termed *photosynthetically active radiation* (PAR) and comprises the wavelengths from 400 to 700 nanometers. Transmission of PAR through polyethylene can vary with the brand of polyethylene used and the chemical additives it contains (Table 2). UV-stabilized polyethylene, on average, transmits about 87 percent of light. The amount of light passing through two layers of a greenhouse covering is approximately the square of the decimal fraction of the amount passing through one layer. Where 87 percent (0.87) passes through one layer of UV-inhibited polyethylene, only about 76 percent (0.87×0.87) passes through two layers. IR-blocking polyethylene transmits a modestly lower amount of light. This is one of the reasons that two single sheets of polyethylene, one with and the other without IR block, are preferred to a tube with two layers of IR block. Use of IR block polyethylene is a popular and wise investment in the greenhouse industry.

Table 2
LIGHT TRANSMISSION VALUES FOR VARIOUS GREENHOUSE COVERINGS

Greenhouse Covering	Number of Layers	Percent Transmission[1]
Glass, float	1	88
Glass, tempered	1	90
Glass, tempered, low-iron	1	93
Glass, tempered	2	82
Glass, tempered, low-iron	2	86
Polyethylene	1	87
Polyethylene	2	78
FRP, corrugated or flat	1	89
Vinyl film	1	91[2]
Polyvinyl fluoride film	1	92[2]
Polycarbonate, corrugated	1	90
Polycarbonate, corrugated, diffused	1	85[2]
Polycarbonate, twin, 8 mm	2	81[2]
Polycarbonate, twin, 8 mm, diffused	2	79[2]
Polycarbonate, triple, 8 mm	3	74[2]
Polycarbonate, triple, 16 mm	3	76[2]
Acrylic, twin, 8 mm	2	84[2]
Acrylic, twin, 16 mm	2	86[2]

[1]Light transmission values are from Bartok et al. (2001) unless otherwise specified.
[2]Manufacturer's specifications.

UV light is in the wavelength range of 100 to 380 nanometers. Most standard polyethylene types block UV light up to the wavelength of about 350 nanometers. This works well for most crops. UV-clear polyethylene is available that blocks wavelengths of UV light only up to 280 nanometers. This is recommended for herb and vegetable transplant crops. The wavelengths of UV light transmitted result in enhanced aroma, taste, and deeper color, particularly in the purple range, in herbs. Vegetable seedlings exposed to this range of UV light are more compact and stand up better to mechanical transplanting in the field. A third type of polyethylene blocks all UV light, up through 380 nanometers. This is recommended for low-light-requiring crops such as African violet, bedding plants, and ferns.

Light-diffusing polyethylene is also available. Seventy percent of light transmitted is diffused. This scatters incoming light, raising the intensity on the north side of plants and inside the leaf canopy. This increases overall growth. Because light is scattered, intensity at the top of the plant is lower, reducing the risk of adversely high levels and excessively high temperature of that tissue. As a result, less shading is required on the greenhouse during summer months.

While two layers of polyethylene transmit less light than one layer of glass, it is questionable how much less light there is in a polyethylene greenhouse. Kozai, Goudriaan, and Kimura (1978) developed a simulation model for a glass-covered, high-profile greenhouse located at 30°41'N latitude. Although they indicated a light transmissivity of 86 percent at a zero angle of incidence for the glass itself, the light transmissivity for the entire greenhouse varied from 50 percent to 60 percent, depending on the season and the orientation of the greenhouse. The difference between 60 percent and 86 percent was due to the angle of incidence of light (reflection), sash bars, and structural members. Commercially fabricated polyethylene greenhouses typically have less structural material than high-profile glass greenhouses. This could compensate in part for the lower light transmissivity through a double layer of polyethylene compared to a single layer of glass.

The latest technology in polyethylene production for greenhouse films uses the co-extrusion process. Three liquid resins are extruded simultaneously such that a single layer of film can have three different chemistries across it. In the present tri-extruded films, the anti-condensate additive is placed in the inner core and sometimes also in the lower outer layer. This chemical is not entirely compatible with polyethylene. The repelling forces cause it to slowly bleed out of the core through the overlying zones of polyethylene. In this way, it can last a few years. The IR-reducing additive chemical is placed in the core. Typically, this chemical weakens polyethylene. By confining the IR block to the core, a zone of strong and clear polyethylene can be developed over each side of the core.

Average prices for 6-mil (0.15-mm), four-year polyethylene film in quantities sufficient to cover 1 acre of greenhouse are \$0.10/ft^2 (\$1.08/m^2) for standard film, \$0.11/ft^2 (\$1.18/m^2) for anti-condensate plus IR block, and \$0.15/ft^2 (\$1.61/m^2) for diffused plus UV block to 380 nanometers. Several greenhouse construction companies can be hired to re-cover polyethylene greenhouses. The labor cost is about \$0.20 to \$0.25/ft^2 (\$2.15 to \$2.70/m^2) of greenhouse surface. The lower price applies to greenhouses covered with a tube of plastic, since both layers of plastic can be applied in one step. Gutter-connected greenhouse designs also frequently contribute to the lower price because less surface area per unit of ground area is exposed, as compared to Quonset greenhouses. As a general rule, labor to re-cover is about equal to the price of plastic being applied.

Several chemicals used in greenhouses cause degradation of polyethylene film. Contact between the film and chemicals containing bromine, chlorine, iodine, sulfur, petroleum, and copper wood preservatives should be avoided. These are contained in a number of pesticides, bleach, wood preservatives, and soil fumigants.

Vinyl UV light–resistant vinyl (PVC) films of 8- and 12-mil (0.20- and 0.30-mm) thicknesses are guaranteed for four and five years, respectively. This guarantee was a decided advantage years ago when polyethylene lasted for only one or two years. However, with the advent of four-year polyethylene, the advantage is nearly gone. The cost of 12-mil (0.30-mm) vinyl is about three times that of 6-mil (0.15-mm) polyethylene. Although vinyl film is produced in rolls up to 50 inches (1.27 m) wide, any width can be purchased, since the supplier can seal strips of vinyl together. The vinyl films tend to hold a static electrical charge, which attracts and holds dust. This in turn reduces light transmittance until the dust is washed off. Vinyl films are seldom used in the United States. However, in Japan, the majority of greenhouses are covered with film plastic, and within this group a high percentage are covered with vinyl film.

ETFE The most recent category of greenhouse film plastic covering to appear is ETFE (ethylene tetrafluoroethylene) film. Actually, this film has been used for other commercial applications in Japan for over 24 years and for greenhouse use for over 17 years. The anticipated greenhouse life expectancy is in excess of 10 years. Light transmission is over 90 percent and is greater than that of polyethylene. ETFE is available under the product name F-Clean. It is manufactured by Asahi Glass Co. Ltd., 1-12-1, Yurakucho, Chiyoda-ku, Tokyo 100-8405, Japan (http://www.f-clean.com). F-Clean is produced in 60-, 100-, and 150-micrometer (2.4-, 4-, and 6-mil) thicknesses. Sheets can be bonded to desired widths and cut to required lengths for standard greenhouses. ETFE sells for many times the price of polyethylene in the United States. Little has been used to date in the United States.

Polyester For a time, Mylar brand polyester film offered the strong advantage of durability. Films of 5-mil (0.13-mm) thickness were used for roofs and lasted four years, while 3-mil (0.08-mm) films were used on vertical walls and had a life expectancy of seven years. Although the cost of Mylar was higher than that of polyethylene, it was offset by the extra life expectancy. Other advantages included a level of light transmittance equal to that of glass and freedom from static electrical charges, which collect dust. Other industrial uses were found for Mylar in the mid-1960s, and soon its price increased out of the practical realm for floriculture. Polyester is still used frequently, however, in heat retention screens because of its high capacity to block radiant energy.

Film Plastic Greenhouse Designs

Wood-Frame Greenhouses When polyethylene first entered the horticultural scene, the cost of establishing a business was significantly reduced. People who didn't have the funds to set up an expensive glass greenhouse range could now enter the greenhouse industry. Accordingly, inexpensive frames were sought. Pinewood was commonly used. Various frames were designed through the 1950s and 1960s. The A-frame (Figure 8) was one of the more popular. The scissors-truss frame (Figure 9) was particularly strong. These and other designs were used for greenhouses ranging from 20 to 30 feet (6.1 to 9.1 m) wide. Today, wood greenhouses are rarely used by established greenhouse firms in developed nations due to their high maintenance cost and low levels of interior light. They are found mainly in tropical saw-tooth greenhouse designs in developing nations.

A single layer of film plastic was generally used until the early 1960s, when fuel costs significantly entered into the picture. After that time, double-layer coverings of

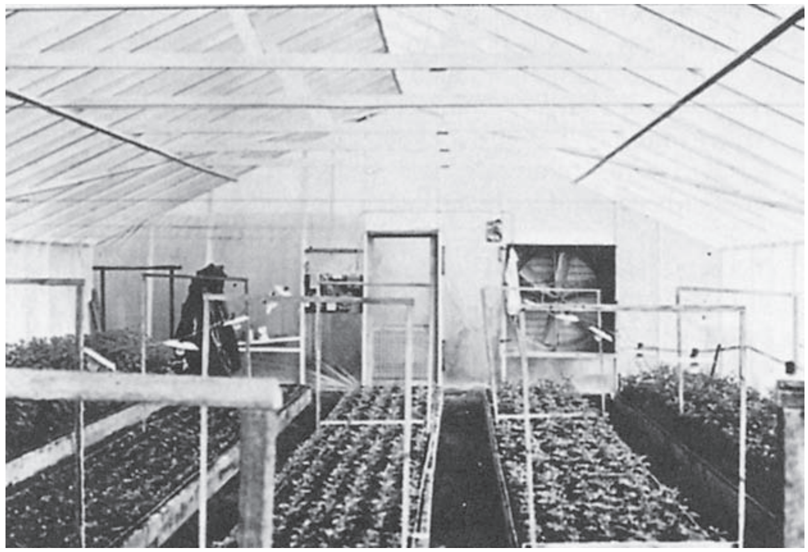


Figure 8
An inexpensive but temporary A-frame film plastic greenhouse, a type that was very popular in the early days of film plastic greenhouses.

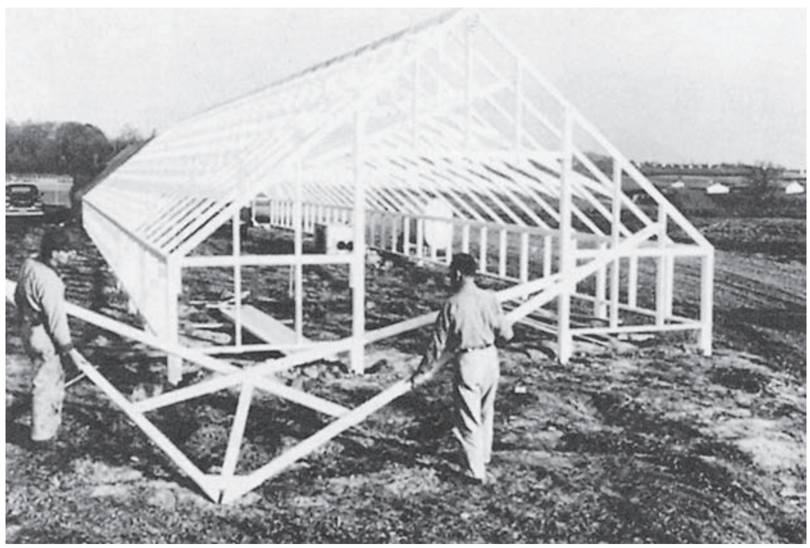


Figure 9
A scissors-truss film plastic greenhouse designed at Virginia Polytechnic Institute. This is a particularly strong design.

film plastic were desired to try to achieve a potential 40 percent savings in fuel cost. At first, the second layer was applied from the inside of the greenhouse. This task was difficult in greenhouses with columns, because holes had to be cut in the inner layer of plastic to maneuver it around these columns. The holes were generally not sealed and thus left avenues of entry for warm air into the dead-air space between the plastic layers, which reduced its insulating property. Today, both layers of plastic are applied from the outside.

Short-life wood used in these greenhouses (typically pine) required frequent painting to prevent rotting. White paint was usually used to increase interior light intensity. Today, as in the past, when paint is applied in or on a greenhouse, a mercury-based paint should be avoided. Mercury will volatilize from the paint for a considerable length of time and cause damage to the crop. Latex and paints sold specifically as greenhouse paints are safe.

Posts and other wooden objects in contact with the ground should be treated with a wood preservative. Treated wood may be purchased for this purpose, or the wood may be treated at the time of use. Several treatments are available, but not all are safe. Pentachlorophenol and creosote should not be used. Creosote in contact with roots and foliage can burn them. Pentachlorophenol produces fumes that can last for more than a year and are toxic to plants. Entire crops can be killed by moving them into a new greenhouse with treated posts. A single treated board can cause abnormal growth throughout the greenhouse. A very suitable wood preservative is copper naphthenate, which is sold under several trade names. Generally used as a 2 percent solution of copper naphthenate, it can be sprayed, dipped, or applied with a brush. It is an excellent preservative for frame members as well as for wooden benches and plant flats. Lumber that has been pressure-treated with Wolman salts is safe for greenhouse use (Beese, 1978). Wood pressure-treated with a similar preservative, CCA (copper chromate arsenate), has likewise been common and safe for plants. Although these former two materials are still available, their use in the residential markets has been voluntarily halted by manufacturers. The chromium and arsenate were environmentally harmful. A series of copper-containing materials are now used in their place, with the more common being ACQ (alkaline copper quaternary) and C-A (copper azole). These are being used in greenhouses.

Quonset Greenhouses With time, the price of wood became objectionably high relative to that of metal. The cost of continual painting was an added burden. By 1970, film plastic greenhouse designs were mainly of two styles. The first, and least expensive, which persists to this day, is the Quonset-style greenhouse (Figure 10). Quonset greenhouses can be purchased prefabricated or can be fabricated on-site. Many excellent designs are available from nearly every manufacturer of greenhouses, in widths up to 36 feet (11 m). Quonset greenhouses fit into two principal niches. First, they are typically less expensive than the gutter-connected greenhouses; therefore, they are a popular choice among individuals entering the industry on a limited budget. This is especially true for growers fabricating their own greenhouses. Second, they are handy when a small, isolated cultural area is needed, such as for cold treatment of azaleas.

Fabrication of a Quonset greenhouse is not very difficult. Often, the trusses are constructed from water pipe that is bent to fit a 180° arc, modified for somewhat more vertical sides. In greenhouses 20 feet (6.1 m) wide, 0.75-inch (1.9-cm) pipe is used; 1-inch (2.5-cm) pipe is used for a 30-foot (9.1-m) greenhouse width. Aluminum electrical conduit should not be used, since it does not have sufficient strength to support snow loads. Slightly larger pipe, into which the pipe arches are inserted for support, is driven into the ground. A 2-inch-by-8-inch (5 cm $\times$ 20 cm) wooden plank, treated for rot resistance, is attached to the base of the pipe arches so that it runs along the ground, partially buried. This provides a basal point of

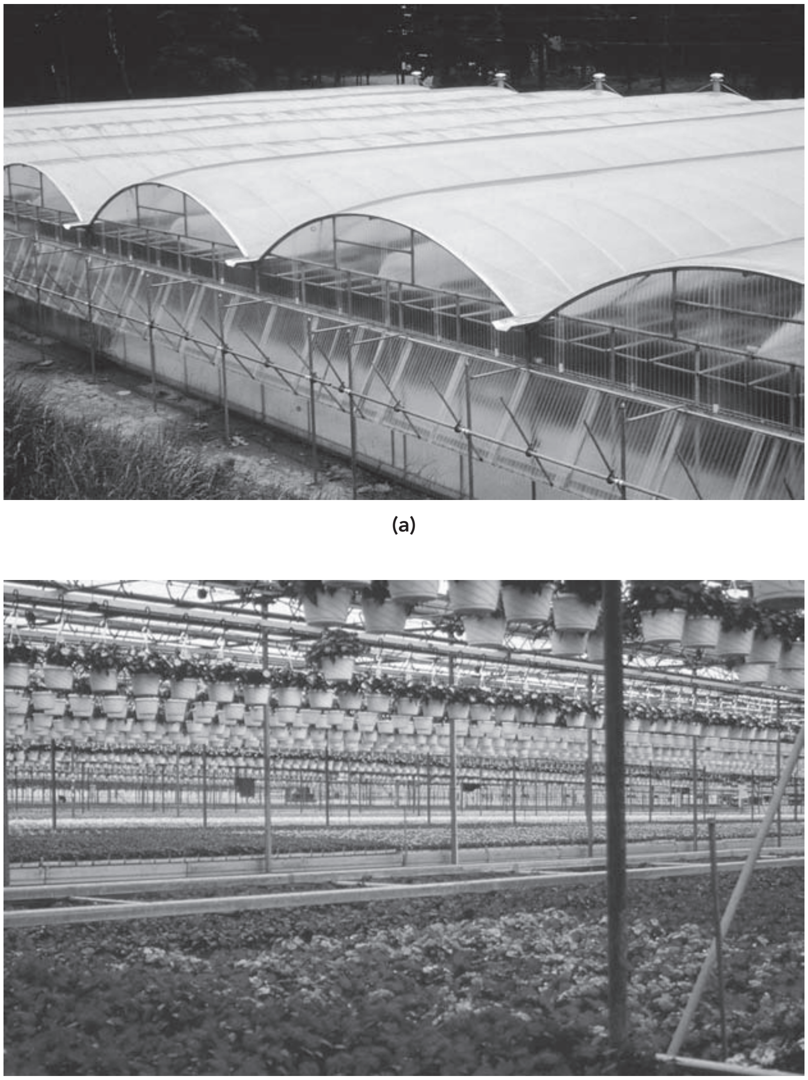
Figure 10
A metal-frame, Quonset-style greenhouse, which is very popular today with users of film plastic. This greenhouse is inexpensive, does not require painting, and is well suited to a double covering of film plastic.

attachment for the film plastic. The pipe arches, or trusses, are supported by pipe purlins running the length of the house. Trusses are spaced 36 to 48 inches (91 to 122 cm) apart. The width of film plastic required to cover a Quonset greenhouse of given width can vary according to the height and shape of the trusses. A 20-foot (6.1-m)-wide greenhouse generally requires a 32-foot (9.8-m)-wide sheet of plastic. The covering width for a 30-foot (9.1-m)-wide Quonset greenhouse varies greatly; the more common widths are 40 and 42 feet (12.2 and 12.8 m). Polyethylene greenhouses are constructed 2 to 3 feet (61 to 91 cm) shorter than the length of the roll of plastic used to cover them. The plastic is metered out onto the roll by weight and may vary in length by 1 or 2 percent. Also, some extra plastic is required to reach over the ends of the greenhouse for clamping onto the end walls.

Quonset houses are either constructed in a freestanding style or arranged in an interlocking ridge-and-furrow manner, as depicted in Figure 11. In the latter case, the trusses overlap sufficiently to place a bed of plants between the overlapping portions of adjacent houses. A single large interior thus exists for a set of houses, an arrangement that is better adapted to the movement of labor and to automation.

Gutter-Connected Greenhouses The gutter-connected house is the most efficient film plastic greenhouse design (Figure 12). It is cheaper, and thus more feasible, to automate the single consolidated space inside a gutter-connected greenhouse than the multiple equivalent spaces in several Quonset greenhouses. For instance, a heat-retention screen in a 1-acre (0.4-ha) gutter-connected greenhouse has a materials plus installation labor cost of about \$1.25 to \$1.50/ft^2 (\$13.45 to \$16.15/m^2), whereas in an equivalent area of Quonset greenhouses, it could be as high as \$3.00/ft^2 (\$32.28/m^2). Management is more efficient when personnel are all in one room with the supervisor, as opposed to being scattered about in multiple locations without supervision. Movement of materials and product into and out of the greenhouse requires less labor in a single large space than in numerous small spaces. The heating cost is less in a gutter-connected greenhouse, because there is less exposed surface area. A 20-foot-by-98-foot (6.1 m $\times$ 30 m) Quonset greenhouse with a 32-foot (9.8-m)-wide covering has 1.65 square feet of exposed surface per square foot of floor space, while a 1-acre (0.4-ha) gutter-connected greenhouse with a 10-foot (3.1-m) gutter height has 1.5 square feet of exposed surface per square foot of floor area. There is 10 percent less exposed surface per unit of floor area in the gutter-connected greenhouse. The modest increase in the price of a gutter-connected greenhouse

Figure 11
An interconnecting arrangement of Quonset greenhouses offering a single large interior for several greenhouses. This greenhouse arrangement is in better harmony with automation and efficiency of movement than single Quonset greenhouses.



(a)

(b)

Figure 12
(a) Exterior view of a gutter-connected polyethylene greenhouse range. (b) Interior view of a gutter-connected polyethylene range at Metroliner Greenhouse in Huntersville, North Carolina.

compared to a Quonset greenhouse is quickly returned with interest. Even if the first unit of a gutter-connected greenhouse is not suitably large for full automation, subsequent additions can make it so. When additions are made, the film plastic is removed from an existing side wall, and the new houses are connected at that point without any resulting discontinuity. In this way, a gutter-connected greenhouse set up with a modest initial investment originally unadaptable for automation can be developed through expansions into a structure well suited to automation.

It is more difficult to reapply film plastic coverings on the end walls than on the roofs. For this reason, many owners of Quonset and gutter-connected film plastic greenhouses use double-layer polycarbonate panels, and occasionally double-layer acrylic panels, on the end walls. The 8-millimeter (0.32-in.)-thick panel is common. Since there is less light load on these vertical walls than on the roof, these coverings can be expected to last for more than 20 years. Side walls of gutter-connected greenhouses were more commonly covered with a double layer of polyethylene film. However, with the current popularity of passively cooled greenhouses, polycarbonate and acrylic panel side walls are becoming more popular. These walls are well adapted for installation of side-wall ventilators. Single-layer corrugated polycarbonate and acrylic are also becoming popular for partition walls within the greenhouse.

The height of gutters above the ground has been increasing over the years to accommodate the continuing evolution of climate-control equipment, automation devices, and hanging-basket crops. The original gutter-connected greenhouses typically had an 8-foot (2.4-m) gutter height. Today, 12 feet (3.7 m) is the minimum recommended height, and 14 to 16 feet (4.3 to 4.9 m) is common. Gutters may be constructed from galvanized steel or from aluminum. Freedom from rust justifies the additional cost of aluminum gutters. Some gutters have an exterior film plastic attachment channel and an interior condensate drip collector molded into them. These are desirable features. The gutters in ridge-and-furrow glass greenhouses and gutter-connected film plastic greenhouses are either sloped to carry water away or level with periodic drains. A slope of 6 inches per 100 feet (0.5 cm/m) is common. Often the floor is sloped at the same angle. If the floor is not sloped, it is important to have adequate drainage built into it. Gutters that are level have periodic drain holes in them connected to pipes that carry water down through the greenhouse to a drain pipe in the floor.

The distance between gutter rows depends on the greenhouse brand purchased. This distance ranges from 10.5 to 40 feet (3.2 to 12.2 m). A number of greenhouse designs, up to and including 18 feet (5.5 m) between gutters, offer a truss frame that permits placement of gutter-supporting columns under every second or sometimes every third gutter. Although these extra-strong truss greenhouses can cost more, they offer the advantage of larger column-free spaces inside the greenhouse. This facilitates the use of automation and can reduce its cost. Greenhouses with wider spaces between column rows are inherently weaker unless stronger, more costly trusses are used. When selecting a greenhouse, it is important to know the wind load of the structure and the live and snow loads of the roof before comparing prices. Greenhouses with spacings between gutters of 12, 17, 21, 22, and 30 feet (3.7, 5.2, 6.4, 6.7, and 9.1 m) can be covered by film plastic sheets 14, 20, 24, 25, and 36 feet (4.3, 6.1, 7.3, 7.6, and 11.0 m) wide.

Another option in gutter-connected greenhouses is the contour of the roof. Traditionally, they had a relatively flat, Quonset-arch shape. Today, they can be obtained with a *Gothic-arch* shape or a *peaked* roof. The Gothic arch has a higher ridge than the Quonset, which results in steeper slopes to the roof. The peaked roof rises straight from the gutters to the ridge, in the typical shape of a glass roof. The steeper slopes of both the Gothic-arch and peaked designs facilitate downward flow of water condensate along the inner surface of the film plastic to the drip collector on the gutter. This reduces condensate drip on the crop and root substrate. Advantages include higher light transmission through the plastic, less disease on the crop, and prevention of waterlogging of the root substrate. The Gothic-arch and peaked designs also facilitate the use of roof ventilators on film plastic greenhouses.

The final choice to make when selecting a gutter-connected greenhouse design is between active and passive cooling. Passively cooled greenhouses are now offered with roll-up or roll-down side curtains that can be installed on two or all four walls (Figure 13), roof ventilators (Figure 14), side ventilators, hinged roofs that completely open (Figure 15), and retractable roofs (Figure 16). The purpose of side and roof ventilation is to replace high-energy-consuming fan-and-pad cooling systems. These passive cooling systems work well in both hot and cold climates. They were initially used for high-light-tolerant crops such as bedding plants, garden chrysanthemums, and many hanging-basket plants. More recently, they are being used for essentially all crops. In the past, it was assumed that sun screens could not be used in these greenhouses because they would impede the passive flow of air. Today, open (porous) sun screens are used that permit a satisfactory rate of air passage. Greenhouses with smaller roof ventilators are often equipped with

Figure 13
A gutter-connected greenhouse range with drop-down sides on four sides. Note that the polyethylene sides have been lowered about one-third of their height.

Figure 14
A range of gutter-connected greenhouses with roof ventilators for passive cooling. Note that end walls are covered with polycarbonate panels and the roofs are covered with polyethylene film. Louvers in the gables are for cold air intake for the winter cooling system.

(Photo courtesy of Westbrook Greenhouse Systems Ltd., P.O. Box 99, Grimsby, Ontario, L3M 4G1, Canada.)

either roll-up-or-down sides or side-wall ventilators. Owners of greenhouses with large roof ventilators, taking up half or more of the roof, more often skip the side-wall ventilation. They find that the roof ventilation alone is sufficient. A recent survey of greenhouse manufacturers indicated that as much as 60 percent of new polyethylene greenhouse construction is of the passively cooled type in southern states, and 40 to 50 percent in northern states.

Roof ventilators and hinged roofs are typically clad with air-inflated double polyethylene. Side-wall ventilators are generally covered with double-wall polycarbonate or acrylic panel. Only the roll-up sides and the retractable roof are single-layer polyethylene. The higher heat loss in these latter single-layer polyethylene situations can be offset by installing thermal screens.

The advantage of all passively cooled greenhouses is energy conservation. Additional advantages that accrue from open-roof designs include better plant quality from higher light intensity and ability to achieve compact plants by DIF-type temperature manipulation. Disadvantages include the higher purchase price

Figure 15
A passively cooled, gutter-connected range of greenhouses at White's Nursery in Chesapeake, Virginia, covered with air-inflated double-layer polyethylene on the roofs and polycarbonate panel on the end and side walls. These greenhouses have peaked roofs that completely open up and side ventilators.
(Photo courtesy of the greenhouse supplier, X S Smith, Inc., P.O. Drawer X, Red Bank, NJ 07701.)

of passively cooled greenhouses and greater difficulty of excluding insects. It is difficult to figure the price for adding ventilators on to a polyethylene greenhouse on a floor area basis. A pair of ventilators attached at the ridge that open on both sides of the roof costs about \$50.00 per linear foot (\$197.00/m) for materials. If the greenhouse is 30 feet (7.6 m) wide, this would equate to \$2.00/ft^2 (\$21.52/m^2) of floor area. Drop-down side curtains cost about \$18.00 per linear foot (\$71.00/m) for materials. An additional disadvantage is the inability to install insect screens, since these would suppress the passive flow of cooling air through the greenhouse.

The gutter-connected greenhouse brings us full circle through the film plastic designs to the category of permanent metal-frame greenhouses, of which the glass greenhouse is a member. The major portion of new greenhouse construction in the world today is gutter-connected film plastic.

Figure 16
A gutter-connected range of retractable-roof greenhouses covered with a single layer of reinforced polyethylene film at Smith Gardens, Marysville, Washington. The greenhouse is open, with the roof film gathered at each truss.
(Photo courtesy of Cravo Equipment, Ltd., R R 1, Brantford, Ontario, N3T 5L4, Canada.)

Double-Layer Covering

A dead-air space provides the cheapest and most effective insulation for greenhouses. Ideally, the dead-air space should be 0.5 to 4 inches (1.3 to 10 cm) thick (U.S. Housing and Home Financing Agency, 1954). When it exceeds 4 inches (10 cm), air currents can become established inside and reduce the insulating property of this space. Warm air immediately above the inner covering rises up into contact with the outer covering, and here it gives up heat. As it cools, the air becomes heavy and drops back to the inner covering to pick up more heat. This loss does not become very significant until a space of 18 inches (46 cm) is reached. Below 0.5 inch (1.3 cm), the insulating property again diminishes, and when the two layers touch, the insulation value is totally lost.

Today, virtually all film plastic greenhouses make use of the air-inflated system. Two layers of film plastic are applied directly on top of each other from the outside of the greenhouse and are held apart by a cushion of air maintained at low positive pressure. This air-inflated system offers the easiest method for covering a greenhouse with two layers of film plastic. It ensures a longer life expectancy of the film because the outer layer of plastic rests on a cushion of air. Plastic applied by techniques other than the air-inflated system is constantly chafed against the trusses by the lifting and dropping action of the wind. This greatly reduces its life expectancy.

If the width of the film sheet needed to cover the greenhouse is 26 feet (7.9 m) or less, a roll of tube plastic can be used. This roll has effectively two sheets of plastic in it. Thus, only one roll needs to be applied to the roof to obtain two layers of plastic. If the covering width needs to be wider than 26 feet (7.9 m), two single layer sheets of plastic will have to be applied. Companies are offering two single sheets of plastic on a single roll so that both are applied simultaneously as the package is unrolled. This works better than the tube for two reasons. First, different plastics can be used in each layer. The anti-condensate and IR block additives can be in the bottom layer only since they are more expensive and not needed in the top layer. Second, the bottom layer can be pulled tighter than it could if it were part of a tube. By pulling it tighter, there is better flow of condensation down to the gutter, and thus less drippage to plants below. Rapid removal of condensation from the plastic also preserves the additives in the plastic for a longer time. Looseness and creasing of the lower layer of tube-applied polyethylene increases over the years. During covering of gutter-connected greenhouses, the roll of plastic is often suspended in the air on a spindle, which is customarily attached to a tractor. The roll is situated just off one end of the greenhouse and is level with and perpendicular to the ridge of the greenhouse. Each of the leading corners of the plastic is drawn by two individuals walking in the gutters on either side of one bay of the greenhouse to the opposite end. The ends of the sheet overlap the greenhouse ends by a few inches and are attached at that point. No attachment is made to the trusses. Two sheets of plastic are attached to each end of the greenhouse as well, unless polycarbonate or acrylic panels are used on the ends.

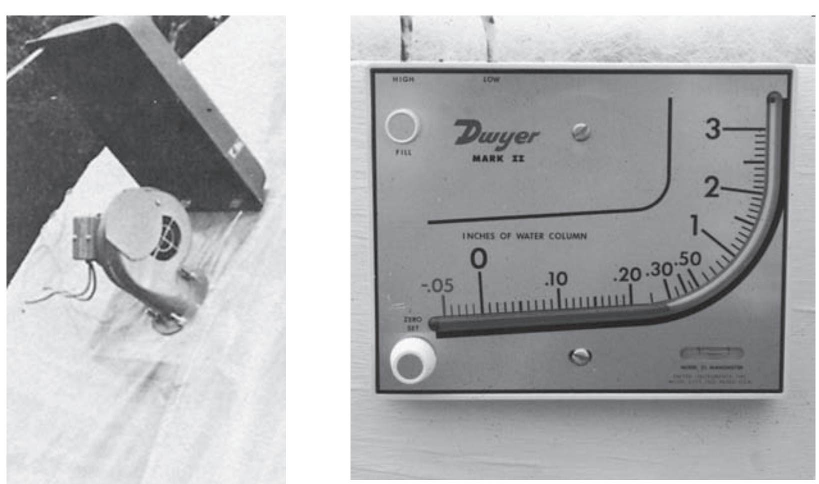
On a Quonset greenhouse, the plastic roof covering sheets are attached to a frame member running along the ground on either side. On a gutter-connected greenhouse, the plastic sheets are attached to a clamping channel located in the gutter. In either type of greenhouse, the ideal method of attachment is a clamping channel (Figure 17). Such channels may be purchased independently of the greenhouse or may be obtained as an integral part of the greenhouse. The layers of film plastic are laid over the channel, and then a metal rod or extrusion is placed over the film plastic and pushed into the channel, locking the plastic in place. Sometimes on self-fabricated Quonset greenhouses, the plastic is attached by placing a batten strip over it and stapling through it into the wooden member running along the ground on either side of the greenhouse. The batten strip is usually a thick plastic strip about

Figure 17
A clamping rail for attaching plastic film to greenhouses. The two layers of plastic are laid over an aluminum extrusion that is fixed permanently to the greenhouse frame. A second aluminum extrusion is pressed over the first extrusion and is locked in place with thumbscrews, thereby locking the plastic in place.

1 inch (2.5 cm) wide, which can be obtained from greenhouse-supply companies. Most prefabricated greenhouses are equipped with metal channel locks.

The tension under which the plastic is installed is important, since film plastics contract and expand to a considerable degree with temperature shifts. When it is applied on a cold day, the film should be pulled taut. On a hot day, with temperatures above 80°F (27°C), about 2 to 3 inches (5 to 8 cm) of slack should be left in the covering all the way along one side of a Quonset greenhouse 20 feet (6.1 m) wide to permit contraction over the truss when cold weather comes. If this slack is not allowed, the film will tear loose from the points of attachment when it contracts during cold weather. Conversely, if it is not pulled taut when applied on a cold day, excess slack will occur during warm weather, resulting in an excessive air space between the two layers.

A small squirrel-cage fan is installed inside the greenhouse to inflate the space between the two film plastic layers (Figure 18a). Air is maintained at between 0.2 and 0.3 inches (5.1 and 7.6 mm) of water-column pressure. Higher pressures are used



(a) (b)

Figure 18
(a) A squirrel-cage fan used to inflate the space between two layers of plastic. The plate on the side of the fan can be moved to adjust the air supply to the fan and, consequently, the pressure between the two coverings on the greenhouse.
(b) A manometer used to measure the air pressure between the two plastic covers.

during heavy winds—up to 0.5 inch (13 mm)—to prevent excessive movement and breakage of the film by the wind. The high pressure should not be maintained because the plastic will stretch. The fan should have an adjustable door on the air inlet for adjusting the pressure between the two films. For a greenhouse measuring 26 feet by 96 feet (8 m × 29.3 m), a fan delivering air at 200 to 400 cubic feet per minute (cfm) (5.7 to 11.3 cubic meters per minute [cmm]) at a static water pressure of 0.5 inch (13 mm) (about 1 amp, 115 W) is sufficient. During a snowstorm, when snow sticks to the roof, it may be necessary to turn off the fan. This will allow the two polyethylene layers to come together, thus eliminating the insulating effect of the dead-air space. More heat will escape through the covering to melt snow and clear it from the roof.

Air pressure between the plastic layers is monitored with a manometer, which can be purchased from greenhouse-supply companies (Figure 18b). Conversely, a manometer can be easily fabricated by the grower as follows:

1. Bend a 2-foot (61-cm)-long piece of clear plastic tubing into the shape of a U, and attach it to a board.
2. Make an X-shaped cut in the inner layer of plastic, and insert one end of the plastic tube.
3. Seal the film plastic to the tube with plastic tape.
4. Put about 8 inches (20 cm) of water in the tube such that it settles at the bottom of the U. Leave both ends of the tube open.
5. Attach a ruler vertically to the board behind or alongside the plastic tube.

Pressure between the layers of plastic will push the water down on the film plastic side of the U and up on the opposite side of the U. A rise in water level of 0.2 to 0.3 inch (5.1 to 7.6 mm) indicates the desired pressure. Coloring the water will help make it more visible.

The fan is generally mounted on the end wall of the greenhouse. A hole is cut in the end wall adjacent to the fan so that air feeding the fan is drawn in from outside. Outside air is colder than the air between the plastic layers. As the cold air warms in the roof cavity, it dries. This helps to control condensation between the layers of plastic. Such condensation leads to light reduction as well as corrosion problems. If warm moist air from inside the greenhouse were used, it would cool, and water would condense in the roof cavity. A second reason why inside air should not be used is that it may contain pesticide residues that cause deterioration of polyethylene. Chemicals containing bromine, chlorine, fluorine, iodine, sulfur, petroleum, and copper wood preservatives have the potential to degrade polyethylene.

A flexible tube, such as that used for a clothes dryer, is installed between the fan and the inner layer of plastic to be inflated. An X-shaped cut is made in the inner layer of plastic, and the tube is inserted through it. The four points of plastic resulting from the cut are pulled out over the tube and taped to it to make an airtight seal. Air is conducted from the fan to the inner space through this tube. This system is sufficient to inflate the entire roof of a Quonset greenhouse. Generally, the two layers of plastic pull tight at the ridge of an A-frame greenhouse, thus separating the roof into two inflatable portions. In this case, air from the fan can be divided in a 4-inch (10-cm) stovepipe tee and introduced to each side of the roof through flexible tubing immediately below the ridge. Side or end walls can be inflated as well without adding additional fans. Flexible connectors are sold for this purpose (Figure 19). Alternatively, pieces of garden hose can be inserted between the layers of plastic to connect the roof cavity to the end- or side-wall cavities.

Figure 19
A flexible jumper tube for connecting the air cavity between the two film plastic layers on the roof with the cavity in the side wall. This permits one fan to pressurize the two cavities.

RIGID-PANEL GREENHOUSES

Four types of rigid panels have been used to cover greenhouses. These are PVC, FRP, acrylic, and polycarbonate. PVC is no longer used and FRP is phasing out, whereas acrylic and polycarbonate are increasing in popularity.

Polyvinyl Chloride

PVC rigid panels have, for the most part, been dropped from use. Initially, they showed promise as an inexpensive covering (about 40 percent of the cost of long-lasting FRP). They had a life expectancy of five years or better at a time when polyethylene lasted one year. Commercial use of these panels soon indicated that this life expectancy was much shorter, sometimes as little as two years. This was unacceptable because the cost of PVC panels was four to five times that of polyethylene film and because they required much more time to install. Rigid PVC, like its film plastic counterparts, was subject to the deteriorating effect of UV light, which caused it to turn dark and become brittle. At first, light transmission was reduced; later, the panels would break apart. Rigid PVC was purchased in corrugated panels 26 or 28 inches (66 or 71 cm) wide and 8, 10, or 12 feet (2.4, 3.1, or 3.7 m) long. The panels were available in various colors; however, clear panels were used for general greenhouse culture.

Fiberglass-Reinforced Plastic

Role FRP was more popular as a greenhouse covering in the past. Its use is rapidly declining and very little is used today. Single layer corrugated polycarbonate sheets were first used to replace FRP because of their similar configuration, greater effective life, higher average light transmission over time, and equivalent price. Today, growers use twin wall polycarbonate panels in the place of FRP because the twin wall reduces heating cost to nearly half.

Where FRP is used, corrugated sheets are preferred because of their greater strength compared to flat sheets. Flat sheets are occasionally used on the end and side walls where the load is not as great. Sheets are available in 51.5-inch (1.3-m) widths, lengths up to 24 feet (7.3 m), and a variety of colors. The panels are flexible enough to conform to the shape of Quonset greenhouses, which makes FRP a very versatile covering material.

Figure 20
A Quonset greenhouse being covered with sheets of corrugated FRP.

FRP can be applied to the inexpensive frames of film plastic greenhouses (Figure 20) or to the more elaborate frames of glass-type greenhouses. In the former case, the price of the FRP greenhouse lies between that of a film plastic greenhouse and that of a glass greenhouse, but the cost is offset by elimination of the need to replace the film plastic. In the latter case, the initial cost of the FRP greenhouse is about the same as the glass greenhouse. However, over the long run, the FRP greenhouse costs more since the covering is replaced about every 10 years.

Prior to the advent of polycarbonate and acrylic panels, FRP offered advantages over glass. FRP is more resistant to breakage by factors such as hail or vandalism. Sunlight passing through FRP is scattered by the fibers in the panels, making light intensity rather uniform throughout the greenhouse compared to a glass covering. Plants on the north sides of beds, and particularly in the north beds as a whole, grow much better. This advantage of light scattering can also be attained with hammered glass, light-diffusing sun screens, some newer polycarbonate panels, and some polyethylene films designed to diffuse light.

There were disadvantages as well. The acrylic surface of FRP panels is subject to etching and pitting by dust abrasion and chemical pollution. Thus, glass fibers become exposed and subject to fraying, and they begin to collect dust as well as to harbor algae. The resultant effect is a darkening of the panels and a subsequent reduction in light transmission. The situation can be corrected by scrubbing the FRP surface clean with a stiff brush or steel wool and then painting on a new surface of acrylic resin. The material is inexpensive, but the labor is extensive. Since light transmission diminishes continually during the life of FRP, many growers in high-light areas such as Denver count on 10 years of use and then replace the FRP to regain maximum light transmission. By contrast, glass can last as long as a grower's life or longer.

Light Transmission The total quantity of light transmitted through clear FRP is roughly equivalent to that transmitted through glass (as shown in Table 2) but diminishes in relation to its color. For greenhouse crops in general, only clear FRP permits a satisfactory level of light transmission (88 to 90 percent). Colored FRP has found a limited use in greenhouses used for growing some houseplants that require low light intensity and in display greenhouses used for holding plants during the sales period.

Heat Transmission FRP has the distinct advantage over glass of being easier to cool. In a 13-month experiment conducted at Colorado State University with two greenhouses of identical size and style, one was covered with clear FRP and the other with glass. At the end of the 13 months, a total of 2,066 hours of cooling had been required in the glass greenhouse versus only 1,668 hours in the FRP greenhouse. This represented a reduction of 19 percent. The winter heat requirement of corrugated FRP greenhouses is about equivalent to that of structurally tight glass greenhouses.

Construction FRP greenhouses require fewer structural members than glass greenhouses since sash bars are not needed. The construction labor input is accordingly lower for an FRP greenhouse. The thickness of FRP is measured in terms of weight per square foot. Where a snow load is expected, 5-ounce weights (37 mil, 0.94 mm thick) are used on peaked roofs. The 4-ounce weight (30 mil, 0.76 mm thick) is common on arched roofs and vertical walls. Trusses are spaced 8 to 10 feet (2.4 to 3.1 m) apart, and purlins 4 feet (1.2 m) apart. FRP panels are 50.5 to 52.6 inches (1.28 to 1.34 m) wide but, with overlap, have an effective covering width of 48 inches (1.22 m).

The greenhouse must be constructed to be as airtight as possible. Corrugated plastic closures (Figure 21) are available for insertion between the FRP panel and frame components, such as the eave and the sill, to seal off outer air. Flashing is used at the ridge to cover the exposed ends of the FRP panels for the purpose of preventing water entry. The flashing can be constructed from aluminum or corrugated FRP. The FRP panels are attached to the purlins by aluminum screw nails or by aluminum wood screws. These nails and screws have a rubber washer immediately beneath the head to seal the hole made by the shaft.

Figure 21
A corrugated plastic closure strip in place, sealing off the outer air at the point of attachment of a corrugated FRP panel to the frame member.

Figure 22
U-shaped metal supports are placed between the purlin and the FRP panel to provide a space so that condensation water can flow along the inner surface of the panel to the ground or to a gutter. The pot label was inserted to demonstrate this space.

When condensation flows along the inner surface of FRP, it does so along the corrugation valleys. If the FRP panels are attached directly to the purlins, the corrugation valleys are in contact with the purlins. Condensation, upon reaching this point, flows onto the purlin and drips from its lower edge, thus causing harm to plants beneath. The FRP panel must be elevated away from the purlin. Metal U-shaped supports are placed between the purlin and the corrugation ridges of the FRP panel. The nail or screw attaching the panel to the purlin passes through the support (Figure 22).

Fire Hazard Many greenhouse structures are insured. One cause of destruction is fire, which is not a significant danger in glass greenhouses but a very definite concern in FRP greenhouses. The glass fibers themselves do not burn, but the polyester and acrylic resins binding them together do. Insurance rates are assessed according to the risk involved, which is greater for FRP than glass greenhouses. Fire-retardant FRP panels are available and carry the best rating for building materials (Class I). These panels offer no support for sustaining flames even when they are directly attacked. Benefits associated with standard greenhouse FRP are not associated with fire-retardant FRP by manufacturers; thus, these panels are not commonly used for greenhouses.

Acrylic and Polycarbonate

Acrylic and polycarbonate double-layer rigid panels have been available for about 25 years for greenhouse use. A number of research institutions have installed these panels, particularly acrylic. The acrylic panels are popular with research institutes due to their higher light transmission and longer life. There has been a steady increase in acceptance of rigid panels in the production greenhouse industry. The heaviest production use in the past was for glazing side and end walls on film plastic greenhouses (see Figures 14 and 15) and for total retrofitting of old glass and FRP greenhouses. Today, many new greenhouses are covered entirely with rigid plastic panels. As mentioned earlier, about 16 percent of greenhouses in the United States are covered with rigid plastics. Almost no FRP is used today, mainly because of its life expectancy and lower energy efficiency of its single layer compared to twin wall polycarbonate and acrylic panels.

Acrylic is preferred by many growers of plug seedlings, cut flowers, and vegetable fruit because these crops have higher light requirements than the other crop categories. For growers of these crops, acrylic is more often seen as an alternative to glass than polycarbonate. Polycarbonate tends to be used more often for bedding plant and perennial crops. The main deterrent to acrylic is its price. There is also an issue of fire risk. For building permit code requirements, polycarbonate is rated CC-1, whereas acrylic is rated CC-2. Plastic with burning extents of 1 inch or less per minute and 2.5 inches or less per minute when nominal thickness is 0.06 inches (1.5 mm) or thickness intended for use are rated CC-1 and CC-2, respectively. The advantages of acrylic over standard polycarbonate are its longer life expectancy, about 2.5 times, higher light transmission, lower transmission of heat, and resistance to hail damage for a much longer period of time.

Acrylic panels are available in thicknesses of 8 millimeters (0.32 in.) and 16 millimeters (0.64 in.). The 16-millimeter panels are more often used for the previously mentioned high-light crops due to their higher light transmission. Panels are warranted for 10 years against more than 4 percent loss in light transmission. The thinner panels can be bent to a radius of 48 inches (1.2 m) and the thicker panels to a radius of 108 inches (2.7 m), which allows these to be applied to curved roof greenhouses. Panels are available with an additive to prevent condensation drip. The two acrylic layers of these panels are held apart by ribs. The panels have a width of 47.25 inches (120 cm) and come in lengths of up to 39 feet (11.9 m). The effective covering width of the panel is 48 inches (122 cm), since the metal support member takes up space between panels. Heat-loss (U) values for 8-millimeter and 16-millimeter panels are 0.56 and 0.49 Btu per hour per square foot per degree Fahrenheit (Btu/hr/ft^2/°F) temperature differential from inside to outside the greenhouse (3.2 and 2.8 W/m^2/K), respectively. The heat-loss value for glass is 1.13 Btu (6.40 W/m^2/K), which is double or more than this. PAR light transmission is 84 and 86 percent for the 8- and 16-millimeter-thick acrylic panels, respectively. The 8-millimeter panels sell for \$2.50/ft^2 (\$26.91/m^2), while the 16-millimeter panels sell for approximately \$3.25/ft^2 (\$34.98/m^2). The aluminum extrusions for holding the panels cost \$1.00 to \$2.50/ft^2 (\$10.76 to \$26.91/m^2) of panel. A main cause of the price differential is an optional gasket seal. Acrylic is available in single layer corrugated sheets that are often used for partitions inside greenhouses. The price of these is \$1.80/ft^2 (\$19.38/m^2).

Polycarbonate panels are available in thicknesses of 4, 6, 8, 10, and 16 millimeters (0.16, 0.24, 0.32, 0.40, and 0.64 in.) and thicker. Today, the 8-millimeter thickness is used almost exclusively for greenhouses. It can be bent to a minimum radius of 55 inches (1.4 m) to fit greenhouse curvatures. Panels are available with and without an additive to prevent condensation drip. Since the cost differential is negligible, essentially all panels used have the anti-condensate feature. Panels used on greenhouses have UV light protection on one side. It is important when installing to place this side on the outer side exposed to sunlight. UV protection on both sides is an option elected by growers who have roofs that open to expose both sides to sunlight. However, anti-drip protection cannot be incorporated into a side that has the UV protectant. PAR light transmission for both lines of 8-millimeter panels is 81 percent. Standard panels are warranted for 10 years against more than 6 percent loss of light transmission and drip control. Polycarbonate panels with additional UV protection are available with a 10-year warranty against more than 2 percent loss of light transmission. The manufacturer estimates that these panels will last for 25 years. The price of these panels is about 20 percent more than that of the standard panels. Panels of 4- and 6-foot (1.2- and 1.8-m) widths are used on greenhouses. The 6-foot width has the advantage of one-third less support members for more light in the greenhouse. Lengths are available up to 48 feet (9.8 m). The heat-loss value is 0.58 Btu/hr/ft^2/°F (3.3 W/m^2/K) for the 8-millimeter panel. The standard 8-millimeter panels sell for

$1.50/ft^2 ($16.15/m^2), while the high-performance line with anti-drip, 100 percent light diffusion, and warranty of not more than 2 percent loss of light transmission over 10 years sells for $1.75 to $2.80/ft^2 ($19 to $30/m^2) of panel. The higher-quality aluminum extrusions that hold polycarbonate panels on the greenhouse cost an additional $1.50 for each square foot of panel.

There is a line of polycarbonate panels that the manufacturer claims will scatter 100 percent of light transmitted. This gives a more uniform distribution of light in the greenhouse. Light transmission in these panels is lower, at 79 percent, than the standard panel transmission of 81 percent. However, claims are made for improved growth. These panels have an added advantage in high-light regions. By breaking up direct rays of sunlight reaching the plant, a higher overall intensity can be allowed without light injury or excessive leaf-tissue temperatures. The increased light intensity promotes increased growth. Some of this effect is obtained from hammered glass, light-diffusing polyethylene, and FRP discussed earlier in this chapter. Heat transmission of these panels is equal to that of the standard panels.

Polycarbonate is also available in flat and corrugated single-layer sheets. Corrugated sheets are used by some growers for end walls of polyethylene greenhouses and by many growers for partitions within greenhouses. The trend has been to move from single-layer polycarbonate on end and side walls to twin-wall panels to reduce heating costs. Corrugated sheets are available with standard or scattered light transmission properties. Both have a heat transmission U value of 1.14 Btu/hr/ft^2/°F (6.40 W/m^2/K) and light transmission percentages of 90 and 85 percent, respectively. The standard sheets cost $1.00 to $1.25/ft^2 ($10.74 to $13.46/m^2). More recently, polycarbonate panels with three layers and two dead-air spaces have become available in 8-, 16-, and 25-millimeter thicknesses. It is the 8-millimeter thickness that is mostly used in greenhouses. The 8-millimeter panels with high UV light protection transmit 73 percent of PAR light and have a heat transmission U value of 0.47 Btu/hr/ft^2/°F (2.6 W/m^2/K). These panels cost about 20 percent more than the twin-wall panels but have 12 percent greater insulation value. There has been only a modest acceptance of these three-layer panels. Rather than use the triple-layer panel to increase fuel savings, many growers use a heat screen inside the greenhouse during the night. If they have installed a screen to reduce light intensity during the day or to block out light during the night for photoperiodic crops, they can use this screen on winter nights for retaining heat in the greenhouse.

BENCHES AND BEDS

Cut Flowers

The first choice in growing cut flowers is whether to grow them in raised benches or in ground beds. If the crop is of moderate height, such as chrysanthemum and snapdragon, raised benches can be used; however, these benches should be located close to the ground to keep the plants at a practical level for disbudding, spraying, and harvesting. Rose plants are grown in excess of five years and become very tall during this time. Most are grown in ground beds to minimize height. Carnations are grown from one to two years and also become very tall. Years ago, they were commonly grown in ground beds without bottoms, but the occurrence of a bacterial wilt disease nearly destroyed this business in the northeastern United States, and since then they have been grown in raised benches. (It was not possible to pasteurize the root substrate deep enough in the bottomless ground beds, and the disease continually recurred.)

If ground beds are selected, they should be constructed in a manner that isolates the root substrate contained within from external soil. In this way, the root substrate can be thoroughly pasteurized on a routine schedule, thus reducing the possibility of disease. Side walls can consist of treated wood or cement blocks. The wall should be at least 8 inches (20 cm) deep and extend down to a well-drained foundation substance, such as gravel (Figure 23). If the base substance is not well drained, drainage tile should be installed in this substance below each bed. Walks should be filled with gravel; paved walks should be sloped for drainage. It is important that walks be separated from beds to ensure that (1) the soil in them, easily contaminated by soil carried in on shoe bottoms, does not spread into the beds, and (2) water remains where it is applied, rather than running off into the walks.

An 8-inch (20-cm) concrete block serves as a good post to separate raised cut-flower benches from the ground. The bottom should have abundant drainage holes along its length. Raised bottoms should be as level as possible to prevent wet and dry areas. Benches are most commonly constructed from concrete or treated wood. Concrete benches can be poured in place or assembled from precast concrete boards. One board is used for each side; several boards, running lengthwise, are used for the bottom. The bottom boards have a 1/2-inch (1.3-cm) space between them for

Figure 23
(a) Drainage tiles embedded in gravel beneath a ground bed. (b) Ground beds with treated wood sides. The root substrate is placed on the gravel base containing the drainage tile.

(a)

(b)

drainage. Galvanized iron brackets are used to bolt the sides to a pipe frame or concrete cross-support beneath the bench floor.

The preferred wood for bench construction are cypress, redwood, locust, and cedar, because of their resistance to decay. Wooden benches should be painted with a copper naphthenate preservative. The natural preservative in redwood is corrosive to iron and steel; therefore, nails, screws, or bolts should be made of other types of metals such as aluminum, brass, or zinc.

The preferred widths of cut-flower benches and beds are 3.5 and 4.0 feet (1.1 and 1.2 m). Roses are conveniently grown in 4-foot (1.2-m)-wide beds because bushes are planted 1 foot (30 cm) apart in each direction. This permits four plants across the bed. The other cut-flower crops may be found in either width of bed. Except in very wide greenhouses, benches run the length of the greenhouse. The beds and benches should be 8 inches (20 cm) deep to accommodate 7 inches (18 cm) of root substrate. Rose beds, which should be 1 foot (30 cm) deep, are an exception. Eighteen-inch (46-cm) walks should be used between all benches, except in the center of the greenhouse, where a 2-foot (61-cm) walk should be established. This longitudinal arrangement of benches allows for the use of about 67 percent of the floor area for growing.

In more recent years, some cut-flower crops such as roses and gerbera have been grown in rows of individual containers filled with substrate such as coir coconut fiber. The containers are placed in troughs. Plastic tubes deliver nutrient solution to the top of each container. Excess solution leaches from the bottom of the container into the trough from which it is captured, pasteurized, and recycled.

Potted-Plant Crops

Raised benches are generally used for pot-plant crops. They should be 32 to 36 inches (81 to 91 cm) high for convenience of working. Benches should not exceed a 3-foot (91-cm) width if they are against a wall, or a 6-foot (1.8-m) width if they are accessible from both sides. It is difficult to handle plants in the center of wider benches, and labor becomes inefficient. It is important to have air circulation around each plant to reduce the incidence of condensation on foliage and thus the possibility of disease. Pot-plant benches should not have sides. The floor of the bench should be as open as possible. Spruce or redwood lath in woven wire, similar to snow fencing but manufactured more precisely for benches, makes excellent bench floors and is sold for this purpose. The spruce lath can be supported with a 2-inch-by-4-inch (5 cm × 10 cm) wooden frame (Figure 24) or by a pipe frame. The frame itself is often supported by concrete blocks. One-inch (2.5-cm)-square, 14-gauge welded-wire fabric and expanded metal also make excellent bench floors. UV-resistant polypropylene bench tops are available in 2-foot-by-4-foot (0.3 m × 0.6 m) modules that interlock to fit most bench configurations (Figure 25). All of these benches permit proper circulation of air.

A special category of pot-plant benches is used for ebb-and-flow culture. These benches are watertight to accommodate periodic flooding with fertilizer solution and are plumbed to a tank below them for holding the solution when it is not in use.

Cut-flower benches generally run lengthwise in a greenhouse to minimize the number of end posts needed for supporting plants and the time necessary to attach and tighten support wires. Since support is not a consideration in pot-plant benches, these benches usually run across the greenhouse to minimize the distance heavy pots need to be carried. A 3-foot-to-4-foot (0.9-m-to-1.2-m)-wide center aisle is provided along the length of smaller greenhouses to permit motorized carts to be used for transporting plants and materials. In larger greenhouse ranges, an 8-foot (2.4-m) center drive should be provided for larger internal transport equipment. Sidewalks

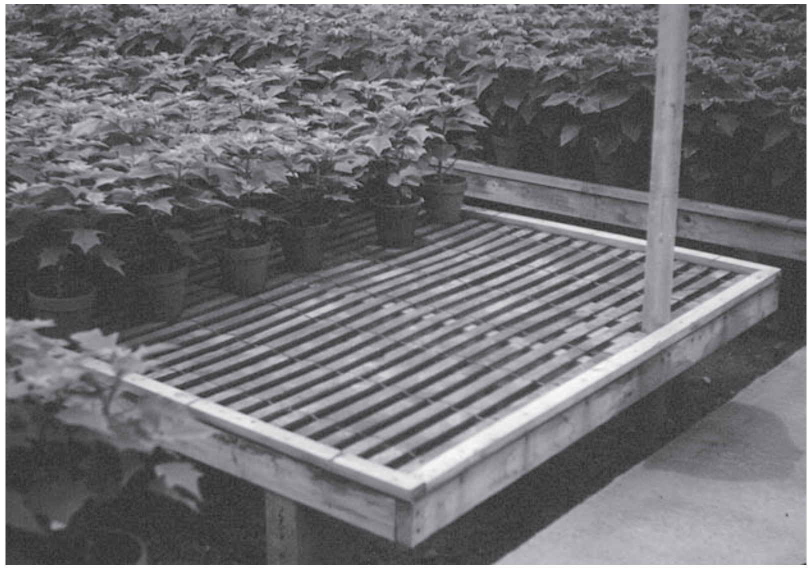


Figure 24
A raised pot-plant bench using spruce lath for the floor and 2-inch-by-4-inch (5 cm × 10 cm) wood frame. Cement blocks are used for legs.

Figure 25
Benches with UV-resistant polypropylene tops comprised of 2-foot-by-4-foot (0.3 m × 0.6 m) interlocking modules. Tops can be placed as shown on the fiberglass leg and frame assembly supplied by the manufacturer or on almost any other self-made frame and legs, including wood.
(Photo courtesy of Agri of Virginia, Inc./A-V International, Inc., P.O. Box 336, Broadway, VA 22815, E-Mail: agriavint@aol.com.)

should be 18 inches (46 cm) wide. Benches may be located at the ends of the walks. Benches in this arrangement are known as *peninsular benches*, and their use can result in as much as 80 percent growing area, as opposed to 67 percent in the longitudinal arrangement.

Movable-bench systems can increase production space up to about 90 percent of the floor space. By turning a crank at the end of the bench or by simply pushing the bench, the bench platform can be moved to either side. As a bench is moved from right to left, an aisle on the left side closes and a new aisle opens up on the right side (Figure 26). When several movable benches are used, only one aisle is needed, which can be shifted to any position.

The number of benches permitted per aisle is a difficult question. In a stationary-bench arrangement, a production operation could be carried out in each aisle simultaneously. This would be a benefit for crops requiring constant attention, such as frequent respacing, disbudding, pinching, or selection of plants for market. A crop such as Easter lily or poinsettia, which does not require as many production operations and is marketed over a short period, is well adapted to movable benches. As many as five benches may be used per 2-foot (61-cm) aisle for such a crop.

(a)

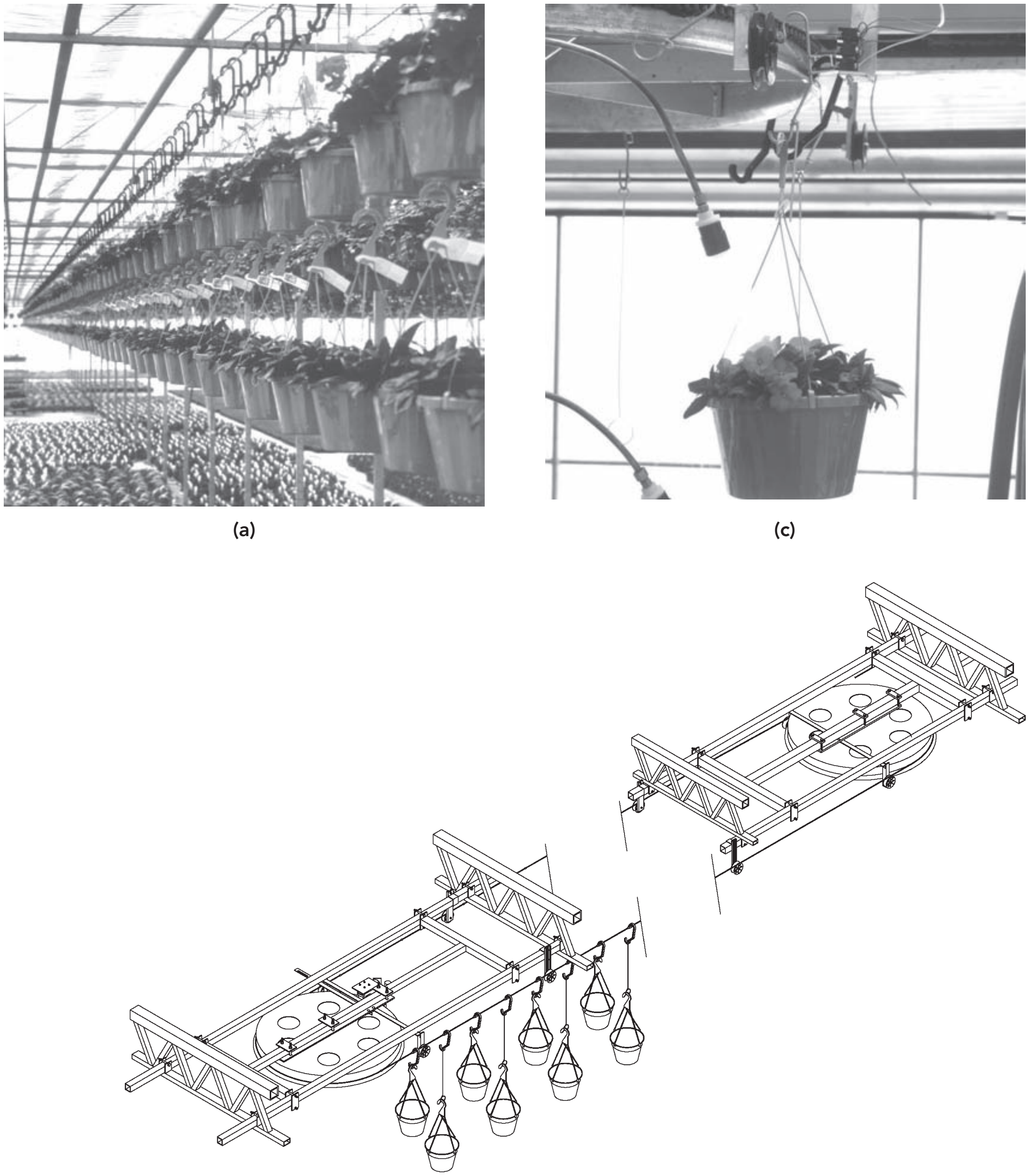
(b)

Figure 26
An aisle-eliminator bench system. (a) The bench on the right is in its extreme left position. (b) The bench on the right has been moved to its right position, thus shifting the aisle to the left of this bench.
(Photos courtesy of Simtrac, Inc., Skokie, IL 60076.)

Benches are an expense that is often forgotten in the pricing of a greenhouse firm. Prefabricated benches are available in many designs and cost approximately \$5.00/ft^2 (\$54.00/m^2) of bench. This figure includes \$0.75 to \$1.00/ft^2 (\$8.07 to \$10.76/m^2) of bench for labor. A high percentage of pot-plant firms raise hanging-basket crops in the air space above benches of pot crops. This allows the firm to use 100 percent of the floor space for production. Most restrict the hanging baskets to the space above aisles, while others place baskets over benches as well. It is best to orientate the rows of baskets in a north–south orientation so shadows cast by them move across the crop during the day rather than remaining stationary. If the baskets are hung in a stationary fashion, two problems arise. Water and nutrient solution drip from the baskets to the plants and floor below, and it is laborious to access these plants for maintenance. These problems are circumvented by a basket conveyor system (Figure 27). As described in the figure caption, these plants are moved to a central point for watering and fertilizing where the excess fluid applied can be captured. Plants below do not receive unwanted water or fertilizer to impair growth, nor do they stay wet to foster disease development. Labor savings are realized because plants are brought to a workstation where operations such as pinching or spraying can be conducted without tedious movement of personnel.

Recently, some growers have stopped growing hanging baskets over another crop. They feel that growth is reduced and flowering is delayed in the crop below. Faust at Clemson University found that overhead hanging baskets at a density of 1 per square yard (1.2/m^2) block about 8 percent of light when empty and 21 percent when full with plants from reaching the crop below.

A different concept for ridge-and-furrow ranges with a large single interior calls for paving the floor with porous asphalt or concrete and growing pot plants directly on the floor (Figure 28). Water percolates through the pavement to a gravel bed beneath, while weeds are unable to grow through this layer. Standard asphalt paving with a reduced quantity of binder can be used, or porous concrete made from a mixture of 2,800 pounds (1 yd^3, 0.76 m^3) of 3/8-inch (10-mm) dust-free gravel, 5.5 bags (94 lb, 43 kg each) of cement, and 23 gallons (87 L) of water can be used (Aldrich and Krall, 1978; Aldrich and Bartok, 1994). Porous concrete is generally poured in a layer 4 inches (10 cm) thick. It will withstand a working compressive strength test of 600 pounds per square inch (psi) (4,137 kPa). Light vehicles may be driven over the floor for setting up and removing crops. This system makes it possible to use 90 percent of the floor area for growing. A disadvantage occurs with crops requiring



(a) (c)

(b)

Figure 27

(a) The Echo system for suspending and moving overhead baskets. This system can hold one, two, or three tiers of baskets through the use of extended length hangers. (b) Baskets hang in a stationary fashion until it is time to water or work on them. Then the cable from which the baskets are suspended rotates, carrying baskets down one row and back the next. (c) As each basket passes a point in a central aisle, it is sensed, and water or fertilizer solution is applied automatically. Excess solution can be captured and discarded or recycled at this point. The conveyor can be stopped at each basket to allow operations such as pinching.

(Photos courtesy of Cherry Creek Systems, 2675 Akers Dr., Colorado Springs, CO 80922, Tel: 1 877-558-3246, Web: www.cherrycreeksystems.com.)

extensive hand labor operations, because working at ground level is fatiguing and takes its toll on labor efficiency. Bedding plants, azalea liners, some foliage plants, and poinsettias are well suited to this system. A concrete floor costs between \$2.00 and \$3.00/ft^2 (\$21.50 and \$32.30/m^2) for materials and labor, depending on its dimensions. Heating pipes in the floor cost an additional \$0.75/ft^2 (\$8/m^2).

Figure 28
A gutter-connected range in which pot plants are grown on a pavement of water-porous asphalt. Growing space is maximized in this greenhouse, and tractors or trucks can be used for moving plants and materials.

A recent evolution of the paved floor concept is the *flood floor*. This is a non-porous concrete floor that slopes from the sides to the center of each greenhouse bay. The perimeter of the floor in each bay has a side wall to contain water. An inlet/drain pipe is situated under the low point at the middle of the bay. When water or fertilizer solution is required, the floor is flooded for about 10 minutes. Water moves into the root substrate of the pot by capillary action. The floor is then drained. A complete flood floor costs around $10.00/ft^2 ($100/m^2) for the concrete floor, hot-water heat pipes in the floor, plumbing, tank, pumps, filter, controls, and labor.

COST OF GREENHOUSE CONSTRUCTION

Presented in Table 3 is the range of 2010 commercial construction prices for 1 acre (0.4 ha) of various types of greenhouses. Included in the basic structure category are the frame, ventilators for the cooling pads, greenhouse ends, doors, and covering. Labor includes placement of the unit heating and cooling systems. The heating systems are of the forced-air unit heater type. The cooling systems include a HAF system for winter cooling and a cross-fluted cellulose pad-and-fan system for summer. Greenhouse prices can vary more than is shown in Table 3. The strength of structural components can be reduced where no snow is expected, or increased in areas of abnormally high snow and wind.

The basic price of a polyethylene greenhouse can be as reasonable as $3/ft^2 ($32.28/m^2). This figure, however, does not include the covering, end walls, erection labor, heating, cooling, wiring, and plumbing. When these items are added, a polyethylene greenhouse can cost $18.50 to $19.50/ft^2 ($199 to $210/m^2). If benches and thermal screens are desired, the price goes up to $25.50 to $26.50/ft^2 ($274 to $285/m^2). Missing yet are the prices of land, grading, service buildings, access drives, and parking areas.

Low-profile glass greenhouses cost about $4.00/ft^2 ($43/m^2) more than polyethylene greenhouses. High-profile greenhouses are not priced in the table because at the present time they are higher in price than low-profile greenhouses. Other greenhouse coverings are not included in the table. Acrylic and polycarbonate panels on permanent frames could cost more than glass greenhouses. FRP on permanent frames would be priced similarly to glass greenhouses.

Table 3
Range of Prices ($/ft^2 of floor area) for 1 Acre (0.4 ha) of Gutter-Connected, Double-Layer Polyethylene and Low-Profile Glass Greenhouses[1]

Item	Polyethylene ($)	Glass ($)
Structure with cover	3.50–4.50	7.00–8.00
Erection labor	2.00–2.50	2.50
Heating system[2]	1.00–1.50	1.00–1.50
Cooling system[2]	2.50–1.50	2.50–1.50
Plumbing	1.00	1.00
Wiring	1.50	1.50
Subtotal	11.50–12.50	15.50–16.00
Benches and installation	5.00	5.00
Thermal screen and installation	2.00	2.00
Total	18.50–19.50	22.50–23.00
Polycarbonate twin wall ends[3]	1.00	—
Central heating system[3]	3.50–4.50	3.50–4.50

[1]Prices are derived from a broad range of greenhouse suppliers in the United States in 2010. $1/ft^2 = $10.76/m^2. Erection labor includes frame, covering, and heat and cooling systems. Greenhouses do not have ventilators other than over the cooling pads.
[2]The lowest heating and highest cooling prices represent firms in warm regions, while the opposite combination represents cold regions. Heating systems are of the forced-air unit heater type. Cooling systems include the summer fan-and-pad system plus the winter HAF system.
[3]Add these prices to the total to upgrade the greenhouse to these features.

Selection of a greenhouse should not be based solely on the total purchase price. Maintenance, such as re-covering polyethylene every 3 to 4 years or rigid panels every 10 to 20 years, must be assigned a cost. The 40 percent fuel savings in a double-layer film plastic greenhouse, or the nearly 50 percent fuel savings of acrylic and polycarbonate panels compared to single-layer glass, must enter into the decision. The predominant choice of the industry today is film plastic. There are, however, valid arguments in favor of glass. The higher light intensity inside modern glass greenhouses compared to double-layer polyethylene greenhouses more than offsets the higher price of the former for some growers. With the numerous options available and the differences in prices for greenhouse frames, coverings, heat-conservation systems, and heating systems, it is extremely important that a greenhouse operator study the available information and perform the appropriate cost analysis. With each additional purchase of energy conservation technology, the benefit per unit of cost declines.

NEW DESIGN INNOVATIONS

The greatest limiting factor to crop productivity in the winter in temperate-climate conventional greenhouses is low light intensity. The largest energy requirements in greenhouses are winter heating and summer cooling. All three of these problems can be addressed by a single design innovation (U.S. Patent #6,131,363) currently offered by Innovative Greenhousing Systems, Inc., of Greeley, Colorado.

During the winter, sunlight strikes greenhouse roofs at a low angle to the earth's surface. As a consequence, approximately 50 percent of this light reflects off the roof. This is unfortunate because this lost light, if captured, could be utilized for increased crop productivity and greater heating of the greenhouse at a time when heat input is required. During the summer, sunlight reaches the greenhouse roof in a more nearly vertical line. Thus, a much higher percentage of sunlight enters the greenhouse in the summer. This is also unfortunate because not all of this light is required, and much of it is converted to heat as it is absorbed by dark objects within the greenhouse. As a consequence, expensive screening systems are required to block part of this light from reaching plants, and high-energy cooling systems are needed to remove the excess heat from the greenhouse.

All of these problems are solved with triangular louvers that are affixed to the outer surface of the greenhouse roof (Figure 29). On greenhouses with north–south-oriented ridges, the louvers run from gutter to ridge. Figure 30 shows that each louver has a 4-inch-wide base (A) with adhesive for fastening to the outer greenhouse roof, an upper reflective surface magenta in color (B), and a lower reflective surface (C). Louvers can be fastened to glass, plastic panels, or corrugated plastic roofs.

The upper and lower reflective surfaces have different angles so that they work in unison with each other. During the short days of winter, the angle of light throughout the day is low enough that it strikes the louvered greenhouse roof in one of three places. First, it strikes the lower reflective surface and is reflected down into the greenhouse. Second, it strikes the upper reflective surface and is mainly reflected as white light (all wavelengths) to the lower reflective surface of the next louver and from there reflected into the greenhouse. Third, it strikes the greenhouse roof between the louvers, where it may either enter the greenhouse or be reflected to the lower reflective surface of the next louver and from there be reflected into the greenhouse. Virtually all light is transmitted into the greenhouse.

The more vertical light during the brighter months of the year, between the spring and fall equinoxes, may strike the roof between louvers and enter the greenhouse. If some of this is reflected from the glazing, it will strike the lower reflective surface of the next louver and then be reflected away from the greenhouse. The remaining light strikes the upper louver surface, where it can be reflected away from the greenhouse, absorbed by the louver, and converted into heat that is dissipated to air outside the greenhouse, or a small portion may be reflected as blue and red light to the lower surface of the next louver and reflected into the greenhouse.

Magenta is a combination of blue and red light, the two colors of light preferentially used in photosynthesis. Light striking the upper magenta louver surface during the brighter period of the year is divided into blue and red light that is reflected, with the remaining colors being absorbed and converted to heat. By

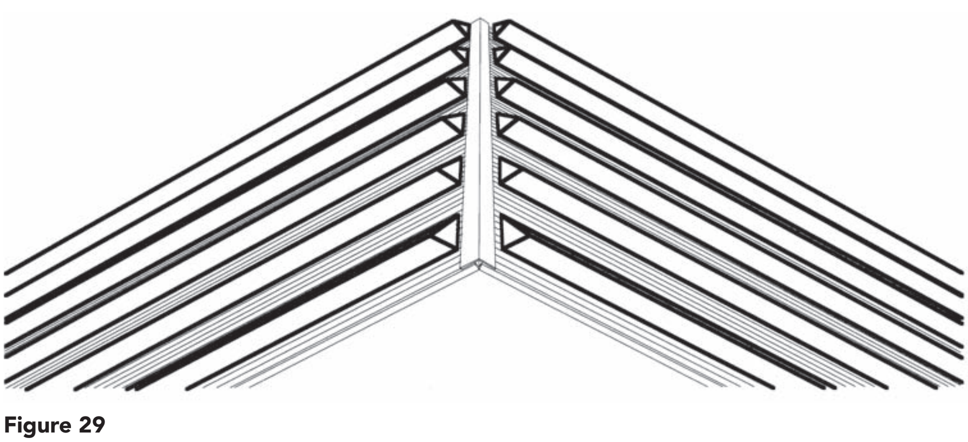


Figure 29

A view from the south of a greenhouse with a south-to-north-oriented ridge, showing the eave-to-ridge orientation of IGS (Innovative Greenhousing Systems) light-reflecting louvers.

(Picture courtesy of Robert D. Phillips, Architect, Innovative Greenhousing Systems, Inc. 512 N. 8th. St., Beresford, SD 57004, E-Mail: phillipsigs@aol.com.)

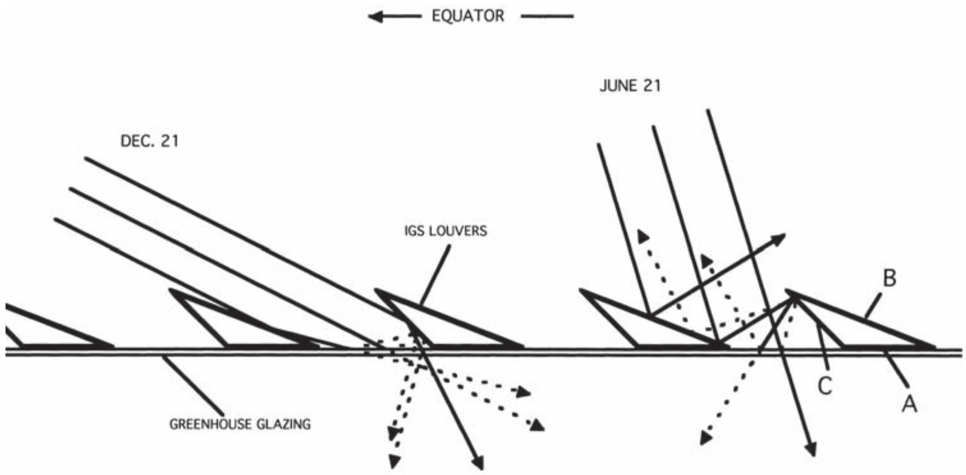


Figure 30
Paths of light enter into a greenhouse at 40°N latitude equipped with IGS light-reflecting louvers (attached to the greenhouse glazing with adhesive at point A) at solar noon on the shortest (December 21) and longest (June 21) days of the year. During the short days of winter, light can strike the lower reflective surface (C) and be reflected down into the greenhouse, strike the upper reflective surface (B) and be mainly reflected as white light (all wavelengths) to the lower reflective surface of the next louver and from there be reflected into the greenhouse, or strike the greenhouse roof between the louvers where it either enters the greenhouse or is reflected to the lower surface of the next louver and from there is reflected into the greenhouse. The more vertical light during summer can strike the roof between louvers and enter the greenhouse. If some of this is reflected from the glazing, it will strike the lower reflective surface of the next louver and then be reflected away from the greenhouse. The remaining light strikes the upper louver surface, where it can be reflected away from the greenhouse, absorbed by the louver, and converted into heat that is dissipated to air outside the greenhouse, or a small portion may be reflected as blue and red light to the lower surface of the next louver and reflected into the greenhouse. Virtually all light is transmitted into the greenhouse during the short days of the year, whereas half or more is blocked from entering the greenhouse during the bright days of the year.

(Picture courtesy of Robert D. Phillips, Architect, Innovative Greenhousing Systems, Inc., 512 N. 8th. St., Beresford, SD 57004, E-Mail: phillips@aol.com.)

restricting light reflected into the greenhouse during the summer to blue and red, the most efficient wavelengths for photosynthesis are preserved, while the others are blocked to reduce the greenhouse heat load.

While louvers raise the cost of a greenhouse, they have many compensating features, including greater yield from higher winter light levels; lower winter heating bills; no need for a summer light screening system; lower summer cooling costs; and a lower crop water consumption during the summer, because excess plant temperatures are avoided.

This development offers numerous additional possibilities. Magenta pigment could be selectively painted onto specific slopes of corrugated FRP or polycarbonate sheets. Second, ridge-and-furrow greenhouses could be constructed in such a way that each serves as a louver, thereby capturing most of the winter light. Such ranges would be oriented with ridges from east to west. The south transparent roof would then be constructed with a steeper and shorter slope than the north-sloping opaque magenta roof. In this way, each greenhouse would serve as a louver, gathering light through the south slope and reflecting light from the north slope into the next greenhouse. Since light would not enter through the north roof, it could be heavily insulated for heat conservation.

SUMMARY

1. Greenhouse location is as important as the greenhouse design itself. Factors to be sought in a location are as follows:
   1. Room for expansion.
   2. A level, well-drained site.
   3. Reasonable tax structure at present and in the future.
   4. A climate favorable for the crop intended.
   5. Available labor.
   6. Reasonable proximity to utilities and shipping routes.
   7. A plentiful supply of high-quality water.

2. The greenhouse-business floor plan is crucial to efficiency. Greenhouses should be consolidated into a square block to minimize distances for material movement, increase ease of personnel management, and reduce heating and automation costs. There should be a single service building centrally situated. The whole range should be on a single elevation.

3. Glass greenhouses are permanent and can last as long as the owner's life or longer. The material expense and labor of periodically replacing the covering are eliminated with glass, but the overall cost of a glass structure is higher. There are two general styles: high-profile greenhouses, which can be freestanding or connected in a ridge-and-furrow fashion, and low-profile Dutch-type greenhouses, which are constructed in a ridge-and-furrow style only because of their narrow bay width, which was originally 10.5 feet (3.2 m) but now extends up to 31.5 feet (9.6 m).

4. Film plastic greenhouses are the least expensive to build. They lend themselves well to temporary business ventures, businesses operated for only one season of each year, and locations where there is a tax advantage for nonpermanent structures. Film plastic greenhouses offer an inexpensive means of entering the flower-growing business. However, film plastic ranges can be built on permanent, metal, gutter-connected frames, permitting the full degree of automation and efficiency of any glass or rigid plastic panel range. Polyethylene is the most common film plastic in use and is usually applied as an air-inflated double layer. The insulating property of the double layer reduces fuel consumption by about 40 percent over a greenhouse with a single covering of polyethylene, glass, or FRP, which makes the double-layer polyethylene greenhouse less expensive to purchase and operate in spite of the periodic labor and the cost of replacing the plastic. Film plastic greenhouses constitute the greatest portion of new greenhouse construction.

5. Acrylic and polycarbonate double-layer panels are commonly used for side and end walls on film plastic greenhouses and for retrofitting old glass and FRP greenhouses. Many new greenhouses are fully covered with these panels. These panels reduce heat loss by about 50 percent compared to single layer glass. They transmit more light than a double layer of polyethylene. The acrylic panels transmit more light and hold heat a little better than the polycarbonate panels but they cost more. The common thickness of polycarbonate panel is 8 millimeters and its width is 6 feet (1.8 m). Eight- and 16-millimeter thick acrylic panels by 4 feet (1.2 m) wide are used with the 16-millimeter panels more popular on greenhouses used for high-light-requiring crops. Both types of panels can be bent to fit most greenhouse roof curvatures.

6. Cut-flower crops are grown in either ground beds or raised benches. Such beds are either 3.5 or 4 feet (1.1 or 1.2 m) wide and are generally 8 inches (20 cm) deep, but 1 foot (30 cm) depth is best for rose beds. Cut-flower beds are oriented along the length of the greenhouse with 18-inch (46-cm) aisles between them. This arrangement of beds allows for 67 percent utilization of floor space for growing.

7. Pot plants can be grown on raised benches or directly on the floor. Raised benches have open bottoms constructed from wire hardware cloth, expanded metal, spruce lath, or treated boards with at least a 1/2-inch (1.3-cm) space between them. Sides are either not used or are low. Benches are usually 5 to 6 feet (1.5 to 1.8 m) wide and are arranged in a peninsular style. A central aisle, 3 feet (91 cm) wide in small greenhouses and 8 feet (2.4 m) in large greenhouse blocks, runs the length of the greenhouse. Benches and smaller aisles radiate out from the central aisle to either side. Such an arrangement makes more efficient use of floor space—up to 80 percent growing area—and minimizes hand carrying of plants. Some pot crops are grown directly on floors paved with porous asphalt or concrete. Water penetrates the floor, while weed growth is inhibited. Others grow on nonporous concrete ebb-and-flood floors. These latter two systems permit use of up to 90 percent of the floor space.

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Greenhouse Heating

Heat is measured by the *British thermal unit* (Btu), defined as the amount of heat required to raise the temperature of 1 pound of water 1°F. When the number of Btu's required becomes large, as in heating greenhouses, it is more convenient to use the larger unit, *horsepower* (hp). One boiler horsepower is equivalent to 33,475 Btu. To convert from Btu to boiler horsepower, divide Btu's by 33,475. In the metric system, a *calorie* (cal) is defined as the amount of heat required to raise 1 gram (g) of water 1°C. One *kcal* equals 1,000 cal, or 3.968 Btu. In international units, the *joule* (J) is used, which is equivalent to 0.239 cal or 0.00095 Btu. Reciprocally, 1 Btu equals 252 cal, or 1,055 J. One *watt* (W) is equal to 1 J per second.

TYPES OF HEAT LOSS

The requirements for heating a greenhouse reside in adding heat at the rate at which it is lost. Most heat is lost by *conduction* through the covering materials of the greenhouse. Different materials, such as aluminum sash bars, glass, polyethylene, and cement curtain walls, vary in the rate at which each conducts heat from the warm interior to the colder exterior. For instance, aluminum sash bars conduct heat faster than wood, which results in more rapid loss of heat. (Since the upkeep of wood, however, is much greater, its use is not justified.) Listed in Table 1 are heat-loss (U) values for several greenhouse coverings. A greenhouse covered with one layer of polyethylene, for example, loses 1.10 Btu of heat through each square foot of covering every hour when the outside temperature is 1°F lower than the inside. When a second layer of polyethylene is added, only 0.7 Btu is lost. This is a reduction of almost 40 percent of the heat loss.

There are limited ways of insulating the covering material without blocking light transmission. A dead-air space between two coverings appears to be the best system. Forty percent of the heat requirement can be saved when a second covering is applied. The savings diminish when the air space between the two coverings increases to the point where air currents can be established in the space—generally with a spacing of 18 inches (46 cm) or greater—and the insulation value is completely lost when the two layers touch each other.

Table 1
HEAT LOSS THROUGH VARIOUS GREENHOUSE COVERINGS

Covering Material	Heat Loss (U)[1] Btu	Heat Loss (U)[1] W	Radiation Loss[2] (percent of total)
Glass, single layer	1.13[3]	6.4	4.4
Glass, double layer	0.65	3.7	
Glass, triple layer	0.5[4]	2.8	
Glass, single layer with thermal blanket in greenhouse	0.7	4.0	
Glass with single layer plastic over it	0.85[3]	4.8	
Glass with double layer separated plastic over it	0.60[3]	3.4	
Polyethylene film, single layer	1.1	6.2	70.8
Polyethylene film, double layer	0.70	4.0	
Polyethylene film, double layer with thermal blanket in greenhouse	0.44	2.5	
Polyvinyl fluoride film, single layer, Tedlar	0.92[5]	5.2	30.0[6]
Polyester film, single layer, Mylar[5]	1.05[5]	6.0	16.2
PVC, (polyvinyl chloride) single, corrugated, rigid panel[5]	0.92[5]	5.2	
FRP (fiberglass reinforced plastic) single, corrugated, rigid panel	1.0	5.7	1.0
Polycarbonate, single, corrugated, rigid panel	1.14[5]	6.5	
Polycarbonate, single, corrugated, rigid, light diffused panel	1.14[5]	6.5	
Polycarbonate, twin wall, 8-mm panel	0.58[5]	3.3	
Polycarbonate, twin wall, 8-mm light diffused panel	0.58[5]	3.3	
Polycarbonate, triple wall, 8-mm panel	0.51[5]	2.9	
Polycarbonate, triple wall, 16-mm panel	0.42[5]	2.4	
Acrylic, twin wall, 8-mm panel	0.56[5]	3.2	
Acrylic, twin wall, 16-mm panel	0.49[5]	2.8	
Curtain Wall Materials			
Corrugated cement asbestos board	1.15[3]	6.5	
Concrete, 4-inch (10-cm)	0.78[3]	4.4	
Concrete, 8-inch (20-cm)	0.58[3]	3.3	
Concrete block, 4-inch (10-cm)	0.64[3]	3.6	
Concrete block, 8-inch (20-cm)	0.51[3]	2.9	

[1]Btu/hr/ft^2/°F, W/m^2/K; U is the combined loss of heat due to conduction and radiation. From American Society of Agricultural and Biological Engineers (ASABE) (2008) unless otherwise indicated.
[2]Radiation loss is the amount of radiant heat passing through the covering expressed as a percentage of the total radiant heat beaming upon it. From Duncan and Walker (1973).
[3]From National Greenhouse Manufacturers Association (2010).
[4]From Bartok et al. (2001).
[5]Manufacturer's specifications.
[6]From Whillier (1963).

Although thermopane glass panels (two layers of glass factory-sealed with a dead-air space) significantly reduce heat loss, they have been too expensive to justify. Sash bars that hold two and even three layers of glass are available from some manufacturers. This establishes one or two dead-air spaces between the layers of glass and yields overall U values of 0.65 and 0.5 Btu (3.7 and 2.8 W), respectively. Double-layer rigid panels of either acrylic or polycarbonate plastic also utilize the concept of dead-air space for heat conservation. Although more expensive than conventional coverings, these materials have lower U values of 0.49 to 0.58 Btu (2.8 to 3.3 W).

A second mode of heat loss is air *infiltration*. Spaces between panes of glass or rigid plastic sheets and around ventilators and doors permit the passage of warm air outward and cold air inward. A general assumption holds that the volume of air held in a greenhouse can be lost as often as once every 60 minutes in a double-layer film plastic greenhouse; every 40 minutes in a twin-wall panel or new glass greenhouse; every 30 minutes in an old, well-maintained glass greenhouse; and every 15 minutes in an old, poorly maintained glass greenhouse (Table 2).

Table 2
AIR INFILTRATION IN GREENHOUSES[1]

Type of Greenhouse Construction	Air Exchanges per Hour
New construction: double layer plastic film	0.5–1.0
New construction: glass, FRP, polycarbonate and acrylic panels	0.75–1.5
Old construction: glass, good condition	1.0–2.0
Old construction: glass, poor condition	2.0–4.0

[1]From Bartok et al. (2001).

About 10 percent of the total heat loss from a structurally tight glass greenhouse occurs through infiltration loss.

A third mode of heat loss from a greenhouse is *radiation*. Warm objects emit radiant energy, which passes through air to colder objects without warming the air significantly. The colder objects become warmer. Glass, vinyl plastic, fiberglass-reinforced plastic (FRP), and water are relatively opaque to radiant energy (do not readily permit the passage of radiant heat), whereas polyethylene is not (see Table 1). Polyethylene greenhouses can lose considerable amounts of heat through radiation to colder objects outside, unless a film of moisture forms on the polyethylene to provide a barrier.

HEATING SYSTEMS

The heating system must provide heat to the greenhouse at the same rate at which it is lost by conduction, infiltration, and radiation. There are three popular types of heating systems for greenhouses. The most common and least expensive is the *unit heater* system. In this system, warm air is blown from unit heaters that have self-contained fireboxes. Heaters are located throughout the greenhouse, each heating a floor area of 2,000 to 6,000 square feet (186 to 558 m^2). A second type of system is *central heat*, which consists of a central boiler that produces steam or hot water (more commonly hot water), plus a radiating mechanism in the greenhouse to dissipate the heat. The third type of system is *radiant heat*. In this system, gas is burned within pipes suspended overhead in the greenhouse. The warm pipes radiate heat to the plants. There is a fourth possible type of system, although it has gained almost no place in the greenhouse industry: the *solar heating* system. Solar heating is still too expensive to be a viable option.

In all greenhouse heating systems, it is important that the exhaust not contact the crop. Exhaust from all heaters should be vented to the outside of the greenhouse. Woody plant nurseries sometimes overwinter their sensitive stock in white polyethylene greenhouses heated to a minimal temperature to avoid freezing. Often they use inexpensive unvented heaters that expel exhaust directly into the greenhouse. They get by with this because heaters are not used many nights, they run for short periods when they are used, and plants are not actively growing. This system should never be used in floral and vegetable greenhouses.

When the fuel source is of high purity and thoroughly combusted, only carbon dioxide and water vapor are produced—but it is rare that fuels are completely combusted. Products of incomplete combustion, including ethylene gas, are injurious to plants (Figure 1). Ethylene gas can cause a distorted, corkscrew type of stem growth, curling of leaves, narrow leaves, and abortion of buds. The threshold concentration of ethylene for injury is 0.01 to 0.1 ppm. Exposure to 0.1 ppm for 24 hours is generally injurious, and exposure to 10 ppm for a few hours usually kills

Figure 1
Ethylene gas injury to chrysanthemums caused by fumes escaping from an improperly vented unit heater inside the greenhouse. Leaves are distorted and abnormally narrow, and the terminal bud has aborted.
(From J. W. Love, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.)

the plant. Butylene and propylene, contaminants in butane and propane gases, cause similar injuries but at higher concentrations of these contaminants. It is easy to draw air samples and have them analyzed for ethylene. For sample vials and instructions, contact the Plant Disease and Insect Clinic, Campus Box 7211, North Carolina State University, Raleigh, NC 27695-7211. The price is $25 for samples from North Carolina and $100 for out-of-state samples.

Fuels also contain impurities. Sulfur is commonly found in coal, oils, and gases. Upon combustion, it is released as sulfur dioxide gas (SO_2). Sulfur dioxide gas dissolves into moisture films on the plant surfaces and is converted to sulfurous acid and, after oxidation, sulfuric acid, which burns the cells it contacts (Figure 2). Small tan spots appear, or in severe cases, the entire leaf may die.

Unit Heater Systems

Unit heaters are often referred to as *forced-air heaters*. The price of a unit heater system varies with the climate in which it is located. The typical cost, including installation labor, is $1.00 to $1.50/ft^2 ($10.76 to $16.15/m^2) of greenhouse floor.

Figure 2
Sulfur dioxide injury on Rieger begonia foliage. Improperly vented heaters can emit the gas. Carbon dioxide generators burning fuel with an undesirably high sulfur content also produce toxic levels of this gas inside the greenhouse.

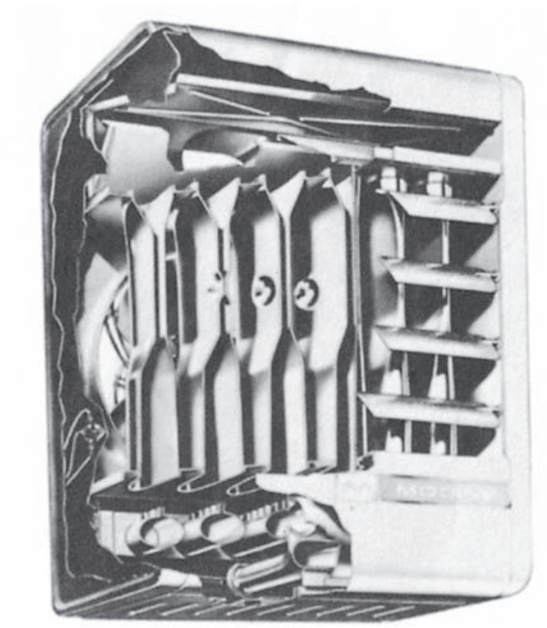


Figure 3
Interior view of a horizontal unit (forced-air) heater. Fuel is combusted in the chamber at the bottom. Hot fumes rise inside the heat-exchanger tubes, giving up heat to the walls of the tubes. Smoke exits at the top rear into a stack. A fan behind the unit forces cool greenhouse air over the outside of the tubes, where it picks up heat.
(Photo courtesy of Modine Manufacturing Company, Racine, WI 53401.)

The low initial investment for the unit heater system is suitable for greenhouse firms that start small and expand steadily, purchasing heaters as needed.

Unit Heaters These heaters consist of three functional parts, a firebox, heat exchanger, and fan, as illustrated in Figure 3. Fuel is combusted in a firebox to provide heat. The heat is initially contained in the exhaust, which rises through the inside of a set of thin-walled metal tubes on its way to the exhaust stack. The warm exhaust transfers heat to the cooler metal walls of the tubes. Much of the heat is removed from the exhaust by the time it reaches the stack through which it leaves the greenhouse. A fan in the back of the unit heater draws in greenhouse air, passing it over the exterior side of the tubes and then out the front of the heater to the greenhouse environment again. The cool air passing over hot metal tubes is warmed. In short, the metal tubes serve as heat exchangers, absorbing heat from the hot exhaust passing through the inside of them and transferring it to the cool greenhouse air passing over the outside of them.

Generally, the fuel supply and fan are controlled by a temperature sensor located in an appropriate area of the greenhouse. Heat is supplied only as needed. Unit heaters burn a variety of fuels, including No. 2 oil, kerosene, LP gas, and natural gas. Fuel types, however, cannot be changed without alteration to the unit heater.

Unit heaters come in vertical as well as horizontal designs (Figure 4) based upon the direction in which the heated air is exhausted from the heater. Vertical heaters take in air from the ridge area of the greenhouse and expel it downward toward the floor. These heaters are purchased in a size capable of heating a square area having sides equal to the width of the greenhouse. They are suspended from the ridge of the greenhouse, well above head height, and are spaced along the length of the greenhouse at intervals equal to its width. When unit heaters first became popular in the 1940s, the vertical type was believed best for greenhouse application. Uneven temperatures and drying of the soil sometimes occurred, which resulted in nonuniform growth. Horizontal unit heaters are the standard heaters used today. The uneven temperature and drying problems are reduced with horizontal air distribution. It is possible to use fewer but larger heaters, thus reducing the initial cost of the heaters as well as the labor of installation. Horizontal heaters are also adaptable to the newer integrated systems of heating, cooling, and horizontal airflow (HAF).

Figure 4
(a) A vertical unit heater typical of the early types used for greenhouse heating. (b) Horizontal unit heaters commonly used today.

(a)

(b)

Whenever fuel is combusted, oxygen is consumed. Old glass greenhouses may or may not have sufficient air leaks to provide the needs of the firebox. Plastic greenhouses are tighter, and there have been many cases where burners have gone out during the night after consuming the available oxygen, causing the crop to freeze. A shortage of oxygen often leads to the formation of odorless carbon monoxide gas before the flame goes out. *An employee entering such a greenhouse could lose his or her life.* As a general rule, 1 square inch of opening from the outside should be provided near the heater for every 2,500 Btu capacity of the heater (1 cm^2/114 W). A stovepipe, tile, or flexible clothes dryer tube may be placed near the burner intake, extending outside. It is frequently buried for convenience. An 8-inch (20-cm)-diameter pipe would provide the 50 square inches required for a 125,000-Btu (5,700-W) heater. The end of the tube should be covered with a screen to prevent the entry of animals.

Figure 5
A horizontal unit heater connected to a transparent polyethylene convection tube with holes along either side for uniform distribution of heat.

The exhaust stack on unit heaters must be sufficiently tall to develop an updraft to draw fumes out of the heater and must be high enough above the greenhouse roof to permit dissipation of the smoke without reentry into the greenhouse. The stack should extend 8 to 12 feet (2.4 to 3.7 m) above the firebox to ensure a proper air draft.

Heat Distribution: Convection Tubes In very small greenhouses, the fan in the unit heater may be sufficient to distribute the heat uniformly throughout the greenhouse. But most commercial greenhouses are too large for such simplicity. For these, two warm-air distribution systems exist: *convection tubes* and *horizontal airflow*. In the convection-tube system, a transparent polyethylene tube is connected to the air outlet of the unit heater (Figure 5). The polyethylene tube is installed along the length of the greenhouse above plant height and is sealed at the distant end. Round holes 2 to 3 inches (5 to 8 cm) in diameter are located in pairs at opposite sides of the tube every few feet (0.5 to 1.0 m) along the tube length. Warm air from the heater moves through the tube and out the side holes. The warm air comes out at a high velocity in a jet stream and quickly mixes with the surrounding air. This system ensures that heat is distributed from one end of the greenhouse to the other. When neither heating nor cooling is required, many growers keep the fan in the unit heater running without heat so that air from the greenhouse is continuously circulated through the tube. Air circulation gives more uniformity of temperature in the greenhouse, conserves heat, and reduces the occurrence of disease by reducing condensation on plant foliage. The polyethylene tube is also used to bring in cold air and distribute it when cooling is needed during the winter.

Care must be taken to locate unit heaters and air distribution tubes below any thermal screens and photoperiodic shade blankets that may be used in the greenhouse. Some firms have installed air distribution tubes beneath benches. This is feasible only where long benches are situated in such a manner that the tubes do not need to cross aisles.

Heat Distribution: Horizontal Airflow A more recent and more desirable system for establishing uniform temperature in greenhouses is the HAF system developed at the University of Connecticut. This system uses small horizontal fans for moving the air mass (Figure 6).

The greenhouse may be visualized as a large box containing air. It is difficult to start the air moving, but once it is moving in a circular pattern, like water in a

Figure 6
Horizontal airflow (HAF) fans in a gutter-connected greenhouse range. These fans are used to distribute warm air from the heaters, incoming cold air during winter cooling, and interior greenhouse air when neither heating nor cooling are on.

bathtub, it is easy to keep it moving. The horizontal airflow pattern of the HAF system also results in the movement of warmer air from the gable to plant height, thereby reducing heating costs. Temperatures at plant height are more uniform with the HAF system than with other systems.

Minimum and maximum airflow velocities for this system are 50 and 100 feet per minute (fpm) (0.25 and 0.5 m/sec). Below this level, airflow is erratic, and uniform mixing of air cannot be assured. A velocity of 50 fpm (0.25 m/sec) causes slight leaf movement on plants with long leaves, such as tomato. This system should move air at 2 to 3 cfm/ft^2 (0.6 to 0.9 cmm/m^2) of floor space. Fans of 1/30 to 1/15 horsepower (31 to 62 W) and a blade diameter of 16 inches (41 cm) are sufficient. Commercial, continuous-duty motors should be used. With approximately one fan per 50 feet (15.2 m) of greenhouse length, fans should be aimed directly down the length of the greenhouse and parallel to the ground. The first fan should be installed no closer than 10 to 15 feet (3.1 to 4.6 m) from the end of the house; the last one should be placed, 40 to 50 feet (12.2 to 15.2 m) from the end toward which it is blowing.

Specifications for the HAF system are shown in Figure 7 and can be described as follows.

1. For individual houses, install two rows of fans along the length of the greenhouse, each row one-quarter of the width of the greenhouse in from the side wall. The row of fans on one side of the greenhouse should blow air opposite to the direction of the row of fans on the other side of the greenhouse to form a circulating pattern. Fans should be 2 to 3 feet (0.6 to 0.9 m) above the plants. A unit heater serves as the first fan in one row of small greenhouses of approximately 2,000 ft^2 (186 m^2). In larger greenhouses, particularly in cold climates, two unit heaters are installed in opposite corners of the greenhouse such that each heater substitutes for the first fan in each row of fans. This places the heat source in the path of the airflow. The fan in the unit heater serves to circulate the air.
2. For ridge-and-furrow houses, install a row of fans down the center of each greenhouse. A unit heater should be substituted for the first fan in each greenhouse. If the block contains an even number of greenhouses, move air down one house and back in the adjacent greenhouse. In this way, each pair of greenhouses has a circulating air pattern. Connecting gutters must be sufficiently high to permit air

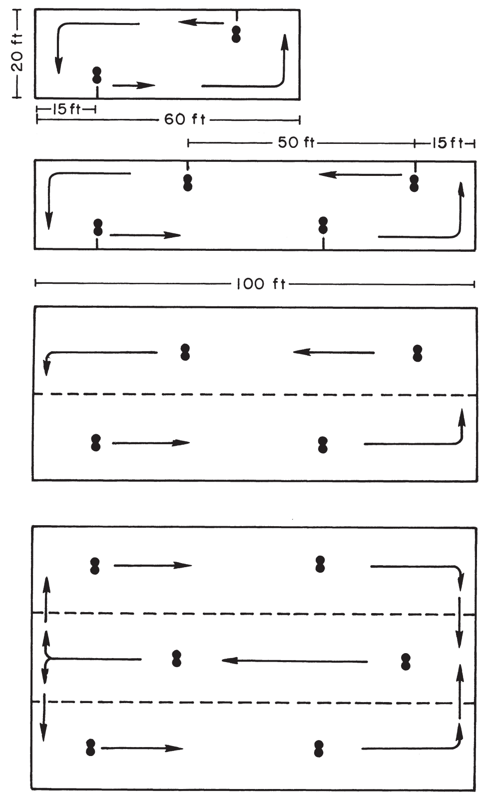


Figure 7
Fan arrangements for a horizontal airflow (HAF) system in various greenhouse sizes. Fans are located one-quarter of the width of the greenhouse in from the side walls in the first two single greenhouses illustrated. They are located under the ridge in the ridge-and-furrow greenhouse diagrams.
(Adapted from Aldrich and Bartok, 1994.)

movement beneath them. If the block contains an odd number of greenhouses, move air in the same direction in the first and third houses and back the opposite way in the second house. Again, the first unit in each greenhouse is a unit heater.

Central Heating Systems

A central heating system consists of one or more boilers in a central location that provide steam or hot water to the various greenhouses. The typical cost of a central hot-water boiler system for a 1-acre installation (0.4 ha), including the heat distribution pipe coil components in the greenhouse and installation, can range from \$4.50 to \$6.00/ft^2 (\$48 to \$65/m^2) of greenhouse floor space, depending on the number of heat zones and the heat requirement. The materials cost proportions into 35 percent for the boiler with controls and pumps and 65 percent for the pipe coils and/or unit heaters. Installation cost is approximately equal to 15 to 20 percent of the materials cost.

The extra \$3.50 to \$4.50/ft^2 (\$37.67 to \$48.44/m^2) spent on a central heating system compared to a unit heater system must be made up somewhere. This is accomplished in five ways over the long term. (1) Boilers can burn cheaper fuels than unit heaters and radiant heaters. Biofuels such as wood chips, logs, switch grass, and bark; coal; and the heavier No. 4, 5, and 6 grades of oil can be burned in boilers. Unit heaters are restricted to gas and No. 2 or lighter oil. The cost of wood is only 20 to 25 percent that of oil. Larger firms realize further savings in the (2) cheaper maintenance of one or two large boilers compared to numerous unit heaters, and in the (3) longer life expectancy of the boilers. (4) When the boilers are used to supply hot water to floor heating systems, it is possible to keep the greenhouse air temperature 5° to 10°F (3° to 6°C) cooler, thereby reducing heat loss from the greenhouse. (5) Unlike unit heater systems, a portion of the heat from central boiler systems is delivered to the root and crown zone of the crop. This can lead to improved growth of the crop and to a higher level of disease control. Each of these factors translates into higher monetary returns from the crop. Over the long haul, central heating systems pay for themselves; otherwise, there wouldn't be as many in use in the industry today.

The first choice to be made after deciding to use a central heating system is whether it will be a hot-water or a steam system. Today, hot water is the system of choice worldwide. Traditionally, European greenhouses were equipped with hot water, while larger American greenhouses used steam for heating. Those who chose steam probably did so because of the faster response time from the boiler when heat was needed, because less heating pipe was required in the greenhouse, and because hot-water circulating pumps were not required in the steam system. Hot water is now the most popular medium for carrying heat from the boiler to the greenhouse for several reasons. The uniformity of temperature across the greenhouse and over time is greater with hot water. There is a larger reserve of heat in a hot-water system in the event of boiler failure. The temperature of hot water can be sufficiently low to use it to heat pipes located in the greenhouse floor or in pipes suspended within the foliage canopy of cut flowers or vegetable plants, whereas steam would be too hot. Such distribution of heat, compared to that of overhead coils, improves plant growth and conserves heat.

The Boiler Boilers function in a similar fashion to unit heaters (Figure 8). In the illustration, fuel is seen burned in a firebox. The resulting hot smoke follows a pathway to the back of the boiler, where it rises up into flue tubes that first bring it to the front of the boiler and then on to the back of the boiler, where it exits into the chimney flue. As the smoke passes through the flues, it transfers much of its heat to the

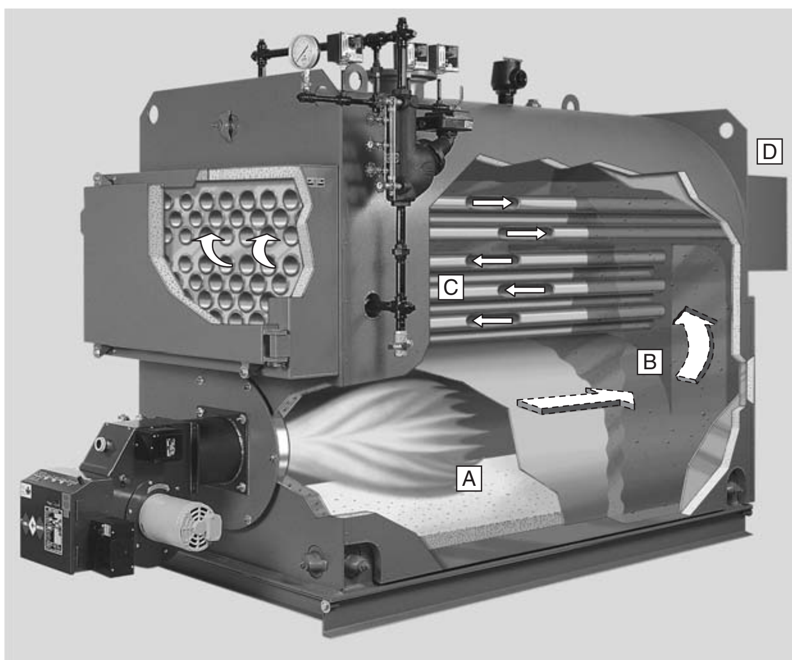


Figure 8

A cutaway view of a firetube design boiler. The burner mounted on the lower front of the boiler provides a flame inside the firebox (A). The firebox and firetubes are jacketed with water (B). The hot exhaust from the flame moves to the rear of the firebox where it rises and enters the firetubes (C). The exhaust moves through the firetubes to the front of the boiler, at which point it enters the upper firetubes and passes back to the rear of the boiler where it exits into the chimney flue (D). Water over the firebox and surrounding the firetubes picks up heat from the exhaust and is used to heat the greenhouse.

(Photo courtesy of Boilersmith, Ltd., P.O. Box 70, Seaforth, Ontario N0K 1W0, Canada.)

iron flue tubes. A jacket of water surrounding the fire box and the flue tubes absorbs heat from the hot fire and flue tubes. In the case of a hot-water boiler, the heated water is pumped to the greenhouse, where it passes through a heat exchanger that releases the heat to the greenhouse air. If it is a steam boiler, the water is heated to a temperature sufficiently high to allow it to turn to steam—at or above 212°F (100°C). The steam is under pressure, which propels it through pipes to the greenhouse, where its heat is also released to the air through a heat exchanger.

Three general types of hot-water boilers are used in greenhouses today. The first is the traditional *high-mass boiler*, which is constructed with steel or cast-iron tubes and also known as a *fire-tube boiler*. This is a large boiler; it is the type that must be used if the fuel is wood, coal, or oil. The second is the newer *low-mass boiler*, which generally contains copper *fin tubes*. It is also known as a *compact boiler*. The compact boiler burns only natural gas or manufactured gas, since soot from oil or coal could plug the narrow spaces between the fins of the heat-exchanging copper tubes. The compact boiler is typically cheaper to purchase and occupies considerably less space. A 3-million-Btu (877,193-W) compact boiler would contain only about 10 gallons of water, compared to several hundred gallons in a high-mass ferrous metal boiler of equal heat output. Because of this, compact boilers are more efficient at either end of the heating season, when heat is required for short periods with long nonheating intervals between them. Larger quantities of heat need to be put into the high-mass ferrous boilers to bring them to operational temperature. This difference in efficiency diminishes as the season turns colder and the greenhouse heat requirement becomes more constant. Growers who have natural gas available tend to find an economic advantage in compact boilers. Those who don't would have to purchase propane, which is considerably more expensive. This could more than negate the lower purchase price of the compact boiler. The third boiler is the *condensing boiler*. These boilers have an additional heat exchanger to extract more heat from the flue gas before it is released up the chimney. The flue gas temperature is lowered to the point where water condenses out of the gas. More expensive metal alloys are used in the additional heat exchanger. These boilers have thermal efficiencies up to 94 percent. But, they can cost two times or more than the conventional boilers. The extra cost is compensated by higher fuel efficiency plus tax incentives for complying with environmental guidelines.

The boiler may be located in the greenhouse or in the service building. In either location, heat that escapes from the boiler jacket, the pipes carrying steam or hot water from the boiler, and the return lines carrying condensate or cool water back to the boiler serve a useful purpose at that location. However, when the boiler is located in the greenhouse, the high humidity results in corrosion and premature breakdown of switches, pumps, and motors. Most growers today consider it more desirable to locate the boiler in the service building where the atmosphere is drier.

Attention should be paid to the placement and height of the smokestack in a central system. The stack should be sufficiently tall that shifting winds cannot sweep emitted gases into the greenhouses, where they can cause plant injury. It is best to position the stack such that the prevailing winds will carry the smoke away from the range and also such that the stack does not cast a shadow on the crop. The north side and the northeast corner, for instance, would be good locations for the boiler and stack under conditions of prevailing winds from the west.

Heat Distribution Heat is delivered from the boiler to the greenhouse in either steam or hot water. In the greenhouse, heat is then exchanged from the steam or hot water to the crop through pipe coils, unit heaters, or a combination of the two.

Pipe Size and Quantity. Hot water has been customarily supplied at a temperature of 180°F (82°C) in 2-inch (51-mm) iron pipe in American greenhouses and at a

Table 3
Heat Available from Various-Diameter Pipes Heated by Hot Water or Steam[1]

Heat Source	Pipe Diameter	Heat Supplied	
		Btu/hr/ft	W/m
Steam, 215°F (102°C)	1.25 in. (32 mm)	180	173
Steam, 215°F (102°C)	1.5 in. (38 mm)	210	202
Hot water, 180°F (82°C)	2 in. (51 mm)	160	154
Hot water, 203°F (95°C)	2 in. (51 mm)	200	192
Hot water, 180°F (82°C)	0.75 in. (19 mm) with 2 long fins[2]	160	154
Hot water, 180°F (82°C)	0.75 in. (19 mm) with 2 short fins[2]	105	101

[1]The inside air temperature of the greenhouse is 60°F (16°C).
[2]Delta T pipe.

temperature of 203°F (95°C) in 2-inch (51-mm) iron pipe in Dutch greenhouses. Steam systems, on the other hand, usually supply steam at a temperature of 215°F (102°C), which is 3°F (2°C) above the temperature at which water turns to steam and is possible because the system is under a low pressure of 5 pounds per square inch (psi) or so. Since there is less resistance to the flow of steam, smaller iron pipes of 1.25- or 1.5-inch (32- or 38-mm) diameter are used in the greenhouse coil. More recently, aluminum pipes (often 0.75 in. diameter, 19 mm) have been used as well. These typically have two aluminum fins running along the length of the pipe for increasing heat release to compensate for their smaller diameter.

The amount of pipe needed in a greenhouse coil can be determined by referring to the heat-supply values listed in Table 3 for various types of pipe. A greenhouse requiring 160,000 Btu/hr would need 1,000 linear feet (305 m) of 2-inch (51-mm) hot-water pipe to provide this heat. This was determined by dividing the total heat requirement for the greenhouse by the amount of heat that 1 linear foot (0.3 m) of pipe can provide. In this case, 160,000 Btu/hr is divided by 160 Btu per linear foot of 2-inch hot-water pipe, which yields an answer of 1,000 feet of pipe. If a system of 1.5-inch (38-mm) steam pipes were used instead, the need would be 160,000 Btu/hr divided by 210 Btu/hr, or 762 feet (232 m) of pipe.

Wall Pipe Coils. Placement of heating pipes is very important. Considerable heat is lost through the side walls of the greenhouse. In addition, warm plants radiate heat energy to colder objects outside the greenhouse. The result is a disproportionately high cooling effect in the outer beds of plants. To counteract this heat loss, pipes are installed on the inside of the four perimeter walls of the greenhouse. Side pipes should have a few inches of clearance on all sides to permit the establishment of air currents and should be located low enough to prevent blockage of light entering through the side walls. They are generally attached to the opaque curtain wall. The side-wall coil of pipes should have a heat-supplying capacity equal to the heat loss through the walls of the greenhouse.

When several pipes are stacked above one another, their effectiveness is reduced. Additional pipes must be added to compensate. Table 4 shows the effect. For two pipes, the effect is insignificant. Five pipes in a stack, however, are only as effective as four pipes placed apart from one another. In a heating design where the heat of four pipes is needed in the side coil, five pipes would have to be installed. Overhead pipes are spaced sufficiently far apart to avert the problem.

If more than one row of pipe is required in a side-wall stack, *fin pipe* can be used so that only one pipe is required (Figure 9). Fin pipe is a conventional pipe with

Table 4
HEAT-SUPPLY RELATIONSHIP OF PIPES IN A VERTICAL STACK COMPARED TO PIPES LOCATED SEPARATELY FROM ONE ANOTHER[1]

Number of Pipes in Vertical Stack	Number of Individual Pipes Giving an Equivalent Amount of Heat
1	1.00
2	2.00
3	2.67
4	3.33
5	4.00
6	4.33
8	5.00

[1]From Gray (1956). See Aldrich and Bartok, Jr. (1994) for a more complete list of heat outputs from bare and finned pipes.

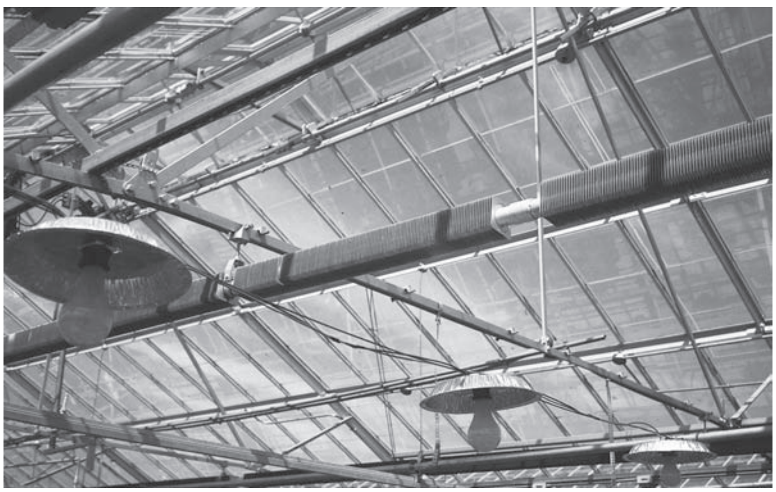


Figure 9
Fin pipe installed in the overhead pipe coil of a high-profile glass greenhouse.

numerous thin metal plates radiating outward from it to increase the surface area of the pipe and thus the rate at which it transfers heat from the hot water or steam contained inside to the surrounding air. Depending on the design, 1 linear foot (0.3 m) of fin pipe can be equivalent to 4 or more linear feet (1.2 m) of conventional pipe. It should be remembered that heat released from fin pipe is much more intense than heat from conventional pipe. It is therefore important to distribute fin pipes evenly throughout a greenhouse. If a single continuous coil of fin pipe is not needed around the entire greenhouse, then the fin pipe should be alternated with conventional pipe at equidistant intervals.

Overhead Pipe Coils. The wall pipe coil counteracts heat lost through the four perimeter walls. Heat lost through the roofs and gables is supplied through an overhead or in-bed coil of pipes that is situated across the entire greenhouse (Figure 10a). The overhead coil is not the most desirable source of heat because it is located above the plants. Heat rises from the coil to the top of the greenhouse, where it serves no function and is quickly lost to the outside. Energy needs to be expended to drive the heat down to the plant zone. However, overhead coils are popular because they place the pipe out of the way of pedestrian traffic and automation.

In-Bed Pipe Coils. A better pipe arrangement, when the greenhouse layout allows it, is the in-bed coil (Figure 10b). By placing the heating pipes near the base of the

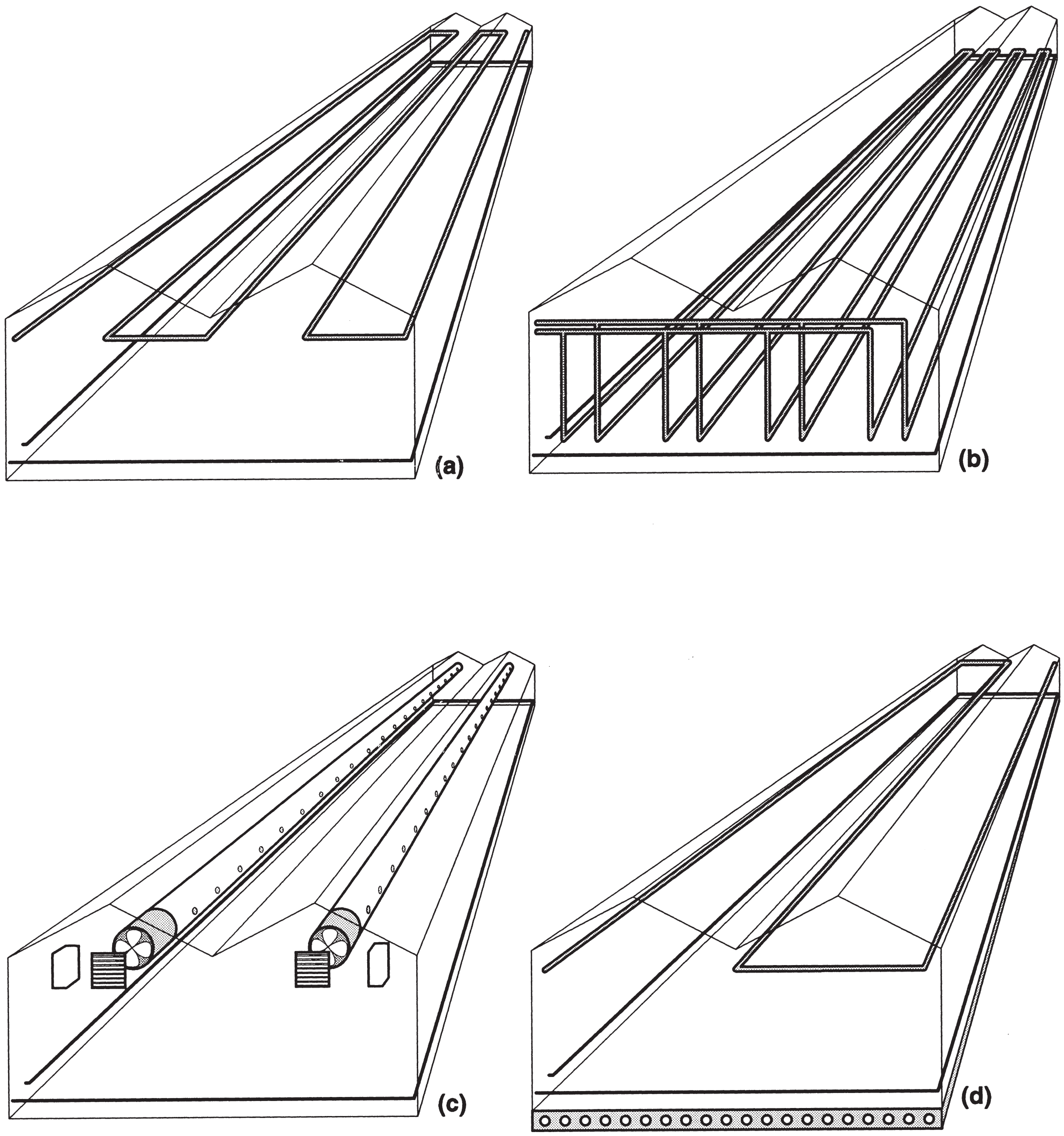


Figure 10

Sketches showing the arrangement of heating pipe coils in a ridge-and-furrow greenhouse heated by (a) a wall coil and overhead coil, (b) a wall coil and an in-bed pipe coil, (c) a wall coil and overhead unit heaters, and (d) a wall coil, a limited overhead coil, and an in-floor coil.

plants, the roots and crown of the plants are heated better than in the overhead-coil system. This leads to improved growth and greater disease control. Also, heat is kept lower in the greenhouse (where it is needed), resulting in better energy efficiency. For pot crops on benches, pipes are installed in the framework of the bench beneath the tabletop (Figure 11). This arrangement is also possible for movable benches because the frame remains fixed in place. Cut-flower and vegetable beds can likewise be heated with hot-water pipes, which are suspended by flexible rubber hoses from overhead mains (Figure 12). The heat pipe is confined to the bed and does not cross aisles. For crops such as roses, these pipes may be located in the bed of plants, while for others they are located on either side of each bed. Hot water is used in these systems because temperatures lower than that of steam are required to avoid burning the plants. Hot water also ensures a uniform temperature throughout the greenhouse. To facilitate removal of plants, root substrate pasteurization, and replanting, the heating pipes can be lifted and tied overhead without disconnecting them.

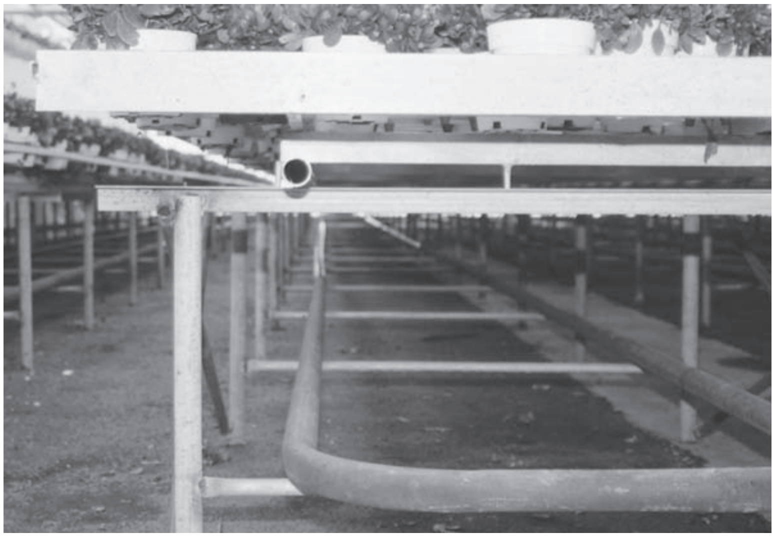


Figure 11
A 2-inch (51-mm) hot-water heat pipe supported by the lower frame of a movable potted-plant bench.

Figure 12
The hot-water pipes heating this tomato crop growing in rock wool are located between the plant rows and just above the floor for maximum efficiency of heat distribution. The hot-water pipes are suspended from overhead mains by flexible rubber hoses. This permits the pipes to be raised overhead when the crop is finished for cleaning-up purposes.

Hot-water heating pipes are also being installed under slabs of rock wool in a more recent cultural system to ensure that the roots are warmed. The nutrient solution itself is being heated in some nutrient film technique (NFT) hydroponic systems to deliver heat directly to the roots, rather than only to the air above the plants

Box Versus Trombone Pipe Coils. Pipe coils can be arranged in two styles, either box or trombone (Figure 13). Box coils are used in hot-water systems. Hot water entering the greenhouse through the pipe main is distributed in a header, or branch tee, to several smaller pipes, through which it passes simultaneously to the opposite end of the greenhouse. There, it combines and returns to the boiler to be reheated. There is a resistance to the flow of water in the pipe. The box coil minimizes this

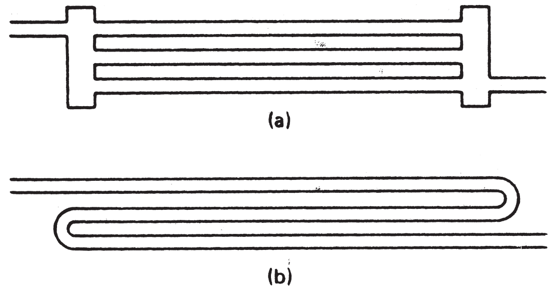


Figure 13
(a) A box coil used to distribute hot water through a greenhouse. (b) A trombone coil used in a steam system of heating.

resistance by reducing the length of pipe through which any given portion of the water must flow and by increasing the cross-sectional area of the combined pipe through which the water passes.

Trombone coils are used for steam systems. Resistance to flow is not a problem for steam, but the rapid drop in pressure and temperature along the pipe is. If a box coil were used for steam conduction, the entry end would be hot and the exit end much cooler, resulting in an intolerable temperature gradient in the greenhouse. A continuous pipe is used in a trombone coil. Steam enters at the top of the coil and passes to the distant end of the greenhouse. It returns to the entry end in the second pipe down and then back to the distant end in the third pipe down. This arrangement continues until, at the end of the coil, water condensate and steam enter a trap that permits the return of water, but not steam, to the boiler. No temperature gradient exists along the length of the coil. The gradient exists from the top to the bottom of the coil and is of no consequence. The overhead pipe coil is usually a trombone coil, whether hot water or steam is used. In the case of a hot-water system, two overhead trombone coils are used to reduce resistance.

Unit Heaters. Some firms substitute unit heaters for overhead or in-bed pipe coils (see Figures 10c and 14). The wall pipe coil is still used. These unit heaters differ from those previously described in that they do not contain a firebox. The heater consists of a steam or hot-water fin-pipe coil and a fan. Steam or hot water from the boiler passes through the coil while the fan passes cool greenhouse air over the coil to heat the air. Two examples of these unit heaters can be seen in Figure 4. Hot air emitted from these unit heaters can be circulated through convection tubes. Alternatively, the unit heaters can be placed in line with HAF fans for heat circulation. Reasons for using unit heaters rather than an overhead pipe coil include the lower initial cost of

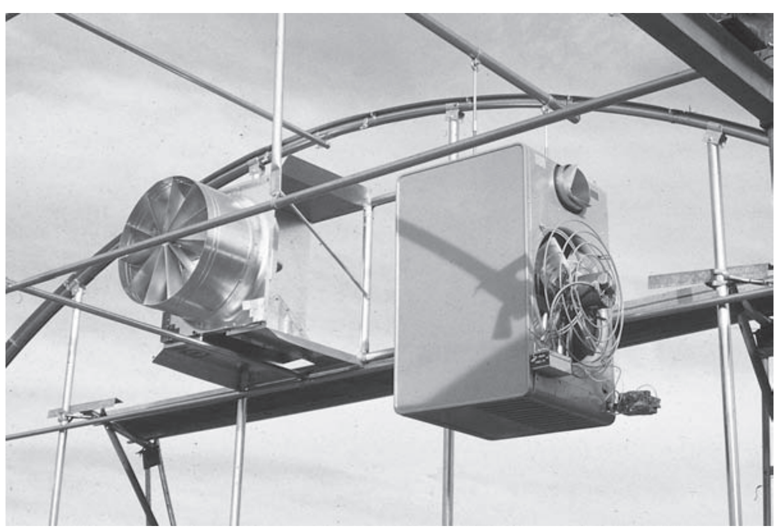
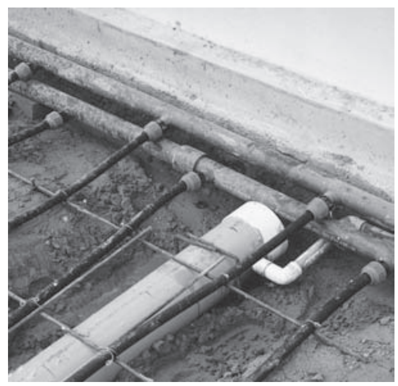


Figure 14
A newly installed horizontal unit heater on the right and convection tube housing on the left. Note the pressurizing fan in the cylindrical housing. The convection tube will be attached to the outside of the cylindrical housing.

the system and the function it serves in moving warm air from the gable of the greenhouse down to the plant zone to lower fuel consumption.

Floor Pipe Coil. Thus far we have seen that there are two distribution systems for heat from central boilers: The wall coil combats heat loss through the walls, and the overhead coil, the in-bed coil, or overhead unit heaters compensate for heat lost through the roofs and gables. In this final option, a portion of the heat generally supplied through the overhead coil or overhead unit heaters is redirected to an in-floor pipe coil (Figures 10d and 15). Floor heating is more effective than in-bed pipe coil heating and therefore enhances the three advantages previously cited for in-bed coils: increased yield, greater disease control, and less fuel consumption. A fourth advantage associated only with floor heating is the ability to dry the floor quickly. This is essential when flood floors are used for irrigation/fertilization. In this system, plants are set on the floor, which makes drying the floor difficult. Unless the floor is dried quickly after watering, the humid environment in the plant canopy fosters disease development.

(a)



(b)

(c)

Figure 15

An installation sequence for an in-floor hot-water heating system. (a) Three-quarter-inch (19-mm) hot-water tubing in place on the subsoil that will support the concrete floor. Note the large PVC pipe in the center of the picture that will both supply and drain away water or nutrient solution when this concrete floor is completed and used as an ebb-and-flow irrigation/fertilization system. (b) Attachment of the hot-water tubing to the inlet and outlet manifold pipes at one end of the greenhouse. (c) Placement of concrete over the hot-water tubing.

(Photos courtesy of Green Link, LLC, P.O. Box 2118, Asheville, NC 28802-2118.)

In-floor pipe coils often consist of 0.75-inch (19-mm)-diameter pipes buried in the floor 6 to 12 inches (15 to 30 cm) apart, depending upon the heat requirement. Half-inch pipe is also becoming popular because it is spaced closer together, giving more even heat, and less water is required in the floor at any point in time. The floor may consist of porous or solid concrete. Standard polyethylene pipe is not used because of the possibility of breakage. PVC pipe can be used, but is not popular because of its inflexibility and cost. Polybutylene has been a popular choice for its flexibility, strength, and high temperature tolerance. More recently, cross-linked polyethylene (PEX) pipe has become the most popular due to its lower cost and freedom from breakage. Polypropylene and EPDM (ethylene propylene diene polymer) (a synthetic rubber) are also effective pipes for floors.

Hot water, generally at a temperature of 90° to 120°F (32° to 49°C), is circulated through the pipe to maintain the desired temperature in the plant canopy. During periods of maximum heat requirement, the water temperature can be as high as 140°F (60°C). Hot water is pumped the length of the floor and then back to the inlet end to provide a bidirectional flow for the purpose of uniform heat distribution along the length of the greenhouse. In general, heat is applied at the rate of 20 Btu/hr/ft^2 (63 W/m^2) of floor. During periods of high heat demand, these systems may be called upon to supply 30 Btu/hr/ft^2 (95 W/m^2). Since the root zone and plant area are heated first, the air temperature above the plants is commonly set 5° to 10°F (3° to 6°C) lower than in conventionally heated greenhouses, with no loss in plant growth. As in the case of radiant heating, this lowers the temperature differential across the greenhouse covering and thereby cuts fuel costs. The supply of hot water to the floor is generally tied into a soil-temperature sensor rather than an air-temperature sensor. In computer-controlled greenhouse firms, the temperature of the water circulating in the floor is determined by the computer. As the rate of demand for heat increases to hold the soil at the set point, the temperature of the water circulated in the floor is increased. The water-temperature decision can be based on the rate of decline in soil temperature along with the outside temperature. Circulating water temperatures may be as low as 90°F (32°C) and as high as 140°F (60°C). By using the minimum temperature of water necessary to accomplish the task, the efficiency of the boiler is raised.

Heat is first supplied via the floor in floor heating systems, and only when this is insufficient are other coils or unit heaters used. With experience, an air temperature can be found that allows the floor heating system to maintain the desired soil temperature. The air temperature is usually 5° to 10°F (3° to 6°C) lower than the air temperature customarily recommended for the crop. A floor heating system can provide all of the required heat during the fall and spring. On cold winter days, supplemental heating, such as an above-ground pipe coil or unit heaters, will be required. Over the whole year, floor heating may provide from 20 to 50 percent of the total need and may average out to 25 percent. This percentage is highest in warm climates. If the floor is covered with a crop of potted plants or bedding-plant flats, a high percentage of the total heat need will be met because the plants are near the heat source and tend to hold the heat down. When plants are grown on benches, the efficiency of this system is reduced. Higher air temperatures are required at the elevation of the plants. Also, heat is able to escape more freely from the uncovered floor to the greenhouse gable, where it is not desired. Hanging baskets reduce the efficiency even more. The total heat requirement cannot be supplied through the floor in cold climates because the amount of heat supplied to the floor would result in excessive cement and plant temperatures. The total system, including a concrete floor with heating tubes, the perimeter wall pipe coil, the overhead pipe coil, a hot-water boiler, controls, and installation labor, costs about \$6 to \$7.50/ft^2 (\$65 to \$80/m^2) of greenhouse floor.

Figure 16
EPDM hot-water heat tubing used at the surface of a greenhouse bench for heating a crop. Note that pots are placed directly on the heating tubes.

Another recent method for heating the root zone is available in various commercial packages (Figure 16). Flexible EPDM (synthetic rubber) tubing can be placed on the floor or on or beneath a bench surface. Tubes are usually spaced 2 inches (5 cm) apart along the length of the floor or bench, but may be spaced closer together or farther apart to meet local heat needs. The inlet and outlet mains for the tubing are located on the same end of the floor or bench to provide bidirectional flow. Tubing is 5/16 inch (8 mm) in outside diameter. The tubing is sufficiently strong to withstand placement of pots directly on it as well as people walking on it. As in the case of the in-floor hot-water coil, control of the system is generally dependent on soil-temperature sensors. Similar water temperatures are used.

Many firms without central hot-water boilers have installed EPDM tube heating systems for specialized purposes such as plant propagation in small zones within their greenhouse range. Smaller hot-water heaters independent of the primary heat source of the firm are used in these cases for the tube heating system.

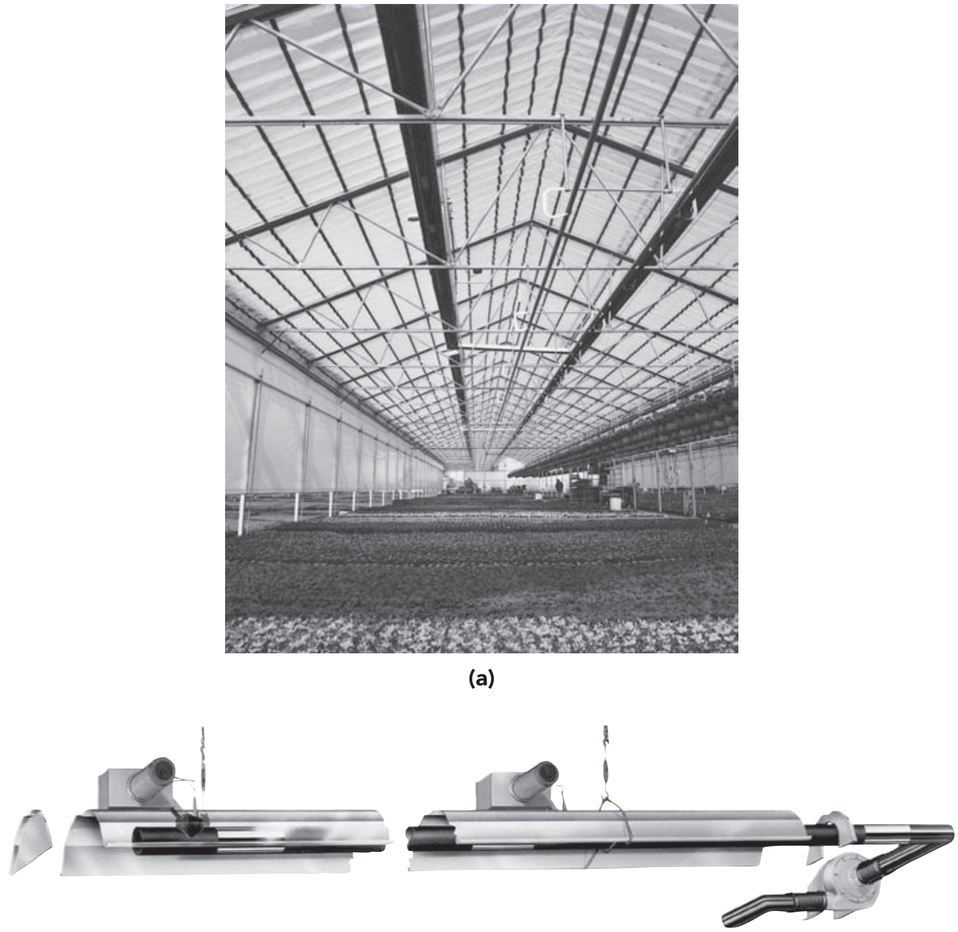
Radiant Heater Systems

Grower reports on fuel savings suggest a 30 to 50 percent fuel bill reduction with the use of low-intensity infrared-radiant heaters, as compared to the unit heater system (Figure 17). These heaters emit infrared radiation, which travels in a straight path at the speed of light. Objects in the path absorb this electromagnetic energy, which is immediately converted to heat. The air through which the infrared radiation travels is not heated. After objects such as plants, walks, and benches have been heated, they will warm the air surrounding them. It is the soil and plant temperatures that are important to growth. Air temperatures in infrared-radiant-heated greenhouses can be 5° to 10°F (3° to 6°C) lower than in conventionally heated greenhouses with equivalent plant growth. In the conventional system, the air is heated first; the air then heats the plants. Thus, air temperatures tend to be higher than plant temperatures at night. This encourages condensation on plant surfaces. Disease is discouraged by the lesser amount of condensation in infrared-radiant-heated greenhouses. A very thorough booklet covering background, installation, and applications of IR heating in greenhouses is available free online from Roberts-Gordon, Inc., at www.greenhouse-heater.com/Greenhouse-heating-Manual.htm.

Infrared-radiant heaters used in greenhouses are available in sizes from 20,000 to 120,000 Btu/hr (5,860 to 35,160 W) in 20,000 Btu/hr increments. The distance between heaters can be 30 to 40 feet (9.1 to 12.2 m). They are placed in tandem overhead along the length of the greenhouse. Above the line of heaters, running the length of the greenhouse, is a deep-dish metal reflector to direct all rays down toward the plants and to give the proper uniformity of heat across the production area. The composition of this reflector is important to ensure that maximum reflectivity is

Figure 17
(a) A greenhouse installation of an infrared-radiant heating system with two overhead radiant heat pipes. (b) Schematic of a radiant heat system showing a burner installed at the front end of a radiant heat pipe, a second burner located in tandem further along the radiant heat pipe, and a vacuum pump located at the outlet end of the radiant heat pipe to expel exhaust from the pipe to the outside.

(Photos courtesy of Growth Zone Systems, LLC, P.O. Box 2401, Mt. Vernon, WA 98273.)



(a)

(b)

achieved. A high-quality metal for this use is aluminum. Each heater mixes air from the greenhouse with fuel and injects it into a 4-inch (10-cm) steel pipe. Fuel (natural gas or propane) is ignited by a direct-fire ignition system rather than by using a pilot light or a spark plug. The pipe heats to a temperature of around 800°F (430°C). This is not sufficiently hot, as is the case in radiant heaters used for other commercial purposes, to cause the pipe to emit visible red light. Such a light emission would interfere with the photoperiodic timing of some crops. Actually, the temperature can be varied by the manufacturer to suit specific greenhouse spatial needs. The pipe extends the length of the greenhouse, where it exits to the outside. Fumes are drawn along the length of the pipe through a vacuum developed by a pump in the exit end of the pipe. A vacuum of 2 inches (5 cm) of water column is developed in the pipe. A 0.5-horsepower (370-W) pump can handle up to 16 smaller heaters. Since the pipe in the vicinity of each heater can be 900°F (480°C), it is important that plants not be placed within 5 feet (1.5 m) of the pipe. Radiant heaters today can heat a width of plant surface up to two times the height of the heaters above the plant surface.

Reasons for fuel savings fall into two categories. First, fuel gases in this system exit at 150° to 200°F (65° to 93°C) as opposed to 400° to 600°F (204° to 315°C) in conventional greenhouse heaters. Thus, more heat is derived from the combusted fuel. The efficiency of combustion is claimed to be about 90 percent. Second, cooler air temperatures in the greenhouse ensure a smaller temperature differential from outside to inside. Therefore, less heat is lost from the greenhouse. It is important that high-velocity air circulation as generated by convection tubes not be used in infrared-radiant-heated greenhouses. Air currents set up by such fans would cool the plants and carry the air warmed by the plants and floor to the cold greenhouse covering. A HAF system (discussed earlier in this chapter), having a gentler airflow, works well with this system. Another advantage of radiant heating is the reduction of about 75 percent in electrical consumption over a conventional unit heater system. The only motor required in the infrared-radiant heating system is in the exhaust fan.

Installation and materials for an infrared-radiant heating system can range from about \$2.50/ft^2 (\$27.00/m^2) in warm southern states to about \$4.50/ft^2 (\$48.00/m^2) in northern states and provinces. Although capital costs of this system are higher than those of the conventional unit heater system, the fuel savings could pay for the additional cost over a few years. However, one should be aware that in recent years unit heaters and boilers have become available with low stack temperatures (300°F, 150°C), which allow them to share in part the benefit that formerly belonged exclusively to radiant heaters. Second, the advantage of the lower inside-to-outside temperature differential across the greenhouse covering offered by radiant heating systems can be achieved in floor heating systems (discussed earlier in this chapter). Finally, radiant heaters burn either natural gas or propane. While natural gas can be competitive with other fuels, propane tends to be expensive relative to other fuels.

A choice of radiant heating products exists. Factors to consider in selecting one include thermal efficiency, emissivity, reflectivity, fixture efficiency, and pattern efficiency. *Thermal efficiency* is the ratio of heat potential in the fuel consumed to the energy released in the heater. *Emissivity* is a measure of the capacity of the heater tubes to release infrared energy. *Reflectivity* is a measure of the ability of the reflector to redirect energy. *Fixture efficiency* refers to the amount of infrared energy that is absorbed by the heating fixture and converted to heat, ultimately to be convected away. This amount should be as low as possible. *Pattern efficiency* is a measure of the ability of the heater to distribute radiant energy to the space in a manner consistent with the needs of the space. The overall efficiency of the system is a combination of all of these factors.

Solar Heating Systems

Solar heating is often considered as a partial or total alternative to fossil-fuel heating systems. Few solar heating systems exist in greenhouses today. As will be seen, the economics of such a system bear scrutiny. In this section, we will consider the fundamental principles and components of solar heating. The components (Figure 18)

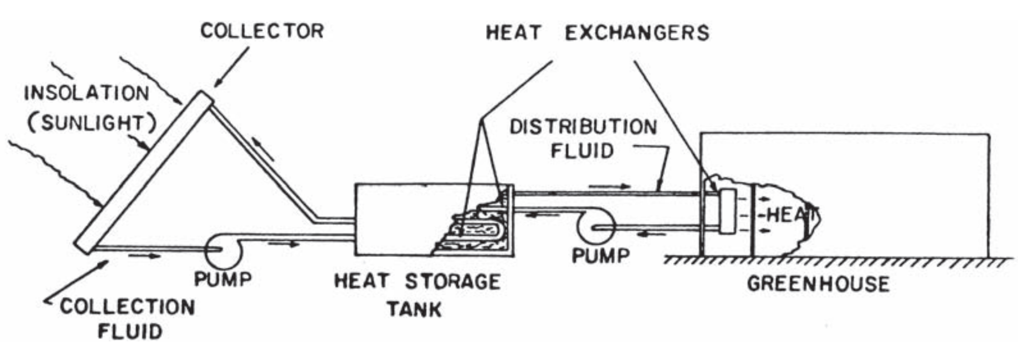


Figure 18
A typical solar heating system for greenhouses.
(From D. H. Willits, Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC 27695-7625.)

consist of (1) a collector, (2) a heat storage facility, (3) an exchanger to transfer the solar-derived heat to the greenhouse air, (4) a backup heater to take over when solar heating does not suffice, and (5) a set of controls.

Collector Various solar heat collectors are possible, but the type that has received greatest attention is the flat-plate collector. This consists of a flat black plate (rigid plastic, film plastic, or board) for absorbing solar energy. The plate is covered on the sun side by two or more transparent glass or plastic layers and on the back side by insulation. The enclosing layers hold the collected heat within the collector. Water or air is passed through or over the black plate to remove the entrapped heat and carry it to the storage facility.

A greenhouse itself is a solar collector. Some of its collected heat is stored in the soil, plants, greenhouse frame, walks, and so on. The remaining heat can be excessive for plant growth and is therefore vented to the outside. The excess vented heat could just as well be directed to a rock bed for storage and subsequent use during a period of heating. Heat derived in this manner could provide up to half of the total heat requirement for greenhouses in the southern United States and perhaps 10 to 20 percent of the total requirement in northern states.

Collection of heat by flat-plate collectors is most efficient when the collector is positioned perpendicular to the sun at solar noon. The required angle of tilt with respect to the ground is equal to the latitude on March 21 and September 21 (the spring equinox and fall equinox). The angle should be gradually increased to a maximum of the latitude plus 23° on December 21 (the winter solstice) and then decreased thereafter. Since movable collectors add considerable expense, a stationary compromise angle of the latitude plus 15° is often used (Figure 19).

The amount of solar radiation reaching the earth's surface varies with such factors as weather conditions and elevation. Average daily quantities of solar radiation striking a square foot of horizontal surface during July and January are presented in Figure 20. While an average solar input of 600 Btu/ft^2 (1,625 kcal/m^2, 6,800 kJ/m^2) of surface per day is expected in the Washington, DC, area (38°N latitude), not all can be trapped by a solar collector. At solar noon, a flat-plate collector using water can have an efficiency of 65 percent, but the efficiency diminishes at either side of that point to 0 percent in the early morning and late afternoon. Considering an over-

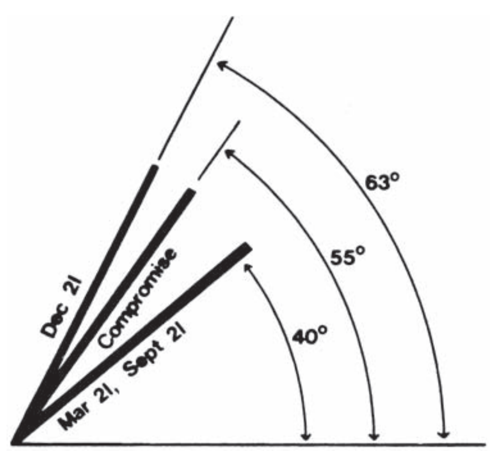


Figure 19
The best angle of tilt with respect to the ground for a solar collector at 40°N latitude (Philadelphia, Denver) is 40° on March 21 and September 21. During the 91 days from September 21 to December 21, it increases by 23° to 63°. After December 21, it decreases continually to a value of 40° by March 21. A stationary collector is generally oriented at a compromise angle equal to the latitude plus 15° or 55° in this example.

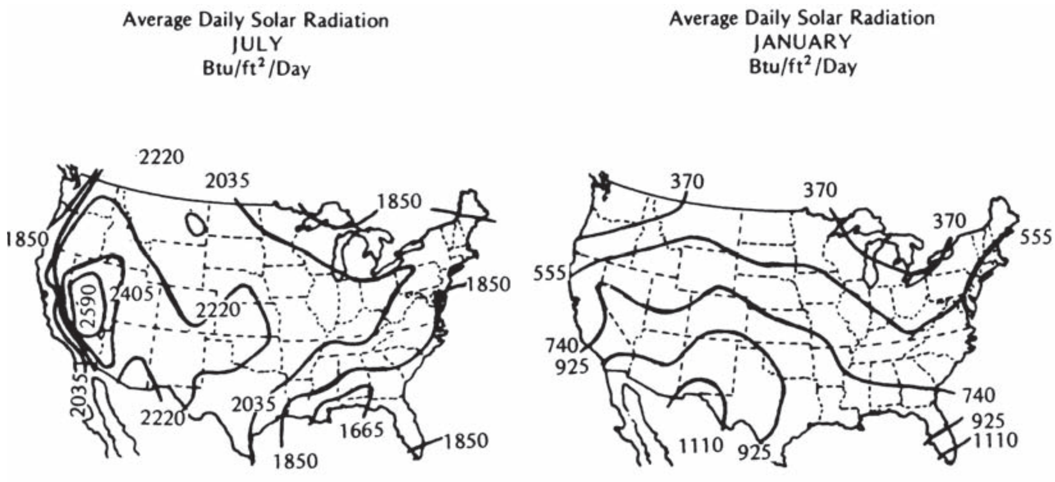


Figure 20
Average daily solar radiation received on a square foot of horizontal surface throughout the United States in July and in January. One Btu/ft^2 is equivalent to 2.7 kcal/m^2 or 11.4 kJ/m^2.
(From Ross et al., 1978.)

all efficiency of 40 percent, 240 of the 600 Btu impinging on a square foot of collector in a day can be trapped for heating a greenhouse. Based on a heat output of about 100,000 Btu per gallon of oil, 417 ft^2 of collector would be required to equal in one day the heating capacity of 1 gallon of oil (10.25 m^2 of collector/L oil). At least 0.5 square foot of collector surface is required per square foot of greenhouse floor area, and in northern areas, 1 square foot may be needed.

Heat absorbed by the black plate inside the collector is often removed by water or air. The black plate may be a sheet of black plastic tubes fused together. In this case, water can be passed through the interior of these tubes. If it is a solid black sheet, such as polyethylene, water may be passed over its surface. Water picks up the heat and is then transferred to a storage tank. Air may likewise be passed through or over the black plate to remove heat from it. Water collectors require a flow rate of 1 to 3 gallons per minute (gpm) per 100 ft^2 (0.4 to 1.2 L/min/m^2) of collector surface. Correspondingly, air-heating collectors require a flow rate of 5 to 15 cfm/ft^2 (1.5 to 4.6 cmm/m^2) of collector.

Heat and Storage Exchange Water and rocks are the two most common storage materials for heat in the greenhouse at the present. One pound of water can hold 1 Btu of heat for each 1°F rise in temperature (4.23 J/g water/°C). Thus, its specific heat is 1. Rocks can store about 0.2 Btu per pound for each 1°F rise in temperature (0.83 J/g rock/°C). The specific heat in this case is 0.2. To store equivalent amounts of heat, a rock bed would have to be three times as large as a water tank. A rock storage bed lends itself well to an air-collector and forced-air heating system. In this case, heated air from the collector, along with air excessively heated inside the greenhouse during the day, is forced through a bed of rocks. The rocks absorb much of the heat. The rock bed may be located beneath the floor of the greenhouse or outside the greenhouse, assuming that it is well insulated against heat loss. During the night, when heat is required in the greenhouse, cool air from inside the greenhouse is forced through the rocks, where it is warmed and then passed back into the greenhouse. A clear polyethylene tube with holes along either side serves well to distribute the warm air uniformly along the length of the greenhouse. Conventional convection tubes (discussed earlier in this chapter) can be used for distributing solar-heated air.

A water storage system is well adapted to a water collector and a greenhouse heating system making use of a pipe coil or a unit heater with a water coil contained within. Heated water from the collector is pumped to the storage tank during the day. As heat is required, warm water is pumped from the storage tank to a hot-water or steam boiler or into the hot-water coil within a unit heater. Although the solar-heated water will be cooler than the thermostat setting on the boiler, heat will be saved, since the temperature of this water will not have to be raised as high to reach the output temperature of water or steam from the boiler.

Low-temperature solar systems have been the most popular for greenhouses thus far because of their lower price. Solar input during the daytime can cause a storage-unit temperature rise in these systems of up to 30°F (17°C) above the evening baseline temperature. Each pound of water can thus supply 30 Btu of heat, and each pound of rock 6 Btu, as it cools 30°F. A 20-foot-by-100-foot (6.1 m × 30.5 m) double-layer polyethylene greenhouse has been reported to lose about 3,500 Btu/hr/°F (1,848 W/K) of temperature differential between inside and outside. If an inside temperature of 60°F (16°C) and an average outside night temperature of 35°F (2°C) are experienced and the heating period is considered to be 13 hours long, about 1.1 million Btu (1.17 million kJ) of heat will be required. This would require a 4,400-gallon (16,600-L) water storage tank. (Note that a 1.1-million-Btu heat requirement divided by [(Btu/lb × °F) × 30°F × (8.3 lb/gal water)] equals 4,400 gal.) To store the same quantity of heat, about 2,000 ft^3 (57 m^3) of rock would be required.

The water or rock storage unit occupies a large amount of space and a considerable amount of insulation if the unit is placed outdoors. Placing it inside the greenhouse offers the advantage that escaping heat is beneficial during heating periods. It is detrimental when heating is not required. Rock beds can pose a problem in that they must remain relatively dry. Water evaporating from these beds would remove considerable heat.

Backup Heater Today, a solar heating system is considerably more expensive than a conventional system. Current strategy calls for sizing a solar system to meet the average winter needs. A conventional fossil-fuel backup system is installed to meet the additional heating needs of the coldest nights. This compromise increases the chances of justifying the cost of a solar heating system.

Controls To illustrate typical controls in a solar-heated greenhouse, a water system is considered. The first control activates when the water in the collector becomes 10°F (6°C) warmer than the water in the storage tank and cuts off when the differential is 5°F (3°C). Water is pumped from the collector to the top of the storage tank. Cooler water at the bottom of the storage tank returns to the collector. A second control activates the storage tank to the greenhouse heat-exchanger pump when the greenhouse air temperature drops and turns it off when the desired temperature is reached. A third control turns on the backup heater at a temperature 2°F (1°C) below the desired air temperature in the event that the solar system fails to hold the desired temperature. A fourth control empties water from the collector into an underground tank when the collector temperature approaches freezing and refills it when the collector temperature rises.

Economics High-capacity collectors capable of raising the storage unit temperature more than 30°F (17°C) have the advantage of requiring less collector area and storage capacity. High-capacity systems are very expensive; thus, low-capacity collectors are more typically used in greenhouses. Costs in the mid-1980s for a low-capacity system were about \$4 to \$5/ft^2 (\$43 to \$54/m^2) for the collector and \$8 to \$10/ft^2 (\$86 to \$108/m^2) for the total system.

Even at \$8/ft^2 (\$108/m^2) of collector for the total system, the price per acre for a solar heating system would have been \$348,500 (\$871,000/ha). This is assuming a ratio of 1 ft^2 of collector per square foot of greenhouse floor area. Such a system might meet total heat requirements in southern regions where 0.6 gallon of oil is consumed per square foot of floor area per year (25 $L/m^2/yr$) for double-glazed greenhouses. The annual savings in fuel in the mid-1980s based on $1/gal for oil ($0.27/L) would have been $43,500/acre ($108,750/ha). Taking into account interest on invested capital, repairs, electrical consumption, and implicit costs, the payoff period for this system was and still is highly questionable.

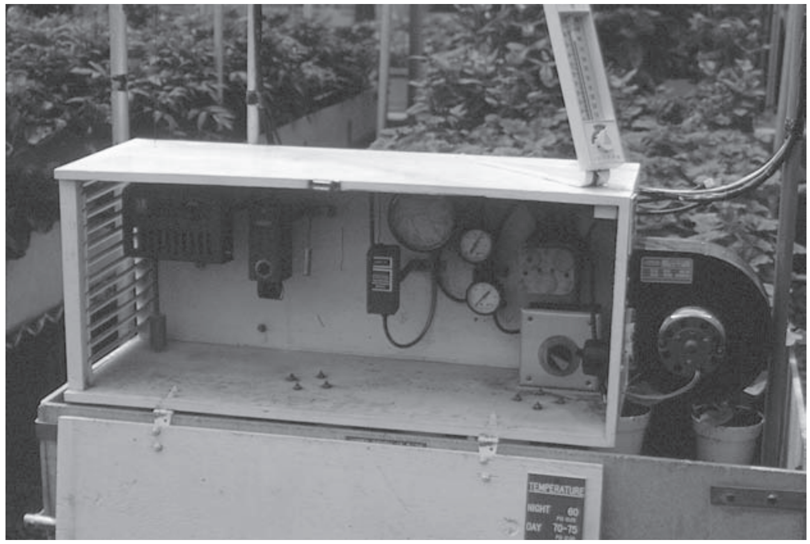
Little research has been directed toward solar greenhouse heating since. The deterrent lies in the realization that the standard greenhouse is an effective solar collector already and that fuel efficiency gains are best achieved by improving methods to hold heat in during heating times. Recent efforts have been directed toward thermal screens, triple layer coverings, and infrared blocking coverings. Current solar collectors block light to some degree, thereby reducing or eliminating crop growth. Thus, they need to be installed on land additional to the greenhouse space. The current perspective is that it would be more profitable to build additional greenhouse production capacity in that space. One must consider that even if all heating fuel were to be eliminated by an exterior collector system, this would eliminate only about 5 percent of the operating costs of the greenhouse, which would be done with the expense of the solar system plus the lost opportunity cost of the land tied up in the system. If there is an answer in the future, it will come in the form of a solar collector system that uses the greenhouse as the collector without reducing crop growth.

Solar heating systems do exist in commercial greenhouse firms. Generally, these firms are small, and the owner may have been satisfied to overlook portions of the true cost of the system. The owner may have constructed the system personally without placing a value on his or her labor. The firm also may have financed the system out of prior profits and failed to calculate an interest cost for the money. The profits could otherwise have been invested and yielded interest. The lost interest is a real opportunity cost, which should be added into the total cost of the solar system.

GREENHOUSE TEMPERATURE SENSING

Cooling and heating systems are controlled by temperature sensors. Since temperature gradients exist in greenhouses with even the best of heating systems, placement of the sensor is very important. Its location should reflect the average temperature in the greenhouse. If it is placed in a location near the heater or in a direct flow of warm air, the heater will turn on and off according to conditions in that warm spot, and the remainder of the greenhouse will run colder than desired. Consequently, the majority of the crop might be delayed. Sensors need to be placed in an average temperature location, usually near the center of the greenhouse. The height of the sensor placement is also very important with respect to the vertical temperature gradient. The sensor should be located at the height of the growing points of the plants. For potted-plant crops, this height is usually 6 to 12 inches (15 to 30 cm) above the pot rim. For cut flowers, the height varies, and the sensor should be attached to a post or chain on which it can be raised or lowered.

Direct or indirect rays of sunlight will raise the sensor temperature well above the air temperature. This will prevent operation of the heater on cold but bright winter days, when heat is needed. The sensor should therefore be shielded from the sun's rays. The sensor housing pictured in Figure 21a is a homemade unit that has the following features. The outer surface of the box is painted in a reflective color, such as white or aluminum, to reduce heat buildup. The ends of the box have louvers to permit air passage but prevent entry of the sun's rays. A fan is installed to



(a)

(b)

Figure 21

Greenhouse sensor housings. (a) A homemade housing consisting of an aspirated box that houses the heat sensor, a low-temperature alarm thermostat, and a thermometer. The box has a reflective outer surface, louvered ends, and a fan to provide a minimum airflow of 600 feet per minute (3 m/sec). It is located at the height of the growing points of the plants. (b) A commercial sensor housing, less than 6 inches (15 cm) in diameter that contains an aspirating fan.

(Photo courtesy of Q-Com, Inc., 17782 Cowan Ave., Irvine, CA 92614.)

provide a minimum airflow through the box of 600 fpm (3 m/sec). This ensures that a large mass of air is continually monitored by the sensor and that the temperature inside the box does not rise. The fan should draw air through the box rather than blow it through the box since in this latter case heat from the fan motor would be expelled into the box. The sensor station should have an alarm capability. If the temperature drops to a low set point, such as 50°F (10°C), an alarm in the manager's or owner's home would be activated. The alarm system should have a battery backup to maintain it during an electrical power failure. More often than not, firms purchase sensor housings from companies that sell sensors and computers. These are typically small, plastic, aspirated units that can contain multiple sensors, as pictured in Figure 21b.

Thermostats have historically been used for temperature sensing and control in the greenhouse. Common thermostats operate around a bimetallic strip. The strip curves to conform to the air temperature because two metals fused together in the strip have different thermal expansion coefficients. Such a thermostat generally has a switch built into it. It might be a mechanical switch activated by contact with the end of the bimetallic strip as the strip curves, or it could be a mercury switch attached to the end of a bimetallic coil. A second type of thermostat in use today features a thin metal tube filled with liquid or gas. The tube is shaped into a coil. As the liquid or gas inside changes volume in response to temperature, the end of the tube moves in such a manner that it activates a switch. Depending on the number of settings, such thermostats can cost $100 or more. These thermostats are not highly accurate, nor are they reproducible over time. They need to be calibrated regularly. One problem has been the variation from one thermostat to another within a brand. Even an individual thermostat may slip upward out of calibration one time and downward the next time.

More accurate and reproducible temperature sensing is obtained by growers who use thermocouples and thermistors. Of the two, the thermistor is the more common. Temperature-sensing computer control of greenhouses is most often accomplished with thermistors. A thermistor is a solid-state chip that changes its voltage output according to the temperature. This sensor requires a circuit to carry the signal to a switch. The switch may be a conventional one for smaller equipment or a relay switch for larger equipment. The circuit can be adjusted to activate switches at specific voltage (temperature) settings. The response is specific to temperature, and no other factors are integrated.

The thermocouple consists of two wires of dissimilar metals attached together. Current flow through the junction of the two metals is measured. It is necessary to have a reference temperature in order to convert the current flow rates at each thermocouple into temperature. The reference temperature is usually measured with a thermistor. Thus, when temperature is measured in one zone, a thermistor provides the less expensive alternative. When several temperature sensors are required, it can be cheaper to use thermocouples because they are considerably cheaper than thermistors.

EMERGENCY HEATERS AND GENERATORS

The risk of electrical power failure is always present. If a power failure occurs during a cold period, such as a heavy snow or an ice storm, crop loss due to freezing is likely. Heaters and boilers depend on electricity. Solenoid valves controlling fuel entry, safety-control switches, thermostats, and fans providing air to the firebox all depend on electrical energy.

Power failure can be equally devastating during the summer. Temperature control in greenhouses lacking ventilators is dependent upon electrical exhaust fans. It is likely that the temperature will rise to more than 120°F (49°C) in a closed greenhouse on a clear summer day if a ventilation system is not in effect. High temperatures cause delay in flowering of many crops and, if prolonged for several days, can cause flower bud abortion. Many other types of equipment used in growing crops, including the water pumps, depend upon electrical power. For these reasons, it is important that a standby electrical generator be installed (Figure 22).

The generator can be wired into the greenhouse circuit in such a way that it automatically turns on in the event of a power failure. Some thought should be given to the types of equipment that will be run in this situation. It is rare that the cost can be justified for a generator to handle all power needs. Lights used during the night

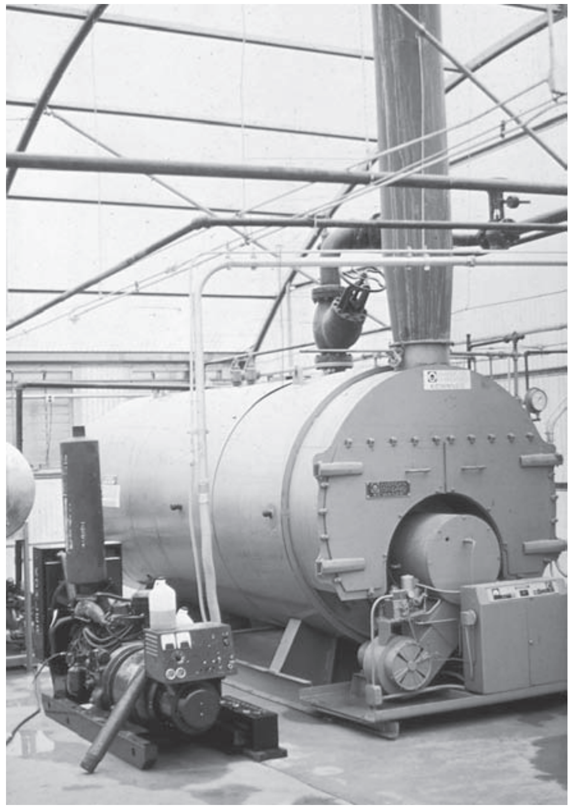


Figure 22
A standby electrical generator (left) used in the event of power failure to maintain operation of the boiler (right), cooling system, and possibly a portion of the lights used for photoperiodic timing of the crop.

(From J. W. Love, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.)

for control of crop flowering draw considerable power and often cannot be handled by available generators. It is possible to use cyclic (flash) lighting, in which the crop is divided into three to five zones. Only one zone is lighted at a time, thus reducing the load demand. During the summer, if the entire cooling system cannot be handled, a proportion of the fans should be maintained to prevent excessive temperatures.

A standby electrical generator is essential to any greenhouse operation. It may never be used, but if required for even one critically cold night, it becomes a highly profitable investment. Generators are available from a number of used-equipment sources, such as government-surplus stores. A firm with a tractor might consider an electrical generator that is powered by the power takeoff on the tractor. A minimum of 1 kilowatt (kW) of generator capacity is required per 2,000 ft^2 (186 m^2) of greenhouse floor area.

It is equally likely that the heating system will fail. Temperatures can drop rapidly in a greenhouse if the insulating properties of the coverings are poor. The rate of temperature decline is increased by lower outside temperatures and increases in wind velocity. Frequently, time is insufficient to seek assistance or to repair the heater before the inside temperature reaches the freezing point. In northern latitudes, this period can be as short as three or four hours. Greenhouse owners using a central boiler system sometimes purchase two boilers to do the job of one. If one fails, the other can still maintain temperatures above freezing. In greenhouses heated by unit heaters with self-contained fireboxes and by infrared-radiant heaters, there is little to fear since there are many heaters. It is unlikely that more than one or two could fail at any one time. Situations where there is only one heater in a given greenhouse or only one central boiler require a backup heating system.

Some growers have installed inexpensive natural-gas or LP-gas burners on flexible fuel lines in the greenhouse (Figure 23). When needed, these burners can be

Figure 23
A 250,000-Btu/hr portable propane heater used for heating the greenhouse during periods of heater failure.

moved out into aisles from their storage places under benches or along walls. Because they are already connected to a fuel source and are ready to light manually, no electricity is required.

For dire emergencies, salamander radiant heaters have been used. In this heater, a kerosene supply is maintained in a pot at the bottom of a stovepipe. It is combusted within the bottom part of the vertical stovepipe. The fumes rise up the pipe and move out through the top into the greenhouse. For this reason, a door should be opened or a ventilator should be opened about 0.5 inch (1.3 cm) to prevent concentration of the fumes. The stovepipe turns red and radiates considerable quantities of heat. One such heater can raise the temperature of 12,000 ft^3 (340 m^3) of air 25 to 30°F (14° to 17°C) and is considered adequate emergency heat for up to 1,500 ft^2 (140 m^2) of greenhouse floor area. The heater burns 0.5 to 1 gallon (1.9 to 3.8 L) of kerosene per hour. One-gallon (3.8-L) cans have been used as well for emergency heat. The top is removed, and two 1-inch (2.5-cm) holes are cut in opposite sides 2 to 3 inches (5 to 8 cm) down from the top to provide air circulation. The can is half-filled with alcohol and ignited. Many other systems are feasible. It is important that one be available.

FUEL

Solid, liquid, and gaseous fuels, represented by wood, coal, oil, and gas, are used for greenhouse heating. Each has advantages and disadvantages. The choice can be influenced by antipollution regulations. The use of coal and high-sulfur-content oils has been disallowed in some areas.

Heating efficiency is an important factor for any greenhouse firm when selecting a fuel and a heater or boiler. It is also a very elusive factor because it has many forms. *Combustion efficiency* is of little value, since it is merely the percentage of heat contained in a fuel that is released during combustion of that fuel. Much of the released heat may be lost up the chimney. Heat that is not released remains in the unburned fuel. *Thermal efficiency* is far more important, because it is the percentage of heat supplied in the consumed fuel that leaves the boiler in the hot water or steam. The difference between combustion efficiency and thermal efficiency is due mainly to heat lost up the smokestack, and to a lesser degree, to heat lost from the jacket of the boiler. A far more valuable measurement would be *seasonal efficiency*. This is the average of the thermal efficiency over the total heating season. Thermal efficiency is highest when a boiler is operating near full capacity, as in the middle of winter. At the beginning and end of the heating season, efficiency is lowest since heat is supplied infrequently, and thus a higher percentage of heat is consumed in warming and maintaining the boiler temperature. Unfortunately, few seasonal efficiency figures are available for the greenhouse application. Thermal efficiencies in the range of 82 to 88 percent can be expected for oil- and gas-fired heaters and boilers. Thermal efficiencies for coal are much lower and range from about 55 percent for subbituminous (soft) coal to 70 percent for anthracite (hard) coal. Wood boilers can have a thermal efficiency of 65 percent. The preceding values are reasonable at this time but do vary with the style and brand of heater or boiler.

Natural gas is the most desirable fuel because the initial installation of a natural gas system is cheaper, storage tanks are not required, and the gas burns clean, which reduces the labor of adjusting and cleaning the boiler. In some parts of the world, natural gas is cheaper than oil. Propane and butane gases have many of the advantages of natural gas, but are much more expensive.

Oil is generally the next choice. An oil-fueled system is easily automated, but storage tanks are necessary, and considerably more ash and soot result. The boiler exhaust passages, or tubes, must be cleaned often, and the burner needs to be adjusted at least annually. Fuel oils are available in five grades, designated Nos. 1, 2, 4, 5, and 6. No. 1 is slightly heavier than kerosene and is generally used to heat private homes. The oil becomes heavier (more viscous) as the number increases. No. 6 oil must be preheated, before ignition, or it will not flow through the nozzle in the burner. No. 2 oil is used in small greenhouse heaters, and the heavier grades are used in large boilers. The heavier oils cost slightly less and have a higher heat content. Large central boilers, which can burn heavier grades, offer a fuel cost advantage.

Used motor oil, which is similar in viscosity to No. 4 heating oil, is an economical alternative to the virgin heating oils. Used motor oil can sell for 40 to 60 percent of the price of No. 2 heating oil. In addition to a lower price, it has a heat content of approximately 154,000 Btu/gal (42.9 kJ/mL) compared to No. 2 heating oil with an average heat content of 138,800 Btu/gal (38.8 kJ/mL). Reprocessing companies collect used vehicular motor oil and filter it to remove sludge. It is then heated to lower antifreeze and water content to less than 2 percent. Halogens, including chlorine, are tested to determine if steps are necessary to lower the content to below 1,000 ppm. Halogens would otherwise form acids such as hydrochloric acid during combustion. Used motor oil requires the use of specialized burners with aluminized steel heat exchangers and ample access for vacuuming out the extra soot that is produced. It is important to locate these burners in a service building and not in moist greenhouses, where high humidity could react with exhaust to form acids. Unit heaters as small as 175,000 Btu/hr (184,600 kJ/hr) and boilers of most sizes are available for burning used motor oil.

Coal is available in many grades. The terms *anthracite* and *bituminous* refer to hard and soft coals, respectively. Many intermediate kinds exist, with no distinct lines of demarcation. Materials softer than bituminous also exist, ranging all the way to peat. All are the compacted remains of plant material. Coal requires considerable above-ground storage space and more handling labor than oil, and yields large volumes of ash, which must be removed and disposed of.

Boilers are commercially available for burning wood. These systems can be completely automated. Owners of moderate-sized greenhouses requiring a boiler of 100 hp (980 kW) output and larger could consider this option. A few have done so and are realizing considerable savings in their heating costs. Fuel can consist of green chips made from entire trees, green chips intended for paper pulp, or sawdust. Green chips have a heat content of about 4,500 Btu/lb (10.5 kJ/g) and a moisture content of about 40 to 50 percent, depending on tree species. Dried wood has a heat content of about 8,500 Btu/lb (19.8 kJ/g) and a moisture content of 18 percent. Taking into account a thermal efficiency of 65 percent for wood boilers and 85 percent for oil boilers, a price of $1/ton for green wood chips is equivalent to $0.02/gal for No. 2 oil ($1/metric ton of wood = $0.0048/L oil). The current price of $30/ton for green whole-tree chips is equivalent to an oil price of $0.60/gal (15.9¢/L). Not all of the fuel price differential is profit, since the price of chips cited here is FOB the chipping plant, and a more complex fuel handling system is required for wood. A storage shed is needed to keep rain off the wood. Remember, 1 ton of wood is required for every 50 gallons of oil normally consumed (1 metric ton of wood/206 L oil). A silo is required to continuously supply wood to an auger, which feeds it into the boiler. An existing coal boiler can often be converted to burn wood. A tractor is needed for moving wood around in the storage shed and into the silo. Finally, a large bin is needed to collect ash from the boiler. Although the system can be automated, additional labor is required to remove ash from the boiler and dispose of it. In spite of these costs and others, one large greenhouse firm was able to pay back the additional capital cost over an oil system in less than two years and has since realized considerable savings in heating costs. Modern systems burn wood clean enough to meet federal clean air standards. The key to successful burning of wood lies in having a steady source of wood. Often, this is not available.

During the 1970s and 1980s, log-burning boilers made their way into the greenhouse industry. They can be purchased for heating requirements as small as 200,000 Btu/hr (56,600 W). The firebox can accommodate 6-foot (1.8-m) logs, which are loaded by tractor. These open-system hot-water boilers generate no pressure. As such, they are free of governmental inspection requirements for pressurized boilers. The thermal efficiency is about 65 percent. Cracked logs, undesirable sizes, and species normally left behind after harvesting the forest can be used for fuel in these boilers. Taking into account the thermal efficiencies, 1 cord (128 ft^3) of green wood provides the heat output of approximately 125 gallons of No. 2 oil (1 m^3 of wood = 126 L of oil). At a current price of $85/cord, this would be equivalent to buying oil at $0.68/gal (18¢/L). For other conversion purposes, it is handy to know that 1 cord of green wood can range in weight from 3,200 lb/cord (400 kg/m^3) for white pine to 5,700 lb/cord (714 kg/m^3) for white oak. Log-burning boilers cost much less than boilers used for burning oil or gas. Logs can be left out in the rain prior to burning; therefore, storage sheds are not required. Labor is required to cut the logs and to load them two to three times daily into the firebox. For this latter reason, many firms have discontinued the use of log-burning boilers.

The quantity of fuel required for one night, or for any given period of time, can be predicted by knowing the heat value of the fuel to be used, the thermal efficiency of the heater burning the fuel, and the heat required in the greenhouse. The heat requirement can easily be calculated (as will be seen later in this chapter). The heat values of common greenhouse fuels are listed in Table 5, along with some common thermal efficiencies.

The data in Table 5 can be used to determine that the heater in a greenhouse requiring 100,000 Btu of heat per hour would burn 11.9 pounds of anthracite coal, or 0.85 gallons of No. 2 oil, or 118 ft^3 of natural gas. All are equivalent in heat value.

Table 5
Typical Heat Contents for Various Types of Fuel Used for Greenhouse Heating[1]

Fuel	Heat Value	
Moist Coal—Mine Run	**Btu/lb**	**kJ/g**
Anthracite (hard)	12,910	30.0
Semi-anthracite	13,770	32.0
Low-volatile bituminous	14,340	33.3
Medium-volatile bituminous	13,840	32.2
High-volatile bituminous	10,750–13,090	25.0–30.4
Subbituminous	8,940–9,150	20.8–21.3
Fuel Oils	**Btu/gal**	**kJ/mL**
No. 1	132,900–137,000	37.1–38.2
No. 2	135,800–141,800	37.9–39.6
No. 4	140,600–153,300	39.2–42.8
No. 5	148,100–155,900	41.43.5
No. 6	149,400–157,300	41.7–43.9
Gases	**Btu/ft^3**	**kJ/dm^3**
Natural	1,000	37.3
Manufactured	550	20.5
Propane[2]	2,570	95.7
Butane	3,225	120.1
Wood	**Btu/lb**	**kJ/g**
Green chips	4,500	10.5
Dried pellets	8,500	19.8

[1]The heat value is the amount of heat contained in the fuel. The useful amount of heat in the fuel can be determined by multiplying the heat content by the decimal fraction of the thermal efficiency of the fuel in a given boiler. Current thermal efficiencies can be 55 percent for softer coals to 70 percent for hard coal, 85 percent for oil and gas, and 65 percent for wood. Efficiency will vary from one boiler design to another.
[2]One gallon of propane has a heat value of 91,690 Btu (25.6 kJ/mL), while 1 gallon of butane has a heat value of 102,000 Btu (28.5 kJ/mL).

Each is determined by multiplying the heat value of the fuel by the decimal value of the thermal efficiency of burning that fuel to obtain the heat output of the fuel. The heat output is then divided into the Btu's of heat required in the greenhouse. The thermal efficiencies were assumed to be 65 percent for coal and 85 percent for oil and gas. In the case of anthracite coal, the heat value of 12,910 Btu/lb was multiplied by 0.65 (the decimal fraction of the 65 percent thermal efficiency that can be achieved when burning this coal) to obtain a heat output of 8,392 Btu/lb. The 100,000 Btu required in the greenhouse was then divided by 8,392 Btu, which is the heat output of 1 pound of coal, resulting in a need for 11.9 pounds of coal.

The cost of fuel is a strong factor in its selection. Equivalent costs of three types of fuel are listed in Table 6. The five figures on any line in the table are equivalent. That is, a given amount of heat would cost the amount shown for each of the three fuels within a given line. Taking the ninth line, for example, 10.0¢ per kilowatt hour (kWh) is equivalent to paying $2.35 per gallon of No. 2 oil or $1.93 per therm of gas. One should check local prices for fuel. If oil is available for $2.35 per gallon and electricity for $0.12 per kWh, it is much cheaper to heat with oil. On the other hand, if gas costs $1.75 per therm, each Btu of heat would cost less from gas than oil at $2.35 per gallon.

Table 6
COMPARATIVE COSTS OF ELECTRICITY, OIL, AND GAS[1]

An Electric Rate of:	Is the Same as Heating with			
	Fuel Oil at:		Gas at:	
¢/kWh	¢/gal[2]	¢/L[2]	¢/therm	¢/m^3 (natural gas)[2]
2.6	61.0	16.1	50.2	5.4
3.2	75.1	19.8	61.9	6.6
4.0	93.9	24.9	77.3	8.3
5.0	117.4	31.0	96.6	10.4
6.0	140.8	37.2	115.9	12.4
7.0	164.3	43.4	135.2	14.5
8.0	187.7	49.6	154.5	16.5
9.0	211.2	55.8	173.9	18.6
10.0	234.7	62.0	193.2	20.7
12.0	281.7	74.5	231.9	24.9
14.0	328.6	86.9	270.5	29.1
16.0	375.5	99.3	309.2	33.2
18.0	422.5	111.7	347.8	37.4

[1]Adapted from a table by Clifford M. Tuck and Associates, Athens, GA 30604.
[2]Heat values: kWh = 3,416 Btu; gal = 139,000 Btu; therm = 100,000 Btu.
Thermal efficiency of boiler = 85 percent for No. 2 fuel oil and for gas.

CALCULATION OF HEAT REQUIREMENTS

A-Frame Greenhouse

In order to determine the heat requirement, the surface of an A-frame greenhouse must be divided into four components, as illustrated in Figure 24. They are the roof, gable, wall, and curtain wall. Heat lost under standard conditions through each of these areas can be found in Tables 7 and 8. All values in the tables are listed as thousands of Btu's/hr (MBtu). A figure of 5 in the table, for example, means 5,000 Btu/hr. One MBtu/hr is equivalent to 293 W or 252 kcal/hr. The gable and roof losses can be found in Table 7. There are two wall components: (1) the wall, covered with a transparent covering, and (2) the curtain wall below it, which has a nontransparent covering such as poured concrete or concrete block. The heat loss from each is determined separately in Table 8. The wall length in each case refers to the total perimeter of the greenhouse, since the wall extends around four sides of the greenhouse.

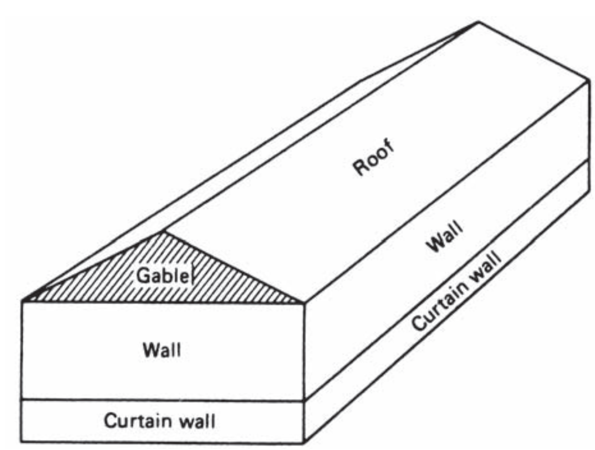


Figure 24
Diagram of an A-frame greenhouse showing component areas needed to determine the heat requirement of this greenhouse.

Table 7
Standard Heat-Loss Values for Gables and Roofs of A-Frame Greenhouses[1]

Greenhouse Length in ft (m)	Greenhouse Width in ft (m)														
	16 (4.9)	18 (5.5)	20 (6.1)	22 (6.7)	24 (7.3)	26 (7.9)	28 (8.5)	30 (9.1)	32 (9.8)	34 (10.4)	36 (11.0)	38 (11.6)	40 (12.2)	50 (15.2)	60 (18.3)
	Gable Loss (both) in MBtu/hr[2]														
	5	6	8	10	11	13	15	18	20	23	26	29	32	50	72
	Roof Loss (both) in MBtu/hr														
5 (1.5)	7	8	9	10	11	12	12	13	14	15	16	17	18	22	26
10 (3.0)	14	16	18	19	21	23	25	27	28	30	32	34	35	45	54
20 (6.1)	28	32	35	39	42	46	50	53	57	60	64	67	71	88	106
30 (9.1)	42	48	53	58	64	69	74	80	85	90	96	101	106	133	160
40 (12.2)	57	64	71	78	85	92	99	106	113	120	127	135	142	177	212
50 (15.2)	71	80	89	97	106	115	124	133	142	151	159	168	177	222	266
60 (18.3)	85	96	106	117	127	138	149	159	170	181	191	202	212	265	318
70 (21.3)	99	112	124	136	149	161	173	186	198	211	223	235	248	310	372
80 (24.4)	113	127	142	156	170	184	198	212	227	241	255	269	283	354	424
90 (27.4)	127	143	159	175	191	207	223	239	255	271	287	303	319	398	478
100 (30.5)	142	159	177	195	212	230	248	266	283	301	319	336	354	443	532
200 (61.0)	283	319	354	390	425	460	496	531	567	602	637	673	708	885	1,062
300 (91.4)	425	478	531	584	637	690	743	797	850	903	956	1,009	1,062	1,328	1,594
400 (121.9)	566	637	708	779	850	920	991	1,062	1,133	1,204	1,274	1,345	1,416	1,770	2,124
500 (152.4)	708	797	885	974	1,062	1,150	1,239	1,328	1,417	1,505	1,593	1,682	1,770	2,213	2,666

[1]Adapted from Acme Engineering and Manufacturing Corp. (2004).
[2]One MBtu/hr = 239 W or 252 kcal/hr.

Table 8
Standard Heat-Loss Values for Greenhouse Walls[1]

Wall Length in ft (m)	Wall Height in ft (m)						
	2 (0.61)	4 (1.22)	6 (1.83)	8 (2.44)	10 (3.05)	12 (3.66)	14 (4.27)
	Wall Loss in MBtu/hr[2]						
5 (1.5)	1	2	2	3	4	5	6
10 (3.0)	2	3	5	6	8	10	11
20 (6.1)	3	6	9	13	16	19	22
30 (9.1)	5	9	14	19	24	29	34
40 (12.2)	6	13	19	26	32	38	45
50 (15.2)	8	16	24	32	40	48	56
60 (18.3)	9	19	28	38	47	58	67
70 (21.3)	11	22	33	44	55	67	78
80 (24.4)	13	25	38	51	63	77	90
90 (27.4)	14	28	43	58	71	86	101
100 (30.5)	16	32	47	64	79	96	112
200 (61.0)	32	63	95	128	158	192	224
300 (91.4)	47	95	142	192	237	288	336
400 (121.9)	63	127	190	256	316	384	448
500 (152.4)	79	158	237	320	395	480	560

[1]From Acme Engineering and Manufacturing Corp. (2004).
[2]One MBtu/hr = 293 W or 252 kcal/hr.

Table 9
CLIMATE FACTORS (K) FOR VARIOUS AVERAGE WIND VELOCITY AND TEMPERATURE CONDITIONS[1]

Inside-to-Outside Temperature Difference in °F (°C)	Wind Velocity in mph (m/sec)				
	15 (6.7)	20 (8.9)	25 (11.2)	30 (13.4)	35 (15.6)
30 (16.7)	0.41	0.43	0.46	0.48	0.50
35 (19.4)	0.48	0.50	0.53	0.55	0.57
40 (22.2)	0.55	0.57	0.60	0.62	0.64
45 (25.0)	0.62	0.65	0.67	0.70	0.72
50 (27.8)	0.69	0.72	0.74	0.77	0.80
55 (30.6)	0.77	0.80	0.83	0.86	0.89
60 (33.3)	0.84	0.88	0.91	0.94	0.98
65 (36.1)	0.92	0.96	0.991	1.03	1.07
70 (38.9)	1.00	1.04	1.08	1.12	1.16
75 (41.7)	1.08	1.12	1.17	1.21	1.25
80 (44.4)	1.16	1.21	1.26	1.30	1.35
85 (47.2)	1.25	1.30	1.35	1.40	1.45
90 (50.0)	1.33	1.38	1.44	1.49	1.54

[1]Standard heat-loss values from Tables 7, 8, and 12 are multiplied by a factor (K) to correct them for local wind and temperature conditions. From Acme Engineering and Manufacturing Corp. (2004).

All heat losses thus far determined are for standard conditions, which include a 70°F (39°C) temperature difference from the outside to the inside and an average wind velocity of 15 miles per hour (mph) (6.7 m/sec). It is likely that you will have different temperature and wind conditions or a different type of greenhouse construction. You can change the heat-loss values in Tables 7 and 8 by multiplying them by two correction factors. First, determine the difference in temperature between your desired inside night temperature and the coldest outside temperature you expect to encounter during the winter. (Local temperature probabilities can be obtained online from the National Climatic Data Center.) Next, determine the average wind velocity for your area. For most areas, 15 mph (6.7 m/sec) will suffice. (However, this too can be checked out with the nearest U.S. Weather Bureau office.) Select a climate factor (K) from Table 9 for your particular temperature difference and wind velocity, and multiply each heat-loss value from Tables 7 and 8 by the factor. Select a construction factor (C) from Table 10 for the type of greenhouse you have, and multiply this by the heat-loss values for the gable, roof, and wall (transparent covering only). Determine a curtain-wall construction factor (CW) from Table 11, and multiply the curtain-wall heat-loss value by this factor. All greenhouse component heat losses have now been corrected. The four corrected values should be added together to determine the total heat input required to heat the greenhouse for 1 hour.

If the heating system is located inside the greenhouse, you are finished with your calculations. Purchase a boiler with a net rating equal to the heat requirement calculated. If a central heating system is located in a separate building, an additional quantity of heat will be necessary to compensate for heat losses from the delivery and return lines to and from the greenhouse. An engineer should be consulted to determine what this loss is, and it should be added to the heat requirement calculated for the greenhouse.

Table 10
Greenhouse Construction Factors (C) for the Common Types of Greenhouses in Use Today[1]

Type of Greenhouse	C
All metal (tight glass house—20- or 24-inch [51- or 61-cm] glass width)	1.08
Wood and steel (tight glass house—16- or 20-inch [41- or 51-cm] glass width—metal gutters, vents, headers, etc.)	1.05
Wood house (glass with wooden bars, gutters, vents, etc.—up to and including 20-inch [51-cm] glass spacing)	
Good tight house	1.00
Fairly tight house	1.13
Loose house	1.25
FRP-covered wood house	1.06
FRP-covered metal house	1.09
Double glass with 1-inch (2.5-cm) air space	0.70
Plastic-covered metal house (single thickness)	1.08
Plastic-covered metal house (double thickness)	0.70
Acrylic or polycarbonate twin-wall panel, 6 mm thick	0.67
Acrylic or polycarbonate twin-wall panel, 8 mm thick	0.60
Acrylic or polycarbonate twin-wall panel, 16 mm thick	0.54

[1]Standard heat-loss values for transparent components of greenhouses such as gables and roofs in Table 7, transparent side walls in Table 9, and ends as well as covering in Table 12 are multiplied by a factor (C) to correct them for the type of construction. From Acme Engineering and Manufacturing Corp. (2004).

Table 11
Curtain-Wall Construction Factor (CW) for Various Types of Coverings Used in the Nontransparent Curtain Wall[1]

Type of Covering	CW
Glass	1.13
Asbestos-cement	1.15
Concrete, 4-inch (10-cm)	0.78
Concrete, 8-inch (20-cm)	0.58
Concrete block, 4-inch (10-cm)	0.64
Concrete block, 8-inch (20-cm)	0.51

[1]The standard heat-loss value for the curtain wall from Table 8 is multiplied by this factor to correct it for the type of covering. Adapted from National Greenhouse Manufacturers Association (2010).

EXAMPLE PROBLEM

The following steps are taken to determine the heat requirement for an all-metal, glass-covered greenhouse measuring 30 feet (9.1 m) wide by 100 feet (30.5 m) long. The curtain wall is 2 feet (0.61 m) high and is constructed of 4-inch (10-cm) concrete block. The glass wall above the curtain wall is 6 feet (1.83 m) high. An average wind velocity of 15 mph (6.7 m/sec) is expected. A 60°F (33°C) temperature difference is expected between the outside low temperature of 0°F (–17°C) and the inside temperature of 60°F (16°C).

1. Set up a chart as illustrated here:

Greenhouse Component	Standard Heat Loss (MBtu/hr) (from Table 7 or 8)	K (from Table 9)	C or CW (from Table 10 or 11)	Corrected Heat Loss (MBtu/hr)
Gable			(C)	
Roof			(C)	
Wall (transparent)			(C)	
Curtain wall			(CW)	_____
Total heat requirement				

2. In Table 7, find the appropriate heat-loss value for both gables combined, immediately below the figure for the greenhouse width. For a 30-foot (9.1-m) width, it is 18 MBtu (18,000 Btu) per hour.
3. In Table 7, find the heat-loss value for the combined roofs, at the point where the 30-foot (9.1-m) greenhouse-width column and the 100-foot (30.5-m) greenhouse-length row intersect. In this case, it is 266 MBtu/hr.
4. Figure the length of the side wall. It is equal to the perimeter of the greenhouse, which equals 100 + 30 +100 + 30 ft, or 260 feet (79.3 m). Find the heat-loss figure for the transparent wall measuring 6 feet (1.83 m) high and 260 feet (79.3 m) long and for the curtain wall measuring 2 feet (0.61 m) high and 260 feet (79.3 m) long in Table 8. Since there are no figures in the table for a wall length of 260 feet (79.3 m), look up the values for 200 feet (61.0 m) and for 60 feet (18.3 m) and add them together to arrive at the answer. For the transparent wall, 95 MBtu/hr are lost through a 200-foot (61.0-m) wall, and 28 MBtu/hr more are lost through an additional 60 feet (18.3 m) of the wall. The total loss is equal to 95 + 28, or 123 MBtu/hr. The curtain-wall heat loss is equal to 32 + 9, or 41 MBtu/hr.
5. Determine the K factor from Table 9 for a wind velocity of 15 mph (6.7 m/sec) and a temperature difference of 60°F (33°C). The K value is 0.84, which lies at the intersection of the wind-velocity column and the temperature-difference row. Enter this value in the chart in the appropriate spaces after each of the four greenhouse components.
6. Determine the C factor from Table 10 for the type of greenhouse construction. The example greenhouse is constructed with a metal frame and a glass covering and has a C factor of 1.08. Enter this value in the appropriate spaces after the gable, roof, and transparent-wall components. These are the three components constructed with the given materials.
7. Find the CW factor for the curtain wall in Table 11, and enter it in the chart in the appropriate space in the curtain-wall row. For a 4-inch (10-cm) concrete-block wall, the CW factor is 0.64.
8. Correct each of the standard heat-loss values in the chart by multiplying each by the K factor and then, in turn, multiplying each answer by the C or CW factor in the same row. Enter these four values in the chart.
9. Add the four corrected heat-loss values together to arrive at the total heat loss. This value is the amount of heat that must be applied to the greenhouse each hour to maintain the desired temperature if the heater is located in the greenhouse. For the example greenhouse, a heater or boiler with a net rating of 391,273 Btu/hr is needed.

Greenhouse Component	Standard Heat Loss (MBtu/hr) (from Tables 7 and 8)	K (from Table 9)	C or CW (from Tables 10 and 11)	Corrected Heat Loss (MBtu/hr)
Gable	18 ×	0.84 ×	1.08 =	16.330
Roof	266 ×	0.84 ×	1.08 =	241.315
Wall (transparent)	123 ×	0.84 ×	1.08 =	111.586
Curtain wall	41 ×	0.84 ×	0.64 =	22.042
Total heat requirement				391.273

10. If the heater is located in a building apart from the greenhouse, the loss from the boiler, the steam or hot-water mains, and the return lines must be determined and added to the preceding figure.
11. In a mild climate, all heat could be provided by an overhead unit heater system. In a cold climate, a wall coil of pipes should provide an amount of heat equal to the loss through the transparent wall plus the curtain wall. In this example, the requirement would be 111.586 + 22.042, or 133.628 MBtu/hr. The remaining heat, gable plus roof (257.645 MBtu/hr), is provided by the overhead system.
12. If desired, the fuel consumption could be calculated for an hour during the night described. Divide the total heat requirement by the heat output of the fuel used:

$$\text{Anthracite coal: } \frac{391{,}273 \text{ Btu/hr}}{8{,}392 \text{ Btu/lb coal}} = 46.6 \text{ lb/hr}$$

$$\text{No. 2 oil: } \frac{391{,}273 \text{ Btu/hr}}{117{,}980 \text{ Btu/gal oil}} = 3.32 \text{ gal/hr}$$

Quonset Greenhouse

Determination of the heat requirement for a Quonset greenhouse requires a few modifications because of the difference in shape, as diagrammed in Figure 25. Quonset greenhouses are covered with film plastic, FRP, polycarbonate, or acrylic, and a curtain wall is rarely used. The transparent covering usually extends to the ground. Two surface areas are considered in the heat calculation: (1) the two ends collectively, and (2) the covering that extends for the length of the greenhouse, which covers the roof and walls but not the ends. Heat-loss values under standard conditions through these two components are found in Table 12. The values must be corrected for your own conditions in the same way that the heat values for an A-frame greenhouse were corrected. The same K and C factors are located in Tables 9 and 10,

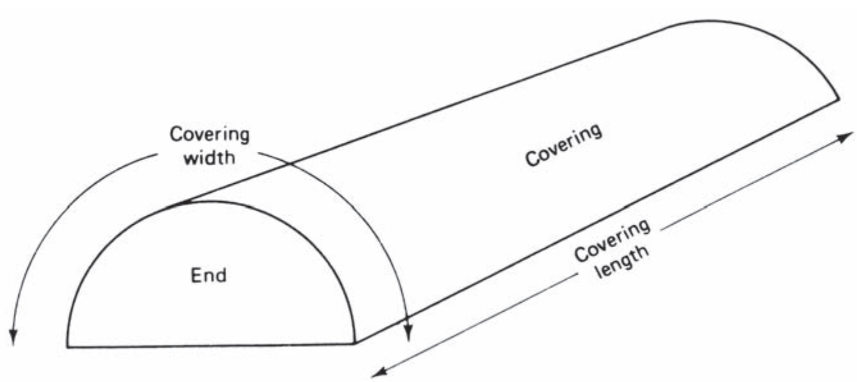


Figure 25
Diagram of a Quonset greenhouse showing component areas needed to determine the heat requirement of this greenhouse.

Table 12
Standard Heat-Loss Values for Quonset-Type Greenhouses for the Combined Ends and for the Entire Covering along the Length of the Greenhouse[1,2]

House Length in ft (m)	Covering Width in ft (m): 18 (5.5)	20 (6.1)	22 (6.7)	24 (7.3)	26 (7.9)	28 (8.5)	30 (9.1)	32 (9.8)	34 (10.4)	36 (11.0)	38 (11.6)	40 (12.2)
End Loss in MBtu/hr[2]	8	10	12	15	17	20	23	26	29	33	36	40
Covering Loss in MBtu/hr[2]												
5 (1.5)	7	8	9	9	10	11	12	13	13	14	15	16
10 (3.0)	14	16	17	19	21	22	24	25	27	28	30	32
20 (6.1)	28	32	35	38	41	44	47	51	54	57	60	63
30 (9.1)	43	47	52	57	62	66	71	76	81	85	90	95
40 (12.2)	57	63	70	76	82	89	95	101	103	114	120	127
50 (15.2)	71	79	87	95	103	111	119	127	134	142	150	158
60 (18.3)	85	95	104	114	123	133	142	152	161	171	180	190
70 (21.3)	100	111	122	133	144	155	166	177	188	199	211	222
80 (24.4)	114	127	139	152	164	177	190	202	215	228	240	253
90 (27.4)	128	142	157	171	185	199	214	228	242	256	271	285
100 (30.5)	142	158	174	190	206	221	237	253	269	285	301	316
200 (61.0)	285	316	348	380	411	443	475	506	538	570	601	633
300 (91.4)	427	475	522	569	617	664	712	759	807	854	902	949
400 (121.9)	570	633	696	759	822	886	949	1,012	1,075	1,139	1,202	1,265
500 (152.4)	712	791	870	949	1,028	1,107	1,187	1,265	1,345	1,424	1,503	1,582

[1]These values are for standard conditions, including a 70°F (39°C) difference from outside to inside temperature and an average wind velocity of 15 mph (6.7 m/sec). From Acme Engineering and Manufacturing Corp. (2004).
[2]One MBtu/hr = 293 W or 252 kcal/hr.

respectively. The end and covering heat-loss values are multiplied by each of these factors to determine the corrected heat-loss values. The two corrected heat-loss values are added together to arrive at the heat requirement for the greenhouse.

EXAMPLE PROBLEM

Listed next are steps to follow in calculating the heat requirement of a metal-frame Quonset greenhouse measuring 30 feet (9.1 m) wide by 100 feet (30.5 m) long and covered with two layers of polyethylene, each measuring 40 feet (12.2 m) wide. A temperature difference of 60°F (33°C) and an average wind velocity of 15 mph (6.7 m/sec) are expected.

1. Locate the heat-loss value for the two ends combined in Table 12. It is the value immediately below the covering width of 40 feet (12.2 m), or 40 MBtu (40,000 Btu) per hour.
2. Locate the heat-loss value for the covering in Table 12. It is the value located at the intersection of the column below the covering width of 40 feet (12.2 m) and the row for a greenhouse length of 100 feet (30.5 m). In this example, the covering heat loss is equal to 316 MBtu/hr.
3. Determine the K factor from Table 9 for a wind velocity of 15 mph (6.7 m/sec) and a temperature difference of 60°F (33°C). The K factor is 0.84.

4. Find the C factor from Table 10 for this metal-frame greenhouse covered with a double layer of polyethylene. The C factor is 0.70.
5. Multiply each of the standard heat-loss values by the K factor and then by the C factor to determine the corrected heat-loss values:

$$40 \times 0.84 \times 0.70 = 23.520 \text{ MBtu/hr}$$
$$316 \times 0.84 \times 0.70 = 185.808 \text{ MBtu/hr}$$

6. Add the two corrected heat-loss values together to determine the heat requirement of the greenhouse. This is the net load of the heater when it is located within the greenhouse.

Greenhouse Component	Standard Heat Loss (MBtu/hr) (from Table 12)	K (from Table 9)	C (from Table 10)	Corrected Heat Loss (MBtu/hr)
Combined ends	40 ×	0.84 ×	0.70 =	23.520
Covering	316 ×	0.84 ×	0.70 =	185.808
		Total heat requirement		209.328

Total required kcal/hr = 209.328 MBtu/hr × 252 = 52,750 kcal/hr

Total required W = 209.328 MBtu/hr × 293 = 61,333 W

Gutter-Connected Greenhouse

A gutter-connected greenhouse generally has three components in terms of heat-requirement computation. They are the roof, the gables, and the walls (Figure 26). Standard heat loss from the walls is determined from Table 8. The wall height is the distance from ground to gutter, while the wall length is the perimeter of the greenhouse. The heat loss from each roof is determined from Table 12. The heat loss calculated for one roof is multiplied by the number of roofs in the greenhouse. The heat-loss values for ends listed in Table 12 yield values too large for the loss from gables. The end of a Quonset greenhouse equates to the gable plus part of the side wall of a gutter-connected greenhouse. Gable heat loss is best determined by calculating the surface area of a gable and then figuring 0.08 MBtu/hr standard heat loss for every 1 ft^2 (2.52 W/m^2, 2.17 $kcal/hr/m^2$). The gable area can be satisfactorily estimated by multiplying the gable height by the gable width and finally by 0.55:

$$\text{height} \times \text{width} \times 0.55 = \text{area of one gable} \tag{1}$$

Actually, a different equation is needed for each manufacturer's design, but this equation will come close enough for all. Be sure to multiply the area of one gable by the number of gables. There are two gables per roof. When the standard heat losses have been determined for the roofs, walls, and gables, each must be multiplied by the appropriate K value from Table 9 and C value from Table 10. The sum of the three corrected heat-loss values is the total heat loss for the greenhouse.

EXAMPLE PROBLEM

The following steps are taken to determine the heat requirement for a gutter-connected greenhouse with four bays (as shown in Figure 26) each measuring 21 feet (6.4 m) wide by 100 feet (30.5 m) long. The walls are 12 feet (3.66 m) high, the gables are 5 feet (1.5 m) high, the covering width of each bay is 24 feet (7.3 m), the

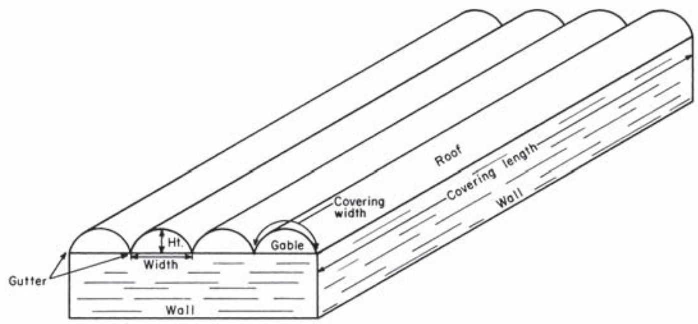


Figure 26
Diagram of a gutter-connected greenhouse showing component areas needed to determine the heat requirement of this greenhouse.

greenhouse frame is metal, and the entire greenhouse is covered with a double layer of polyethylene. A temperature difference of 65°F (36°C) and a wind velocity of 20 mph (8.9 m/sec) are expected.

1. Figure the length of the side wall. It is equal to the perimeter of the greenhouse, which equals 100 + (4 bays × 21 ft) + 100 + (4 bays × 21 ft) = 368 ft (112.2 m). Find the heat-loss value for the wall measuring 12 feet (3.66 m) high and 368 feet (112.2 m) long in Table 8. Since there are no figures for 368 feet (112.2 m), look up values for 300 feet (91.4 m) and 70 feet (21.3 m) and add them together to arrive at an answer that is sufficiently accurate. The total loss is 355 MBtu/hr, the sum of 288 MBtu/hr for the 300-foot (91.4-m) length and 67 MBtu/hr for the 70-foot (21.3-m) length.
2. Determine the heat loss through the four combined roofs. In Table 12, the heat loss through a roof covering width of 24 feet (7.3 m) and length of 100 feet (30.5 m) is 190 MBtu/hr. This is multiplied by 4 (for the four greenhouse bays) to arrive at a total of 760 MBtu/hr.
3. Calculate the heat loss through the eight gables. First determine the area of these gables. Each gable has an area equal to 0.55 × base × height, or 0.55 × 21 ft × 5 ft, which equals 57.75 ft^2. The total area for the eight gables is 462 ft^2. Multiply this value by 0.08, since there is a standard heat loss of 0.08 MBtu/hr for each square foot of surface area. The heat loss for the eight gables is 37 MBtu/hr.
4. Determine the K factor from Table 9 for a wind velocity of 20 mph (8.9 m/sec) and a temperature difference of 65°F (36°C). The K factor is 0.96.
5. Find the C factor from Table 10 for this metal-frame greenhouse covered with a double layer of polyethylene. The C factor is 0.70.
6. Construct a heating chart and enter the standard heat-loss values for the walls, roofs, and gables. Multiply each by the appropriate K and C factors just determined. Add the three resulting corrected heat-loss values to determine the required net load of the heater when it is located in the greenhouse.

Greenhouse Component	Standard Heat Loss (MBtu/hr) (from Tables 8) and 12	K (from Table 9)	C (from Table 10)	Corrected Heat Loss (MBtu/hr)
Walls	355 ×	0.96 ×	0.70 =	238.56
Roofs	760 ×	0.96 ×	0.70 =	510.72
Gables	37 ×	0.96 ×	0.70 =	24.86
			Total heat requirement	774.14

Significance of K, C, and CW Factors

Standard heat-loss factors are multiplied by K, C, and CW factors to correct them for local conditions. When local conditions are the same as the standard conditions for which the heat-loss values of Tables 7, 8, and 12 were determined, these factors are equal to 1. Obviously, multiplication by 1 does not change the heat-loss values. Note in Table 9 that the K factor has a value of 1 for an average wind velocity of 15 mph (6.7 m/sec) and a temperature difference of 70°F (39°C).

If the wind velocity remains at 15 mph (6.7 m/sec) and the inside temperature is reduced by 10°F (6°C) so that the temperature difference is now 60°F (33°C) rather than 70°F (39°C), less heat will be required in the greenhouse. This can be seen in the K factor, which would become 0.84. Since 0.84 is 16 percent less than 1, there is a 16 percent savings in heat realized. When a factor less than 1, such as this factor of 0.84, is multiplied by the standard heat-loss value, the heat loss, or in other words the heat requirement, diminishes.

C values are based on a value of 1.00 for a tight, single-layer glass, wood sash bar greenhouse (Table 10). The C value compensates for shifts in heat transmission (U value; Table 1) of the covering material and infiltration loss of the greenhouse structure from the standard situation of a tight, single-layer glass, wood sash bar greenhouse. Any factor that increases the loss of heat from the greenhouse increases the C value, and conversely any factor that reduces heat loss lowers the C value. Substituting metal sash bars for wood bars causes C to increase to 1.08, an 8 percent increase in heat loss. Loose glass raises the C value to 1.25. Applying two layers of glass reduces heat loss by 30 percent to yield a C value of 0.70. The most highly resistant coverings to heat transmission, those that retain heat best in the greenhouse, have the lowest C factors in Table 10. The same is true for the curtain-wall covering materials in Table 11. C factors are not available for single-layer polycarbonate or polycarbonate and acrylic panels. It stands to reason that corrugated polycarbonate would have C values essentially the same as FRP. These values would be 0.95 for a polycarbonate-covered wood greenhouse and 1.0 for a polycarbonate-covered metal greenhouse.

HEAT CONSERVATION

Greenhouse Design

Fuel economy can be designed into a greenhouse firm. Heat loss is a function of the amount of exposed greenhouse surface area. Quonset greenhouses can have close to 1.65 ft^2 of exposed surface per square foot of floor area, while for large blocks of gutter-connected greenhouses, the ratio can come close to 1.50 ft^2 of exposed area per square foot of floor area. This is a 10 percent reduction in surface area. Thus, a sizeable decrease in heat loss can be realized through greenhouse design.

Double Covering

A double-layer polyethylene greenhouse will consume about 40 percent less fuel than an equivalent single-layer glass, FRP, or polyethylene-covered greenhouse. Polycarbonate and acrylic panels will reduce the heat requirement by approximately 50 percent, compared to a single-layer greenhouse.

Thermal Screens

Greenhouses with a maximum distance between supporting post rows lend themselves more economically to the installation of *thermal screens*. A thermal screen is a curtain of material such as polyethylene, polyester film, aluminized polyester film strips, or polyester cloth that is drawn from eave to eave or gutter to gutter as well as around the inner perimeter of the greenhouse each night to box in the crop. It is drawn off in the morning by a motorized mechanism. Polyester is superior to polyethylene because it blocks radiant heat better (see Table 1). Often, the curtain has an aluminized surface on one side to further reflect radiant heat back to the soil and plants at night so that it cannot leave the greenhouse. Thermal screens serve also to block convection of heat, keeping it around the plants and away from the greenhouse covering. Less heat is lost because the temperature differential across the greenhouse covering is lower. Heat curtains can reduce fuel consumption by 20 to 60 percent, with 40 percent being a realistic mean value.

Thermal-screen systems are available at a cost of \$ 1.75 to \$3/ft^2 (\$ 18.84 to \$32.29/m^2) of floor area covered, including installation. The price differential relates to the number of obstacles within the greenhouse (such as supporting post rows), the number of zones to be independently covered, whether the greenhouse was designed to accommodate a screen, whether the screen is drawn from truss to truss or eave to eave (the latter being cheaper), and the type of screen material. This system is not nearly as practical for Quonset greenhouses because the higher price would apply due to the small installation needed for each greenhouse. The composition of screen materials varies depending on the roles the screen is intended to play. There are three roles: (1) heat retention on winter nights, (2) partial sun screening on bright summer days, and (3) total exclusion of light for lengthening the night in summer for photoperiodic crops. Screens are available to perform any one of these functions singly. Screens are also available for the combination of heat retention plus sun screening or for the combination of heat retention plus photoperiodic control. If all three functions are required in a greenhouse, two automatic screen-pulling systems will have to be installed, which is often done.

Firms that grow photoperiodically timed crops, which require covering with opaque shade cloth to lengthen the night, might be more inclined to install a thermal screen. The mechanism that automatically pulls the thermal screen during the winter is also used to pull the same shade cloth from spring to fall. One opaque curtain material can be used for both functions. Thus, a single investment can be recouped in two ways.

Thermal screens result in a lower greenhouse-covering temperature, which reduces the tendency to melt snow. There is a greater risk of collapse from snow load, which can be remedied by leaving the screen open during a snowstorm. A snow-sensing device should be installed on the roof for this purpose. Some growers have a problem with condensation collecting on the thermal screen, but porous screens are available to solve this problem. Finally, the rush of cold air on the plants when the screen is drawn open in the morning troubles some growers. To get around this problem, many screens have recently been installed immediately below the roof covering material in a way that the screens are drawn from truss to truss. There is less of a shading problem with this arrangement.

Air Circulation

Use active air circulation systems, such as convection tube or HAF, during the heating season. These systems move warm air from the gable to the plant zone, thereby reducing the length of time that heating is required. The HAF system is more energy efficient.

Lower Air Temperature

Heating systems that permit lower air temperature result in considerable heat conservation. Heated floors and radiant heaters allow for at least a 5°F (3°C) reduction in air temperature. As seen in Table 9, this can result in an 8 percent reduction in heat requirement if the air temperature is lowered from 60°F (16°C) to 55°F (13°C). (The K value for 15-mph (6.7-m/sec) wind velocity and a temperature differential of 60°F is 0.84, while for a 15-mph (6.7-m/sec) wind velocity and a temperature differential of 55°F, it is 0.77. The latter K value is 8.3 percent lower than the former.)

Radiant Heat

Low-energy radiant heaters can also be designed into the heating system for a fuel savings of 30 percent or more where natural gas is available. In high-ridge greenhouses, it is possible to lower the radiant heating system and to install a thermal screen above the radiant heaters.

Wall Insulation

Little benefit is derived from scattered light entering through the north wall of a greenhouse. A 5 to 10 percent savings in fuel can be realized by constructing a solid, insulated north wall with a reflectorized inner surface. Another 3 to 6 percent savings can be gained by installing insulation over the curtain walls of the greenhouse. Further savings are possible by installing insulation 12 inches (30 cm) into the ground around the perimeter of the greenhouse.

Sealing Air Leaks

A number of techniques for sealing air leaks can be applied to existing energy-inefficient greenhouses. Some leaky glass greenhouses have been covered with two layers of air-inflated polyethylene for a fuel savings of 40 to 60 percent. One problem that goes along with this system is the reduction in light transmission. In an Ohio State University study, a solar radiation reduction of 35 percent was measured within a conventional glass greenhouse as a result of glass, sash bars, and frame. An additional 18 percent reduction occurred from a double layer of polyethylene over the glass. For high-light-requiring crops, this situation would not be tolerable, but for many others, it appears to be acceptable. Considerable heat can be lost through cracks between overlapping panes of glass or sheets of FRP. Aging causes these cracks to open up and may also cause the glazing compound to become brittle and fall away from the area between the glass and the sash bar. Cracks may occur in the glass, with corners falling out, or some panes of glass may slide, opening up holes. Eventually, reglazing of a glass greenhouse becomes necessary. Reglazing should be done as soon as the need becomes evident to prevent heating costs from rising. Under the present fuel situation, it could be false economy to put off a reglazing job.

Windbreaks

The climate factors in Table 9 give a good indication of the effect of wind on the heat requirement. For every 5-mph (2.2-m/sec) rise in average wind velocity above 15 mph (6.7-m/sec), there is a 4 percent increase in heat loss from the greenhouse. The velocity of wind striking a greenhouse can be reduced by providing windbreaks of trees. Fast-growing evergreen trees serve well. In some cases, trees are already growing prior to construction of the greenhouse range. Care should be taken to leave these where they can perform a strategic role. While windbreaks are important, they must never cast a shadow over the growing area. This would result in loss of productivity, which would be more costly than the fuel saved by the windbreak. Windbreaks on the east, west, or south side should be located away from the greenhouse a distance equal to 2.5 times the height of the windbreak to prevent winter shadows from interfering with crop growth. In general, a 5 to 10 percent fuel savings can result from windbreaks.

High-Efficiency Heaters

High-efficiency heaters are available today that have more extensive heat exchangers than previous models. As a consequence, more heat is removed from the exhaust gases. Exhaust temperatures of 600°F (315°C) and higher can now be reduced to about 300°F (150°C). Where one is operating an inefficient boiler, the efficiency can be increased by installing a chimney heat reclaimer in the furnace flue pipe. This consists of a heat exchanger through which air in some models and water in other models is passed. The warmed air may be used to heat the service building or part of the greenhouse, while the warm water may be used for irrigation. Care should be taken not to lower the stack temperature below the manufacturer's recommendation. At low temperatures, water, acids, and other corrosive compounds can condense and cause deterioration of the chimney.

Heater Maintenance

Heaters will consume fuel at varying efficiencies, depending upon adjustment of the fuel-to-air ratio. For this reason, heaters should be maintained in good condition. Omission of a periodic service call can cost far more in increased fuel consumption. Soot may build up in the flue passageways of boilers, providing insulation on those iron surfaces that are in actuality the heat exchanger of the boiler. Less heat is transferred to water, and more goes up the smokestack, thus increasing fuel consumption. A soot layer 1/8 inch (3 mm) deep can cause a heat loss of up to 15 percent, and a 3/16-inch (5-mm) layer can cause a 21 percent loss in heat captured by the boiler. Boilers should be cleaned on a regular basis. Special materials for coating flue tubes can reduce the tendency for soot to adhere to the surface, allowing more to pass out in the smoke effluent. On the average, these tubes are more efficient heat exchangers, assuming that a cleaning schedule is still maintained.

Thermostat Maintenance

Many other maintenance possibilities exist for reducing heat loss. Thermostats or sensors should be accurately calibrated so that higher-than-desired temperatures are not maintained. This maintenance needs to be done periodically (about every six months) against a calibrated thermometer. Highly precise thermostats should be used. Bimetallic-strip thermostats generally activate a heater at the desired temperature setting and turn it off when a higher temperature is reached. The interval between is known as the *dead load*. A dead load of 2°F (1°C) is quite acceptable for these thermostat types. The dead load can be 6°F (3°C) or more in a malfunctioning thermostat. Considerable heat is wasted each time the thermostat activates. Such a thermostat should be replaced. Actually, it would be better to use thermistors rather than mechanical thermostats.

Maximum Greenhouse Plant Occupancy

Plants can be consolidated to keep heated greenhouses full. The use of movable benches can achieve 90 percent floor coverage with plants. Seedlings and cuttings can be established in germination and/or growth chambers within a greenhouse rather than in the open heated greenhouse when only a small area is being used.

Cool-Temperature Crops

Within some crops are cultivars that can be satisfactorily produced at lower temperatures than others. This is particularly true for poinsettias and chrysanthemums. Greenhouse crops as a whole can be produced at lower temperatures than are generally recommended, but the cropping time is increased. In some cases, an overall economic advantage is realized. In other cases, the fuel savings are lost in forms such as overhead costs and fuel consumption during the period of extended growth.

Combined Economics

It should be obvious that if several heat-saving options are adopted, the total heat savings will not be equal to the sum of the savings of each option. If a second layer of polyethylene is applied to a plastic greenhouse, a savings of 40 percent might be realized on the original heat bill. The fuel consumption now equals 60 percent of the original. Further installment of a thermal screen, predicted to save 40 percent of the fuel consumption, would not lower the fuel consumption to 20 percent of the original value. It would reduce the fuel consumption after installing the second layer of polyethylene by 40 percent. This would be a 24 percent fuel reduction ($0.40 \times 0.60 = 0.24$). The price of energy conservation must always be measured against the value of the energy conserved.

SUMMARY

1. Heat must be supplied to a greenhouse at the same rate with which it is lost in order to maintain a desired temperature. Heat can be lost in three ways—by conduction, by infiltration, and by radiation. Heat is conducted directly through the covering material in conduction loss. In infiltration loss, heat is lost as warm air escapes through cracks in the covering. In radiation loss, heat is radiated from warm objects inside the greenhouse through the covering to colder objects outside.
2. A unit heater system, in which each heater has a firebox, is the cheapest and consequently the most popular system, especially in warmer climates. Heat is distributed from the unit heaters by one of two common methods. In the convection-tube method, warm air from unit heaters is distributed through a transparent polyethylene tube running the length of the greenhouse. Heat escapes from the tube through holes on either side of the tube in small jet streams, which rapidly mix with the surrounding air and set up a circulation pattern to minimize temperature gradients. The second method of heat distribution is HAF. In this system, fans located above plant height are spaced about 50 feet (15 m) apart in two rows such that the heat originating at one corner of the greenhouse is directed down one side of the greenhouse to the opposite end and then back along the other side of the greenhouse. Both of these distribution systems can be used for circulating air when neither heating nor cooling are used and for introducing cold outside air during winter cooling.
3. A central heating system can be more efficient than unit heaters, especially in large greenhouse ranges. They are particularly popular in northern European greenhouses. In this system, two or more large boilers are in a single location. Heat is transported in the form of hot water or steam (mainly hot water) through pipe mains to the growing area. There, heat is exchanged from the hot water in a pipe coil on the perimeter walls plus an overhead pipe coil located across the greenhouse or an in-bed pipe coil located in the plant zone. Some greenhouses install a heating pipe coil in the concrete floor in lieu of the overhead coil across the greenhouse. A set of unit heaters obtaining heat from hot water or steam from the central boiler can be used in lieu of the overhead pipe coil.
4. Low-intensity infrared-radiant heaters can save 30 percent or more in fuel over more conventional heaters. Several of these heaters are installed in tandem in the greenhouse. Lower air temperatures are possible since the plants and root substrate are heated directly.
5. Solar heating systems are found in hobby greenhouses and small commercial firms. Both water and rock storage systems are used. The high cost of solar systems has discouraged any significant acceptance by the horticulture industry to date.
6. Emergency equipment is a necessity and should include a heat source as well as an electrical generator. The generator can be installed to start automatically upon power failure. The need for heat should be signaled by a temperature sensor-activated alarm system in the manager or owner’s home.
7. Temperature sensor placement is very crucial. The sensor should be at the height of the growing point of the plants and in a location typical of the average temperature of the greenhouse. It should be in a light-reflecting chamber that is aspirated at a minimum airflow rate of 600 fpm (3 m/sec). The aspirated chamber should also contain other temperature-sensing controls and a thermometer for testing and correcting the sensors.

8. Relatively easy procedures have been outlined for calculating the heat requirement of greenhouses. Information necessary for determining the heat requirement for an A-frame greenhouse is contained in Tables 7 through 11 and for a Quonset greenhouse in Tables 9 through 12. Calculations for a gutter-connected greenhouse use a combination of all tables.

9. The heat requirement of a greenhouse can be reduced by installing double greenhouse coverings; by using a greenhouse design with minimal exposed surface area; by using thermal screens; by repairing broken glass and tightening existing glass; by using a windbreak of trees to reduce wind velocity; by using high-efficiency (low-stack-temperature) heaters and boilers; by periodically adjusting and cleaning heaters, boilers, and thermostats; and possibly by using cool-temperature-tolerant varieties of plants.

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Greenhouse Cooling

Greenhouses require two distinctly different forms of cooling, one for summer and the other for winter.

Most localities, with the general exception of those in higher elevations, experience periods of summer heat that are adverse to greenhouse crops. Temperatures inside the older standard ventilator-cooled (*passive cooling*) greenhouses were frequently 30°F (17°C) higher than those outside, in spite of open ventilators. Detrimental effects from this excess heat include loss of stem strength, reduction of flower size, delay of flowering, and even bud abortion. The problem of high summer heat accumulation was solved with the development of active evaporative cooling systems (*active cooling*). Evaporative cooling systems are based on the process of heat absorption by water during its evaporation. The two evaporative cooling systems in use today are *fan-and-pad* and *fog*.

Excess heat can likewise be a problem during the winter. Even when the outside temperature is below the desired inside temperature, the entrapment of solar heat can raise the inside temperature to an injurious level if the greenhouse is not ventilated. The challenge during winter cooling is to temper the excessively cold incoming air before it reaches the plant zone. Otherwise, crop injury could occur, and hot and cold spots in the greenhouse could lead to uneven crop timing and quality. Two active winter cooling systems that have been developed to solve this problem are *convection-tube cooling* and *horizontal airflow* (HAF) cooling.

The cost of these four active summer and winter cooling systems has recently stimulated major improvements in passive ventilator summer cooling of greenhouses. Thus, a third viable summer cooling option today is passive cooling.

Regardless of the summer cooling system used, a lower temperature can be achieved in a greenhouse that is full of plants as opposed to one that is only partially full. Plants transpire considerable quantities of water. As this water evaporates from crops, it absorbs heat from these plants and the surrounding air, thereby cooling both. Under conditions of low transpiration, plant temperatures rise to adverse levels that slow growth and injure the plants. Crops can transpire up to 1.23 pounds of water per square foot of growing area per day (6 $kg/m^2/day$) (Kamp and Timmerman, 1996). Growers can take advantage of this cooling assistance by ensuring that transpiration is fostered. The substrate should not be allowed to dry excessively, and the greenhouse should be kept as full of plants as possible.

SUMMER COOLING SYSTEMS

Passive Ventilator Cooling

Until the 1950s, all greenhouses were glass and were cooled by passive air movement through ventilators. Ventilators were located on both roof slopes adjacent to the ridge and on both sides of the greenhouse. The combined roof ventilators had an opening area equal to about 10 percent of the total roof area. The combined side ventilators on single greenhouses were also equal to about 10 percent of the roof area. During the winter cooling phase, the south roof ventilator was opened in stages to meet cooling needs. As greater cooling was required, the north ventilator was opened in addition to the south ventilator. In the summer cooling phase, after opening the roof ventilators, the south-side ventilator was opened first, followed by the north-side ventilator. Air entered the side ventilators. As the incoming air moved across the greenhouse, it was warmed by sunlight and by mixing with the warmer greenhouse air. With the increase in temperature, the incoming air became lighter and rose up and out the roof ventilators. This set up a chimney effect that, in turn, drew in more air from the side ventilators. Due to insufficient ventilator area, this system did not adequately cool the greenhouse. To compensate, the interior walls and floor were frequently syringed with water on hot days.

Beginning in 1954, a series of active cooling systems were introduced to achieve greater and more uniform cooling. The first were the summer fan-and-pad and fog cooling systems. These were followed by the winter convection-tube system and later by the HAF system. These systems are more expensive to operate than a passive ventilation system. During the past two decades, engineers have revisited the passive system and have improved it to where it is now functionally and economically effective for a number of applications. The current trend is toward passively cooled greenhouses. Rough estimates by several greenhouse manufacturers indicate that about 60 percent of new polyethylene greenhouse construction in southern states and 40 to 50 percent in northern states are of the passively cooled type. Open roof designs are also becoming popular in glass greenhouses.

Many standard low-profile glass greenhouses in cooler climates today have roof ventilators equal to approximately 20 percent of the roof area. Models of these greenhouses are also available with roof ventilators equal to 40 percent and greater of the roof area and are preferred in warmer climates. More recently, low-profile greenhouses have become available with roofs that open up completely.

Similar changes have been made in film plastic greenhouses. Roofs can be partially opened via ventilators or completely opened by using hinged roofs or retractable roofs. Sides can also be opened with roll-up or drop-down curtains or ventilators. Greenhouses equipped with various combinations of these side and roof ventilation options or only with roofs that can open up are adequately cooled even in warm climates. Roof ventilators on film plastic greenhouses generally have a double layer of plastic, and the side ventilators are often double-layer polycarbonate, both of which are heat efficient. On the other hand, the roll-up or drop-down side ventilators are generally constructed from a single layer of plastic, which is not heat efficient. Retractable roofs are mostly single-layer, although a double-layer version is available. The heat loss from single-layer coverings can offset part of the gains in cooling energy unless a thermal screen is installed in these greenhouses.

When drop-down side-wall curtains are first activated, the opening occurs initially at the top of the curtain, well above the crop. This direction of opening works well in cold climates. It allows the entering cold air to mix with warm air before reaching the crop. If air entered directly on the crop, the outer beds of plants could freeze or be delayed in development. Roll-up side-wall curtains are used in warm climates, such as in Florida. The opening begins at the bottom of the curtain. Use of the roll-up curtain has a disadvantage in sprinkler-irrigated greenhouses in windy climates. Beds on the windward side of the greenhouse may not receive adequate water when the wind blows it away from them.

One advantage of passive cooling is obvious. It is cheaper to operate than active cooling systems. However, an initial construction cost is incurred. The materials cost is about \$50.00 per linear foot for polyethylene and \$70.00 per linear foot for glass greenhouses to add ventilators (\$197.00 and \$275.00/m). Of course, part of this cost is offset because the cooling pad and at least half of the exhaust fan capacity of the fan-and-pad summer cooling system is not required in the passive system. This is a large portion of the \$1.50 to \$2.50/ft^2 (\$16.15 to \$26.91/m^2) cost of active greenhouse cooling systems. Both passively and actively cooled greenhouses still require a winter convection-tube or HAF system for air distribution during heating and between heating and cooling. Bedding-plant growers with retractable-roof greenhouses often state that plants produced in this system are compact and hardier. They feel this is due to the full light intensity that is possible during warm days in late winter and early spring and to the cool temperatures that are possible during the early morning.

A potential problem of passively cooled greenhouses arises when sun screens are desired. These are necessary for crops other than bedding plants grown in the warmer months of the year when flower scorch is a threat. Loose-weave (open) sun screens should be used to permit passage of air for passive cooling. The open screen can serve a dual role as a thermal screen in warm climates. However, in cold climates it is more desirable to install two screens, an open sun screen and a tight (closed) thermal screen. Another problem is encountered when insect-excluding screening is desired. Such screening severely restricts passive cooling and is generally not used in passively cooled greenhouses.

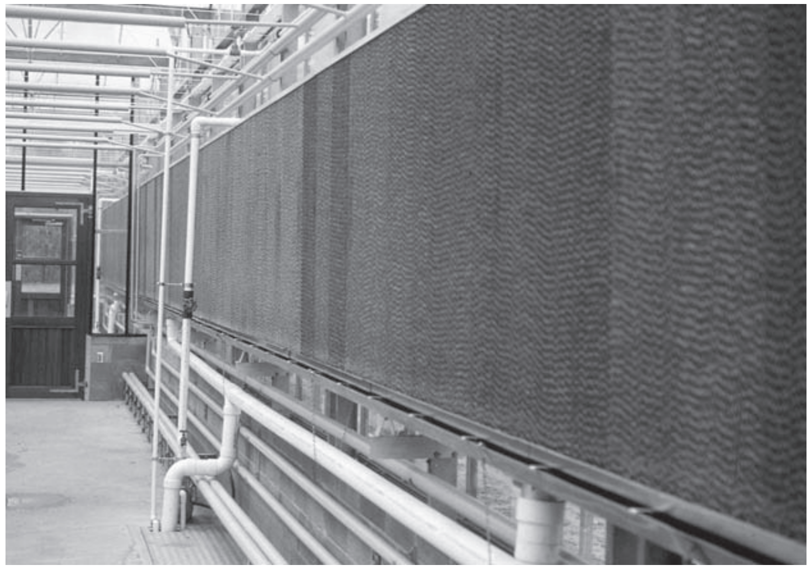
Active Fan-and-Pad System

The fan-and-pad evaporative cooling system has been available since 1954 and is still the most common summer cooling system in greenhouses (Figure 1). Along one wall of the greenhouse, water is passed through a pad that is usually placed vertically in the wall. Traditionally, the pad was composed of excelsior (wood shreds), but today it is commonly made of a cross-fluted cellulose material somewhat similar in appearance to corrugated cardboard. Exhaust fans are placed on the opposite wall. Warm outside air is drawn in through the pad. Water in the pad, through the process of evaporation, absorbs heat from the air passing through the pad as well as from the surrounding pad and frame.

The main considerations of the fan-and-pad system, in the order in which they will be discussed, are (1) the rate at which warm air must be removed from the greenhouse to allow cool air to be drawn in, (2) the types of pads used for evaporating water and their specifications, (3) the placement of fans, and (4) the path of the airstream.

Rate of Air Exchange The rate of air exchange is measured in cubic feet of air per minute (cfm) or cubic meters per minute (cmm). The National Greenhouse Manufacturers Association (NGMA) indicates in its 2010 standards for ventilating

Figure 1
An installation of (a) a 4-inch (10-cm)-thick cross-fluted cellulose evaporative pad, and (b) exhaust fans in the opposite wall used for evaporative cooling of a greenhouse during the summer.



(a)

(b)

and cooling greenhouses that a rate of removal of 8 cfm/ft^2 (2.5 cmm/m^2) of greenhouse floor is sufficient. This applies to a greenhouse under 1,000 feet (305 m) in elevation, with an interior light intensity not in excess of 5,000 foot-candles (fc) (53.8 klux) and a temperature rise of 7°F (4°C) from the pad to the fans. In warmer climates, it is advisable to remove one full greenhouse volume per minute. Since this volume can be tedious to calculate, it is easier to use the recommendation of Willits (2000), which calls for removal of 11 to 17 cfm/ft^2 (3.4 to 5.2 cmm/m^2) of floor area. The NGMA recommendation of 8 cfm has an origin at the time when greenhouse eaves and gutters were typically 8 feet (2.4 m) high. Many greenhouses today have gutters 12 to 16 feet (3.7 to 5.7 m) high.

The rate of air removal from the greenhouse must increase as the elevation of the greenhouse site increases. Air decreases in density and becomes lighter with increasing elevation. The ability of air to remove solar heat from the greenhouse depends upon its weight, not its volume. Thus, a larger volume of air must be drawn through the greenhouse at high elevations than is drawn through at low elevations in

Table 1
FACTORS USED TO CORRECT THE RATE OF AIR REMOVAL FOR ELEVATION ABOVE SEA LEVEL[1]

Elevation above Sea Level in ft (m)

	Under 1,000 (300)	1,000 (300)	2,000 (600)	3,000 (900)	4,000 (1,200)	5,000 (1,500)	6,000 (1,800)	7,000 (2,100)	8,000 (2,400)
F_{elev}	1.00	1.04	1.08	1.12	1.16	1.20	1.25	1.30	1.36

[1]From National Greenhouse Manufacturers Association (2010).

order to have an equivalent cooling effect. Listed in Table 1 are factors (F_{elev}) used to correct the rate of air removal for elevation.

The rate of air removal is also dependent upon the light intensity in the greenhouse. As light intensity increases, the heat input from the sun increases, requiring a greater rate of air removal from the greenhouse. Factors (F_{light}) used to adjust the rate of air removal are listed in Table 2. An intensity of 5,000 fc (53.8 klux) is accepted as a desirable level for crops in general and is achieved with a coat of shading compound on the greenhouse covering or with a screen material above the plants in the greenhouse.

Solar energy warms the air as it passes from the pad to the exhaust fans. Usually, a 7°F (4°C) differential across the greenhouse is tolerated. If it becomes important to hold a more constant temperature across the greenhouse—that is, to reduce the rise in temperature—it will be necessary to raise the velocity of air movement through the greenhouse. Factors (F_{temp}) used for this adjustment for various permissible temperature rises are given in Table 3.

Table 2
FACTORS USED TO CORRECT THE RATE OF AIR REMOVAL FOR MAXIMUM LIGHT INTENSITY IN THE GREENHOUSE[1]

Light Intensity in fc (klux)

	4,000 (43.1)	4,500 (48.4)	5,000 (53.8)	5,500 (59.2)	6,000 (64.6)	6,500 (70.0)	7,000 (75.3)	7,500 (80.1)	8,000 (86.1)
F_{light}	0.80	0.90	1.00	1.10	1.20	1.30	1.40	1.50	1.60

[1]From National Greenhouse Manufacturers Association (2010).

Table 3
FACTORS USED TO CORRECT THE RATE OF AIR REMOVAL FOR GIVEN PAD-TO-FAN TEMPERATURE RISES[1]

Temperature Rise in °F (°C)

	10 (5.6)	9 (5.0)	8 (4.4)	7 (3.9)	6 (3.3)	5 (2.8)	4 (2.2)
F_{temp}	0.70	0.78	0.88	1.00	1.17	1.40	1.75

[1]From National Greenhouse Manufacturers Association (2010).

Table 4
FACTORS USED TO CORRECT THE RATE OF AIR REMOVAL FOR GIVEN PAD-TO-FAN DISTANCES[1]

Pad-to-Fan Distance in ft (m)

	20 (6.1)	25 (7.6)	30 (9.1)	35 (10.7)	40 (12.2)	45 (13.7)	50 (15.2)	55) (16.8)
F_{vel}	2.24	2.00	1.83	1.69	1.58	1.49	1.41	1.35

Pad-to-Fan Distance in ft (m)

	60 (18.3)	65 (19.8)	70 (21.3)	75 (22.9)	80 (24.4)	85 (25.9)	90 (27.4)	95 (29.0)	100 (30.5) and over
F_{vel}	1.29	1.24	1.20	1.15	1.12	1.08	1.05	1.02	1.00

[1]From National Greenhouse Manufacturers Association (2010).

The pad and fans should be placed on opposite walls. These walls may be the ends or the sides of the greenhouse. The distance between the pad and the fans is an important consideration in determining which walls to use. A distance of 100 to 225 feet (30 to 69 m) is best. Distances greater than this can result in higher temperature rises across the greenhouse than are desired. When the distance is reduced below 100 feet (30 m), the cross-sectional velocity of air movement becomes lower, and the air often develops a clammy feeling. This situation must be compensated for by increasing the size of the exhaust fans or, in other words, the velocity of air movement. This increases the cost of the system. Factors (F_{vel}) used to compensate for various pad-to-fan distances are listed in Table 4.

It is now possible to calculate the rate of air removal required for a specific greenhouse by using the factors given in Tables 1 through 4. First, determine the rate of air removal required for a greenhouse under standard conditions using equation 1 or 2, where L and W represent the greenhouse length and width, respectively. This equation calls for the removal of 8 cfm/ft^2 (2.5 cmm/m^2) of floor area, which is acceptable in cold climates. However, in warm climates it is best to enter the height of the greenhouse into equation 1 in the place of the constant “8” and into equation 2 in the place of the constant “2.5.” Height can simply be estimated as the sum of the side wall height plus half of the height from gutter to ridge of the gable.

$$\text{standard cfm} = L \times W \times 8 \tag{1}$$

or

$$\text{standard cmm} = L \times W \times 2.5 \tag{2}$$

Now, correct the standard rate of air removal by multiplying it by the larger of the following two factors, F_{house} or F_{vel}. F_{vel} is read directly from Table 4. F_{house} is calculated as follows:

$$F_{house} = F_{elev} \times F_{light} \times F_{temp}$$

Thus, the final capacity of the exhaust fans must be as shown in equation 3 or 4:

$$\text{total cfm} = \text{standard cfm} \times (F_{house} \text{ or } F_{vel}) \tag{3}$$

or

$$\text{total cmm} = \text{standard cmm} \times (F_{house} \text{ or } F_{vel}) \tag{4}$$

Table 5
Air-Delivery Ratings and Required Pad Areas for Various Sizes of Steel Fans[1]

Fan Size (inch)	Horsepower (hp)	cfm at 0.1 Inch Static Pressure	Pad Area per Fan (ft²)		
			Excelsior	Cellulose (4-inch)	Cellulose (6-inch)
24	0.25	4,530	30	18	11
	0.33	5,655	38	23	14
	0.50	6,450	43	26	16
	0.75	7,625	51	30	19
30	0.33	7,400	49	30	19
	0.50	8,840	59	35	22
	0.75	10,230	68	41	26
36	0.33	8,790	59	35	22
	0.50	10,555	71	43	26
	0.75	12,650	85	51	32
	1.00	14,160	95	57	35
42	0.50	12,490	84	50	31
	0.75	15,000	100	60	38
	1.00	16,760	112	68	42
48	0.50	14,650	98	59	37
	0.75	17,795	119	72	45
	1.00	19,600	131	78	49
54	1.00	22,660	153	92	57
	1.50	26,295	172	104	66

[1]The data in the first three columns are from Acme Engineering and Manufacturing Corp., Muskogee, OK.

Next, the size and number of exhaust fans must be determined. The collective capacity of the fans should be at least equal to the rate of air removal required and should be rated to do so at a static water pressure of 0.1 inch (30 Pa). If slant-wall-housing fans are used, the fans should be rated at a static water pressure of 0.05 inch (15 Pa). The static pressure figure takes into account the resistance the fans meet in drawing air through the pad and the fan itself. Air-delivery ratings for various sizes of fans are listed in Table 5. Fans should not be spaced more than 25 feet (7.6 m) apart. If the end of the greenhouse is 60 feet (18.3 m) wide, a minimum of three fans will be necessary. The required capacity of each fan in this example can be determined by dividing 3 into the total cfm (or cmm) of air removal required. It is then a matter of finding fans in the table that are rated for this performance level. These fans should be evenly spaced along the end of the greenhouse, at plant height if possible, to guarantee a uniform flow of air through the plants.

Pad Types and Specifications Originally, excelsior (wood fiber) pads were used that were 1 to 1.5 inches (2.5 to 4 cm) thick. They had to be replaced annually. Excelsior pads had to be encased in a 1-inch-by-2-inch (2.5 cm × 5 cm)-mesh wire frame for support. Other types of pads have emerged through the years, including aluminum fiber, glass fiber, and plastic fiber. Most cooling pads installed today are constructed of cross-fluted cellulose material (Figure 2a). These pads have the appearance of corrugated cardboard. They can last 10 years if properly handled. They should be protected from beating rain and heavy water streams and should be moved only if dry. These pads have sufficient strength to stand alone without a mesh wire support. The cellulose is impregnated with soluble antirot salts, rigidifying saturants, and wetting agents to give it lasting quality, strength, and wettability.

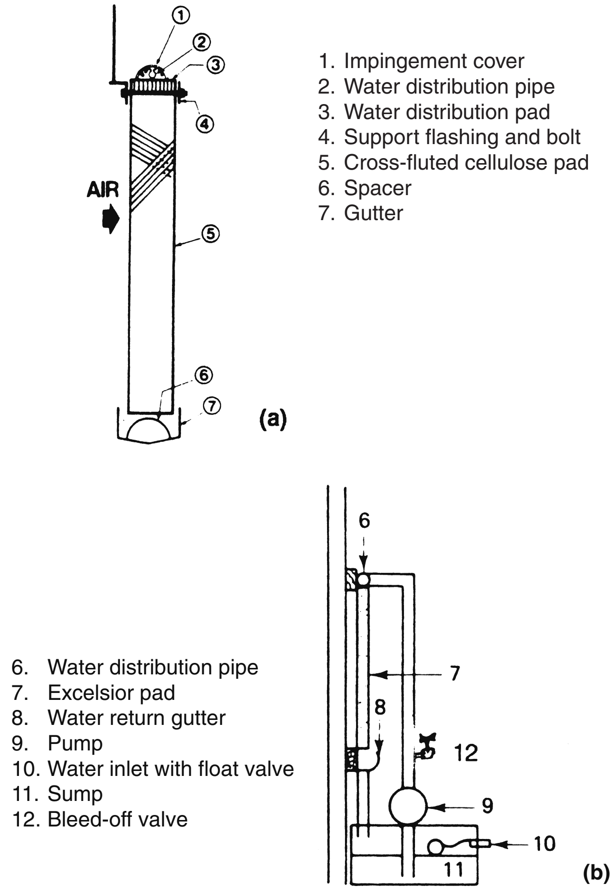


Figure 2
(a) The components of a cross-fluted cellulose pad system for evaporative cooling, and (b) the water distribution system for the cooling pad, including sump, float valve, and pump.

Cross-fluted cellulose pads come in units of 1 foot (30 cm) wide and 4 or 6 inches (10 or 15 cm) thick. Heights are available in 1-foot (30-cm) increments. Units are oriented vertically so that each adds 1 foot (30 cm) to the length of the overall greenhouse pad. Four inches is the most common thickness used today. Pads 6 inches thick are useful in walls that are too small to accommodate the greater pad area required for a 4-inch-thick pad. A 4-inch-thick pad will accommodate an air intake of 250 cfm/ft^2 (75 cmm/m^2) of pad, while a 6-inch-thick pad will accommodate 400 cfm/ft^2 (105 cmm/m^2) of pad. Pads 12 inches thick can be used in excessively hot and humid locations. The earlier excelsior pads supported an airflow rate of 150 cfm/ft^2 (45 cmm/m^2).

The total area of pad required is determined by dividing the volume of air that must be removed from the greenhouse in 1 minute by the volume of air that can be moved through a square foot of pad in 1 minute. Alternatively, the pad area may be read directly from Table 5. The cooling pad should extend over the entire length of the wall of the greenhouse in which it is installed, to ensure that all plants receive cooled air. The height of the pad is determined by dividing the total area of the pad by the length of the pad. Pads are most often placed immediately inside the side or end wall. The pad wall should be equipped with ventilators exterior to the pad to permit air entry during hot weather and for sealing off the outside air during cooler spring and fall nights. In this case, the ventilator arms and gears are located exterior to the greenhouse (Figure 3). Exhaust fans must be located in the wall opposite the pad to ensure that an even blanket of cool air passes through all parts of the greenhouse. Pads and fans should be at plant height to keep the cooling air in the plants.

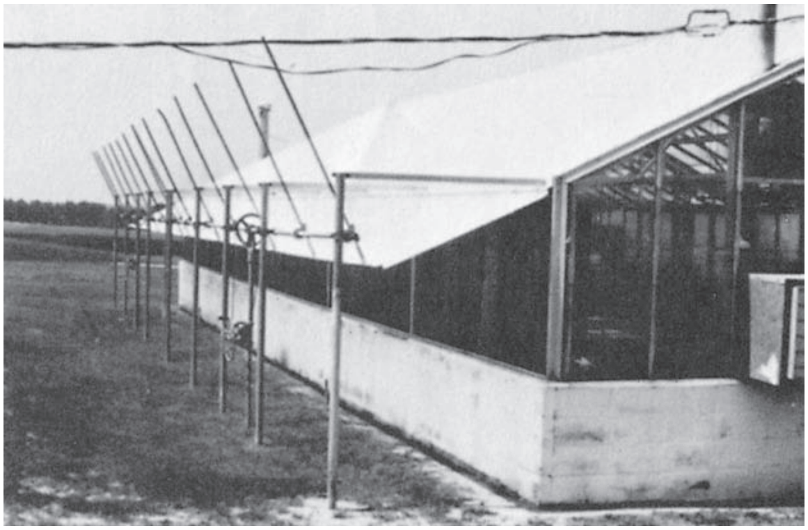


Figure 3
An evaporative cooling system arrangement, with the pad located inside the greenhouse and the ventilator mechanism exterior to the greenhouse. This system permits cooling on warm autumn days when the evenings are too cold for the side wall to be left open.

Water must be delivered to the top of a 4-inch (10-cm)-thick pad at the rate of 0.5 gpm per linear foot of pad (6.2 L/min/m of pad). For pad lengths of 30 to 50 feet (9.1 to 15.2 m), a 1.25-inch (32-mm) water distribution pipe is required, while for lengths of 50 to 60 feet (15.2 to 18.3 m), a 1.5-inch (38-mm) pipe is needed. Sixty feet (18.3 m) is the longest recommended pipe length. A 120-foot (36.6-m) pad length could be serviced from a water supply at the midpoint supplying two 60-foot (18.3-m) distribution pipes. At every 3 inches (7.6 cm), 1/8-inch (3-mm) holes should be made in the pipe.

The flow rate for a 6-inch (15-cm) pad is 0.75 gpm per linear foot of pad (9.3 L/min/m of pad). A 1.25-inch (32-mm) distribution pipe is used for pads 30 feet (9.1 m) and shorter, while a 1.5-inch (38-mm) pipe is used for 30- to 50-foot (9.1- to 15.2-m) pad lengths. The longest pipe length recommended is 50 feet (15.2 m). Again, 1/8-inch (3-mm) holes are spaced 3 inches (7.6 cm) apart in these distribution pipes.

Holes in the distribution pipes for cross-fluted cellulose pads are oriented upward. An impingement cover is placed over the distribution pipe. Water squirting upward from holes in the distribution pipe strikes the inner side of the impingement cover and is dispersed. Half of a 4-inch (10-cm) plastic pipe provides a good impingement cover. Deflected water drips onto a distribution pad that is 2 inches (5 cm) high and the thickness of the cellulose pad below it. This pad further disperses the water to more thoroughly wet the top of the cellulose pad. It is important that all of the pad is wet. There is less resistance to the flow of air through dry pad; thus, air will channel through dry areas and reduce the overall effectiveness of the pad. A gutter at the base of the pad collects water and permits it to flow to a sump, where it is pumped back to the top of the pad. Between the gutter and the base of the pad is a spacer. Half of a 4-inch (10-cm) plastic pipe provides a good spacer. The sump volume should be 0.75 gal/ft^2 (30.5 L/m^2) of 4-inch-thick pad and 1 gal/ft^2 (40.7 L/m^2) of 6-inch-thick pad. These sump volumes are designed for an operating water level at half the depth of the tank and will provide room to accommodate water returning from the pad when the system is turned off. The sump should be covered to prevent debris from falling into it and block sunlight that encourages algae growth.

As much as 1 gallon of water per minute can evaporate from 100 ft^2 of pad (0.4 L/min from 1 m^2 of pad) on a hot, dry day. Therefore, a water line with a float valve should be plumbed into the sump tank to automatically maintain the water level. As water evaporates from the pad surface, salts in the water are left behind.

If this occurs for long, a white salt deposit will solidify on the pad whenever the system is turned off. Depending upon the salt content of the water used, it may be necessary to bleed off 1 to 2 percent of the recirculating water to avoid a salt buildup. A 3/8-inch (9.5-mm) bleed-off valve can be located on the pump discharge pipe. It should be adjusted to a flow rate that just eliminates signs of scale on the pad. The fan-and-pad system can be automated or operated manually. When cooling is demanded in the automated system, the ventilator over the pads is opened, and the exhaust fans are turned on in stages. If this does not satisfy the cooling requirement, the pump providing water to the pads is turned on. When the cooling requirement is satisfied, the system turns off step by step in the reverse order.

Buildup of algae is a major problem in cooling pads. Bacteria and fungi also grow in the pads. These organisms together can reduce airflow through the pad. A few operational steps can minimize this problem. Water should be turned off in the evening and the fans left running for a short period longer to dry the pads each evening. This goes a long way toward killing algae. Little cooling occurs during the night because the level of cooling is proportional to the difference between the dry and wet bulb temperatures of the air. At night the wet bulb temperature is close to the dry bulb temperature. Make-up water added to the system should come from a clean source free of algae. The sump should be covered to keep out light that is required for algal growth. The system should have a bleed-off line to prevent excessive salt buildup. Salt concentration in the recirculating water should be below 50,000 ppm and in the make-up water it should be below 40,000 ppm. The pH level of water in the system should be between 6 and 9. Outside this range, protective chemicals are leached from the pad. This allows for quick breakdown of the pad.

The pad should be cleaned monthly, or more often if required. Treatment chemicals should be registered for use in evaporative coolers. The quaternary amine group of biocides work well if registered for this use. Several can be obtained as non-chlorine swimming-pool disinfectant tablets. They generally work well at one quarter of the rate recommended for swimming pools. Some approved products include Agri-cool II by RXV Products, Aquamax, Bio Stop, Evap 100, Ice Guard AP Nu-Calgon Wholesaler, Inc., Ice Wand, Kool-N-Clean, PWT by Jones Hamilton Co., and Virocide. The chlorine-containing swimming-pool disinfectants, such as the calcium hypochlorite group, are harmful to the pads. Liquid household bleach, sodium hypochlorite, is also very harmful to the pads. Chlorine products raise the pH adversely. The oxidizing biocides are in general harmful. These include chlorine, as mentioned above, as well as bromine and hydrogen peroxide. Copper ions are effective in killing algae but can be corrosive to stainless steel, galvanized stainless steel, and aluminum. Pad manufacturers recommend periodic treatment rather than continuous low concentration treatment. However, some growers are known to use continuous low levels.

If the required pad area exceeds the area of the greenhouse wall, it is necessary to place it exterior to the greenhouse wall (Figure 4). The opening in the greenhouse should be at least half the area of the pad. The pad should be set back from the opening half of the distance by which the height of the pad exceeds that of the opening. Ideally, the extra height of the pad should be equally divided above and below the opening. It is important that the pad is connected to the greenhouse on the top and ends by a transparent covering material to ensure that any air drawn through the pad enters the greenhouse.

Fan Placement Whenever possible, it is best to place the fans on the leeward side of the greenhouse and the pads on the side toward the prevailing winds, so that the winds will assist rather than counteract the cooling system. If fans exhaust into the windward side, their capacity should be increased 10 percent or more. When two or more houses

Figure 4
A cooling pad exterior to the greenhouse. This arrangement can accommodate a pad larger than the wall of the greenhouse. The pad is set back from the wall a distance at least half the excess height of the pad over the wall and is connected to the greenhouse by a transparent covering to ensure that air entering the greenhouse comes through the pad.

are located adjacent to one another, factors more important than wind direction dictate the placement. Fans from one greenhouse should not exhaust warm moist air toward the pads of an adjacent greenhouse if the adjacent greenhouse is within 50 feet (15.2 m) of the fans. When 50 feet (15.2 m) or more exists between the greenhouses, it is acceptable for fans from one to blow toward the pads of the second.

When fans are located in adjacent walls of greenhouses located within 15 feet (4.6 m) of each other, they should be alternated so that they do not blow directly against each other. Adjacent service buildings can also present a problem. There must be a clearance of 1.5 fan diameters between the fan and adjacent obstacles. If this is not possible, special roof-mounted fans should be installed.

A waterproof housing should enclose the fan to protect it from the elements. Air-activated louvers give protection on one side. It is imperative that a screen or welded-wire guard be placed on the other side of the fan to protect workers and visitors from serious injury.

The Airstream The pads should be located at and slightly above plant height in order to bring the cool air in on the plants. Because of resistance of the foliage and plant supports, as well as the rising temperature, the airstream will rise at an angle of 7° (1 foot in every 8) and will soon pass over the plants, leaving a pocket of hot air below at the plant height. If air is drawn across ridge-and-furrow or gutter-connected greenhouses, the gutters will keep the flow of air down on the plants. If air is drawn longitudinally along the length of the greenhouse, it will rise. In this case, transparent film or rigid plastic vertical baffles should be installed in the gable of the greenhouse, perpendicular to the airstream, to direct the flow of air down to the plants. Baffles should be installed every 30 feet (9.1 m). The bottom of the baffle should be well above the plant height to permit passage of air.

If pads are located near the floor and the benches are tall, considerable air may pass beneath the benches, by which little benefit occurs. In this case, baffles should be placed beneath the benches near the pads.

The situation encountered in a greenhouse more than 225 feet (69 m) long and less than 100 feet (30 m) wide can be remedied by placing pads at each end of the greenhouse and exhaust fans in the side walls or roof halfway between the ends. In this situation, the greenhouse is cooled by the equivalent of two systems, each half the length of the greenhouse. When roof fans are used, a transparent baffle should be installed about 5 feet (1.5 m) before the fan and just above plant height to force the cooling air down into the plants.

EXAMPLE PROBLEM

The following example illustrates the calculations involved in designing an evaporative cooling system. Consider a low-profile, glass, ridge-and-furrow single greenhouse with six bays, each measuring 10.5 feet (3.2 m) wide, for a total of 63 feet (19.2 m) in width and 100 feet (30 m) in length. The side walls are 12 feet high (3.66 m) and the gutter-to-ridge height is 4 feet (1.22 m). The greenhouse is located at an elevation of 3,000 feet (915 m). The greenhouse is equipped with an automated sun screen that maintains light intensity inside at or below 5,000 fc (53.8 klux). A 7°F (4°C) rise in temperature can be tolerated from pad to fans. Step-by-step calculations for developing a 4-inch (10-cm)-thick cross-fluted cellulose cooling system for this greenhouse follow.

1. Multiply the greenhouse floor width by the length and by the height (sum of the wall height plus half of the gutter-to-ridge height) to determine the quantity of air to remove per minute under standard conditions:

$$\text{cfm}_{\text{standard}} = W \times L \times H = 63 \times 100 \times 14 = 88{,}200 \text{ cfm}$$

or

$$\text{cmm}_{\text{standard}} = W \times L \times H = 19.2 \times 30 \times 4.3 = 2{,}477 \text{ cmm}$$

2. Determine a factor for the house (F_{house}) by multiplying the three factors together: elevation, light intensity inside the greenhouse, and temperature rise from pad to fans. These factors are found in Tables 1 through 3, respectively:

$$F_{house} = F_{elev} \times F_{light} \times F_{temp} = 1.12 \times 1.0 \times 1.0 = 1.12$$

3. Look up the factor for velocity (F_{vel}) in Table 4. Select two opposite walls that are 100 to 225 feet (30 to 69 m) apart or as close to 100 feet (30 m) apart as possible, for installation of the pad and fans. The end walls, which are 100 feet (30 m) apart, should be used in this example:

$$F_{vel} = 1.00$$

4. Multiply the standard cfm value from step 1 by either F_{house} or F_{vel}, using whichever factor is larger—F_{house} in this case. This is the volume of air to be expelled from the greenhouse each minute:

$$\text{cfm}_{\text{adjusted}} = \text{std cfm} \times F_{house} = 88{,}200 \text{ cfm} \times 1.12 = 98{,}784 \text{ cfm}$$

or

$$\text{cmm}_{\text{adjusted}} = 2{,}477 \text{ cmm} \times 1.12 = 2{,}774 \text{ cmm}$$

5. Determine the number of fans needed. Since they should not be over 25 feet (7.6 m) apart, divide the length of the wall housing the fans by 25 (7.6):

$$\frac{63 \text{ ft}}{25 \text{ ft}} = 2.5 \text{ fans}$$

or

$$\frac{19.2 \text{ m}}{7.6 \text{ m}} = 2.5 \text{ fans}$$

6. Determine the size of the fans needed by dividing the adjusted cfm of air to be removed (from step 4) by the number of fans needed:

$$\frac{\text{cfm}_{\text{adjusted}}}{\text{number of fans}} = \text{size of fan}$$

$$\frac{98{,}784}{3} = 32{,}928 \text{ cfm per fan}$$

or

$$\frac{2{,}774 \text{ cmm}}{3} = 925 \text{ cmm per fan}$$

7. Purchase three fans of the size determined in step 6 and space them equidistantly on one end of the greenhouse. If the fans were to be purchased from the manufacturer of the equipment listed in Table 5, it would be necessary to purchase four fans since the capacity of each of the three fans just calculated would be larger than the fans offered by this manufacturer. In this case, divide the total cfm that needs to be exhausted by four fans to arrive at a fan size of 24,696 cfm (694 cmm). The required fan from this manufacturer would be the 54-inch fan with 1.5-hp motor, which moves 26,295 cfm of air (745 m^3).
8. The pad area is determined next. One square foot of pad is required for each 250 cfm (1 m^2 per 75 cmm) of fan capacity. Divide the capacity of the required fan (26,295 cfm) by 250 cfm to arrive at a required pad area of 105 ft^2 per fan (745 cmm divided by 75 cmm = 9.9 m^2 of required pad area per fan). Since there are four fans, a total of 420 ft^2 (39.6 m^2) of pad is required. Approximately the same value could be read directly from Table 5.
9. The pad must cover the width of the wall in which it is to be installed—63 feet (19.2 m) in this example. The height of the pad is determined by dividing the total pad area by its width. A 7-foot (2.1-m) tall pad should be purchased:

$$\text{pad height} = \frac{\text{pad area}}{\text{pad width}} = \frac{420 \text{ ft}^2}{63 \text{ ft}} = 6.67 \text{ ft}$$

or

$$\text{pad height} = \frac{39.6 \text{ m}^2}{19.2 \text{ m}} = 2.06 \text{ m}$$

10. The pump capacity is equal to 0.5 gpm multiplied by the length of the pad in feet (6.2 L/min/m of pad) and must be selected to have this flow rate for the given head under which it must operate. The head is the distance from the water surface in the sump to the top of the pads:

$$\text{pump capacity} = 0.5 \text{ gpm} \times 63 \text{ ft} = 31.5 \text{ gpm}$$

or

$$\text{pump capacity} = 6.2 \text{ L/min} \times 19.2 \text{ m} = 119 \text{ L/min}$$

11. The sump size is equal to 0.75 gal/ft^2 (30.5 L/m^2) of pad:

$$\text{sump volume} = 0.75 \text{ gal} \times 420 \text{ ft}^2 = 315 \text{ gal}$$

or

$$\text{sump volume} = 30.5 \text{ L} \times 39.6 \text{ m}^2 = 1{,}208 \text{ L}$$

Active Fog Cooling System

The second active summer cooling alternative is fog cooling. The fog evaporative cooling system, introduced in greenhouses in 1980, operates on the same cooling principle as the fan-and-pad system but uses quite a different arrangement. A high-pressure pumping apparatus generates fog containing water droplets with a mean size of less than 10 microns (one-tenth the thickness of a human hair). These droplets are sufficiently small to stay suspended in air while they are evaporating and extracting heat from the air. This occurs without water condensing out on surfaces, so people and plants stay dry throughout the process. Fog is dispersed throughout the greenhouse, cooling the air everywhere. This system is particularly useful for seed germination and cutting propagation since it eliminates the need for a mist system. Installation cost of a fog cooling system relative to a fan-and-pad system can range from less (when pure water is available) to more (when extensive filtering and chemical treatment of water is needed). However, the subsequent cost of electrical power is much less for the fog cooling system.

The speed of evaporation of water and, consequently, the rate of cooling of air increase proportionately as water droplet size decreases. Mist droplets are in the range of 1,000 microns (0.040 in.) in diameter. If a cup of water were converted to mist, it would have 400 times as much surface area and would evaporate 400 times faster than the same water left in the cup. Mist droplets are large and will settle out of air, wetting surfaces of plants, soil, and people. In contrast, fog droplets are 40 microns or smaller (0.0016 in.). The surface area and rate of evaporation of 40-micron droplets is 10,000 times greater than that of the same volume of water in a cup. Greenhouse fog cooling systems are available that can convert 99.5 percent of the water in the system to 40 microns or smaller, with an average droplet size less than 10 microns (0.0004 in.) (Figure 5). These 10-micron droplets evaporate at 40,000 times the speed with which water evaporates from a cup. Pumps used to provide fog

(a)

(b)

(c)

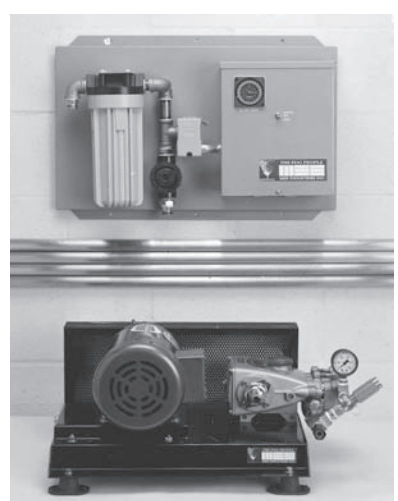


Figure 5
(a) A nozzle emitting 10-micron fog droplets in an evaporative greenhouse cooling system. (b) A fog system being used in a propagation greenhouse for cooling and for maintaining moisture in cuttings. (c) Water treatment and pumping apparatus for a fog cooling system.

(Photos courtesy of Mee Industries, Inc., 4443 N. Rowland Ave., El Monte, CA 91731.)

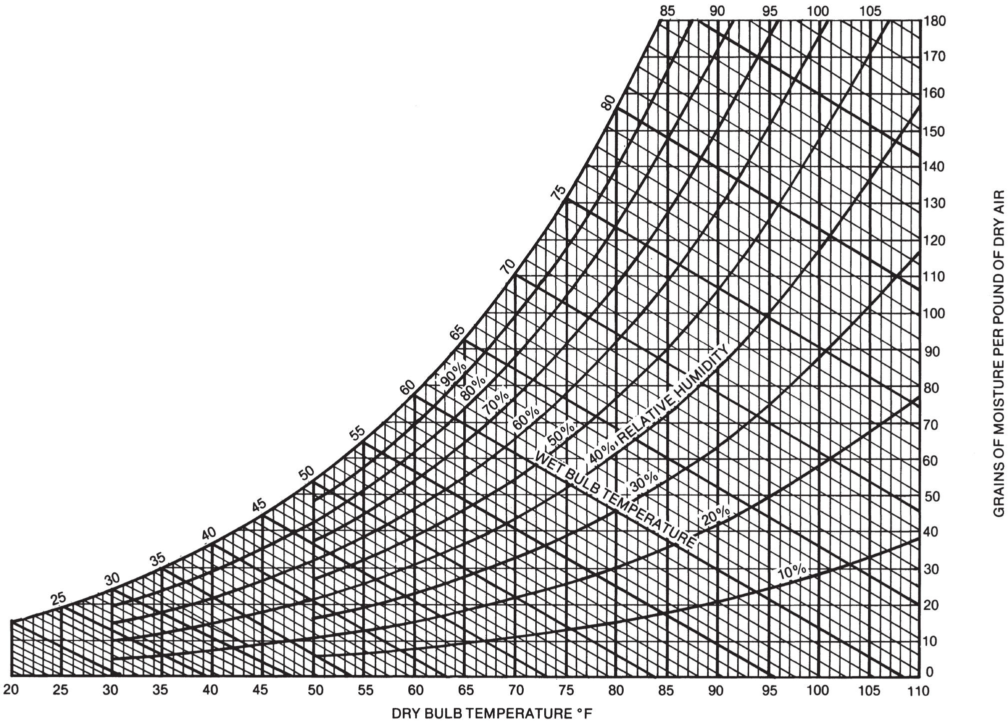


Figure 6

The relationship between dry bulb temperature, wet bulb temperature, and relative humidity. To determine the wet bulb temperature (the lowest cooling temperature possible), start with the dry bulb temperature (read on a standard thermometer) along the lower horizontal axis, follow the vertical line above that temperature up to its intersection with the curve for the relative humidity level in the outside air, move from this intersection along the diagonal line toward the upper left corner of the chart until the leftmost curve is reached, and read the wet bulb temperature from this leftmost curve.

(Graph courtesy of Acme Engineering & Manufacturing Corp., P.O. Box 978, Muskogee, OK 74402.)

droplets can typically operate at 1,000 psi (6.9 MPa) and possibly at pressures up to 1,500 psi (10.3 MPa).

Both fan-and-pad and fog summer evaporative cooling systems can reduce the greenhouse air temperature well below the outside temperature. The fan-and-pad system can lower the temperature of incoming air by about 80 percent of the difference between the dry and wet bulb temperatures, while the fog cooling system can lower the temperature by nearly the full difference. Thus, the drier the air, the greater the cooling that is possible (Figure 6). Consider air at a dry bulb temperature of 90°F (32°C) but at relative humidities of 20 percent in Arizona and 60 percent in Florida. The wet bulb temperatures (lowest cooling points) would be 63° and 78°F (17° and 26°C), respectively. The fan-and-pad system could lower the temperature to approximately 68°F (20°C) in Arizona and 80°F (27°C) in Florida.

The fog cooling system can be used in greenhouses built to be cooled by ventilators alone. Fog nozzles are spaced above plants throughout the greenhouse. Fog comes on intermittently to cool air that has entered the greenhouse through side-wall ventilators. As the humid, cooled air begins to warm and leave the greenhouse through roof ventilators, more outside air is drawn in and, in turn, is cooled by subsequent fog.

Greenhouses equipped with exhaust-fan cooling lend themselves well to fog cooling. A line of fog nozzles is installed just inside the inlet ventilators. Exhaust fans on the opposite wall draw outside air in through the open ventilators and then through the fog, where the air is cooled. Only about half the exhaust-fan capacity—4 to 5 cfm/ft^2

(1.2 to 1.5 cmm/m^2) of floor area—of fan-and-pad systems is used. As the cooled air continues to cross the greenhouse toward the exhaust fans, it absorbs heat. To prevent this, a second row of fog nozzles is installed further inside the greenhouse, parallel to the first row.

Water quality is extremely important. Particles of sand or clay can clog the fog nozzles. Multiple filters capable of screening down to 5-micron (0.0002-in.) particles are used. To prevent scale formation, carbonates and bicarbonates are removed. Sulfur and iron can support growth of slime organisms, which also plug nozzles. All of these factors are assessed, and appropriate filters and chemical treatment are provided by the firms that supply fog cooling systems.

Various control systems have been used for fog cooling. A 24-hour timer is often used to select the time of day during which cooling is needed, which is usually the daylight hours. In the past, growers often used a recycle timer during the fog application period to apply fog from 30 seconds to 4 minutes out of each cycle of 1 to 20 minutes. Today, more consistent control is achieved through the use of a humidistat. When temperature goes up in the greenhouse, humidity goes down. By holding a constant relative humidity, maximum cooling is achieved. The response time of the cooling system is much faster when a humidistat rather than a thermostat is used, since air can be cooled 20°F (11°C) or more in 30 seconds.

When fog cooling is used for growing crops to market stage, a relative-humidity level is set on the humidistat. This level is often in the range of 80 to 90 percent. However, growers fine-tune this setting by relating relative-humidity levels to responses of their crops over time. In this application, visible fog originating from the nozzles generally disappears for a few minutes before coming on again.

Fog is also used as a substitute for mist systems in cutting-propagation greenhouses. The object here is to stop water loss through transpiration by holding 100 percent relative humidity. In this case, fog is turned on just as the visible appearance of the previous fog pulse begins to disappear. Since fog cooling does not wet the foliage, less disease has been reported in greenhouses using this system compared to those using the mist propagation system.

Fog is used in a similar manner in seed-germination greenhouses. The goal here is to greatly reduce evaporation and transpiration, to the point where water is needed only at the frequency at which liquid fertilizer needs to be applied. In this way, the application of water between fertilizations is eliminated. The problem with watering, whether it occurs through mist or larger droplets, is the film of water that forms in the root substrate. This water film adversely reduces oxygen supply to the seeds and roots. A relative-humidity setting slightly lower than the 100 percent level used for cutting propagation is used in seed germination.

It is possible to fertilize seedlings, cuttings during rooting, and roots of plants in an aeroponic system by injecting nutrients into the water supplying the fog system. The system is then controlled to hold the air saturated so that moisture condenses on plant surfaces. Fog very effectively penetrates the plant canopy or root system, depositing a nutrient film on all upper as well as lower leaf and root surfaces for foliar uptake.

Advantages cited by greenhouse firms that have installed fog cooling include the following:

1. There is less electrical consumption, since the sum of the wattage of the fog pump and exhaust fans is less than that of the exhaust fans and pad water pumps in the fan-and-pad system.
2. Heat rise across the greenhouse is controlled.
3. Cooler average temperatures can be achieved across the greenhouse.
4. The system is a good substitute for the mist system in cutting-propagation greenhouses, where it uses less water and causes less disease.

WINTER COOLING SYSTEMS

The fundamental difference between summer and winter cooling systems lies in the temperature of the air that is external to the greenhouse. It is desirable to cool the air during the summer before passing it over the plants. Large volumes of cooled air are introduced directly and uniformly into the plant canopy. During the winter, cold external air must be introduced indirectly above the plants and mixed with the undesirable warm air within the greenhouse prior to making contact with the plants in order to prevent cold spots at the plant level.

Originally, greenhouses were constructed with ventilators adjacent to the ridge and on the side walls. When cooling was required on winter days, the ridge ventilators were opened. Cold air, being more dense than the warm air inside, would drop to the floor beneath the ventilators, where it would spread laterally and increase in temperature as it mixed with the warm air. The result was a temperature gradient across the house at plant height. This led to uneven growth rates and subsequently to variation in maturation dates. The convection-tube and HAF ventilation systems used today for winter cooling correct the horizontal temperature gradient problem. Each circulates the air in the greenhouse.

Active Convection-Tube Cooling

When the temperature set point for winter greenhouse cooling is reached, three events are activated simultaneously (Figures 7 and 8). An exhaust fan, located anywhere in the greenhouse, is turned on to create a vacuum. A louver is opened in a gable, or high in a side wall, through which cold air enters in response to the vacuum. A pressurizing fan in the end of the clear polyethylene convection tube turns on to pick up the cool air entering the louver, since the end of the convection tube is separated from the louvered inlet by 1 to 2 feet (0.3 to 0.6 m). Cold air under pressure in the convection tube shoots out of holes on either side of the convection tube in turbulent jets. The cold air mixes with the warm greenhouse air well above plant height. The cooled mixture of air, being heavier, gently falls to the floor, cooling the plant area.

The pressurizing fan directing incoming cold air into the convection tube must be capable of moving at least the same volume of air as the exhaust fan. If it moves less, excess incoming cold air will drop to the ground at the point of entry and cause a cold spot. When cooling is not required, the inlet louver closes, and the pressurizing fan

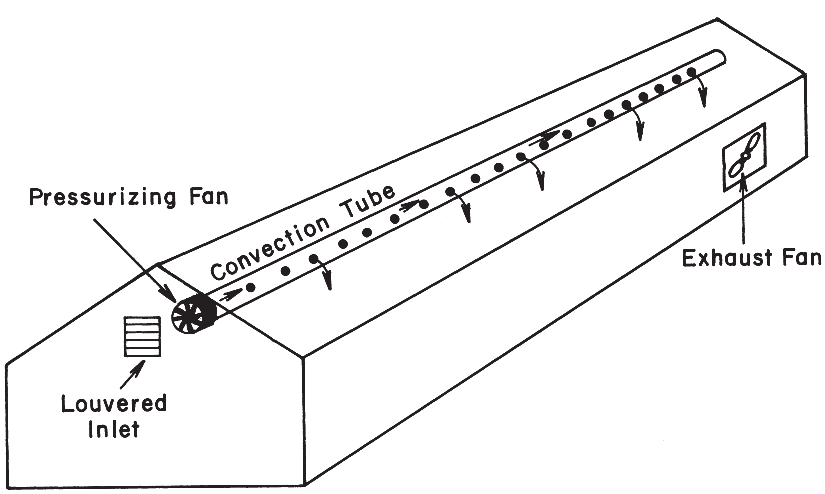


Figure 7
Diagram of a greenhouse showing the components of a convection-tube winter cooling system. When cooling is required, a thermostat activates an exhaust fan, opens the louvered inlet, and turns on the pressurizing fan. Cold air enters the louver and is directed down a transparent polyethylene convection tube by a pressurizing fan. Jets of cold air leave the tube through holes along both sides of the tube and thoroughly mix with warm greenhouse air before reaching the plants.

Figure 8
Air inlet components of a convection-tube winter cooling system, including the louvered inlet, a polyethylene convection tube located a short distance from the louvered inlet, and a pressurizing fan to direct air into the tube under pressure.

continues circulating air within the greenhouse. This step replaces the HAF circulation system, but requires more power.

Under standard conditions, a volume of 2 cfm of air should be removed from the greenhouse for each square foot of floor area (0.61 cmm/m^2 of floor). (Remember that a minimum of 8 cfm of air for each square foot of floor [2.5 cmm/m^2] is required for summer cooling.) The volume obtained by multiplying the floor area by 2 would therefore define the capacity of the exhaust fan in terms of cubic feet of air movement per minute.

Various recommendations over time have called for as little as 1.5 cfm and as much as 4 cfm of air to be exhausted for each square foot of floor area (0.46 and 1.22 cmm/m^2 of floor area). The high-capacity system costs more to set up but can substitute for the pad air inlet earlier in the fall and later in the spring. During this time, incoming air can still be colder than desired.

Standard conditions, when convection-tube ventilation is used, specify a maximum inside temperature of 15°F (8°C) above the outside temperature. The temperature inside the greenhouse can become adversely high on a winter day when the sun is shining, even though the outside temperature is below the desired level. The convection-tube cooling system is designed to reduce the internal temperature to within 15°F (8°C) of the outside temperature.

If a lower inside temperature is desired, cold air must be introduced into the greenhouse at a greater rate. The compensating factors to be used in this case are given in Table 6. As in the case of the summer cooling system, standard conditions also specify an elevation under 1,000 feet (305 m) and a maximum interior light intensity of 5,000 fc (53.8 klux). If other elevation or light intensity specifications are desired, factors must be selected from Tables 1 and 2 and used to correct the rate of air entry.

Convection tubes are conventionally oriented from end to end in the greenhouse. Each convection tube can be used to cool up to 30 feet (9.1 m) of greenhouse width, although it is desirable to use two tubes for greenhouses 30 feet (9.1 m) wide. One tube placed down the center of the house will cool houses up to 30 feet (9.1 m) in width. Greenhouses 30 to 60 feet (9.1 to 18.3 m) wide are cooled by two tubes placed equidistantly across the greenhouse. Holes along the tube exist in pairs on the opposite vertical sides. The holes vary in size according to the volume of greenhouse to be cooled. The number and diameter of tubes needed to cool a greenhouse can be determined from Table 7. If two or more tubes are needed, they should be of equal size and should be spaced evenly across the greenhouse. Recommendations in Table 7 are based on an air-

Table 6
FACTORS (F_{WINTER}) FOR ADJUSTING THE STANDARD RATE OF AIR REMOVAL IN A WINTER GREENHOUSE COOLING SYSTEM FOR THE TEMPERATURE DIFFERENCE BETWEEN THE INSIDE AND OUTSIDE OF THE GREENHOUSE[1]

Greenhouse Temperature Above Outdoor Temperature in °F (°C)	18 (10.0)	17 (9.4)	16 (8.9)	15 (8.3)	14 (7.8)	13 (7.2)	12 (6.7)	11 (6.1)	10 (5.6)	9 (5.0)
F_{winter}	0.83	0.88	0.94	1.00	1.07	1.15	1.25	1.37	1.50	1.67

[1]From National Greenhouse Manufacturers Association (2010).

flow rate of approximately 1,700 cfm/ft^2 (518 cmm/m^2) of cross-sectional area in the tube. When the greenhouse is large and the required number of 30-inch (76-cm) diameter tubes becomes cumbersome, tubes may be installed with air inlets in both ends. These inlets double the amount of cool air that can be brought in through a single tube.

The winter cooling system requirements should be taken into consideration when fans are ordered for the summer cooling system. In this way, one or more of the summer fans could be used for the winter exhaust fan requirement. Fans used for the summer system should all be of equal size or at least nearly equal. However, one fan could be purchased with a two-speed motor that provides half its capacity at the lower speed. In this way, the winter cooling system could operate at 25 percent of the summer system through use of one fan at half capacity.

EXAMPLE PROBLEM

Determine the winter cooling specifications for a greenhouse measuring 50 feet (15 m) wide by 100 feet (30 m) long and situated at an elevation of 3,000 feet (915 m). The maximum interior light intensity anticipated is 5,000 fc (53.8 klux), and the desired interior-to-exterior temperature difference is 15°F (8°C).

1. The capacity of the exhaust fan is equal to 2 cfm (0.61 cmm) times the greenhouse floor area under standard conditions:

$$\begin{aligned} cfm_{standard} &= 2 \times \text{length} \times \text{width} \\ &= 2 \times 100 \times 50 = 10{,}000 \text{ cfm} \end{aligned}$$

   or

$$cmm_{standard} = 0.61 \times 30 \times 15 = 275 \text{ cmm}$$

2. Correct the exhaust-fan capacity just calculated for deviations from standard conditions. The only deviation in the sample problem is the elevation of 3,000 feet (915 m), which has an F_{elev} value of 1.12 (from Table 1). An exhaust fan with a capacity of 11,200 cfm (308 cmm) at a static water pressure of 0.1 inch (30 Pa) is needed:

$$\begin{aligned} cfm_{adjusted} &= cfm_{standard} \times F_{winter} \times F_{elev} \times F_{light} \\ &= 10{,}000 \times 1.0 \times 1.12 \times 1.0 = 11{,}200 \text{ cfm} \end{aligned}$$

or

$$cmm_{adjusted} = 275 \times 1.0 \times 1.12 \times 1.0 = 308 \text{ cmm}$$

Table 7
Number (N) and Diameter (D) of Air-Distribution Tubes Required for Winter Cooling of Greenhouses of Various Widths and Lengths[1]

Greenhouse Length in ft (m)

Greenhouse Width in		50 (15)			100 (30)			150 (46)			200 (61)			200 (61) IBE			250 (76)			250 (76) IBE		
			D			D			D			D			D			D			D	
ft	(m)	N	in	cm	N	in	cm	N	in	cm	N	in	cm	N	in	cm	N	In	cm	N	in	cm
15	(4.6)	1	18	46	1	18	46	1	24	61	1	30	76	—	—	—	1	30	76	1	24	61
20	(6.1)	1	18	46	1	24	61	1	30	76	1	30	76	—	—	—	2	24	61	1	24	61
25	(7.6)	1	18	46	1	24	61	1	30	76	2	24	61	1	24	61	2	30	76	1	30	76
30	(9.1)	2	18	46	2	18	46	2	24	61	2	30	76	—	—	—	2	30	76	—	—	—
35	(10.7)	2	18	46	2	24	61	2	24	61	2	30	76	—	—	—	3	30	76	2	24	61
40	(12.2)	2	18	46	2	24	61	2	30	76	2	30	76	—	—	—	3	30	76	2	24	61
50	(15.2)	2	18	46	2	24	61	2	30	76	3	30	76	2	24	61	3	30	76	2	30	76

[1]Tubes run the length of the greenhouse and are spaced equidistantly across the greenhouse. Tubes derive cold air from a louvered air inlet on one end only, unless otherwise specified. Those open to louvered inlets on both ends are identified as IBE.

3. The number of air-distribution tubes can be determined from Table 7. Two 24-inch (61-cm) tubes are needed for this greenhouse with its 50-foot (15-m) width and 100-foot (30-m) length.
4. The diameter of individual holes along the side of distribution tubes and the distance between them must be decided next. The catalogs of greenhouse-supply companies include tables that specify the model of tube required for given tube diameters and greenhouse lengths. The model identification, unfortunately, does not indicate the size or distance between holes in these tubes.

   The hole specifications can be calculated if you wish to purchase unpunched tubing or tubing from a company that punches holes to your specifications. G. A. Carpenter in England found that the total area of all holes in a single tube should be 1.5 to 2 times the cross-sectional area of the tube. The cross-sectional area of a 24-inch (61-cm) tube is 3.14 ft^2 (890 cm^2). Thus, the combined area of all holes in a tube should be between 4.71 and 6.28 ft^2 (1,334 and 1,778 cm^2). As the required tube length increases, the distance between holes should increase to maintain a reasonable diameter hole. Distances of 2 to 4 feet (61 to 122 cm) are common.
5. The pressurizing fan in the inlet end of the convection tube should be equal to the exhaust fan in capacity. If this is not possible, then the pressurizing fan should be larger. The two pressurizing fans needed in the example greenhouse should have a combined capacity of 11,200 cfm (308 cmm), which is equal to the exhaust-fan capacity. Each pressurizing fan thus has half the capacity, or 5,600 cfm (154 cmm) at a static water pressure of 0.1 inch (30 Pa).

Active HAF Cooling

An HAF ventilation system makes use of the same exhaust fans, inlet louvers, and controls as the convection-tube system. The only difference is the use of HAF fans in the place of convection tubes. Cold air entering through the louvers high in the gables of the greenhouse is picked up in the air-circulating pattern of the HAF fans and distributed throughout the greenhouse. Just like the convection tubes, the HAF fans can be used to distribute heat in the greenhouse as well as for air circulation when neither heating nor cooling is in operation.

COOLING HOBBY GREENHOUSES

The principles are basically the same for cooling hobby greenhouses. A fan-and-pad system is used during the summer. To ensure proper vertical distribution of cool air, the pad should be at least 2 feet (61 cm) in height. Cooling problems inherent in these small greenhouses demand a higher-capacity system. A minimum of 12 cfm/ft^2 (3.66 cmm/m^2) of floor area should be exhausted from the greenhouse. If the greenhouse is attached to the east, west, or especially the south side of another building, then considerable solar heat will be collected inside the greenhouse by this wall. Half the area of the wall should be added to the floor area in calculating the ventilator requirement.

Package evaporative coolers are practical for small greenhouses. A package cooler, as pictured in Figure 9, consists of a cubical structure with evaporative pads on three sides. Water conduction and collection lines, as well as a pump, are built into the package. A fan is located inside the package to draw air in through the pads and expel the cool air to the greenhouse interior. A ventilator or automatic shutter must

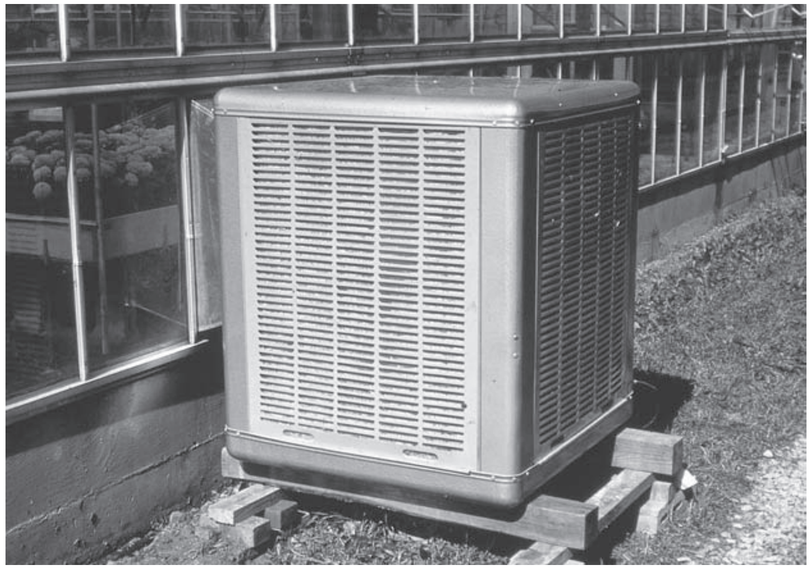


Figure 9
An Arctic Air package evaporative cooler for a small or hobby-type greenhouse. Water is circulated through pads on three sides of the package. A fan is located within the unit to draw air in through the pads.
(Photo courtesy of J. W. Love, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.)

be open at the opposite end of the greenhouse to serve as an air exit. Package coolers should be sized to provide 15 cfm of air per square foot (4.5 cmm/m^2) of floor area. Package coolers can be less expensive for small greenhouses. They are easier to install and are more aesthetically pleasing than conventional fan-and-pad systems.

The winter cooling system for a hobby greenhouse follows the principles of a larger greenhouse. Convection-tube ventilation works well, except that 4 cfm/ft^2 (1.2 cmm/m^2) of floor area should be exhausted under standard conditions. The HAF system may be used in lieu of the convection tube. The fan within a heater in one corner of the greenhouse and an opposing fan in the diagonal corner will handle a greenhouse up to 50 feet (15 m) long.

An alternative arrangement of the convection-tube cooling system saves the price of the inlet louver and the pressurizing fan in the tube. In this system, the convection tube may be connected directly to a stovepipe elbow mounted in the wall of the greenhouse, with the end outside pointing down. The elbow serves as an air inlet. When this system is off, the polyethylene tube hanging from attachments along its upper side collapses and seals itself off from the outside. The tube inflates when an exhaust fan in the greenhouse turns on. An elbow inlet should be used rather than a straight pipe, to prevent wind from blowing into the system and bringing about cooling at times when it could not be tolerated. To further prevent wind entry, it is best to place the inlet for this type of cooling system on the leeward side of the greenhouse. Although heat cannot be distributed through this convection-tube arrangement, the fan in most heaters is generally powerful enough to circulate heat in small hobby greenhouses.

INTEGRATION OF HEATING AND COOLING SYSTEMS

There are periods in the spring and fall when it is necessary to use the heating, winter cooling, and summer cooling systems during the same day in order to maintain the desired temperature settings. All three systems, as pictured in Figure 10, can be integrated to operate in the following way. Suppose that the fan-and-pad evaporative cooling system is operating on a hot autumn afternoon. As the afternoon wears on and outside temperatures drop, the cooling requirement diminishes. A reduction in the inside temperature is translated into a signal that turns off the water-circulation pump in the evaporative pad. The exhaust fans continue to operate, drawing air in

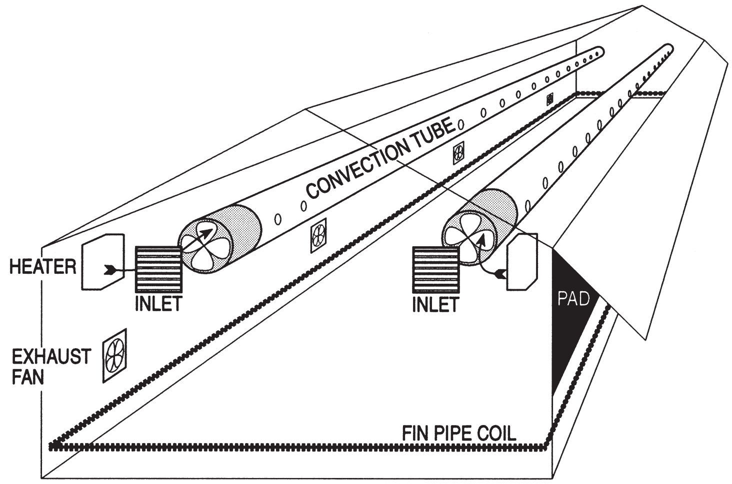


Figure 10
A completely integrated system for fan-and-pad evaporative summer cooling, convection-tube winter cooling, and heating.

through the dry pads. As the need for cooling diminishes further, half of the exhaust fans turn off. With further cooling, an additional quarter of the exhaust fans turn off, leaving only those needed for the winter fan-tube cooling system in operation. At the same time, the ventilators adjacent to the pads close. The winter cooling system is now in operation, with the pressurizing fan in the convection tubes running and the louvered inlet in the end wall open. As evening approaches, the temperature drops further, and no cooling is necessary. The exterior louvered inlet closes. Air is now circulated within the greenhouse through the convection tubes. (If HAF fans were used as an alternative to the convection tubes, the HAF fans would have circulated the cold air entering through the inlet louver during winter cooling and would now circulate interior air in the greenhouse.) Temperatures continue to drop during the night. Heat is first supplied through the perimeter pipe coil. When this cannot hold the desired temperature, half of the overhead unit heaters are activated and later, if necessary, the remaining half. When the overhead unit heaters turn on, they blow warm air toward the convection-tube inlet, where it is picked up by the pressurizing fan in the tube inlet and forced down the tube (Figure 11). In the morning, the reverse sequence of events begins to occur.

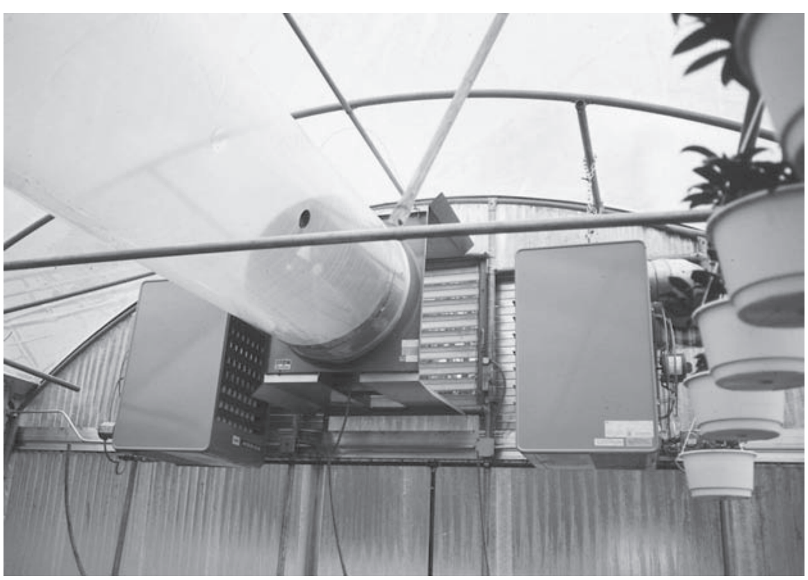


Figure 11
General view of an alternative winter cooling–heating system with two unit heaters mounted apart from the tube inlet. Warm air is expelled from the heaters toward the tube inlet, where it is picked up by the pressurizing fan. The air-intake louver is located in the end wall opposite the inlet of the convection tube. Note the pressurizing fan in the inlet of the convection tube.

Some greenhouses have a more complex heating system consisting of in-floor heat tubes and an overhead pipe coil extending across the greenhouse. In this situation, floor heating is activated first, followed by the overhead coil when the floor system cannot maintain temperature. If the overhead system consists of unit heaters, in lieu of a coil, these unit heaters would be turned on in the second stage of heating.

This complex system of heating and cooling devices might be handled in a single greenhouse zone by a staged controller. If the firm had several similar production zones or several more types of equipment and sensors to coordinate, a computer would serve best.

SUMMARY

1. Summer cooling requires that large volumes of air be cooled and brought into the greenhouse. The cool air must pass in a smooth pattern throughout the entire plant zone. A fan-and-pad system is one evaporative cooling alternative used for this purpose. It consists of pads on one wall, through which water is circulated, and exhaust fans on the opposite wall. Air entering through the pads is cooled and then drawn across the greenhouse to the exhaust fans. Air is drawn through the greenhouse at the minimum rate of 8 cfm/ft^2 (2.5 cmm/m^2) of floor area under standard conditions of an elevation under 1,000 feet (300 m), a maximum interior light intensity of 5,000 fc (53.8 klux), an air-temperature rise of 7°F (4°C) between the pads and the exhaust fans, and a distance of 100 feet (30 m) or more between the pad and the fans. In warm climates, it is more desirable to exhaust one complete greenhouse volume per minute.
2. Fog cooling is an alternative to the fan-and-pad system. Water droplets of 40 microns or smaller (0.016 in.) are generated under high pressure (1,000 psi; 6.9 MPa). Fog introduced into the incoming air, just inside the intake ventilators along one wall, cools the air as it evaporates. A second set of fog nozzles, arranged perpendicular to the path of air, counteracts any temperature rise as cooled air moves toward the exhaust fans opposite the intake ventilators. An air exhaust rate of 4 to 5 cfm/ft^2 (1.2 to 1.5 cmm/m^2) of floor area is used.
3. Winter cooling calls for the introduction of a small volume of already cold air from the outside. This air needs to be mixed with the warm greenhouse air above the plants before it is introduced into the plant zone. The convection-tube system is one option for winter cooling. The system consists of an exhaust fan used to develop a negative pressure in the greenhouse, a louvered air inlet in the gable, a clear polyethylene convection tube situated above plant height along the length of the greenhouse that has holes along opposite sides for turbulent air emission, and a pressurizing fan in the inlet end of the convection tube to pick up the air entering through the louver. A flow rate of 2 cfm of air for each square foot (0.61 cmm/m^2) of floor area is satisfactory for standard conditions, which include elevation under 1,000 feet (305 m), a maximum interior light intensity of 5,000 fc (53.8 klux), and a capacity to bring the inside temperature down to within 15°F (8°C) of the colder outside temperature. An exhaust rate up to 4 cfm/ft^2 (1.2 cmm/m^2) is used by some firms.
4. A more frequently used alternative for winter cooling is the HAF system. The same exhaust fan and air-intake louver as in the convection-tube system are used. The difference lies in the distribution of air throughout the greenhouse. Small fans are placed above plant height at 50-foot (15-m) intervals down one half of the greenhouse and back up the other half. The fans are designed to set up a horizontal circular flow of air, which will conserve fuel by bringing hot air down from the gable and will also minimize temperature gradients at plant height.
5. Passive cooling has been greatly improved in recent years and can effectively handle summer and winter cooling requirements for glass, plastic panel, or film plastic greenhouses. Hot-air release at the top of the greenhouse is achieved through large ventilators, hinged roofs that open completely, or retractable roofs. Air intake through side and end walls can be accomplished through roll-up or drop-down sides or ventilators. These greenhouses typically have convection-tube or HAF air-distribution

mechanisms for distribution of the heated air during heating. When neither cooling nor heating is required, the convection-tube or HAF fans are used to bring warm air down from the gable and to provide uniform temperatures in the plant zone.

6. The principles are the same for cooling hobby greenhouses. Somewhat simpler systems can be utilized. When the greenhouse is attached to an existing building on any side but the north, half of the attachment wall area is added to the floor area in calculating summer ventilation rates. For summer cooling, a minimum airflow of 12 cfm/ft^2 (3.66 cmm/m^2) of floor area is necessary. For winter cooling, an exhaust rate of 4 cfm/ft^2 (1.2 cmm/m^2) of floor area is used.

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Environmental Control Systems

From the origin of greenhouses to the present, there has been a steady evolution of controls. Five stages in this evolution include manual controls, on/off switches, staged controllers, integrated-control computers, and model-based computers. This chain of evolution has brought about a reduction in control labor and an improvement in the conformity of greenhouse environments to their set points. The achieved benefits from greenhouse environmental uniformity have been better timing of crops, higher quality of crops, disease control, conservation of energy, and increased profit.

TYPES OF CONTROLS

Manual Controls

Through the first half of the 20th century, it was common for greenhouse firms to hire a night watchperson to regulate temperature. This person made periodic trips through the greenhouses during the night, checking the temperature in each greenhouse and opening and closing valves on heating pipes as required. During the day, employees opened and closed ventilators by hand to maintain temperature (Figure 1). Temperatures had to be manually controlled on weekends and holidays as well. Obviously, there were large deviations above and below the desired temperatures. Humidity was controlled by turning on a hose and syringing the walks and walls of the greenhouse when it was too dry or hot and by opening ventilators when it was too moist, all by hand. For photoperiodic control of crops, black cloth was hand pulled over beds at the end of the day and off again in the morning. Crops were watered by turning a faucet on and applying water from a hose by hand. Sunscreens were set up at the start of the warm season and were removed at the end of the season. Of course, there were dark days when this shade was detrimental to the crop.

On/Off Switches

As motorization of manual control methods took hold, the next logical step was to connect the motors to on/off switches. Growers adopted thermostats, which are simple temperature-sensing devices that

From Chapter 5 of *Greenhouse Operation and Management*, Seventh Edition, Paul V. Nelson.

Figure 1
A manually operated greenhouse roof ventilator in the process of being opened.

turn a switch on at one temperature and off at another. The thermostat allows for manual adjustment of the on and off settings. Timeclocks were used as on/off switches for other functions. For instance, photoperiodic lights were turned on (and later off) during each night by timeclocks. Black cloth could now be pulled on and off by timeclock control, a decided advantage on Saturday evening and Sunday morning. Automatic watering systems that took hold in the 1960s were initially turned on and off by hand. With time, they were turned on by hand and off by timeclock. This was an advantage in firms with large numbers of watering stations because it allowed the person applying water to go on to other tasks once the water stations were turned on.

A common range of prices for thermostats is \$50 to \$200. Simple on/off thermostats were used at first. These have the advantages of being inexpensive and simple to install. Their disadvantages include poor accuracy, which can lead to low energy efficiency, and no coordination of equipment—each piece of equipment in the heating or cooling system requires its own thermostat. For this reason, heating and cooling systems are restricted to one or two steps each when using simple thermostats. Simple thermostats are often used in Quonset greenhouses where there is one stage each of heating and cooling. One thermostat might turn the heater on at 60°F (16°C) and off at 62°F (17°C). The second thermostat might turn the exhaust fan on and open the air-intake louver for the winter cooling system when the temperature reaches 75°F (24°C) and then deactivate this equipment at 73°F (23°C). The set points of the thermostats are far enough apart that the inaccuracies that develop in each of them will not cause them to overlap so that heating and cooling occur simultaneously. Some more recent thermostats do offer two stages of control. These can be used to control two stages of heating or perhaps one stage of heating and one stage of cooling in a coordinated manner that prevents overlap of the two climate control systems.

Staged Controllers

Staged controllers were developed based on the same on/off principle as the thermostat. A staged controller can activate several pieces of equipment from a single temperature sensor in a coordinated manner that prevents any one piece of equipment from getting out of sequence with the others (Figure 2). A typical example would be the following six-stage temperature control system. Half of the unit heaters are turned on at a temperature setting of 60°F (16°C) and in the event that these cannot supply the required heat, the remainder are turned on at 58°F (14°C). When cooling is required, the winter cooling equipment is turned on first at 75°F (24°C). If this is insufficient, half of the summer cooling system fans are turned on, without water in the pads, when the temperature continues to rise to 77°F (25°C). If the temperature continues to rise to 79°F (26°C), the remaining summer cooling system fans are turned on, again without water in the pads. Finally, water is turned on in the pads if the temperature reaches 81°F (27°C). Because there is only one temperature sensor, there is no risk of the six functions falling out of sequence. This system reduces energy input and wear on the equipment. When less than full capacity is needed, some equipment is not turned on. If thermostats were used in lieu of the staged controller, two options could be used. First, all heaters would be activated by one thermostat, all winter cooling by a second thermostat, and all summer cooling by a third thermostat. Because the full capacity of heating and cooling are used, large temperature overrides would be experienced. Second, each of the six stages of equipment would be activated by an individual thermostat. Since accuracy of thermostats is poor, events could easily get out of sequence unless large differences were set for the activation temperature of each heating or cooling device. These large differences would result in large deviations from the desired temperatures.

In addition to being able to give a stepped response to a single sensor such as a temperature sensor, staged controllers can receive signals from two or more sensors, such as temperature and humidity as seen in Figure 2. The number of sensors is limited, and the type of sensor is predetermined in the staged controller purchased. For example, a temperature-sensing staged controller cannot be used to sense wind velocity or carbon dioxide (CO_2) level.

The advantages of thermostats and staged controllers are evident. Compared to manual systems, they provide better control of the greenhouse environment, save

Figure 2

A STEP Up Control™ staged controller and aspirated temperature sensor. This controller can sense temperature and relative humidity for controlling two stages of heating, four stages of cooling, and excessive relative humidity in the set point temperature range between heating and cooling. Independent temperature settings can be set for day, night, and DIF periods. It has the capability to record temperature in 15-minute intervals for seven days and to graph data.

(Picture courtesy of Wadsworth Control Systems, 5541 Marshall St., Arvada, CO 80002, Web: www.wadsworthcontrols.com.)

money on energy, and provide some conveniences to the grower for a reasonable price of $100 to $1,200 per climatic zone. The main disadvantage is the basic on/off control. Even with multiple stages, the greenhouse climate is always somewhere between 2°F (1°C) above or below the desired set point. The other disadvantage is their dedication to the tasks for which they are purchased. They must be restructured or replaced when it is necessary to perform a different task—that is, to sense humidity rather than temperature. This is not the case with computers.

Computers: Integrated Control

Virtually all large- and most intermediate-size firms have adopted computer control for their greenhouse environments. The current generation of greenhouse computers is referred to as integrated-control computers because a single computer controls all equipment in a climate zone by using all available sensors and measurements. The ventilation, for example, is not only controlled by the temperature, but is at the same time influenced by the humidity, outside temperature, solar radiation, wind speed, wind direction, and rain. The integrated computer controls the ventilation, heating, cooling, air circulation, CO_2 dosing, boilers, pump units, and irrigation valves based on multiple settings entered by the grower. In this system, the on/off control has been advanced to a modulating control that can apply varying proportions of any input. The end result is more stable and accurate climate (within 1°F [0.5°C] of the desired setting), energy conservation, and improved crop quality.

The entry level of integrated-control computers is identified under various names including integrated controller and greenhouse controller. The integrated controller is a simple integrated-control computer that typically costs from $1,000 to $4,000. It is distinguished from the higher-level computers by typically having a keypad or a touch screen rather than a keyboard and a two- to eight-line LCD screen of perhaps 80-character length for programming rather than a monitor. It generally does not have a CD drive. Simple graphing and data logging can be done on the LCD screen. It can have far more output connections than the staged controller; some can control 40 devices. With this number of devices, it is cheaper to use an integrated controller than several staged controllers. Integrated controllers permit integration of a diverse range of devices, which is not possible with a thermostat and is impractical with staged controllers. The accuracy of an integrated controller for temperature control is quite good. Unlike a thermostat that is limited to a bimetallic strip or metallic (mercury) tube for temperature sensing, the integrated controller more often uses a thermistor. The bimetallic-strip sensor has less reproducibility and a greater range between the on and off steps.

The simplest computer arrangement used today consists of an integrated controller located in a greenhouse section. Each controller receives input signals from sensors within the greenhouse section in which the controller is located. These signals are integrated in the controller and output signals are sent to equipment in that section. With each new expansion of a greenhouse section, either an additional controller can be added in the new section or a controller that allocates the sensor inputs and control outputs to multiple greenhouse sections can be purchased (Figure 3). This is handled by the software in the controller that calls for settings and displays results by section. A problem can occur with this latter scenario when a large number of sensors and control devices are desired in each greenhouse section since the limited number must be divided over the number of sections controlled.

As the number of controllers increases, the advantage of a more complex central computer to coordinate these controllers also increases. The price of central greenhouse computers begins around $10,000 and ranges upward considerably with additional features and ports for sensors and controlled devices. Most of

Figure 3

*A Versi*STEP™ *integrated controller with 32 analog input channels from sensors and capacity for up to 40 outputs for equipment control. Software in this controller allows inputs and outputs to be allocated from one to eight greenhouse sections and to handle separate settings for day, night, and DIF time periods. Four analog output channels allow control of variable speed fans and modulating valves.*

(Picture courtesy of Wadsworth Control Systems, 5541 Marshall St., Arvada, CO 80002, Web: www.wadsworthcontrols.com.)

this cost is for the software. See Figures 4 and 5 for the physical arrangement of this system.

The central computer is distinguished from the controller by having the capacity for more sensor input and control output ports, a monitor, a CD drive, greater

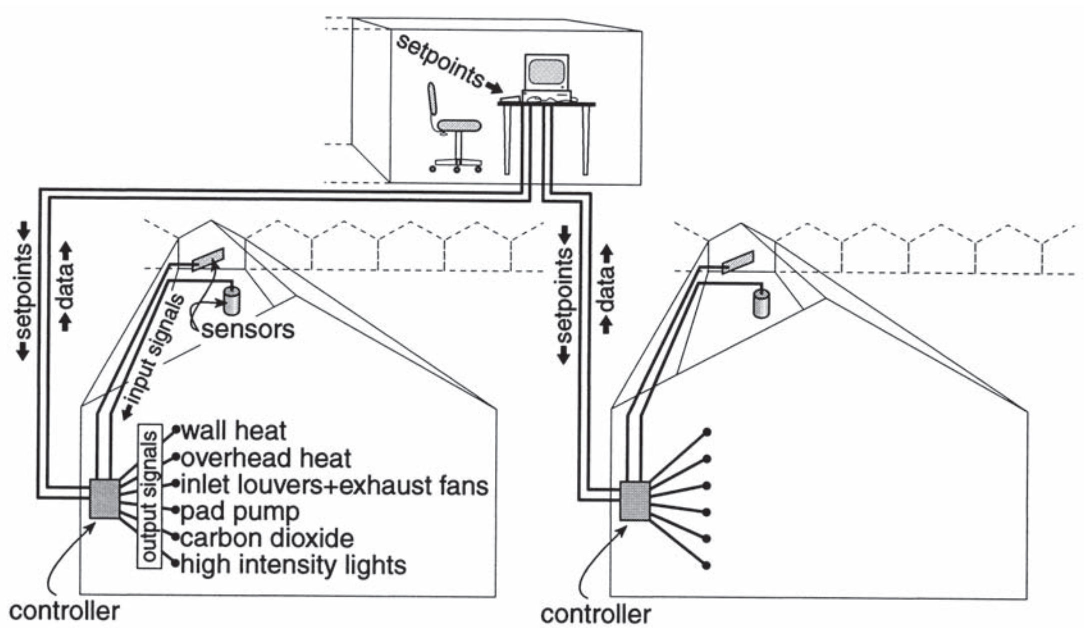

Figure 4

Schematic plan for integrating a central computer into the control system for a multiple-zone greenhouse range. Greenhouse environment set points are transmitted from the central computer to an integrated controller in each greenhouse zone. Set points may also be entered at the controller. Signals from environmental sensors in a given greenhouse zone are received by the controller within that zone where they are processed. An output signal is then sent from the controller to the environmental control devices in that same greenhouse zone.

Figure 5
A computer system operating under the scheme described in Figure 4. The computer (lower left in picture) is located in the manager's office, while the controller (center of picture) and the aspirated housing holding the sensors (lower right in picture) are located in the greenhouse.

(Photo from Priva Computers Inc., 3468 South Service Rd., Vineland Station, Ontario, L0R 2E0, Canada, Web: www.priva.ca.)

capacity to store, tabulate, and graph data, and in particular, the capacity to coordinate numerous integrated controllers each located in a different greenhouse section. Expanded record logging and graphing capabilities are important. Records from each sensor, including indoor and outdoor temperature, light intensity, relative humidity, CO_2 level, and outside wind speed and direction, can be stored in the computer for future study. Tables and plots of these records are handy when evaluating the efficacy of various pieces of equipment, or assessing the cause of crop quality or timing problems. The central coordinating computer is located in the production manager's office. From this computer, the manager can program the desired set points for any individual section or all greenhouse sections. These set points can also be entered in the controller within each greenhouse section. Regardless of where the set points are entered, data from sensors within each greenhouse section are fed into the controller in that section. That controller integrates these data and sends signals out to environmental control equipment in that section. The following examples demonstrate the level of integration that is possible in computers.

The trend in pest management is away from high-volume (HV) pesticide sprayers toward low-volume (LV) pesticide applicators. LV applicators fill the greenhouse volume with a pesticide mist or fog for a period of several hours. This is best done during the night when no one is around. However, the greenhouse atmosphere needs to be exchanged with outside air before employees return to work. A firm with a computer can easily add these control functions into its program. Without a computer, the firm would have to purchase a separate timeclock controller. While the timeclock is feasible, it further complicates the control system because it offers no coordination between temperature control, purging of greenhouse air during the night for humidity control, and pesticide application. The system must ensure that no ventilation occurs during the pesticide treatment period and that ventilation is assured during the subsequent pesticide purge period, regardless of heating needs. This is a simple task for a computer.

Another example of the utility of an integrated computer system is seen in air humidity control in the greenhouse. A humidity sensor could be installed that would call for evacuation of warm, moist air via the winter cooling system whenever the relative humidity increased to a set point, such as 90 percent. The incoming cold air would cause the heaters to turn on, thereby warming and drying this air. The air purge would continue, regardless of the need for heating, until the relative humidity was lowered to a predetermined point. If the air purge were under the control of a timeclock, it would be necessary to purge for a fixed length of time, usually four minutes, to achieve one full air exchange. However, the amount of air that must be purged is dependent on the relative humidity and temperature of the incoming air. Many times, less than one air exchange will suffice. A computer will exchange air only as long as necessary to bring the relative humidity down to the desired level. This would save heating fuel because less incoming air would have to be heated. An additional overlying function could be the application of LV pesticide mist and its ensuing purge phase. Humidity control would have to be deactivated during the pesticide exposure period so that the pesticide would remain in the greenhouse, in contact with the crop, and not be evacuated. Then, during the following pesticide purge phase, greenhouse air would have to be exchanged with the outside air even if heat was required. The combined complexity of temperature control, humidity control, and pesticide application favors the computer.

Computers: Model-Based Control

Several new dimensions are under development for computer software. Many of the initial advances that occur in software are generic across a broad spectrum of industries, including the greenhouse industry. This is fortunate because it allows the relatively small greenhouse industry to be swept along with the mega-industries. It is the final stages of adaptation to greenhouse application that must occur within our industry. Toward this end, a sufficient number of companies are now well positioned to bring this about. Without question, the availability of new computer applications for control of greenhouse climate and operations will continue to escalate. Soon it will be unthinkable to operate any greenhouse without a computer.

The latest development in greenhouse computers is the model-based environmental control. Model-based environmental computers have more sophisticated software available, allowing more proactive control possibilities. The integrated computer senses changes in crop production inputs, such as temperature, light intensity, and available water level in root substrate, and acts accordingly to ensure that each is maintained at an adequate level for the crop. The problem with this system is that the optimum levels of each input were determined in previous research and may not always apply to the crop at hand. The model-based computer calculates real-time needs of the plant as it grows. Thus, the difference between these two systems lies in the software rather than the hardware. A good example is the vapor pressure deficit model for determining water needs. The rate of water loss from the plant is calculated based on the cumulative measurement of the force that drives water loss from the plant. This force is the difference in water vapor within and outside the leaf and is calculated from continual measurements of leaf and air temperatures and air relative humidity.

Current limitations to model development are our limited knowledge of (1) the relationship between balances of cultural/environmental inputs and crop physiological response (yield) and (2) the relationship between crop yield and profit. This second relationship will be the most difficult to procure.

To illustrate, let's consider the balance among temperature, CO_2, and ambient light intensity. The temperature at which a given crop will yield an optimum response increases as light intensity in the greenhouse increases from suboptimum to optimum intensity. The optimum concentration of CO_2 in the greenhouse atmosphere for supporting photosynthesis likewise increases with increasing light intensity, up to the optimum light intensity for photosynthesis. In order to realize an increased plant response from an increase in either temperature or CO_2, both of these factors must be increased in proportion. Otherwise, the factor in lowest supply will limit the plant response, rendering the increased level of the other factor ineffective. This three-way relationship becomes much more complicated if we add in the possibility of supplemental lighting in the greenhouse to bring light intensity closer to the optimal level during darker periods of the year. Now it becomes even more important to adjust temperature and CO_2 levels appropriately so that costly increases in supplemental light are not wasted. One day, an algorithm based on physiological response data will be developed that will identify optimum levels of temperature and CO_2 for every possible light-intensity level.

To be economically practical, this model will need the capacity to determine the cost of each heat, CO_2, and light input, to predict the increase in yield, and to determine the impact on profit. Such a program will guard against achieving a yield increase where the cost of the inputs to achieve the increase is greater than the economic return of the yield increase.

A model-based system can be supplied with a curve of optimum plant height for all points in time during production. Such a model would be capable of making daily judgments as to whether the rate of plant height increase needs to be hastened or slowed. This would be accomplished by adjusting the day-to-night temperature ratio. While doing so, the model would adjust levels of CO_2 and any supplemental light to augment the new temperature settings.

The possible realm of model-based systems spreads even further to encompass humidity control, fully automated pesticide application, and fertilization. Obviously, the challenge before those developing such systems is the procurement of crop physiology and economic data. More intricate relationships must be understood between levels of environmental factors and plant response. For instance, what is the best rate of decline in temperature from the high day setting to the lower night setting? How long should the lower light intensity in the greenhouse caused by an occasional cloud in the sky exist before corrective action is taken in the form of lower temperature and CO_2 level? Would the quality of crops be better if all environmental stresses were eliminated? This is the direction in which control programs are currently moving. Or, are growers dependent on temperature, water, nutritional, or other stresses to achieve the quality levels that they have come to expect? If this latter question is answered in the affirmative, these stresses and their magnitudes will need to be programmed into the model-based systems.

SUMMARY

1. Over the years, control of the greenhouse environment has undergone a steady evolution. Various stages have included manual controls, on/off switches such as thermostats and timeclocks, staged controllers, integrated-control computers, and now model-based computers.
2. Thermostats respond to temperature signals only. They are generally the simple on/off–type switches. Several thermostats may be used together to offer two stages of heating along with one or two stages of cooling. However, these thermostats are not coordinated and are not as accurate as other control alternatives.
3. Staged controllers can receive inputs from one or two predetermined sensors, such as temperature and humidity, and can control several pieces of equipment in a coordinated method. A staged controller receiving an input from a single temperature sensor could function as follows. As the temperature rises through perhaps nine settings, the staged

controller can shut down full heating capacity through three settings, circulate ambient air, and ramp up cooling through five stages. Each piece of equipment remains coordinated because it is turned on or off at a different temperature, all reported from a single temperature sensor. Staged controllers are dedicated to the type of equipment and sensor for which they are designed.

4. Integrated-control computer systems can integrate signals from numerous sensors to control all equipment in the greenhouse. They can be updated and expanded with time by replacing their software. In this system, a simple integrated-control computer is located in an individual greenhouse section where it receives signals from multiple sensors, integrates these signals, and sends out commands to the control equipment in that greenhouse. Integrated controllers often have a keypad or touch screen in lieu of a keyboard, a LCD screen with two to eight lines of about 80 characters rather than a monitor, and limited record logging and plotting capability. As the number of greenhouse sections and integrated controllers increases, a more sophisticated central integrated computer is added into the manager's office. The central computer has a monitor, keyboard, greater logging and plotting capabilities, and control over all the integrated controllers. Settings for each greenhouse section can be entered into the controller in that section or into the central computer.

5. Future model-based computer control of greenhouse production will handle real-time computation of cultural/environmental inputs to establish desired crop yield and have the capacity to assess the cost of inputs and monetary value of crop increases in order to identify yield levels with the best economic return.

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Root Substrate

Once the greenhouses are constructed and the heating and cooling systems are established, it is time for the first cultural consideration—selecting a root substrate. For growers who mix their own substrate, this appears to be a monumental task. Some 10 or more components, including field soil, sand, calcined clay, perlite, vermiculite, peat moss, pine bark, hardwood bark, coconut fiber, and rock wool, are to be found in numerous formulations. Many growers develop effective formulations. Those who fail do so because of poor combinations of components and the use of more components than are needed or can be justified economically. Selection of a self-mix formulation or an off-the-shelf commercial product should be an easy matter once the fundamentals covered in this chapter are understood.

Until the 1960s, virtually all greenhouse root substrate was based on soil. The most typical mix was equal volumes of loam soil, sphagnum peat moss, and concrete grade sand. Soilless mixes were primarily adopted by the greenhouse industry during the 1960s and 1970s. Initially, most soilless substrate was formulated by growers. During the 1980s, half of soilless substrate was purchased from formulation companies; today, the majority is purchased from formulation companies. The shift away from soil-based substrates was fostered by three factors: (1) soilless substrates do not need to be pasteurized as soil-based substrates do; (2) soilless substrates are lighter in weight, thereby reducing handling and shipping costs; and (3) unlike soil that can vary greatly from batch to batch, soilless substrate components tend to be more consistent over time. The switch from growers making their own substrates to purchasing them from formulation companies occurred as the cost of prepared soilless substrates fell relative to other production costs during the 1980s. When growers purchase substrate, they are in effect purchasing automation. Substrate production is a separate business, complete with outlay of capital for production equipment, input of labor, and management responsibility. The firm's resources can be more fully dedicated to the main objective, crop production, when substrates are purchased.

FUNCTIONS OF ROOT SUBSTRATE

A root substrate must serve four functions in order to support good plant growth:

1. It must serve as a reservoir for plant nutrients.
2. It must hold a reasonable reservoir of plant available water.
3. It must provide for the exchange of gases between roots and the atmosphere outside the root substrate.
4. It must provide anchorage (support) for the plant.

Some individual materials can provide all four functions, but not at the required level of each. Sand, for instance, provides excellent support and gas exchange but has insufficient water- and nutrient-supplying capacities. The coarse particles of sand have little surface area per unit of volume compared to the finer particles of soil or peat moss. Since water is held on the surfaces of particles, sand has a small water reserve. Plants grown in sand would need to be watered three or more times per day in the summer. Since most nutrients in a sand medium are held in the water films, there is likewise little nutrient reserve.

Clay, however, has high nutrient- and water-holding capacities and provides excellent plant support, but the small particles of clay are close to one another. The water films of adjacent particles come into close contact, leaving little open space for gas exchange. Oxygen, which is needed to keep the process of respiration going, cannot adequately diffuse into the clay. Conversely, carbon dioxide produced by roots and microorganisms cannot adequately leave the clay. In high concentration, carbon dioxide suppresses respiration, which in turn slows growth. Consequently, clay is a poor medium for plant growth.

Water is sometimes used as a root substrate. It provides water and nutrients but lacks the properties of gas exchange and plant support. When plants are grown in water, air must be bubbled into it, and the plants must be supported in some sort of frame. This cultural procedure is known as hydroponics. Aside from hydroponics, greenhouse root substrates typically contain two or more components to ensure that all four functions are met.

ADAPTATION OF FIELD SOIL TO CONTAINERS

You might ask, why not use only field soil in greenhouse containers? Greenhouse crops often can be grown in the field without significant alteration of the soil, but when this soil is transferred to containers and the same crop is grown, failure ensues. While all four functions are provided by soil in the field, the function of aeration is usually not adequately provided by this soil in containers.

Water retention and aeration go hand in hand. Drainage is proportional to the depth of the soil above the water table (free water). The bottom of any container is equivalent to a water table. Most cut (fresh)-flower beds contain a 7-inch (18-cm) depth of soil. Plant pots, flats, and plug seedling trays can range from greater depths down to 0.75 inch (1.9 cm). The water content in a bedding-plant flat shortly after watering would be similar to that in a soil situated 2 inches (5 cm) above freestanding water—in other words, a swamp situation. The soil pores would be filled mostly with water, and little room would remain for gas exchange.

One dimension by which soil is classified is texture. *Texture* is the size distribution of particles in a soil. Field soil is composed of three mineral components (Figure 1). The finest particles, clay, extend up to a maximum diameter of 0.002 mm. Silt is composed of particles from 0.002 mm up to 0.05 mm, and the third component, sand, is everything larger. Moist clay feels sticky to the touch, silt

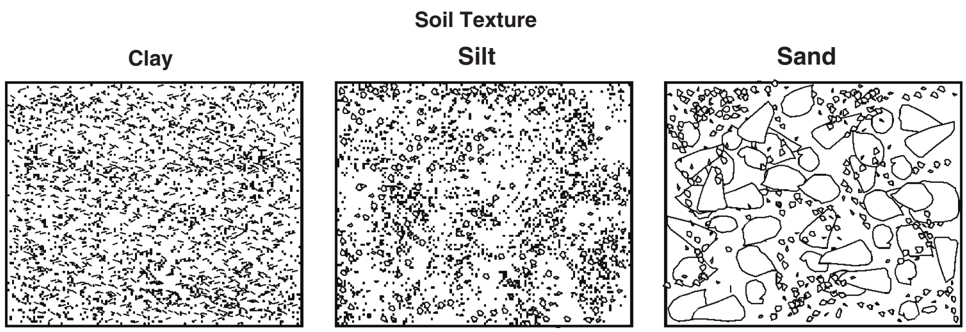


Figure 1
Soil is composed of three mineral components, the relative sizes of which are shown here. Clay particles are the smallest and have a maximum diameter of 0.002 mm. Silt particles have a diameter extending from 0.002 to 0.05 mm. The largest particles, sand, are larger than 0.05 mm. The texture classification of a soil indicates the proportion of these three mineral particles contained in it.

(Illustration by Nancy C. Mingis, Department of Horticultural Science, North Carolina State University, Raleigh, NC.)

is floury, and sand is gritty. Texture terms include *sandy loam*, *silt loam*, and *clay loam* for soils that are predominantly composed of sand, silt, and clay, respectively. *Loam* refers to a reasonable balance of all three materials.

Texture relates to water retention for a very simple reason. Water will remain in soil because it is attracted to the surface of soil particles. It is held to the surface by the *matrix force* (Figure 2). Water exists as a film or layer coating each soil particle.

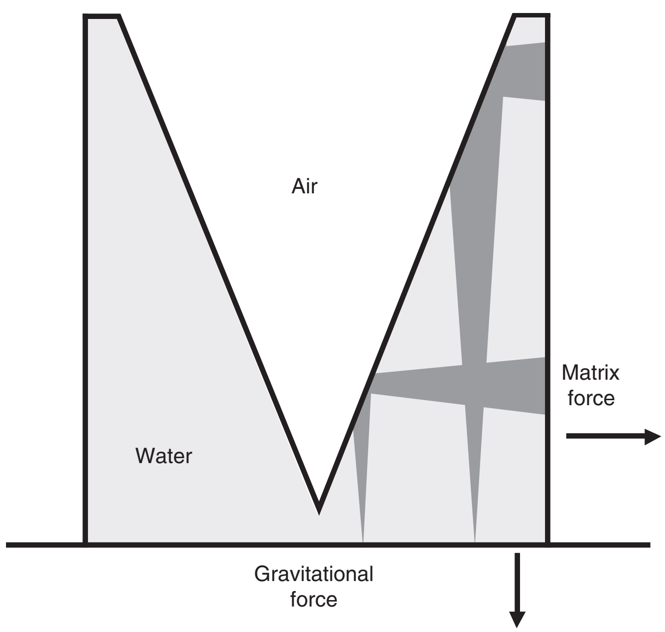


Figure 2
A greatly magnified root substrate pore, showing the relative positioning of air and water. Water is retained in the pore by a matrix force that bonds it to substrate particle surfaces, forming the pore wall. A second force, gravity, acts on water to pull it down and out of the substrate pore. The gravitational force is able to remove more water from the top center of the pore because gravitational force increases with distance from the bottom of the pore. Also, gravity removes water from the center of the pore first because the matrix force counteracting gravity is greatest at the surface of the substrate particles forming the pore wall and least at the center of the pore.

(Illustration by Nancy C. Mingis, Department of Horticultural Science, North Carolina State University, Raleigh, NC.)

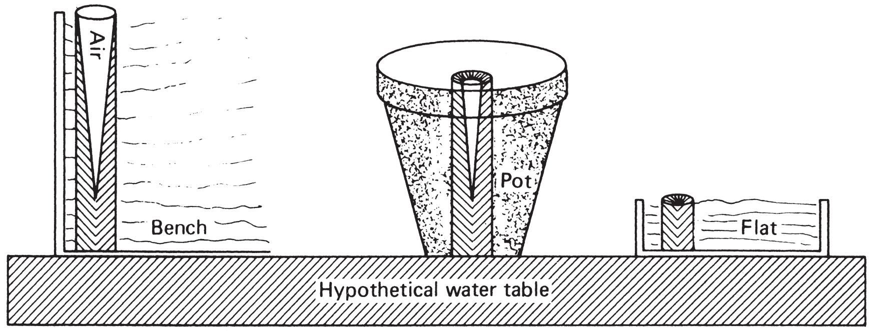


Figure 3
A greatly magnified soil pore is shown in various greenhouse containers filled with soil. All are shown perched on a water table, or reservoir of freestanding water, which is effectively the situation existing in the greenhouse shortly after watering. The pore depicts the moisture situation that exists within each container. Water is attracted to the walls of the pore, and at the base the entire pore fills. Higher in the pore, the downward gravitational pull on the water becomes greater, and the water farthest away from the pore wall is removed. The layer of water in the pore becomes thinner with increasing height. Spaces between soil particles in the container are interconnected and form pores running the depth of the soil. Pores in the bench are filled with water at the bottom and are mostly open at the top. Shortly after watering, roots can grow in the upper layers of soil in this bench but not in the lower layer, where there are no open pores for gas exchange. Pores in the pot do not rise as high above the water table; thus, in the upper layer of soil there is more water and less aeration than in the upper layer of the bench soil. The poorest situation for growth exists in the flat, where the pores are so short that they are completely filled with water.

The thickness of the water layer depends upon the *gravitational force* attempting to pull the water out of the soil and down to the water table. The greater the distance from a given soil particle to the water table, the stronger the gravitational force. Within the water layer, water that is farthest from the soil particle surface is held the least tightly. This water will be pulled away first by the gravitational force. Thus, as the gravitational force, or the depth of the soil, increases, the thickness of the water layer on the soil particle surfaces decreases (Figure 3), and the air-filled center of the pore gets larger, permitting better gas exchange.

The logical solution to the shallow-container problem would appear to be a change toward coarser texture to increase the diameter of the pores. This does solve the problem of aeration, but it creates a new problem by reducing the water-holding capacity of the soil. When the diameter of particles making up a soil is increased, the total surface area of these particles in a given volume decreases. Since water is held on the surface of these particles, the total amount of water in the soil decreases as the particle diameter increases (as the texture becomes coarser).

There is another dimension of soil that can be altered to increase aeration without decreasing its water-holding capacity. *Structure* is the degree of combining of particles into aggregates. A soil with good structure is said to be *friable* (loose). The product of organic-matter degradation is humus, which, along with microbial secretions and hyphae, acts as a cement to bind particles together into aggregates. This is one of the larger benefits of organic matter in field soils. Through the development of structure, a dimension is given to soil that cannot be achieved through alterations in texture. The high water retention of fine-textured soil can be combined with the excellent drainage of coarse-textured soil. This is accomplished by extensive retention of water in the small-diameter pores within each aggregate and rapid percolation of water out of—and, conversely, good gas exchange into—the large pores between the aggregates (Figure 4).

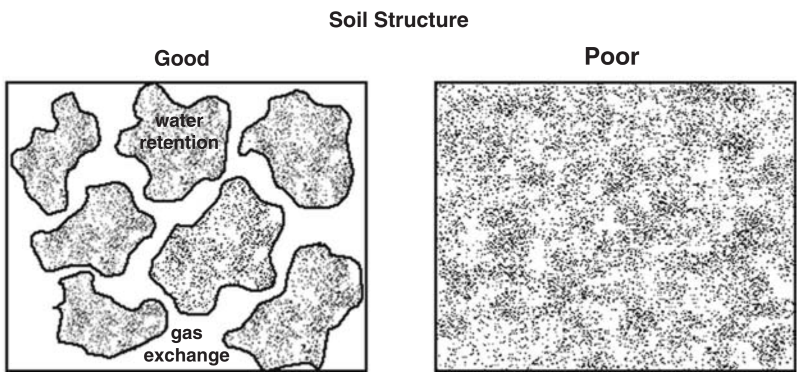


Figure 4
An important property of soil is structure. The soil on the left has good structure because the particles comprising it are cemented together into larger aggregate particles. Small-diameter pores still exist within the large aggregates, and because of the large surface area of these pores, a large volume of water is held in each aggregate. Between the aggregates are very large pores that do not fill with water, thus providing a channel for gas exchange. The soil on the right has very little structure. Only small pores exist. While water retention is good, aeration is poor.
(Illustration by Nancy C. Mingis, Department of Horticultural Science, North Carolina State University, Raleigh, NC.)

It should now be apparent that field soil must be prepared for use in containers by altering it to a coarser texture and by increasing its structure prior to planting. There is no luxury of time to permit the structure to form as a consequence of decomposing organic matter. A coarser texture can be achieved by mixing coarse sand into the soil. Structure can be improved instantly by incorporating large aggregate particles such as sphagnum peat moss and bark into the soil. Numerous materials can be added to the soil, but before a selection can be made, one more set of properties should be understood. These properties pertain specifically to greenhouse root substrates.

DESIRABLE PROPERTIES OF A ROOT SUBSTRATE

Stability of Organic Matter

Most greenhouse crops have a production period of one to four months. Good structure must exist when seed is sown or plants are potted. Typically, organic materials such as peat moss are used for structure. It is important that decomposition of organic matter in the root substrate be minimal. Decomposition of the organic aggregates will lead to finer texture and, consequently, poorer aeration. Also, since the volume of the root substrate available within the pot for root growth is small, any significant reduction in the volume during growth of the plant is detrimental. Straw and sawdust, except redwood sawdust, decompose rapidly and therefore are not desirable in a root substrate used for pot crops.

The situation is somewhat different for cut-flower and vegetable crops in benches where the volume of the root substrate is sufficiently great to tolerate some shrinkage. Substrate is used indefinitely for cut-flower crops. With time, organic matter deteriorates and requires replacement, which is generally done on an annual basis. Direct addition of materials such as sphagnum peat moss or coarse aged bark is made in quantities sufficient to compensate for the lost volume.

Carbon-to-Nitrogen Ratio

The amount of nitrogen (N) relative to carbon (C) in a root substrate amendment is important. Decomposition of organic matter occurs largely through the action of living microorganisms. The largest component of organic matter (50 percent or more) is C, which is utilized by the microorganisms. N in organic matter must be available to microorganisms in the quantity of at least 1 pound for every 30 pounds of C; otherwise, decomposition slows down. Whenever this ratio of 30 C:1 N is exceeded (when more than 30 pounds of C exist for each pound of N), N already present in the root substrate as well as N added as fertilizer will be utilized by the microorganisms rather than by the crop plants. The crop will become deficient in N. If this situation occurs slowly and continuously, a grower can easily compensate for it by increasing the N fertilizer application. The decomposition of materials such as straw and sawdust occurs rapidly, creating a peak of N demand followed quickly by diminishing N demand as the organic matter available to the microorganisms runs out. Only the most experienced growers can compensate for these shifts.

The C:N ratio for sawdust is about 1,000:1. It has been reported that, in addition to the small amount of N already present in the sawdust, 24 pounds of N must be added to facilitate the decomposition of 1 ton of sawdust by microorganisms (12 kg N/ton). Bark has a C:N ratio of about 300:1 and requires an addition of 7 pounds of N to facilitate the decomposition of 1 ton of bark (3.5 kg N/ton). It is not only the C:N ratio that determines the suitability of a root substrate component but also the rate of decomposition. While the bark has an undesirably wide C:N ratio of 300:1, its rate of decomposition is slow and steady, requiring as long as three years to decompose. The drain of 7 pounds of N per ton (3.5 kg N/ton) of bark, carried out over three years, presents a negligible N tax at each fertilization date. Bark is therefore a desirable root substrate component in spite of its wide C:N ratio. Sawdust, however, will decompose in a few months and has a wider C:N ratio of 1,000:1. The N tax in this case is great, and this material should be avoided by inexperienced growers. Redwood sawdust is an exception, since waxes and similar compounds in it slow down its rate of decomposition. It was frequently used in greenhouses in the western United States but is becoming scarce now. Rice hulls also have a wide C:N ratio of 100:1, yet they decompose slowly because their high lignin content suppresses microbial activity. Rice hulls are used as a component of substrate.

Bulk Density

The bulk density of a root substrate relates to support of potted plants in a different sense than anchorage. Nearly any solid substrate will provide for anchorage of the plant roots, but it is also important that the substrate be sufficiently heavy to prevent a pot plant from falling over due to the weight of the plant. A mixture of equal parts of sphagnum peat moss and perlite is sufficiently heavy just after watering. But, when the available water has been used, large plants in this substrate easily topple over when handled. On the other hand, a high bulk density is uneconomical because of the extra labor of handling and freight costs. An acceptable range for bulk density of potting substrate is 40 to 60 lb/ft^3 (640 to 960 g/dm^3) just after watering at container capacity (CC). *Container capacity* is the maximum amount of water that the root substrate in a container can hold against gravity (the amount of water retained in substrate after it has been thoroughly watered and water has finished draining from the bottom of the container).

As mentioned earlier, soil must be amended with coarse particles such as sand to provide aeration. Wet soil and sand at CC can weigh 100 pounds or more per cubic foot (1,600 g/dm^3) (Table 1). Therefore, perlite, with a wet density of 32 lb/ft^3 (500 g/dm^3), is often used as a substitute for sand in spite of its higher cost. The problems of bulk density are not nearly as important for substrates used in greenhouse cut-flower and vegetable benches.

Table 1
PERCENTAGE OF TOTAL VOLUME IN A 6.5-INCH (17-CM) AZALEA-TYPE POT OCCUPIED BY SOLIDS, WATER, AND AIR AT MOISTURE TENSIONS OF CONTAINER CAPACITY (CC) AND 15 BAR FOR VARIOUS ROOT SUBSTRATE COMPONENTS AND FORMULAS[1]

							Bulk Density			
		Water (%)		Air (%)			CC		15 bar	
Material/Mix	Solid (%)	CC[2]	15 bar[3]	CC	15 bar	Available Water[4] (%)	lb/ft³	g/L	lb/ft³	g/L
Soil (sandy clay)	53.3	39.8	6.4	6.9	40.3	33.4	106.0	1,698	85.3	1,364
Sand (concrete-grade)	59.3	35.4	4.4	5.3	36.3	31.0	107.1	1,714	87.8	1,404
Sphagnum peat moss[5]	15.4	76.5	25.8	8.1	58.8	50.7	53.7	859	22.0	352
Coir	6.2	67.4	28.7	26.4	65.1	38.7	46.4	744	22.3	357
Vermiculite (Progro No. 2)[5]	17.3	53.2	29.1	19.5	43.6	24.1	46.1	738	31.1	497
Pine bark (aged, 3/8-inch, ≤10-mm)5	20.7	58.9	30.3	20.4	49.0	28.6	50.6	809	32.7	523
Perlite (Krum, horticultural grade)[5]	36.9	38.3	20.2	24.8	42.9	18.1	32.1	514	20.8	333
Polystyrene beads[5]	64.6	10.5	1.0	24.9	34.4	9.5	7.5	120	1.6	25
Rock wool (Pargro, medium, granular)	8.9	65.0	4.4	26.1	86.7	60.6	54.4	870	16.5	264
1 soil:1 peat moss: 1 sand	37.4	54.8	8.5	7.8	54.1	46.3	99.7	1,595	74.6	1,193
1 peat moss:1 vermiculite	13.1	70.3	24.1	16.6	62.8	46.2	53.3	853	24.4	391
3 pine bark:1 sand: 1 peat moss	29.5	53.4	21.5	17.0	49.0	31.9	58.9	942	38.9	623
1 rock wool:1 peat moss	8.3	70.9	11.3	20.8	80.4	59.6	51.8	829	14.6	233
1 coir:1 peat moss: 1 perlite + vermiculite	15.0	71.0	16.0	14.0	69.0	55.0	53.6	860	19.3	310

[1]Data provided by William C. Fonteno, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609. Components used in the mixes include clay soil, sphagnum peat moss, concrete-grade sand, and aged ≤3/8-inch pine bark.
[2]CC, the amount of water a root substrate can hold against gravity just after watering.
[3]15 bar, the permanent wilting point at which the plant has essentially taken up all available water.
[4]Available water, the amount of water released between CC and 15-bar tension, unless otherwise stated; expressed as a percentage of the total pot volume.
[5]Computation of percentage of water, percentage of air, and percentage of available water is based on a soil moisture tension of 300 cm rather than the stated 15 bar. Since water content for these five components differs very little between 300-cm and 15-bar tension, only small differences occur as a result.

Moisture Retention and Aeration

A wet root substrate is composed of (1) the solid particles of the substrate, (2) the liquid water coating the surfaces of the particles, and (3) the air occupying the center of the pores. To ensure a suitably long interval between waterings and to provide adequate aeration at all times, the balance of water and air in the root substrate pores must be controlled through selection of the particles composing the substrate. After watering, 10 to 20 percent of the volume of the root substrate should be occupied by air in a 6.5-inch (17-cm) azalea-type pot. The water content should be as high as possible, provided that the air porosity and density of the total root substrate are adequate. A survey of Table 1 indicates that the property of aeration can be provided by components such as vermiculite, pine bark, perlite, polystyrene, and rock wool. Excellent components for providing a high available-water content are sphagnum peat moss, rock wool, and coir.

When all three properties—sufficient density, adequate water, and aeration—cannot be met by one component, a mixture is required. Available water is more important than the total water at CC. Available water is a measure of the water that a plant can extract between the point of watering (CC) and the point where irrigation is required (usually 300 cm of soil moisture tension). Five common mixes and their physical properties in a 6.5-inch (17-cm) azalea-type pot are listed at the bottom of Table 1. The first mix would ordinarily be satisfactory, but in this case it is not, due to the use of a clay soil. The fine clay particles result in a high available-water content (46.3 percent) at the expense of aeration (7.8 percent air at CC). A coarser sand is needed in this mix. The sphagnum peat moss and vermiculite mix is excellent, with a wet bulk density of 53.3 lb/ft^3, an air content of 16.6 percent at CC, and an available-water content of 46.2 percent of the volume of the pot. The pine-bark mix has good bulk density and aeration but is lower in available-water content. The water content is acceptable to most growers. But to those faced with long periods of shipping or poor maintenance in the marketplace, a mix with higher available-water content would be better. Finer pine bark would achieve this. The rock wool and coir mixes are excellent.

It should be recalled that water retention is related to the depth of the root substrate. As seen in Table 2, the water content of root substrate just after watering increases with decreasing depth of the container. The matrix force holding water to the surfaces of the root substrate is equal in each pot, but the gravitational force pulling water out of the pot becomes greater as the pot increases in depth. With increasing water content comes decreasing air content. Fortunately, the range in acceptable air- and water-content values is wide. Well-formulated root substrate with high air- and water-retention values is suitable for a wide range of pot sizes. Perhaps the reason the low air contents listed in Table 2 for substrates in the shallow plug trays are acceptable is due to the short distance from any point within the substrate to air outside the substrate.

One should not rely entirely on selection of substrate components for achieving proper aeration. Three steps can be taken after procurement of the substrate to ensure that a desirable level of aeration is achieved and maintained. The first consideration is compaction. When substrate is excessively compacted during planting, pores are compressed to smaller diameters. While this allows for a greater quantity of substrate

Table 2
Percentages of Total Container Volume Occupied by Water and Air at Container Capacity for Three Root Substrates in Five Different Sizes of Containers[1]

	Standard Pots			Flats	
	8 in. (20 cm)	6 in. (15 cm)	4 in. (10 cm)	48 cells	512 plugs
	1 soil:1 sand:1 peat moss				
Water (%)	45.0	47.2	51.2	52.9	54.3
Air (%)	9.5	7.4	3.4	1.7	0.3
	1 peat moss:1 vermiculite				
Water (%)	64.4	67.9	75.2	79.5	84.8
Air (%)	22.5	19.0	11.7	7.4	2.1
	3 pine bark:1 sand:1 peat moss				
Water (%)	48.7	51.5	57.6	61.4	66.9
Air (%)	21.8	18.9	12.9	9.1	3.6

[1]Data provided by William C. Fonteno, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609. Components used in the formulas include heavy clay soil, sphagnum peat moss, concrete-grade sand, and aged ≤$^3/_8$-inch pine bark.

in the pot, which desirably raises the water-holding capacity, it also reduces aeration because of the smaller-diameter pores. Substrate should be compacted during planting only to the extent necessary to support the plant. When flats or plug trays are prefilled with substrate and stacked prior to planting, successive flats should be oriented perpendicular to each other so that each container rather than its substrate supports the units above it.

The second consideration is water content. Shipping costs constitute a sizeable proportion of the price of substrates or of the components used for formulating substrates. As a consequence, many materials are received in a drier state than desired. When water is added to an overly dry substrate, prior to using it, it expands, resulting in an increase in air space. The increased air space persists during crop production. Conversely, if the dry substrate is used for potting plants prior to wetting it, the container walls limit its expansion and increased air space during initial watering. When using a substrate drier than desired, water should be added to it in a mixer and then it should be allowed to sit overnight prior to its use. This will allow it to expand to a coarser texture. Desirable water contents (weight basis) for germination and general substrates at planting time are 67 and 50 percent, respectively. The typical water content of most substrates shipped from the formulators is 50 percent.

The third consideration is the method of water application. A strong force of water beating against substrate can break up aggregates. The finer particles that are released can lodge in the larger pore spaces below, thereby plugging them. This results in a decline in aeration. Automatic watering systems are desirable because of their gentle delivery of water to the substrate surface. When hand watering is necessary, a water breaker should be used on the end of the hose to reduce the pressure of emitted water.

Cation Exchange Capacity

Root substrate components such as clay, silt, organic matter, and vermiculite have fixed negative electrical charges. These charges will attract and hold positively charged nutrient ions (cations). Most fertilizer nutrients have electrical charges, some negative and others positive. Positively charged fertilizer ions are ammoniacal nitrogen, potassium, calcium, magnesium, iron, manganese, zinc, and copper. Field soil and greenhouse substrate electrically attract and hold these nutrients so that they are not washed away during a rain or heavy watering. At the same time, these electrically held nutrients are available to the plant.

Cation exchange capacity (CEC) is a measure of the capacity of the fixed negative electrical charges in substrate to hold positively charged ions. It is generally expressed as milliequivalents per 100 cubic centimeters (me/100 cc) of substrate. A level of at least 6 to 15 me/100 cc is considered desirable for greenhouse root substrate. Higher levels are not common, but are very desirable. With lower levels, the substrate reservoir for nutrients will not be as large, and more frequent fertilizing will become necessary. Clay, peat moss, coir, vermiculite, and most composted organic matter have a high CEC; sand, perlite, polystyrene, rock wool, and noncomposted materials such as rice hulls and peanut hulls have an insignificant CEC. When preparing a root substrate, it is desirable to include a component with a high CEC.

pH

It is sufficient to say that pH level controls the availability of nutrients to the plant. It is often said that half of crop nutritional problems can be averted by holding substrate pH in the desired range. Most greenhouse crops grow best in a slightly acid pH range of 6.2 to 6.8 in soil-based substrates and 5.4 to 6.6 in soilless substrates.

A small number of crops are termed *acid-loving* because they grow best in a strongly acid pH range of 4.5 to 5.8. Sphagnum peat moss, pine bark, and coir are acidic. Peat moss can have a pH level below 4.0. Sand and perlite are neutral (pH 7.0). Vermiculite and some hardwood barks are alkaline (pH above 7.0). Field soil can range from acid (pH 3.5) to alkaline (pH 8.5). Rock wool can range from neutral to mildly alkaline. It is important to check the pH level of the substrate one has formulated and to adjust it to the proper level prior to planting. Commercial root substrates are usually adjusted to the proper pH level by the manufacturer.

COMPONENTS OF ROOT SUBSTRATE

The components of a root substrate can be selected from numerous materials. Listed in Table 3 are the more common components, the functions that each performs, and the cost of each. Alternative components exist for each of the four needed functions of a root substrate. Selection of components is based on the required function, cost, and availability.

Field Soil

Prior to 1970, nearly all substrates used for greenhouse vegetables, cut flowers, and container plants were soil based. The desired soil was a loam. Substrate formulas were based on loam. When soil was sandy, smaller proportions of sand were used, and when soil was clayey, larger proportions of sand were used. Today, the use of soil-based substrate is restricted primarily to cut-flower and vegetable produce growers. Soil-based substrates lost popularity for four primary reasons: (1) Their weight raises handling and shipping costs. (2) Soil invariably comes from an agricultural setting, and with it comes disease pathogens. Thus, all soil-based substrates need to be pasteurized. Soilless substrates are not generally pasteurized. (3) Soil can vary with its sources. As areas around established greenhouse firms become more urban, it becomes increasingly necessary to purchase soil. Over time, soil variations require changes in the substrate formula. Often this is overlooked and crop losses are encountered. (4) Many international borders enforce quarantines on plants in substrates

Table 3
Root Substrate Components, Their Functions, and Cost (FOB manufacturer)[1]

Component	Water Retention	Nutrient Retention	Aeration	Light Weight	\$/ft^3	\$/m^3
Field soil	X	X			0.95	33.55
Sphagnum peat moss	X	X			1.35	47.67
Bark (0–$\frac{3}{8}$ in.)	X	X			0.65	22.95
Coir	X	X			1.15	40.61
Sawdust (rotted)	X	X			0.65	22.95
Manure compost	X	X			0.55–0.93	19.42–32.84
Vermiculite	X	X		X	2.00	70.63
Calcined clay	X	X	X		2.90	102.41
Bark ($\frac{3}{8}$–$\frac{3}{4}$ in.)	X	X	X		0.70	24.72
Sand (concrete-grade)			X		0.95	33.55
Perlite			X	X	2.00	70.63
Rice hulls			X		0.82	28.78

[1]Prices for soil and sand include shipping within 25 miles (40 km). For all other components, shipping costs approximately \$1.90 per loaded mile (\$1.14/km) for a full truckload. A truck can carry 45,000 pounds (20 metric tons), which equates to 100–120 yd^3 (77–92 m^3) of bagged soilless substrate, depending on its moisture content and dry density.

containing soil. Since cut flowers are produced in permanent beds of substrate and the substrate is not shipped with the final product, these factors do not pose a problem. Substrates, whether soil based or soilless, require periodic pasteurization for cut-flower production.

In addition to texture, the CEC of soil is worth considering. Sandy soils of the southeastern United States can have values of 2 me/100 cc and lower. Soils in the great plain of the central United States have values of 40 me/100 cc and higher because of their montmorillonite clay content. Granted, one cannot afford to transport soil any distance. However, large variations in texture and CEC can occur within a single location. It is worth having soil tested prior to selecting the site from which it will be procured.

Peat Moss and Peats

There are different types of peat. Peat moss that is light tan to brown in color is the least decomposed, and is formed from sphagnum or hypnum moss (mostly the former). It has a nitrogen content of 0.6 to 1.4 percent and decomposes slowly; thus, nitrogen tie-up is not a problem. It has the highest water-holding capacity of all the peats, holding up to 60 percent of its volume in water. Sphagnum peat moss is the most acid of the peats, with a pH level of 3.0 to 4.0, and requires 14 to 35 pounds of finely ground limestone per cubic yard (8 to 20 kg/m^3) to bring the pH up to the level that is best for most crops. In areas with alkaline water, the lower rate may be suitable. The CEC of sphagnum peat moss is in a desirable range, from 7 to 13 me/100 cc.

The fine structure of the moss can still be seen in peat moss. Large quantities of water are held on the extensive surface area of the moss, while good gas exchange occurs in the large pores between the aggregates (chunks) of peat moss. For this latter reason, peat moss should not be finely ground down to the level of fibers prior to use. Some soilless substrate formulation companies screen their peat moss into three or more size fractions. By looking upon these fractions as distinctively different components and selectively blending them with each other and other materials such as perlite, they can achieve a wide range of physical properties in the resulting mixes.

Hypnum peat moss has a pH level in the range of 5.2 to 5.5. When it is used with vermiculite, no limestone is needed since vermiculite is mildly alkaline. One successful greenhouse pot-crop mixture calls for 50 volume parts hypnum peat moss to 40 parts perlite to 10 parts vermiculite. Little hypnum peat moss is used compared to sphagnum peat moss.

Reed-sedge peat is brown to reddish-brown in color and is formed from swamp plants, including reeds, sedges, marsh grasses, and cattails. It occurs in varying degrees of decomposition but is generally more highly decomposed than peat moss. As a result, more fine particles are present, giving a poorer structure than that of peat moss. Also, the water-holding capacity of reed-sedge peat is lower than that of peat moss. Depending on the source, the pH level of reed-sedge peat can vary from 4.0 to 7.5. The salt level can also vary with the source. Although sphagnum peat moss is preferred for the general range of greenhouse applications, reed-sedge peat can be used in root substrate for pot and bench crops if pH is properly adjusted, high salt sources are avoided, and proper aeration is built into the final mix. There is little technical information available for using reed-sedge peat. Reed-sedge peat is rarely used for greenhouse production.

Peat humus is dark brown to black in color and is the most highly decomposed of the peats. It is usually derived from hypnum peat moss or reed-sedge peat. Original plant remains are not distinguishable, and water-holding capacity is less than that of other peats. The pH level can range from 5.0 to 7.5. Peat humus has a moderately high nitrogen content, which makes it undesirable in seed-flat substrate or substrate used for salt-sensitive plants. Ammonium nitrogen released from peat humus can build up to levels that are toxic to more sensitive plants such as young seedlings, African violet, azalea, and snapdragon. Ammonium nitrogen is released during microbial decomposition of peat humus because more than 1 pound of nitrogen is present per 30 pounds of carbon. Peat humus is rarely used in the greenhouse.

Sphagnum peat moss remains the premier component of greenhouse substrates. It has superior properties of stability over time, light weight, and high water and nutrient-holding capacities. However, there is rising opposition to its use, particularly in Europe and to a lesser degree in the United States. Opponents question claims that it is a renewable resource since it can require decades and even centuries for a bog to restore itself. There is also concern over disruption of the ecosystem by its removal. There are mandates in the United Kingdom that set forth a scheduled reduction in its use. Already a 40 percent reduction has been achieved in the United Kingdom by substituting alternative components for it and by diluting its content in substrates that contain peat moss. An even stronger force is felt in several countries in Europe where retail outlet chains have required suppliers of potted plants to reduce or eliminate peat moss in response to their customer's wishes. Materials used to achieve these reductions consist of coir coconut fiber, green (plant material) and manure composts, bark, and processed wood.

Bark

Redwood bark and fir bark have been used on the West Coast of the United States for many years as a component of nursery and greenhouse root substrate. Coarse fir bark provides an excellent substrate for orchids. Pine bark (Figure 5) is extensively used throughout the United States. Hardwood barks have been used to a limited degree in many of the interior states. Pine barks of various species are used in Australia. All are highly satisfactory. Spruce bark is commonly used in the United Kingdom but is softer

Figure 5

Barks of various origins are widely accepted today as a substitute for peat moss. Pine bark is pictured here. Typical processing calls for composting in a pile for three months or longer and then screening into different sizes for various markets. Particles passing through a $\frac{3}{8}$-inch mesh screen are used in pot-plant substrate (left); those between $\frac{3}{8}$ inch and $\frac{3}{4}$ inch are used for cut-flower substrate amendment (right); and larger particles are used for landscape mulches (center).

than the others and not quite as satisfactory. Bark is generally inexpensive compared to sphagnum peat moss.

Most bark is purchased by growers after it has been partially composted (aged) and screened. When bark is removed from logs, varying quantities of cambium and young wood are included. These materials decompose faster than bark and accentuate the nitrogen tie-up problem. The wood content tends to be highest in the spring when growth is more active. A period of composting rids the bark of these components and brings it to a stage where the rate of decomposition is slow and steady and nitrogen tie-up is not a problem.

Accounts have been given of fresh hardwood and softwood barks causing growth suppression and injury to plants. Unknown compounds are apparently destroyed during partial composting for a period of 30 days. One explanation is that the toxic material consists of one or more of seven volatile organic acids given off in the initial stages of composting and then quickly destroyed in subsequent stages of composting (Brinton, W., personal communication). These include formic, acetic, propionic, butyric, and valeric acids as well as iso forms of the last two. Terpenes and phenolic compounds have also been suspected. Composting has an additional beneficial effect for bark and sawdust as well. Fresh bark and sawdust do not hold fertilizer nutrients very well because of a low CEC of about 8 me/100 g (about 1.6 me/100 cc). After composting takes place, the CEC rises to a level of 60 me/100 g (about 12 me/100 cc) or higher, which imparts a strong nutrient-retention capacity to the bark and sawdust.

Composting is accomplished in two ways. Nitrogen is mixed in at the rate of 3 pounds of actual nitrogen per cubic yard (1.8 kg/m^3), and the bark is set in piles in the field. Ammonium nitrate is a good source of nitrogen and is used at the rate of 9 lb/yd^3 (5.3 kg/m^3), since it contains 33 percent nitrogen. A period of four to six weeks is sufficient to complete the rapid phase of decomposition. In the second system, no nitrogen is used, and a period of three months to a year is required. Both systems result in destruction of inhibitory compounds, degradation of wood, and fragmentation of larger particles into smaller ones. Because bark used for root substrates is not completely composted, it is often referred to as aged bark.

Compost piles must not be over 12 feet (3.7 m) deep because during the process of composting, heat is given off that—if permitted to become too intense—can set the pile on fire. The surface layer should be turned into the pile after one to two weeks of composting to ensure that all the bark has been processed. The heat given off by fermentation is sufficient to pasteurize the bark. Harmful disease organisms, insects, nematodes, and weed seeds are thus eliminated. It is important that subsequent handling be carried out in a way to maintain this cleanliness. The bark should not be piled where crops have been grown or where the runoff from croplands has accumulated. Equipment used for moving bark should be sterilized first if it has been used on crops. If the bark is bagged, clean handling is almost ensured. Larger growers find economy in purchasing bark in bulk (unpackaged).

Prior to sale, bark is screened for various purposes. Particles ⅛ inch (3 mm) and smaller are used as soil conditioners in applications such as golf-course greens. Particles ⅜ inch (10 mm) and smaller are preferred for greenhouse pot-plant substrates, and those from ⅜ to ¾ inch (10 to 19 mm) are used for organic-matter amendment of greenhouse cut-flower substrate. Particles ⅝ inch (16 mm) and smaller are most typically used for woody plant nursery production. Larger pieces are used for landscape mulching.

Since the largest part of the cost of bark often lies in the shipping expense—\$1.90 or more per mile for a 60-yd^3 (46-m^3) truckload—it is beneficial to obtain bark from local sources. In general, processed bark will cost from one-fourth to two-thirds the price of imported sphagnum peat moss. This price advantage is being challenged by an alternative market for bark. New boiler technology makes it possible to burn bark, wood, and other waste products in compliance with Environmental Protection Agency specifications. Bark is much cheaper than oil, coal, or gas as an energy source. Logging companies see an advantage in selling bark for fuel because it can command a higher price than is currently received from root substrate formulators and they don't need to process it prior to sale. Bark comprises 80 percent or more of the volume of components in substrates used by nurseries producing landscape plants in containers outdoors. The floral products industry will need to face considerably higher prices for bark or quickly find an alternative component.

Coir

A recent, very effective material added to the list of substrate components is coir, which comes from the coconut fruit. Three shells surround the white edible tissue (meat) of the coconut seed. These are the hard inner endocarp, which lies immediately external to the meat; the softer, fibrous middle mesocarp; and the hard, thin outer exocarp. Mature fruits yield coconut meat from the soft inner white tissue. The endocarp is burned in an atmosphere of limited air to yield activated charcoal. The mesocarp–exocarp husks are soaked in water and then shredded to release long fibers. These fibers are used in the manufacture of brushes, automobile-seat and mattress stuffing, filters, twine, and other products. During the process of retrieving the longer construction fibers, a tan-brown material consisting of short fibers along with granular pith material is generated from the mesocarp. This material is often referred to as coir dust. At the point of production, moist coir dust is air dried and screened to remove longer fibers. The resulting product is used as a component in root substrate. It has the consistency of coffee grounds. This coir dust is referred to by different names, including coir pith and sometimes simply coir. It is then compressed into bricks, some the size of standard clay building bricks and others much larger. The bricks are dried for more economical shipment from the various tropical areas in the world where coconuts are grown.

Before use, coir must be rehydrated, either by the supplier or by the grower. This is done by soaking bricks or ground bricks in sufficient water overnight to bring the final mix to approximately 70 percent moisture content by weight. The hydrated bricks yield a ready-to-use material that has a volume between 5 and 10 times that of the dry fiber, depending on the supplier (Figure 6).

The chemical and physical properties of coir are closer to peat moss than any other substrate component. For this reason, coir is used most often as a partial or total substitute for peat moss. Coir holds moderately less water than peat moss but is better aerated. Due to less shrinkage of coir compared to peat moss during crop production, pots of coir and peat moss hold a similar amount of available water. A decided advantage of coir over peat moss is its superior rewetting capacity. When allowed to dry beyond the desired point, peat moss repels water, while coir continues to absorb it. The pH range of coir is from 4.9 to 6.8. This is higher than peat moss, thus mixes with coir require less limestone. Its bulk density at CC in a 6.5-inch (17-cm) pot is about 46 lbs/ft^3 (740 g/L), and its dry bulk density ranges from 3 to 5 lb/ft^3 (48 to 80 g/L). Coir has a CEC of 60 to 130 me/100 g. Assuming an average dry bulk density of 4 lb/ft^3 (64 g/L), this equates to 3.9 to 8.4 me/100 cc. This is moderately lower than peat moss. Coir has a C:N ratio of 80:1. In an alternative material, this could lead to nitrogen tie-up. However, this is not the case for coir. Coir is about two-thirds lignin, which suppresses microbial decomposition. An added advantage of the low decomposition rate is the stability of volume in the pot over crop production time. At this time, the physical and chemical properties of coir can

Figure 6

Various stages of coir during preparation for use in root substrate. Coir is compressed into dry bricks (left) for economy of shipping to consumer countries. Firms in the destination country may sell the bricks directly to growers or may grind the dry bricks and sell the loose, bagged product (center). Growers add water to the bricks or loose coir in sufficient quantity to comprise 70 percent of the final weight and allow the mix to stand overnight for hydration. The resulting hydrated coir can be five to ten times greater in volume than the original bricks (right) and is ready for incorporation into root substrate.

(Photo courtesy of The Scotts Co., Marysville, OH 43041.)

vary from one source to another. Salt content can be a problem in some sources. A major element contained in these salts is potassium, but sodium and chloride can also be present. Knowledge about the supplier is important.

Coir is sometimes used in mixes along with pine bark as a substitute for the peat moss component. To avoid a heavy bulk density of the resulting mix, a lightweight component such as vermiculite or perlite is advisable when bark is used. A good trial formula for a coir-based mix would be 30 percent coir plus 30 to 40 percent pine bark plus 30 to 40 percent vermiculite. Perlite can be partially substituted for vermiculite, commonly up to 20 percent of the mix, by growers who hold their mixes wetter and need the extra aeration. An excellent, simpler mix consists of 1 coir:2 peat moss (v/v). Cut roses are commonly grown in a substrate of 100 percent coir. The price of coir is competitive with sphagnum peat moss. Highly effective coir-based mixes are on the market for the greenhouse industry.

Sawdust

Sawdust (aside from redwood sawdust) in many respects is similar to bark. It should be partially composted because in the fresh state its rate of decomposition and nitrogen tie-up is excessive and it may contain toxic substances such as resins, tannins, or turpentine. Even after composting, sawdust decomposes at a faster rate than bark, and because of its wider C:N ratio (1,000:1), a greater amount of nitrogen is tied up in the root substrate. Whereas the problem is insignificant with bark, it must be taken into account in fertilizing a substrate containing composted sawdust.

Abandoned piles of sawdust are often available for the cost of transportation in forested areas. If a pile has existed for a year or more, the sawdust below the surface layer should be well composted. Care should be taken to avoid unleached areas deep in the pile, which are strongly acidic and injurious to plants. These areas did not receive sufficient oxygen for aerobic composting, thus underwent fermentation. As a result, volatile organic acids were formed and trapped. These problem areas can be identified by the exceptionally dark color of the sawdust and its pungent, acrid odor. This sawdust can be reclaimed by exposing it to the air and to leaching rains for a season, but it still will be more acidic than properly composted sawdust.

Sawdust composted with additional nitrogen for one month, to the stage appropriate for use in root substrates, is itself acidic and requires limestone to neutralize it. In this stage, it is granular and medium-dark brown in color. It continues to decompose during use in the pot or greenhouse bench. Various types of pine and some types of hardwood sawdust require further additions of limestone as time passes. Sawdust, like other plant materials, ends up close to neutral in pH when thoroughly composted; however, this is well beyond the stage at which it is initially used in greenhouse root substrates.

Sawdust, with the exception of redwood sawdust, is rarely used in greenhouse substrates because of its erratic decomposition during crop production. Redwood sawdust is an excellent substrate component because its content of waxes and tannins suppresses decomposition during crop use.

Whole Tree Chips

The woody nursery industry recently adopted whole pine tree chips as a substrate for woody container plants. While the chips work well without any other component, better results have been obtained when aged pine bark and/or sand is added. Current studies show promise for these chips in greenhouse container substrate when steps are taken to reduce average particle size (Jackson et al., 2010). Loblolly pine (*Pinus taeda*) and white pine (*Pinus strobus*) can be used, with the former functioning a little better. Hardwood chips have not been satisfactory due to more rapid decomposition as a result of their lower lignin content. Freshly harvested pine trees can be used immediately upon chipping. Efficacy is the same whether limbs, needles, and bark are included with the trunk or not. Fresh chips have a pH between 5.8 and 6.2 and do not require limestone. They can be stored prior to use, but with time pH will decline and require limestone. Fresh and stored chips are equally effective. Coarse wood chips have been shown to have a similar shrinkage rate to pine bark during 70 weeks of container production.

Finer substrate texture is required for greenhouse containers than that used for nursery production. This can be attained by mixing the coarser nursery chips (ground in a hammer mill without a screen) with about 25 percent fine wood chips (ground through a $\frac{3}{16}$-inch [4.6-mm] screen). One problem with the fine wood chips, compared to coarse wood chips, is their more rapid rate of decomposition and nitrogen tie-up by increased microbial activity. Another problem is the high cost of energy consumed in the long grinding time required to pass wood through the fine screen. Alternatively, coarse wood chips can be mixed with about 25 percent sphagnum peat moss to achieve finer substrate texture (improved water and nutrient-holding capacity) or coarse pine wood chips and aged pine bark can be ground together for the same added benefits. More study is needed for greenhouse application.

Animal Manure Composts

Noncomposted animal manure is rarely used in greenhouse production today. However, until the middle of the 20th century annual addition of 10 to 15 percent manure by volume, generally rotted (aged) cow manure, was a standard practice in cut-flower beds containing soil-based substrate and was quite frequently used in bedding- and pot-plant substrate. Its use ended when soil pasteurization became popular in the mid-20th century. Pasteurization of manure released toxic levels of ammonia.

Today, considerable effort is being put forth to develop methods for using composted animal manure as a component in soilless substrates. This is driven first by the need to provide organic certified substrates to growers of organic floral and vegetable products and second by the need to reduce the use of peat moss in substrates in general. Composts of manures from dairy cows, horses, and poultry show promise for use in root substrates. Currently, pig manure is not suitable because it is flushed from barns as a liquid, but as a solid it would have potential.

Mature composts appear to be the most satisfactory for the following reasons. Immature composts can continue to undergo rapid decomposition during crop production. Microorganisms involved in this decomposition will consume oxygen needed by plant roots. This decomposition will also cause unacceptable shrinkage in substrate volume as well as reduction in particle size. Both of these latter factors reduce aeration in the substrate. Immature composts in which the C:N ratio has not been reduced below 20:1 may also continue to tie up nitrogen due to their rapid rate of decomposition, causing a deficiency in the crop. Weed seeds, pathogens, and insects tend to persist in immature composts. During manure composting, a sizeable level of nitrogen is released as ammonium. As composting continues, this ammonium is converted to nitrate by nitrifying bacteria. Nitrification of each ammonium ion to a nitrate–nitrogen ion results in the release of two hydrogen (acid) ions. Thus, incorporation of immature animal manure into root substrate can cause ammonium toxicity as well as a severe drop in pH. In addition to the threat of ammonium toxicity from immature composts, there is the potential for an adverse pH reaction in the substrate. These problems are avoided when the manure is composted beyond the point of conversion of ammonium to nitrate prior to its incorporation into root substrate.

A common scenario for composting manure calls for blending sufficient high carbon content material, such as bark, wood chips, sawdust, dry leaves, or straw, with the high nitrogen-containing manure to achieve a 30 to 50:1 weight ratio of C:N. A pile of at least 4 feet in depth is required to provide sufficient insulation to allow the heat-releasing microorganisms that decompose the organic matter to build up a temperature of at least 120°F (50°C). The pile needs to maintain this temperature for at least three weeks. It is also necessary to turn the pile periodically to aerate it. When the C:N ratio is below 20:1, preferably 17:1, and nearly all ammonium has converted to nitrate, the compost is mature and ready for use in a root substrate.

The use of compost in substrate necessitates some changes. Manure composts have high pH levels ranging from just below 8 in horse to around 8 in dairy and as high as 9 in poultry composts. It is necessary to use less or no limestone in the substrate. Fortunately, compost has a buffering action against both decline and rise in root substrate pH. Compost has a higher salinity than peat moss. Saturated paste extract electrical conductivity (EC) levels can range from moderately below 4 to unacceptably high levels of 10 or above. The low values are permissible because the salt will be diluted by the other components of the substrate. The salt consists of essential plant nutrients such as nitrogen, phosphate, potassium, and micronutrients. This suggests a reduction in the standard fertilization program. Until more work is done to quantify the extent of this reduction, growers need to conduct their own trials. Poultry manure composts contain higher levels of phosphate and mineral salts in general than other manure sources. This also needs to be taken into account in the fertilization program. Mature dairy manure compost has a CEC around 37 me/100 cc, which is considerably higher than the 7 to 13 me/100 cc found in sphagnum peat moss. The dry bulk density of mature dairy compost (0.3 g/cc) is much higher than that of peat moss (0.07 g/cc). But the bulk density of peat moss and compost-containing substrates at CC is not very different because both hold similar amounts of water at CC and water makes up the majority of the weight of the mix. However, the increase in dry bulk density raises the cost of shipping, which is a problem for substrate formulation companies. Rapid advances in composting technology will occur and much more will be used in substrates as pressure against the use of peat moss increases and the price of bark continues to rise due to its alternative market as a fuel.

Crop By-Products

Straw was occasionally used as a root substrate amendment for cut-flower crops. It must be chopped into pieces 3 inches (8 cm) or less in length to permit uniform incorporation into the substrate. The labor input is expensive. Since straw decomposes rapidly, it must be added two to three times per year, which is also an expensive proposition. A variety of other organic amendments are occasionally used, including peanut hulls, and bagasse (sugarcane fiber). All of these can be used successfully, but require knowledge and careful handling. Materials such as straw, peanut hulls, and bagasse have a wide C:N ratio coupled with rapid decomposition that can cause nitrogen tie-up. If this is gauged and extra nitrogen is added, no problem arises.

Flower-crop stubble—the foliage, stems, and roots left in the benches after the harvesting of cut-flower crops—has logically been looked upon as a source of organic matter. Growers have chopped the stubble into small pieces and rototilled it into the root substrate. However, because this organic material is the very crop being grown, it is an excellent host for carrying diseases over from one crop to another, and should be pasteurized with the root substrate. Since many growers do not pasteurize after each crop, crop remains are generally removed from the greenhouse. Crop remains thoroughly composted outside the greenhouse can be used successfully as a root substrate amendment.

Composted Municipal Garbage-Trash

Many municipalities combine the collection of kitchen wastes and solid household trash. When a compost is produced from this waste, most metals, rags, and large items are first reclaimed, and then the remaining refuse is ground and set out in heaps to compost. The action of microorganisms breaking down the organic matter in these heaps generates heat, which destroys harmful organisms and results in a dark-brown, somewhat granular product. Glass is ground fine enough to prevent it from becoming a safety hazard. The pH level is about 8.5, and the salt content is moderately high but subject to removal by leaching. Processed garbage has worked well as a mulch in landscaping but has not been as satisfactory as a root substrate component. The problem stems from the variation in refuse ingredients. When a high proportion of kitchen waste is present, a product rich in humus is produced that makes a good peat moss substitute. When high proportions of wood, paper, plastic, or other such materials are present, a product is produced that can tie up nitrogen in root substrate or simply act as an inert component that would be a better sand replacement. This variability within single batches of product has led to variable results within trials, ranging from excellent to poor.

Vermiculite

Vermiculite ore is mined principally as a mica-like, silicate mineral. The ore itself has a dry bulk density of 55 to 65 lb/ft^3 (8.8 to 10.4 g/cc), but when expanded to the state used in root substrates, the density drops to 6 to 7 lb/ft^3 (0.96 to 1.12 g/cc) (Figure 7). This lightweight property makes it very desirable in pot-plant substrate. Each particle of vermiculite ore contains numerous thin plates lying parallel to one another. Between the plates is moisture that expands into steam when heated to high temperatures, causing the plates to move apart into an open, accordion-like structure.

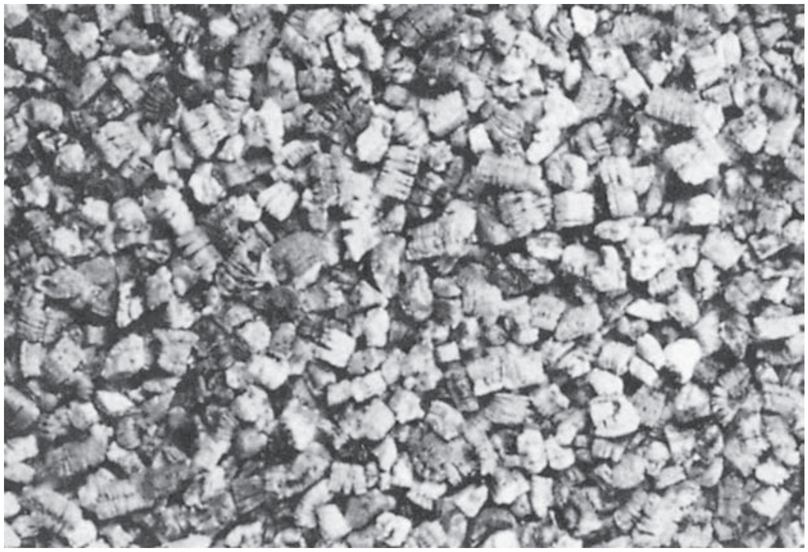


Figure 7
Expanded vermiculite as it is used in greenhouse root substrate. The exceptional water- and nutrient-holding capacities of vermiculite make it an excellent component of soilless substrate.
(Photo courtesy of The Scotts Co., Marysville, OH 43041.)

The expanded volume averages 10 times the volume of the original ore. The water-holding capacity of expanded vermiculite is high because of the extensive surface area within each particle. Aeration and drainage properties are also good when coarse 5⁄16-inch (8-mm and down) or medium 5⁄32-inch (4-mm and down) grades are used.

Numerous negative electrical charges on the surface of each vermiculite platelet give rise to a CEC of 10 to 16 me/100 cc of expanded vermiculite (100 to 150 me/100 g). The predominant fertilizer nutrients in vermiculite are potassium, magnesium, and calcium. The potassium content of U.S. vermiculite will provide part, but certainly not all, of the total needs of a crop. The magnesium content of African Palabora vermiculite is high and has been known to provide the total needs of a greenhouse crop. Vermiculite varies in pH level. U.S. vermiculite is slightly alkaline, while African Palabora vermiculite tends to be very alkaline, with pH levels approaching 9 in some cases. The alkaline African vermiculite constitutes no problem when combined with an acidic substrate component such as peat moss or pine bark. If this vermiculite is used alone, in a propagation bed or in a hydroponic operation, its pH level should be adjusted downward. U.S. vermiculite can be used without alteration.

Vermiculite is a desirable component of soilless root substrate because of its high nutrient and water retention, good aeration, and low bulk density. It is commonly included in soilless substrate in volume quantities of 25 to 50 percent of the mix. Expanded vermiculite can be compressed easily between the fingers. Under the weight of soil-based substrate, expanded vermiculite tends to compress, which greatly reduces aeration. Vermiculite is generally not used with soil.

Calcined Clay

Aggregates of clay particles are heated to high temperatures (calcined) to form hardened particles that resist breakdown in root substrate. These aggregates are large (mostly 8 to 45 mesh; 2.36 to 0.355 mm) and irregularly shaped. As a result, they fit together loosely in a root substrate, creating large pores for drainage and aeration. Within each calcined clay aggregate are numerous clay particles forming a myriad of small water-holding pores. One pound of calcined clay can contain over 13 acres of surface area within its structure. Calcined clay brings the property of structure to root substrate in the form of a hardened, buff-colored aggregate weighing about 30 to 40 lb/ft^3 (0.48 to 0.64 g/cc). The pH levels of different calcined clay products range from acid to alkaline (4.5 to 9.0), but they have only a small influence on the pH level of root media. Calcined clays have a sizeable CEC, 6 to 21 me/100 g (3.4 to 11.8 me/100 cc), which gives them the property of good nutrient retention. The variation in properties of calcined clays stems back to the type of clay used. Examples are montmorillonite clay from the Mississippi Valley and attapulgite clay from Florida and Georgia. Lusoil, a brand of calcined clay made from attapulgite clay, has a pH of 7.5 to 9.0 and a CEC of 21 me/100 g (11.8 me/100 cc). The products Terragreen and Turface are derived from montmorillonite clay.

Calcined clay should be used in a quantity equal to 10 to 15 percent of the volume of cut-flower soil-based substrate. For soilless pot-plant substrate, it generally constitutes 25 to 33 percent of the total volume.

Sand

Sand is used in soil-based root substrate for adding the coarser texture needed to induce proper drainage and aeration. For this reason, concrete-grade sand (a sharp, coarse sand) is used. Concrete-grade sand has the specifications listed in Table 4. Washed sand should be purchased, since it is nearly free of clay, silt, and organic matter. In regions where there are snowfalls, caution should be exercised during the winter to avoid purchasing sand containing road salt (sodium chloride or calcium chloride). Road salt is added to batches of sand to be sold to highway departments because it melts road ice. The level used in sand is injurious to greenhouse crops. Sand is generally not used in soilless substrate because it adds too much weight.

Perlite

Perlite is a good substitute for sand for providing aeration in root substrate. Its main advantage over sand is its light weight of about 6 lb/ft^3 (0.095 g/cc), as compared to 100 to 120 lb/ft^3 (1.6 to 1.9 g/cc) for sand. Perlite is a siliceous volcanic rock that, when crushed and heated to 1,800°F (982°C), expands to form white particles with numerous closed, air-filled cells. Water will adhere to the surface of perlite, but it is not absorbed into the perlite aggregates. Perlite is sterile, is chemically inert, has a negligible CEC (0.15 me/100 cc), and is nearly neutral, with a pH value of 7.5. It is unbuffered, thus does not appreciably affect the pH level of root substrates. Perlite costs considerably more than sand. As a result, it is used when low root substrate density constitutes an economic advantage.

Table 4
ASTM (American Society for Testing and Materials) Specifications for Concrete-Grade Sand

% of Total Passing the Screen	Screen Size	Particle Size (mm)
100	$^3/_8$ in.	9.5
95–100	No. 4[1]	6.4
80–100	No. 8	3.2
50–85	No. 16	1.6
25–60	No. 30	0.85
10–30	No. 50	0.51
2–10	No. 100	0.25

[1]These figures refer to the number of holes per inch. A No. 4 screen has holes slightly smaller than ¼ inch due to the width of the wire between each hole.

There have been reports that perlite releases quantities of fluoride that are injurious to lilies and certain foliage-plant crops. Research has shown this to be unfounded. Quantities of perlite up to 50 percent of the volume of the substrate did not cause injury to sensitive crops including lilies, Chlorophytum, and Tahitian bridal veil.

Polystyrene Foam

Polystyrene foam is known more commonly by trade names such as Styrofoam, Styropor, and Styromull. Like perlite, it constitutes a good substitute for sand, bringing improved aeration and light weight to root substrate. It is a white, synthetic product containing numerous closed cells filled with air. It is extremely light, weighing less than 1.5 lb/ft^3 (0.024 g/cc). Like sand, it does not absorb water and has no appreciable CEC. It is neutral and thus does not affect root substrate pH levels.

Polystyrene can be obtained in beads or in flakes. Beads from ⅛ to ⅜ inch (3 to 10 mm) in diameter and flakes from $^1/_8$ to $^1/_2$ inch (3 to 13 mm) in diameter are satisfactory for pot-plant substrate. Larger particles may be used in bench substrate and for epiphytic plants such as orchids (Figure 8). Depending upon the source, the price of polystyrene can vary considerably. The edges cut from large blocks prior to cutting into sheets or the leftover pieces from shapes stamped from sheets can be ground to form an excellent substrate component. Polystyrene has been banned in some coastal regions due to its movement in wind and surface water to beaches, where it becomes an aesthetic problem. In other localities, it has been banned from landfills. Polystyrene is rarely used in substrates today because of the environmental problems it causes.

Rock Wool

Rock wool is also available in granular form for use as a component in root substrate. As seen in Table 1, the granular form has very high available-water and aeration properties. Although slightly alkaline, it is not buffered. Mixing it with an acid component, such as pine bark or peat moss, will immediately lower the pH level. Rock wool has a negligible CEC. It neither contributes nor holds nutrients to any extent. This

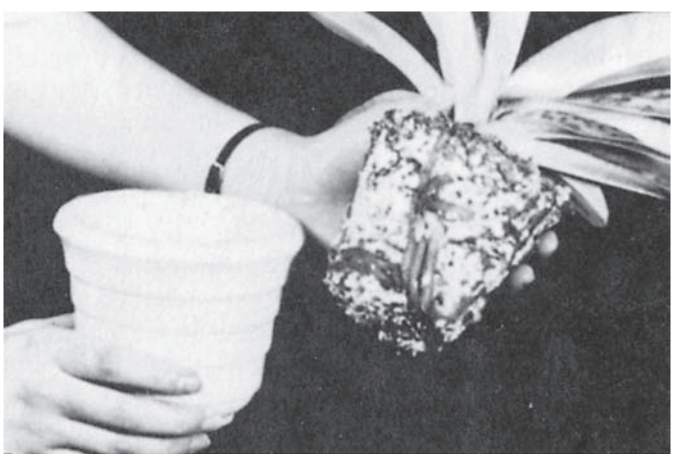


Figure 8
Equal parts of polystyrene foam (Styromull) and sphagnum moss make a good root substrate for the orchid plant shown here. Polystyrene is an excellent lightweight substitute for sand in root substrate.

(Photo courtesy of BASF-Wyandotte Corporation, Wyandotte, MI 48192.)

property should be provided by other components in the mix, such as sphagnum peat moss. Granular rock wool may be purchased by itself or in commercially formulated mixes. A blend of equal volume parts of rock wool and sphagnum peat moss makes an excellent mix. The popularity of rock wool in loose pot-plant substrates has diminished in recent years. One reason for its decline is skin sensitivity during handling by some individuals.

Rice Hulls

Rice hulls were trialed as a component of soilless substrate several years ago but did not gain wide acceptance at that time. More recent studies have led to a moderate level of acceptance by self-mix growers as well as commercial substrate formulators. Rice hulls used in substrates are parboiled and then dried before use. This heat process kills weed and viable rice seeds. The primary function of rice hulls is that of drainage and aeration. Rice hulls provide a less expensive substitute for perlite and add a higher level of aeration than gained by an equal amount of perlite in the substrate. Although rice hulls have a C:N ratio of 100:1, their rate of decomposition is very slow due to their high lignin content. Lignin is very resistant to microbial decomposition. Rice hulls are more often used with peat moss than pine-bark mixes because bark already has good aeration properties. Volume rates of incorporation up to about 30 percent work well. One very effective mix consists of four peat moss to one rice hull by volume.

SOIL-BASED SUBSTRATE

Soil-based substrates have diminished greatly in importance in recent years. Their use is fairly well restricted to ground beds of specialty cut flowers in developed nations, general cut-flower crops in developing nations, and limited vegetable fruit production in developed nations. Virtually all pot-plant and bedding-plant production is in soilless substrate. Most cut-flower and vegetable fruit production in developed nations is in nutriculture systems such as nutrient film technique (NFT) or rock wool or in containers of soilless substrate where nutrient solution is recirculated.

Formulation

When soil-based substrate is used in any elevated situation where it is separated from the ground soil profile, it will be subject to a perched water table effect. In these situations, it is necessary to drastically alter the soil to improve aeration with minimal reduction in water retention. This has been done traditionally by blending equal parts by volume of loamy field soil, concrete-grade sand, and sphagnum peat moss. Sandy field soil is compensated by a decrease in sand, while clay soil calls for more sand.

Sand is used in soil-based substrate to develop large-diameter pores for good aeration. A moist mixture of equal parts of soil, sand, and peat moss weighs about 100 lb/ft^3 (1,600 g/L), which is suitable for use in greenhouse benches but not for pot plants that must be handled in the greenhouse and shipped. Loam soil provides reasonable nutrient (CEC) and water-holding capacities. When one-third of the soil is replaced by sand, these two properties are significantly reduced. To partially restore them, sphagnum peat moss, an amendment with a high CEC and water-holding capacity, has traditionally been added to the substrate at the expense of an additional one-third of the field soil.

Soil-based substrates generally require three nutrient amendments during formulation. First, the pH level should be adjusted to within the range of 6.2 to 6.8 with agricultural limestone. When neutral to alkaline soils are used, no upward adjustment is required. Acidic soils may require as much as 10 pounds of limestone per cubic yard (6 kg/m^3). The second amendment should consist of up to 1.5 pounds of 0-45-0 superphosphate per cubic yard (0.9 kg/m^3) to provide phosphorus for up to one year. The third amendment is a complete micronutrient mixture, of which a number of commercial preparations are available.

Maintenance

Loss of root substrate volume and structure is a problem for cut-flower growers, since they maintain substrate permanently in their ground beds and benches. The action of decomposition results in the loss of organic matter and the periodic need to add more. This is customarily done once each year at the time when the root substrate is pasteurized. The standard additive has been coarse sphagnum peat moss rototilled into the bench in a quantity equal to about 10 percent of the volume of the root substrate in the bench.

Coarse bark from ⅜ to ¾ inch (10 to 19 mm) has proven to be a good alternative to peat moss in bench substrates because it adds both organic matter and aeration. The decomposition rate of bark is slow, requiring up to three years for complete breakdown. In the first year, a quantity equal to 10 percent of the bench volume should be incorporated into satisfactorily drained substrate and 15 percent into poorly drained substrate. As a rule of thumb, each year thereafter a quantity equal to 5 percent of the bench volume is added. In any event, organic matter should be added in sufficient quantity to make up the volume loss in the bench.

Sometimes the organic-matter level is adequate, but the clay content is too high. Poor drainage and excessive cracking of the root substrate upon drying (Figure 9) are symptoms of this condition. This is particularly prevalent when clay soil is used. The problem is remedied by a single addition of concrete-grade sand to the substrate. Perlite is generally not used since weight is not a problem in benches. Calcined clay is sometimes used because, in addition to providing macropores for

Figure 9
A cut-flower substrate containing too much clay. Note the cracks that occur upon drying. This substrate has inadequate gas exchange, as witnessed by symptoms of oxygen deficiency in the chrysanthemum plants. Growth is stunted, leaves are light green in color with veins lighter than the rest of the leaf blade, and the plants wilt on bright days.

drainage and aeration, it contains numerous micropores within each particle to improve water-holding capacity, and it has a high CEC, which improves nutrient retention. A quantity equal to 10 to 15 percent of the bench volume is incorporated into the substrate. It is expensive but needs to be applied only once, since it is resistant to breakdown.

SOILLESS SUBSTRATE

One of the earliest commercially prepared soilless substrates developed was Einheitserde (standardized soil), a mixture of half peat moss and half well-aggregated subsoil clay amended with nitrogen, phosphorus, and potassium and limed to a pH level between 5 and 6. It was introduced by Dr. A. Fruhstorfer in Hamburg, Germany, in 1948. Einheitserde is marketed by several companies in Europe and is used for a wide range of crops and applications, from seed germination to plant finishing.

The University of California mixes were some of the earliest soilless substrates adopted in the United States during the 1950s. These are a series of five substrates ranging from 100 percent sphagnum or hypnum peat moss to 100 percent fine sand, with intermediate combinations of the two. These substrates are formulated by individual growers. The most popular greenhouse pot-plant substrate of this series was the half–peat moss, half–fine sand mixture. It is not popular today due to its heavy weight. The designation of *fine sand* indicates sand between 0.5 and 0.05 mm in diameter, which is equivalent to $\frac{1}{50}$ to $\frac{1}{500}$ inch, or to sand that passes a 30-mesh screen but is retained on a 270-mesh screen.

The Peat-Lite mixes were introduced by Boodley and Sheldrake at Cornell University in the early 1960s. Mix A is composed of half sphagnum peat moss and half horticultural-grade vermiculite. Mix B contains horticultural perlite in place of the vermiculite. While some growers formulate Peat-Lite mixes, there are a number of commercial preparations of soilless substrate on the market similar to these mixes.

The conversion from soil-based to soilless substrates in the United States began slowly in the 1960s, gained considerable momentum during the 1970s, and neared completion in the 1980s. At first, most growers formulated their own soilless substrate. The trend since then has been toward purchasing commercial substrates preformulated by formulation companies. Most self-mix growers are in the very small category or the large category where they can afford elaborate mixing systems.

Commercial Formulations

Any given grower has access to five or more national companies producing root substrates. Each substrate company typically offers about five categories of greenhouse substrates. These categories include *germination* mix for plug trays (Figure 10), *young plant* mix, *general peat moss* mix for intermediate-size containers, *general bark* mix for intermediate-size containers, and *large container* mix. These mixes are formulated mostly from peat moss, vermiculite, perlite, and pine bark. Rice hull and coir mixes are available, but not as popular as these mixes. Many of the mixes sold are custom blended, but the changes are mostly in the limestone and fertilizer additives. Substrate production lines are computerized so shifts can be made frequently and without disrupting the process.

Germination Substrate (Category I) Germination substrates are usually composed of superfine peat moss and fine vermiculite, often in equal amounts. Where greater aeration is needed, fine perlite is used in place of some of the vermiculite. These mixes must be free of sticks. From the earlier discussion of container depth versus

Figure 10
A plug tray containing 512 pepper seedlings.
(Photo courtesy of Brian Whipker, Dept. of Horticultural Science, North Carolina State Univ.)

aeration, it would seem logical to use a very coarse-textured substrate in germination containers because of their shallow depth. However, this is not the practice because of the need for a higher degree of texture uniformity in germination containers than in larger finish-plant pots. The greater uniformity is achieved through the use of smaller component particles. Texture needs to be uniform to ensure that each of the tiny cells in a plug tray has similar water retention and aeration and to ensure that seeds lodge at approximately the same depth during sowing so that they will germinate at the same time. Texture also needs to be finer to ensure adequate water as the seedling grows larger in a very small volume of root substrate. The adverse effect of fine texture on aeration is probably compensated by the short gas diffusion distance between roots and the exterior of the cell. Germination substrates tend to cost more due to the price of their components.

Young Plant Substrates (Category II) Young plant substrates find application in small specialty containers used for germinating seeds and rooting cuttings. Seed crops in this category include vegetable transplants destined for mechanical transplanting into commercial fields, large vegetable seeds such as cucumber, squash, and corn for gardens, and large seeds of ornamental plants such as kale, marigold, and zinnia. Containers typically include 50 to 105 cell trays and sometimes 128 cell trays for cuttings as well as Elle pots. Substrate for this application generally consists of peat moss, vermiculite, perlite, and sometimes coir. The proportion of vermiculite is lower than that in the germination substrates, to give less water retention and more aeration. Perlite is used for aeration at rates of 15 to 30 percent. The components are a little coarser than in the germination substrates but still finer than in the general substrates for larger pots. These substrates utilize peat moss free of sticks because the substrate must flow freely into small containers filled by automatic equipment.

Stabilized substrate is also used for young plants. Stabilized substrate is substrate used in a system where the root ball is bound by a fabric net, a paper sleeve, or a chemical polymer. Substrate in the fabric and paper binders is similar to the loose substrate described in the previous paragraph. Stabilized substrate cemented together with a polymer has the consistency of a light foam rubber and until now has consisted of peat moss alone. The current trend is toward adding 15 to 20 percent perlite with the peat moss and polymer. Growers purchase stabilized substrate already in the container, or in the case of the Elle pot, they may purchase a machine for filling the units. Prefilled trays cost around $1.00 per tray (about 100 cells) more than loose substrate. The added price may be offset by the 33 percent savings in time required to produce a young plant for sale.

General Peat Moss–Based and Bark-Based Substrates (Categories III and IV) Peat moss substrates, without bark, for intermediate-size containers, make up Category III, whereas bark-based substrates for these same containers make up Category IV. These containers include bedding-plant flats and pots as well as hanging baskets up through 6.5 to 7 inches (17 to 18 cm). Growers tend to fall into two groups. *Dry growers* water infrequently and need substrates that hold large amounts of water (Category III). *Wet growers* water frequently and have best success with substrates with high aeration (Category IV). Category III peat moss substrates are composed of peat moss, perlite, vermiculite, and sometimes coir. In specific situations, there can be a cost advantage for this category. In northern states and Canadian provinces where local pine bark is not sufficiently available and is very expensive due to shipping, growers can take advantage of compressed peat substrate. The substrate is compressed into bales in a 2:1 ratio. One compressed volume fluffs into two volumes when used. This lowers shipping cost by accommodating more substrate per truckload. Bark mixes do not lend themselves to compression.

In the southern states where bark is plentiful and less expensive than peat moss, the cost advantage is with the bark substrates. Also, bark mixes include less vermiculite and/or perlite, the two most expensive components of substrates. A second advantage of bark substrates can be that of less shrinkage. Over time substrates shrink as some components break down. This leads to loss of volume and finer particles with less drainage and less aeration. While this is not a problem for peat substrates during the average 6- to 12-week production time of most crops, it can be a problem in long-term crops of six months and longer such as cyclamen and foliage plants. Shrinkage in bark substrates is negligible, even over the long periods. Bark substrates frequently contain a small amount of perlite, 10 to 15 percent, and peat moss. The standard ratio of peat moss to bark is 1:1 while 2:1 may be used where more water retention is desired. A third advantage of bark substrates is found in their higher drainage formulations. Floral crops produced outdoors, where they are subject to rain, require well-drained substrates to avoid low aeration problems. Bark formulations with little or no peat moss can provide this level of aeration.

Large Container Substrates (Category V) Category V substrates are formulated for large containers such as container gardens and foliage plants in 1 gallon (3.8 L) and larger pots. It is also used for perennials since they are often watered by overhead sprinkler and may be grown outdoors subject to rain. The extra quantity of bark gives this mix the added advantage of drainage. Large container substrates are often cheaper than the other substrates. This is a decided advantage for large plant producers who consume great quantities of substrate. These substrates often contain 50 to 60 percent bark. The bark is generally coarser than that in the other substrate categories.

Several formulations are available within each substrate category across formulation companies. Each grower should test the alternatives. Final selection will be based in large measure on cultural practices of the grower. Other factors to consider are the formulation company's consistency of product and provision of technical service.

Self-Formulations

So many materials are available for soilless substrates that growers often make the mistake of mixing too many or the wrong types together. The four functions of root substrate—plant support, aeration, nutrient retention, and moisture retention—

Table 5
SEVERAL CURRENTLY POPULAR GREENHOUSE ROOT SUBSTRATE FORMULAS AND THEIR FUNCTIONS

Substrate Components	Function
1 peat moss:1 vermiculite	Germination mix
2 peat moss:1 vermiculite:1 perlite	Pot-plant mix
3 peat moss:1 perlite	Pot-plant mix
1 pine bark:1 vermiculite	Pot-plant mix
2 pine bark:2 vermiculite:1 perlite	Pot-plant mix
1 peat moss:1 pine bark:2 vermiculite:1 perlite	Pot-plant mix
1 peat moss:3 pine bark:1 sand	Pot-plant mix
1 rock wool:1 peat moss	Pot-plant mix
3 rock wool:7 peat moss	Pot-plant mix
1 coir:2 peat moss	Pot-plant mix

should be considered in developing a formulation. Good root substrates need not contain more than one to three components. Ten root substrate formulas are presented in Table 5. These are the more common mixes produced by growers themselves and are representative of many of the commercially prepared mixes.

Peat moss is often preferred as the organic component for its superior water-holding capacity and CEC. Pine bark is a good substitute for peat moss for any of the four reasons given earlier: price, long-term crops, large containers, and outside production. Coir also makes a good partial substitute for peat moss.

Peat moss comes very close to an ideal substrate by itself if it contains coarse aggregates. European growers have for the last half century grown top-quality crops in peat moss alone. North American suppliers also provide peat moss–only substrates that work very well. These substrates consist of two or more size fractions of peat moss blended together to achieve the physical properties needed for plant growth. If this system is used, it is important to guard against overwatering (watering too frequently).

Growers who self-formulate do not have the variety of particle sizes available to formulate a peat moss–only mix. They need to add a coarse component to increase aeration. The coarse component can be sand, but in most cases this is not desired because of its weight. Perlite is more commonly used. Calcined clay also serves the function of aeration as well as providing water and nutrient retention.

A wetting agent should be incorporated into substrate. Peat moss and bark-based substrates when dried excessively will repel water. For this reason, growers and commercial formulators add a wetting agent into all of their mixes. The wetting agent also aids the grower in the event the substrate is allowed to dry out too much during crop production. Formulators of soilless substrates must remain competitive. A significant part of the expense of these substrates to the grower is the shipping cost. By using a wetting agent, less water is permissible in the substrate before it presents a wetability problem. Commercial mixes typically contain 50 percent water by weight when shipped.

The problem of wetting dry substrate can also be reduced through selection of physical components of the mix. Coir wets much more readily than peat moss and bark when dried. This is an advantage in coir-based mixes. Addition of perlite also fosters easier wetting. Perlite provides large pores that allow quicker penetration of water throughout the substrate. In this way, lateral movement of water into the smaller pores of peat moss can occur more quickly. A number of commercially available substrates contain perlite in addition to peat moss and vermiculite.

An interesting pine-bark formulation used by many self-formulators consists of 3 bark (⅜ inch and smaller, 10 mm):1 concrete grade sand:1 peat moss. The sand is added to bark to increase its water-holding capacity. This occurs because sand particles are smaller than many of the bark particles and, as such, will nest between the bark particles. A unit volume of the bark–sand mixture contains nearly as many bark particles as when there was only bark, but it now contains sand particles in addition. This combination increases the particle surface area per unit volume of substrate and, consequently, the water-holding capacity.

By contrast, the addition of concrete-grade sand particles to soil increases aeration and lowers water retention. This occurs because the sand particles are larger than the soil particles. The sand particles now occupy space formerly held by smaller soil particles. A unit volume of substrate therefore has fewer but larger particles. This reduces the particle surface area per unit volume of substrate and thereby reduces its water-holding capacity.

Fertilizer Amendments As in the case of soil-based substrates, soilless substrates can contain four nutrient amendment packages. If needed, dolomitic limestone should be added to bring the pH level into the general range of 5.4 to 6.6. Most often, 10 lb of agricultural dolomitic limestone per cubic yard (6 kg/m^3) is used for this purpose. Phosphate is added as superphosphate (0-45-0) at a rate up to 2.25 lb/yd^3 (1.3 kg/m^3). The third nutrient additive is a micronutrient mix in a quantity sufficient to last at least one crop time (three to four months). In addition to these three amendments, a wetting agent is almost always included. Quite often, but not always, nitrogen and potassium, in amounts sufficient to last about two weeks, are likewise included. While most commercial formulations contain all of these amendments, they may be purchased with or without each of these nutrient packages.

ECONOMICS OF SUBSTRATE

The decision whether to purchase substrate from a formulator or mix it yourself should be based on economics. The grower needs to calculate the cost of the substrate he or she formulates and compare it with the price of commercial substrate, including shipment. In calculating the formulation cost, be sure to include management time, office expenses, depreciation cost of the mixer, any conveyor belts and front-end loaders used to fill the mixer, buildings used for holding components of the substrate, all labor costs, and shrinkage. When 0.5 cubic foot each of bark and peat moss is mixed together, the resulting volume is less than 1 cubic foot. This loss in volume is known as shrinkage and is in the range of 10 to 15 percent for most mixes. An additional factor to consider is the risk of a formulation error that could impact profitability of a crop. On-site production of substrate is a business aside from that of producing the crops. If undertaken, it is important that this task is handled by an individual with proper knowledge and sufficient time to manage it. Firms that tend to mix their own substrate are the very small firms and some of the very large firms that have invested in state-of-the-art mixing equipment.

Several of the widely available brands of commercial substrate cost $1.75 to $3.25/$ft^3$ ($62 to $115/$m^3$) delivered to the grower. The lower price reflects the lower-priced mixes, packaged in compressed bales rather than in loosely filled bags, a short shipping distance, and a competitive market zone. Shipping itself costs approximately \$1.90 per loaded mile (\$1.14/km) for a 45,000-pound (20-metric ton) truckload of 100 to 120 yd^3 (77 to 92 m^3) of soilless substrate. A fairly average shipping cost is \$550.00, which adds about \$0.19 to each cubic foot of mix. Many local formulators sell at even lower prices, particularly when the substrate is purchased unpackaged by the truckload. The average delivered root substrate figure of \$2.50/ft^3 (\$88/m^3) appears high but is not unreasonable. Fifteen 6.5-inch (17-cm) azalea-type pots used for pot mum culture can be filled from 1 ft^3 of substrate (485 pots/m^3) (Table 6) at a cost of \$0.17 per pot.

Table 6
Number of Pots and Flats That Can Be Filled from 1 ft^3 of Root Substrate

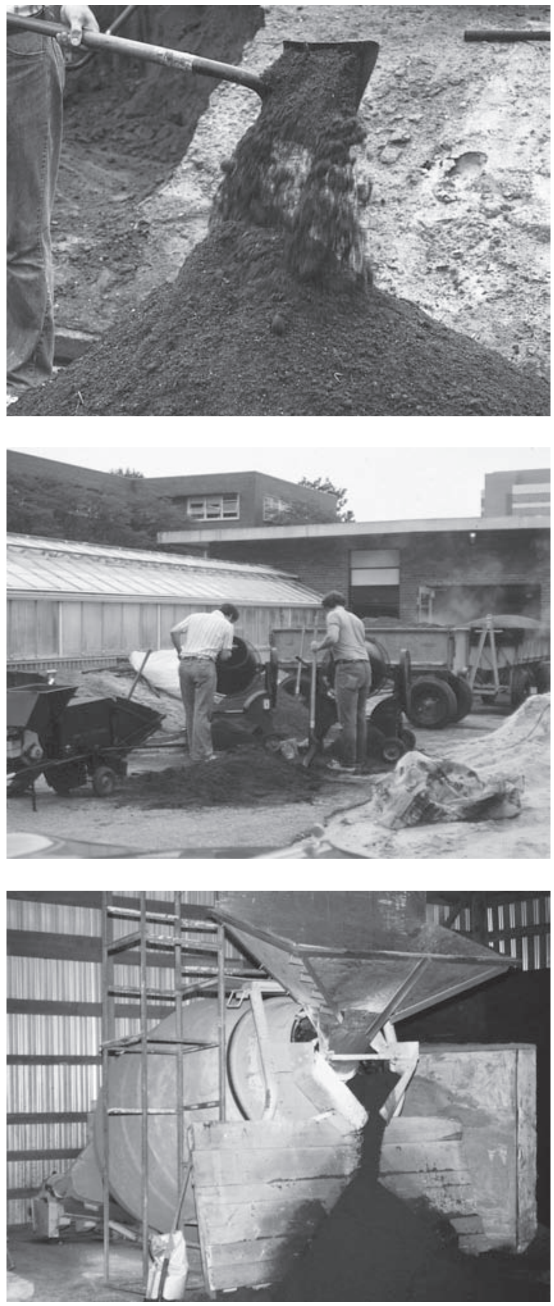
Pot Size (in.)	Number of Pots or Flats/ft^3
Standard Round Pot	
2¼	296
2½	176
3	120
3½	80
4	44
5	24
5½	19
6	14
7	9
8	5.6
10	3
12	1.6
Standard Square Pot	
2¼	283
2½	234
3	151
4	57
4½	50
Azalea-Type Pot	
4	64
5	32
5½	23
6	18
6½	15
7	11
7½	9
8	6.7
10	4
12	2
Low Pan	
5	40
6	31
7	14
Hanging Basket	
6	30
8	14
10	7.4
Bedding-Plant Flat (11.25 in. × 21.25 in. × 2.5 in.)	
32-cell	5.4
48-cell	6
72-cell	7

PREPARATION AND HANDLING OF SUBSTRATE

Various systems are available for mixing substrate. These fall into small, medium, and large categories and will be taken up next.

Small-Batch Handling

Very small batches of a substrate (up to 5 or 6 ft^3, 0.14 to 0.17 m^3) may be mixed by hand shovel on a potting bench or on any hard surface (Figure 11a).



(a)

(b)

(c)

Figure 11
(a) A hand-shovel procedure for mixing small batches of a root substrate. (b) A small-scale root substrate mixing operation. The soil shredder on the left is used to break up clods in field soil. Components of the substrate, including fertilizer amendments, are mixed in the 2-cubic foot (60-L) cement mixers. The freshly prepared substrate is placed in the pasteurizing wagons in the background and is pasteurized. (c) An intermediate-sized root substrate mixing operation making use of the mixer from a concrete truck.

Components are piled on one another, and the nutrient amendments, including limestone, superphosphate, and micronutrient mix, are broadcast over the pile. The pile is thoroughly mixed in three or four shifts. The pile is methodically removed by shovel from its base in the front. As material is removed, other material higher up tumbles downward, mixing as it falls. The new pile is built in front of the original pile by continually dropping material on the top point of this conically shaped pile. As material is added, it tumbles down all sides of the pile, mixing as it goes. This procedure is repeated two to three more times by moving the pile to the side and then to the back.

Intermediate-Volume Handling

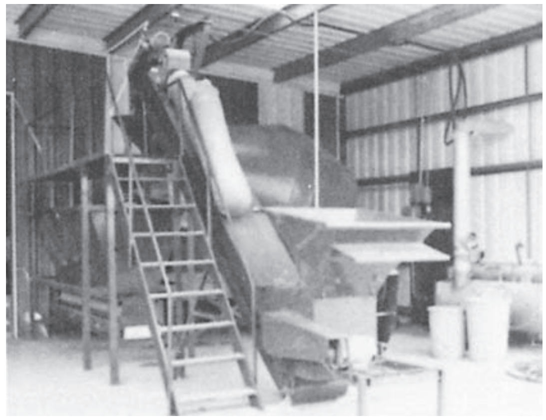
Preparation of larger batches requires motorized equipment. The simplest system calls for a concrete pad and a tractor with a bucket. Components are piled on the pad and then mixed by tractor in a similar fashion to that described for hand mixing. Although this is the most common mixing system, the uniformity of the product is questionable.

A more sophisticated system makes use of a mixer 2 to 10 yd^3 (1.50 to 7.5 m^3) in capacity (Figure 11b and c). Growers sometimes purchase old concrete trucks. The mixer is removed, reconditioned, and set up for greenhouse operation. The mixer is located near storage bins for the root substrate components, which can be filled directly by trucks. Substrate components can then be delivered by tractor to a hopper or conveyor belt feeding the mixer. Chemical amendments are added directly to the mixer. If pasteurization is required, steam is injected into the mixer to pasteurize the root substrate. Upon mixing, the substrate is automatically discharged into a potting trailer by reversing the mixer. Then the trailer is moved to a convenient location for potting plants, and the sides are lowered to a horizontal position to serve as a potting bench (Figure 12).

Large, Fully Automated Systems

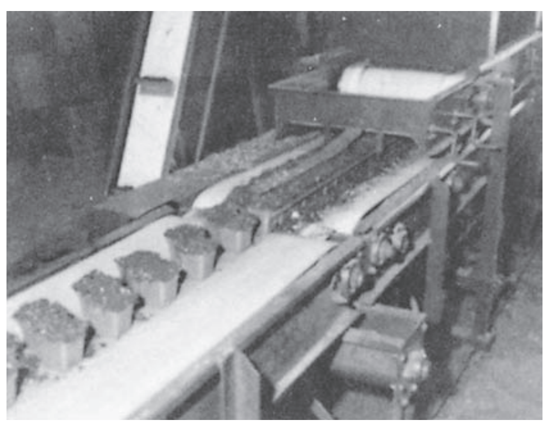
Large growers are in the best position to automate. Where an automated system is justified, it is generally used daily and therefore is placed under a roof to permit its use regardless of weather. A continuous-belt mixing system is most common (Figure 13). Each of the substrate components is loaded by tractor or conveyor belt into a hopper mounted over a belt. A gate at the bottom of each hopper can be adjusted to control the ratio of components in the mix. Nutrient amendments

Figure 12
A potting trailer with sides lowered to the horizontal position to serve as a potting bench.



(a)

(b)



(c)

Figure 13

A soil-based substrate mixing system for large operations: (a) Components of the substrate are placed in the hopper, through which they drop into a shredder and then pass up an elevator into a mixer. Chemical amendments are added directly into the mixer from above. The root substrate is steam pasteurized in the mixer with steam produced in the portable steam generator at the right. After pasteurization, the rotation of the mixer is reversed to expel the substrate into the 6-cubic yard (4.6-m^3) storage hopper on the left. The duct over the elevator is used to blow cool air into the mixer when it is emptying in order to reduce the time before the root substrate can be handled. (b) Further along the system, the root substrate is automatically brought by conveyor belt to a pot-filling machine as needed. In this scene, 157 three-inch (7.6-cm) pots are being filled per minute. Pots leave the filling machine on a belt and can be planted directly or can be removed and planted elsewhere. (c) A close view of the pot-filling machine. Excess substrate is recycled back to the hopper on the filling machine. This machine can fill flats or pots of any size, including 3-gallon (11-L) cans.

(Photos courtesy of Soil Systems, Inc., Apopka, FL 32703.)

are placed in smaller hoppers that meter these out over the other components, such as peat moss, already on the belt. Further along, the belt passes through a box in which spinning tines are located for mixing the various substrate components and nutrient amendments together. The mixed substrate continues along the belt to either a storage bin or the hopper on a flat- or pot-filling machine. When the substrate runs low in the hopper of the potting machine, a button is pushed to turn on the belt mixing system, which results in the hopper being refilled. All that is necessary is to keep the raw-ingredient hoppers in the belt system supplied.

SUMMARY

1. Root substrates must serve four functions: to provide water, to supply nutrients, to permit gas exchange to and from roots, and to provide support for plants.
2. Desirable properties of greenhouse root substrates include the following:
   a. For pot-plant substrates, a stable organic-matter content that will not diminish significantly in volume during growth of a crop.
   b. Organic matter with a reasonable C:N ratio and rate of decomposition, so that nitrogen tie-up is not troublesome.
   c. For pot-plant substrates, a bulk density light enough to enhance handling and shipping but sufficiently heavy to prevent toppling of plants—40 to 60 lb/ft^3 (640 to 960 g/dm^3) when wet at CC.
   d. At least 10 to 20 percent air by volume at CC in a 6.5-inch (17-cm) azalea-type pot with as high an available-water content as possible without sacrificing bulk density or aeration needs.
   e. A high CEC for nutrient reserve (6 to 15 me/100 cc).
   f. A pH level of 6.2 to 6.8 in soil-based substrate and 5.4 to 6.6 in soilless substrate for crops in general, but lower for acid-requiring plants.
3. A long list of potential components exists for use in greenhouse substrates. A grower should select substrate components on the basis of meeting the four functions of substrate, and should also consider economics, steady availability, and use of a minimal number of components.
4. Soil-based substrates were traditionally used in greenhouses. Soil provides water and nutrient retention. Concrete-grade sand is added to increase aeration, and peat moss is used to restore moisture and nutrient retention lost by the addition of sand. A standard formulation of 1 part loamy soil to 1 part sand to 1 part peat moss can be altered to accommodate various soil textures.
5. Nearly all substrates today are soilless. Various root substrates offered to growers fall into five categories: (1) germination mix, (2) young plant mix, (3) general peat moss mix, (4) general bark mix, and (5) large container mix. General contents of these mixes are as follows. Category I consists of fine peat moss and fine vermiculite. Category II has medium fine peat moss, vermiculite, and some perlite for added drainage. Category III uses standard size grades of peat moss, perlite, vermiculite, and sometimes coir. In Category IV, bark substitutes for much of the peat moss and a smaller amount of perlite and vermiculite are used along with some peat moss. Category V mixes contain coarser bark and in larger amounts of 50 to 60 percent along with smaller amounts of peat moss and perlite.
6. Nearly all root substrates must be amended with agricultural limestone to achieve desired pH levels. The remaining amendments, while often not included in germination substrates, are common in most other substrates. These include superphosphate, a micronutrient mixture, and sufficient nitrogen and potassium to last about two weeks. In addition, soilless substrates should be amended with a wetting agent.
7. The preparation and handling of root substrates poses an important economic consideration for growers. A root substrate may be purchased already mixed and chemically amended, thus circumventing considerable labor, or it may be formulated by the grower. Various degrees of automation are available for formulating and handling substrates, and should be considered.

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Root Substrate Pasteurization

Subtropical conditions exist in the greenhouse that are conducive to the development of plant disease organisms. The environment never freezes, the atmosphere is continually moist, and temperatures are always warm. The continuous culture of one or, at best, a few crops accentuates the disease problem by providing a continuous host on which disease organisms can build.

Root substrate pasteurization is a standard practice today for virtually all cut flowers grown in greenhouse beds and in the field as well as vegetables grown in greenhouse ground beds. For these crops, it generally is done on an annual basis, although a number of growers are pasteurizing their root substrate before every crop. The need for increased frequency is occasionally dictated by the buildup of disease. For a relatively short crop, such as chrysanthemums, substrate pasteurization could be required every 12 to 16 weeks. The summer is a preferred time for pasteurization because crop production is usually at a low point, student labor is more available, root substrate is warmer, and in the case of steam pasteurization, all or much of the boiler capacity is available. Bedding plants and ornamental potted crops are grown for the most part in soilless substrate that is not pasteurized. In those cases where soil is used in the substrate mix, pasteurization is generally practiced.

Root substrate pasteurization, in addition to eliminating disease organisms, is used to control nematodes, insects, and weeds. Field operators have been known to pasteurize soil for the single benefit of weed control. Pasteurization may be accomplished by injecting steam into the substrate or by injecting a chemical such as methyl bromide or chloropicrin. These two methods will be discussed separately.

STEAM PASTEURIZATION

Temperature Requirements

A number of organisms are injurious to plants, and each organism has its own conditions under which it is destroyed, as set forth in Figure 1. It has been customary to apply steam for 30 minutes beyond the time when the coldest spot in the batch of root substrate being pasteurized reaches 160°F (71°C). While this practice guarantees 30 minutes at a minimum temperature

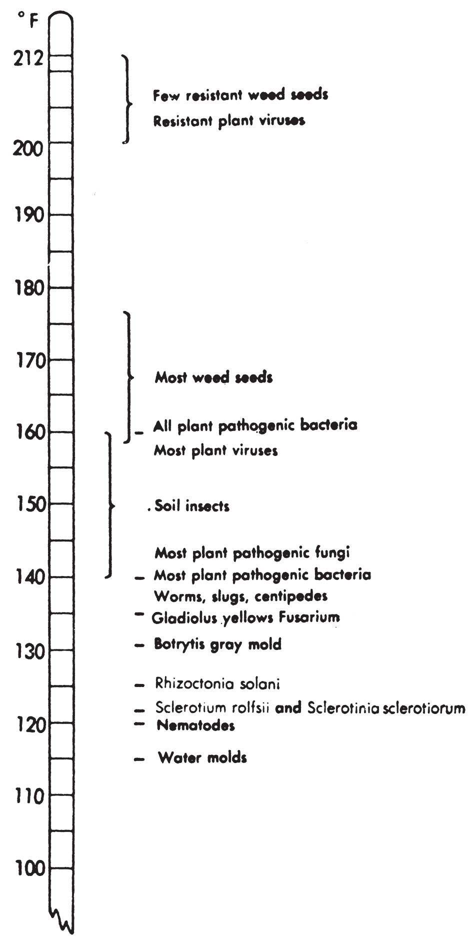


Figure 1
Temperatures necessary to kill pathogens and other organisms harmful to plants. Most of the temperatures indicated here are for exposures of 30 minutes under moist conditions.
(From Baker, 1957.)

of 160°F (71°C), the root substrate temperature usually rises to 212°F (100°C), the temperature of steam.

This chapter refers to pasteurization rather than to sterilization because sterilization would imply destruction of all organisms in root substrates, whereas pasteurization indicates that only selected organisms are killed. Root substrates contain, in addition to the harmful disease organisms, many beneficial organisms. A root substrate heavily occupied by beneficial organisms is not readily infected by disease organisms. By virtue of their strong foothold, the beneficial organisms compete successfully for oxygen, space, and nutrients, and present resistance to the establishment of disease organisms. Pasteurization at a temperature of 212°F (100°C) results in considerable destruction of beneficial organisms. This situation is not harmful if beneficial organisms are the first to reinoculate a root substrate. However, if disease organisms are first, they will develop rapidly without resistance or competition.

Equipment is available today that will mix air with steam (Figure 2). The temperature of the mixture can be adjusted to a desired level below 212°F (100°C) and injected into the root substrate. The root substrate will rise to this desired temperature and no higher. This system is known as aerated steam pasteurization. Several recommendations call for a temperature of 140°F (60°C) for 30 minutes, although many growers pasteurize at a temperature of 160°F (71°C) for 30 minutes. Most harmful organisms are destroyed at either temperature, while only a minimum of beneficial organisms are killed.

Figure 2
A steam aerator that permits pasteurization of root substrate at a temperature of 140° to 160°F (60° to 71°C) rather than at 212°F (100°C), the temperature of steam. Steam from a boiler enters the aerator at the right, while a blower introduces air. The two gases mix in the tank at the top and are then conducted through the hose on the left to a covered potting wagon containing the root substrate to be pasteurized. A hand valve is used to regulate the amount of air introduced, which in turn controls the temperature of the mixture. The temperature is indicated on the temperature gauge shown.

Root Substrate Preparation

Root substrate should be loosened before pasteurizing. If it is in a bench, it should be rototilled. Heat moves more rapidly within root substrate by convection through the pores than it does by conduction from particle to particle. The large pores in loose root substrates facilitate the movement of steam and thereby cut down the length of time required to pasteurize bench or container root substrates.

Root substrate should not be dry. Dry root substrate acts very much as an insulator, resisting the conduction of heat and causing the substrate to warm up slowly. The addition of water speeds up the rate of pasteurization, but there is an optimum level of water beyond which further additions again slow down the speed of pasteurization. Water requires five times as much heat to raise its temperature as does an equal weight of soil. Since all the excess water in the root substrate must also be raised to the desired temperature of pasteurization, the process becomes very slow and consequently expensive. As a general rule, the root substrate should be at the moisture level one would desire at the time of planting a crop.

A few types of weed seed can survive temperatures approaching 212°F (100°C). Some of these are bur clover, buttonweed, Klamath weed, morning glory, and shepherd's purse. This problem can be circumvented by moistening the root substrate a week or two prior to pasteurization. As soon as seed begins the germination process by taking up moisture, it is easily killed at lower temperatures typically used for pasteurization.

Since root substrate must be mixed prior to pasteurization, it is desirable to add the various chemical and physical amendments at that time. Superphosphate, limestone, micronutrients, and inorganic complete fertilizers can undergo the process of pasteurization without adverse effect. Plastic-coated slow-release fertilizers such as Osmocote and Nutricote should not be steam pasteurized. The high temperature can damage the coating, resulting in an increased rate of release. This leads to a high soluble-salt injury.

Cut-flower and vegetable substrates used for a succession of crops in ground beds and benches require periodic additions of organic matter such as peat moss or bark. These are most easily incorporated at the time a root substrate is rototilled prior to pasteurization. It is also a good practice to carry these amendments through the pasteurization process to destroy any harmful organisms that might be in them.

Steam Sources

The temperature of 1 cubic foot of a greenhouse root substrate, on the average, can be raised 1°F by the addition of 24 Btu of heat. (The temperature of 1 cubic meter of a root substrate can be raised 1°C by the addition of 1.6 MJ or 381 kcal of heat.) The lower the initial temperature of the substrate, the greater the quantity of heat that must be applied to pasteurize it. Table 1 lists the heat required to raise soil-based substrate to 180°F (82°C) from various starting temperatures.

Steam pasteurization efficiency may be as low as 50 percent. Half of the heat generated in the boiler may be lost from the boiler itself, the lines leading to the root substrate, the walls of the bench, and the cover over it. It is therefore necessary to double the figures in Table 1 for determining the size of boiler needed. Since 1 boiler horsepower (hp) is equal to 33,475 Btu per hour, a total of about 6 ft^3 (0.17 m^3) of substrate at 65°F (18°C) can be pasteurized in one hour with 1 boiler hp of heat at 50 percent efficiency (5,580 Btu/ft^3). This would be equivalent to about 12 ft^2 of bench area. (One cubic meter of a root substrate requires 208 MJ or 50,000 kcal during pasteurization.)

Boilers can also be rated in terms of pounds of steam generated. In this case, we are referring to 1 pound of water heated to the state of steam. When 1 pound of steam at 212°F changes state to 1 pound of water at 212°F, it releases 970 Btu of heat (1 g steam releases 540 cal). One more Btu is released for each degree the water drops below this point (1 cal released from 1 g water for each decrease of 1°C). If the root substrate is pasteurized at 180°F, the water will drop 32°F, releasing an additional 32 Btu beyond the 970 Btu released when it changed states. Thus, 1 pound of steam contributes 1,002 Btu to the job of pasteurization. About 6 pounds of steam are required to pasteurize 1 ft^3 (96 kg steam/m^3) of a root substrate.

A steam boiler used for heating a greenhouse can be used for pasteurization. A tee and valve should be installed in the main steam line at a convenient point in each greenhouse from which steam can be obtained.

Steam does not have to be generated under high pressure for pasteurization purposes. Once it is released in the root substrate, it is under very low pressure—considerably less than 1 psi (6.9 kPa). Pressure at the boiler drives the steam through the lines to the root substrate. For this purpose, a pressure of 10 to 15 psi (70 to 100 kPa) at the boiler is practical. It is true that the heat content of steam rises as it is put under pressure.

Table 1
Heat Required to Raise 1 ft^3 or 1 m^3 of Greenhouse Root Substrate Containing 15 Percent Moisture from Various Starting Temperatures to 180°F (82°C)[1]

Start (°F)	Heat (Btu/ft^3)	Start (°C)	Heat (kcal/m^3)
70	2,640	20	21,824
60	2,880	15	23,584
50	3,120	10	25,344
40	3,340	5	27,104
30	3,600	0	28,864

[1]Adapted from Gray (1960).

Figure 3
When steam is provided by a central boiler for root substrate pasteurization, it is best to have a permanent steam line in each greenhouse from which steam can be obtained for this purpose. A subsurface steam line with periodic risers is used here to minimize the length of steam hose and the amount of labor required.

However, the increase in heat content is small, and a high-pressure system must be justified on other grounds, such as heat distribution in a large greenhouse range. When steam pressure is increased to 50 psi (345 kPa), the temperature rises to about 297°F (147°C), and the additional heat content of 1 pound of water increases by only 29 Btu over steam at zero pressure (the heat content of 1 kg water increases by 67 kJ, or 16 kcal).

Steam Distribution

Steam should be conducted from the portable steam generator or main steam line in the greenhouse through a low-pressure steam hose at least 1.25 inches (32 mm) in diameter. Couplings on the hose should be full flow. If steam is provided from a central boiler, there should be a valve in each greenhouse section from which steam can be obtained (Figure 3).

Steam is distributed in cut-flower and vegetable ground beds or benches through buried perforated pipes. For beds 3 feet (0.9 m) wide, one row is buried; for 4-foot (1.2-m) beds, two rows are used. Used rain gutters, used boiler flue tubes, irrigation pipe, and other materials can be used for this purpose. A pair of holes from 1/8 to 1/4 inch (3 to 6 mm) in diameter should be drilled on opposite sides every 6 inches (15 cm) to distribute steam. The end of each pipe is plugged with a cap. A simple pipe manifold can be assembled to distribute steam from the inlet hose to each pipe (Figure 4).

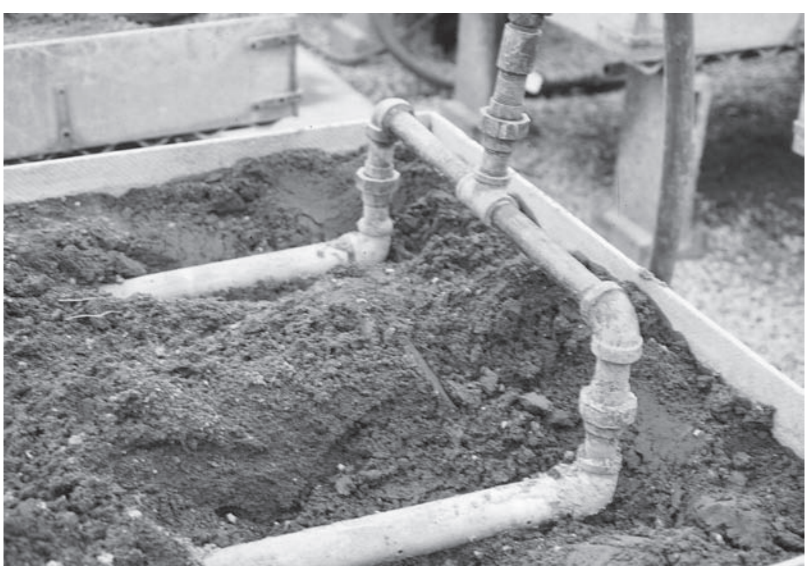


Figure 4
An easily constructed steam line manifold. The 4-foot (1.2-m)-wide bench pictured here is best pasteurized with two perforated steam-conduction pipes buried in the root substrate.

Many older ground beds, particularly in rose ranges, were constructed with a concrete V-shaped bottom. At the lowest point in the V, drainage tile was installed along the length of the bed. Steam can be very effectively applied through this tile, minimizing the equipment and labor of setup needed. Ground beds without bottoms can present another problem. Disease organisms and nematodes can exist below the point to which the soil has been loosened. Steam does not penetrate rapidly into this hard area. Harmful organisms below this point can return after pasteurization to the upper levels where roots grow. It is best to bury the steam-conduction pipes at the bottom of the rototilled root substrate. This results in deeper penetration of steam and also prevents nematodes and symphilids from escaping by burrowing deeper, ahead of the steam.

Raised benches filled with root substrate may be pasteurized with or without buried steam-conduction pipes. If pipes are used, they are buried at half the depth of the substrate. This is the best system. Some growers inject steam between the cover and the root substrate through 5-inch (13-cm)-diameter canvas hoses. Once the cover is inflated, steam readily penetrates the loosened root substrate. Although this system is easier to set up than the buried steam-pipe system, it can require a longer time for steam to penetrate the root substrate.

Empty raised benches can also be pasteurized with steam distributed through a 5-inch (13-cm)-diameter canvas hose. The canvas hose is slipped over the end of the steam hose and tied in place. It is then placed on the root substrate, and the distant end is tied closed with a piece of wire. The hose should be wet before pasteurizing to speed up the initial release of steam.

Potting substrates are best pasteurized in a wagon equipped with perforated steam pipes at the bottom or a perforated false bottom with a steam chamber below. Ideally, the sides of such wagons can be lowered to a horizontal position to serve as potting benches.

Fields of soil can also be steam pasteurized, which is often done in outdoor chrysanthemum production areas. It would be quicker to inject methyl bromide into the soil by tractor, but this practice would not completely kill verticillium wilt—a very devastating and prevalent disease of chrysanthemums in production fields. Steam is effective against this disease. The boiler may be in a fixed central location or mounted on a truck so that it can be moved from field to field. Steam is conducted from the boiler by a steam hose across the field to a steam rake (Figure 5). The rake consists of a 4-inch (10-cm) pipe header 12 feet (3.65 m) long, drawn perpendicular to a cable that pulls it across the field. Projecting down into the soil from the header are 16- to 18-inch (40- to 46-cm) blades spaced 9 inches (23 cm) apart. Behind each blade is a 1/2-inch (1.3-cm) pipe carrying steam from the header to the soil at the lower rear side of each blade. A winch is often used to draw the rake across the field at a rate of 10 to 20 inches (25 to 50 cm) per minute. One acre (0.4 ha) of soil can be pasteurized by a single rake in 40 to 70 hours of operating time. A sterilizing cover is attached to the back side of the header and is thus dragged across the field. The cover should be sufficiently long to require 30 minutes to pass over any given point in the field. The cover should be 50 feet (15 m) long for a rake moving at 20 inches (50 cm) per minute. The cover serves to hold the steam in the soil so that the soil temperature will be maintained at or above 160°F (71°C) for 30 minutes.

The coldest spot during pasteurization is at the end of the bench or trailer where the steam enters and usually near the outer wall at this end. A thermometer should be placed in the coldest spot. Pasteurization should not be stopped until the coldest spot reaches the temperature and time conditions desired. If the thermometer were placed in a warm spot, pasteurization would stop before harmful organisms were killed in the colder areas. These areas would become a source of inoculation for the

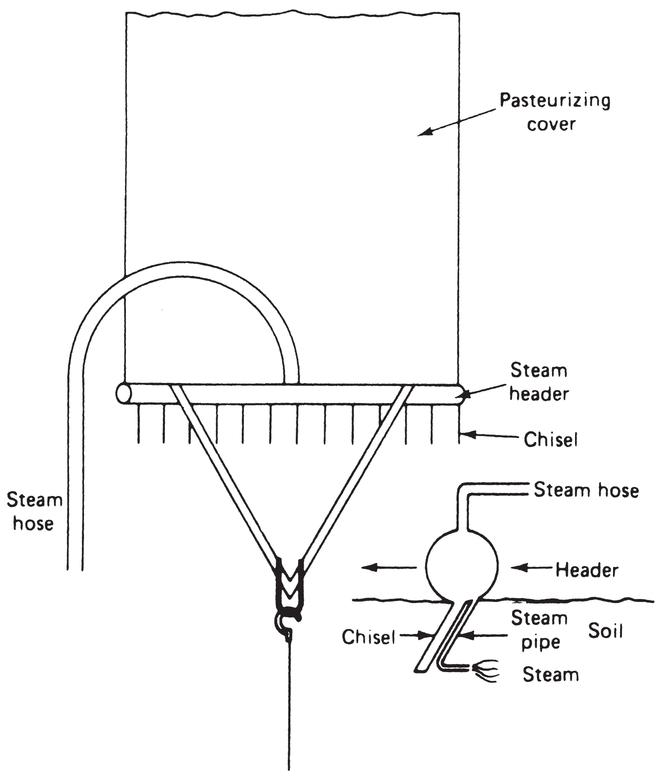


Figure 5
A steam rake used for pasteurizing soil in the field. Steam is conducted via hose to a 12-foot (3.65-m)-long header. Chisels about 9 inches (23 cm) apart project into the soil a distance of 16 to 18 inches (40 to 46 cm). Small pipes behind each chisel carry steam into the soil to the depth of the chisels. A pasteurizing cover is drawn behind the rake to maintain a high soil temperature for 30 minutes. The rake itself often is drawn across the field by a cable and winch.

remainder of the soil. Because of the lack of competition, the harmful organisms would spread rapidly. It would be better not to pasteurize the soil at all than to do an incomplete job such as this.

The cold spot in a greenhouse bench can be corrected by applying an extra quantity of steam at that point. Figure 6 shows a system for doing this. A short piece of pipe is connected to and run parallel to the steam-conduction pipe at the point where it enters the root substrate being pasteurized. The extra piece of pipe runs about a third of the length of the bed and has numerous perforations on opposite sides spaced about 2 inches (5 cm) apart.

Covers

Without a cover, steam will quickly rise through the root substrate and be lost, further reducing the efficiency of an already inefficient use of steam. A cover is placed over the root substrate during pasteurization to catch and hold steam in close contact with the root substrate so that it can be of further value in raising the temperature.

Basically, there are two types of covers: polyethylene and vinyl. Polyethylene film has the shortest life expectancy but is the cheapest. An inexpensive, 4-mil (0.1-mm) construction grade costs about 4¢/ft^2 (43¢/m^2). It may be used several

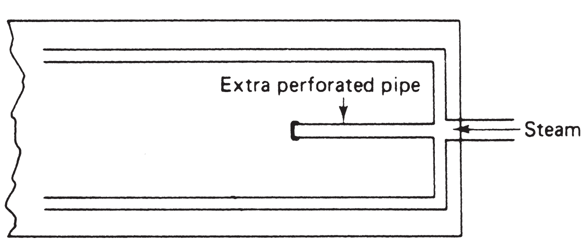


Figure 6
The extra perforated steam conduction pipe in the center of the pictured bed delivers additional steam to the cold end of a bed to prevent excessive pasteurization time.

times during one season of pasteurization but cannot be stored from season to season. Vinyl covers are the most popular and are usually purchased in 8-mil (0.2-mm) thicknesses. They are advertised to last for up to 55 uses. Actually, these covers can last longer with proper handling and storage away from sunlight. Ultraviolet light breaks down vinyl plastic. These vinyl covers cost about 45¢/ft^2 (\$4.84/m^2).

Covers used on benches with smooth outer side walls do not have to be fastened to the benches. They should overhang each side by 1 foot (30 cm) or more. As steam contacts the inner side of the cover, it condenses and moistens that side. The film of water that forms between the outer side of the bench and the inner side of the cover causes the two to stick together, preventing the cover from blowing off as steam builds up under it. Covers used on benches with outside posts or rough side boards must be fastened to the bench. The simplest method is to lay a chain or other heavy object over the cover against the inner side wall of the bench (Figure 7). A reusable plastic tube is commercially available that can be inflated with water for this same purpose. Some growers squeeze the cover between the top of the bench side and a lath strip with a clamp. Other growers with wooden benches place a lath strip over the cover at the top outer sides of the bench and nail the lath to the bench. However, this puts holes in the cover, which is undesirable, particularly in the case of a higher-quality cover that must be used many times.

Figure 7
When the outer side of a bed or bench wall is uneven, rough, or short, the pasteurizing cover must be fastened to prevent lifting by steam beneath. The simplest method is to weight it down with heavy objects, such as chain or pipe.

Thirty minutes after 160°F (71°C) has been achieved, the steam should be shut off. The cover will fall back to the root substrate in a few minutes, and then it can be cautiously removed. When the substrate has cooled to a comfortable working temperature, seeds and young plants may be planted. This cooling can require from four to eight hours, depending upon depth and moisture content. Substrate pasteurized with aerated steam can be cooled much faster by using the aerator to pass cool air through the root substrate for 30 minutes after the cover has been removed.

After-Steaming Problems

Two toxicity problems can occur as a result of steam pasteurization: manganese toxicity and ammonium toxicity. Large quantities of manganese exist in many soils. Fortunately, a small but adequate amount is available for plant use, while the majority is in an unavailable form. Steam pasteurization results in further conversion of unavailable to available manganese. The longer the soil is steamed, the greater the buildup of available manganese and, hence, the greater the risk of manganese toxicity. It is important that substrates containing field soil be pasteurized at the recommended temperature for only the length of time necessary—30 minutes. Soilless substrates usually present no problems, since the components contain little or no manganese.

A high level of manganese in the plant is toxic in itself, causing tip burn of older leaves. A high level of manganese in the root substrate also interferes with root uptake of iron. In fact, iron deficiency is commonly caused by high available-manganese levels.

Root substrates that contain organic matter rich in nitrogen can release toxic levels of ammoniacal nitrogen after pasteurization. Manure, highly decomposed peats, leaf mold, and immature composts are examples of such materials. Microorganisms feed upon the organic matter for the carbon, nitrogen, and other elements contained in it. When an overabundance of nitrogen is present, much will be released for plant use. As illustrated in Figure 8, ammonifying microorganisms convert nitrogen in organic matter to ammoniacal nitrogen, and then nitrifying bacteria convert the ammoniacal nitrogen to nitrate nitrogen.

Most plants grow best in a mixture of ammonium and nitrate forms of nitrogen. Some plants, including poinsettia and gloxinia, are sensitive to a high proportion of nitrogen in the ammoniacal form. Normally, ammoniacal nitrogen is continuously converted to nitrate nitrogen by soil bacteria, so there is a mixture. During pasteurization, ammonifying and nitrifying bacteria are nearly eliminated. In a few weeks, the ammonifying bacterial population builds back to an effective level, and sizeable quantities of ammoniacal nitrogen are released from organic matter. It is not until three to six weeks after pasteurization that nitrifying bacteria generally build back to a population size where they can cope with the ammoniacal nitrogen being released. In the meantime, two to six weeks after pasteurization, toxic quantities of ammoniacal nitrogen

$$\text{ORGANIC MATTER} \xrightarrow[\text{microorganisms}]{\text{Ammonifying}} \text{AMMONIUM} \xrightarrow[\text{bacteria}]{\text{Nitrifying}} \text{NITRATE}$$

Figure 8

Ammonium toxicity can be a problem when organic materials rich in nitrogen are pasteurized with either steam or chemicals. Nitrogen contained in organic matter is released as ammonium when ammonifying microorganisms, including bacteria, fungi, and actinomycetes, break down the organic matter in the process of utilizing its carbon content. Nitrifying bacteria, in turn, convert ammonium to nitrate nitrogen. During pasteurization, both populations of microorganisms are reduced to low levels. The ammonifying organisms build back to an effective level before the nitrifying organisms do. During the interim period, plants are prone to ammonium injury.

may develop. This may burn the roots of plants and cause stunting of the entire plant as well as wilting of the tops. Then, any type of nutrient deficiency can ensue as a result of the root injury. Once the nitrifying population becomes large, the high levels of ammoniacal nitrogen are converted to nitrate nitrogen, which is less toxic to plants and is more readily leached from the root substrate during watering. Because of these lower levels and the fact that many plants can tolerate higher levels of nitrate than ammoniacal nitrogen, the problem usually ends at this time. It is mainly for this reason that the use of manure gave way to peat moss during the 1950s when pasteurization became popular. Peat moss, because of its low nitrogen content and slow rate of decomposition, does not support a toxic buildup of ammoniacal nitrogen.

A third event that can occur from oversteaming of substrate attracts considerable attention but is not harmful. The fungus *Peziza ostracoderma* will build into a large, conspicuous population when competition from other microorganisms is reduced by overpasteurization (too high a temperature or too long a time). The fungus forms spores at the substrate surface that are at first white, then yellow, and finally brown. The fungus *Pyronema* sp. forms pink spores. These fungi do not attack plants. They disappear in a week or two as competitive organisms develop in the substrate. However, the appearance of these fungi serves to illustrate the ease with which a disease organism can get a foothold in overpasteurized substrates where competition has been suppressed.

CHEMICAL PASTEURIZATION

Chemical fumigants offer an alternative to steam for cut-flower growers who do not have a steam boiler and are not in a position to afford a portable steam generator. They would also see a value in chemical pasteurization because it can be set up for less cost.

Counterbalancing these advantages of chemicals are three disadvantages. First, chemically treated substrate cannot be used for young plants for at least 10 days after treatment. For cut-flower crops, costly overhead continues during this time. Second, chemicals are injurious to humans, and stringent safety precautions must be taken. Third, while steam and methyl bromide may be used in a greenhouse that contains plants, chloropicrin may not.

Fumigation of field soils for cut-flower production is most common in the concentrated production areas of Florida and California. In the remaining states where a larger number of floral crops are grown on each farm, it is not common to pasteurize the soil. Instead, crops are rotated to get around disease problems and plastic films are used for weed control. In California, where farms tend to specialize on one or a few floral crops, they may avoid fumigation of the floral crops by rotating with vegetables or strawberries if they grow these. Carryover of fumigant effects from the vegetable or fruit crops often meets the need of the floral crops. Fumigants are used on the floral crops when rotation is not feasible. A description of chemical fumigants used today and their methods of application follow.

Methyl Bromide

Methyl bromide is the fumigant of choice for cut flowers. It is an odorless, colorless gas that is extremely toxic to humans. For this reason, 2 percent of its formulation must be comprised of chloropicrin (tear gas) as an irritant to warn of exposure. Methyl bromide is purchased as a liquid under pressure in cylinders. The cylinders are mounted on tractors for application through chisels into ground beds or fields of soil. Methyl bromide is effective against disease organisms, insects, nematodes, and weed seeds.

Due to the contribution of methyl bromide to the destruction of ozone in the atmosphere, it was technically phased out for crop production in the United States on January 1, 2005. Separate schedules for phaseout exist for the European Union countries and for developing nations. In the United States, critical-use exemptions have been issued by the Environmental Protection Agency for a few crops where no economically and functionally viable option exists. This covers cut-flower crops nationally; however, some states do not accept the exemption. This prevents the use of methyl bromide for flowers in those states. Due to supply-and-demand principles, the price of methyl bromide has risen sharply in recent years.

Great effort is and has been made over the past 20 years to find a substitute for methyl bromide. Basamid (also Mylone, Microfume, and Crag), known by the common name DMTT or dazomet, while commonly used in several countries, is not used to any extent in the United States because of the long (three- to four-week) period between application and planting. Methyl iodide (iodomethane) is showing promise to be an effective substitute for methyl bromide. Also a combination of Telone and chloropicrin is being trialed by growers.

Methyl bromide should not be used in a greenhouse containing plants unless full ventilation can be provided during the process. Carnations are susceptible to even slight concentrations of methyl bromide, so this chemical should not be used for this crop. Cauliflower, salvia, and snapdragon may sustain a moderate degree of distorted growth from substrate not thoroughly aerated.

Methyl bromide, like steam, greatly reduces the populations of ammonifying and nitrifying bacteria. The same toxic buildup of ammoniacal nitrogen can occur if organic matter rich in nitrogen and capable of rapid breakdown is used.

Chloropicrin

This fumigant, also known as tear gas, is a popular choice for carnation crops because of their sensitivity to methyl bromide. Chloropicrin, however, cannot be applied to soil in a greenhouse where plants are being grown. Another disadvantage of chloropicrin is its poor penetration into plant tissue in root substrate. For floral crops other than carnation, chloropicrin is generally used in combination with methyl bromide or Telone. One common combination is 50 percent methyl bromide plus 50 percent chloropicrin. For field crops, chloropicrin, or one of its combinations, is purchased in cylinders for application by tractor as described for methyl bromide. Telone is an effective material for killing nematodes. When used in combination with chloropicrin, it exhibits a synergistic effect by increasing control of pathogenic diseases. This combination is typically applied through drip application, discussed later in this chapter.

Chloropicrin should not be used at substrate temperatures below 60°F (16°C); 70°F (21°C) is best. An exposure time of one to three days is needed, the longer time being needed at 60°F. Substrate should be aerated for 7 to 10 days before planting in it.

Methyl Iodide

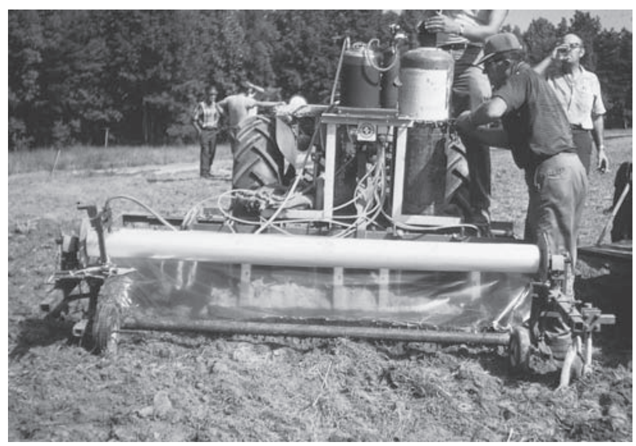
The effectiveness of methyl iodide is similar to methyl bromide, rendering it a potential replacement. Methyl iodide is more environmentally acceptable because it is degraded by UV light much faster than methyl bromide—that is, 1 to 4 days versus 0.7 years.

This scrubs it from the atmosphere before damage is done. Although it has been registered nationally, it must also be registered in each state. Some states have not accepted it. Methyl iodide is applied by tractor in a similar manner to methyl bromide. A few flower growers have adopted it. Problems associated with it center on its lower volatility than methyl bromide and its high density of about 18 pounds per gallon (2.2 kg/L). Low volatility results in liquid rather than gas occasionally reaching the chisel orifices in the soil and plugging them. The high density causes some difficulty in evenly distributing the low 75 pound (4 gal) dose per acre (84 kg/ha; 39 L/ha).

Tractor Application

Methyl bromide, chloropicrin, methyl iodide, or mixtures of methyl bromide and chloropicrin can be applied by tractor in the field (Figure 9). One of these gases, from a pressurized cylinder, is conducted through plastic tubes to a row of chisels mounted behind the tractor 6 to 8 inches (15 to 20 cm) apart. A cylinder of liquid nitrogen under pressure is often used to increase the pressure of the fumigant gas. The gas is released at the bottom of the chisels 4 to 6 inches (10 to 15 cm) deep. Also mounted to the back of the tractor is a roll of plastic film. Polyethylene film was used until recently, but now it is more common to use "virtually impermeable film" (VIF). VIF, by reducing the escape of gas to the atmosphere through the film during exposure time, allows for use of lower dose rates of the fumigant gas. The recent surge in the price of methyl bromide and very high price of methyl iodide necessitate this econ-

(a)



(b)

(c)

Figure 9

Tractor-mounted rig for injecting gaseous chemicals into field soil for pasteurization: (a) Chisels extend into the soil. Behind each is a tube that delivers the gas into the soil. A rake follows to seal the holes made by the chisels. (b) A roll of polyethylene film is located behind the rake. At the beginning of the row, the end of the polyethylene is anchored by burying it in the soil. As the tractor moves across the field, the film unrolls. (c) One side of the film is buried by a disk while the other side is glued to the previous sheet of plastic. Up to 5 acres of field can be treated by three people in one day with a single tractor.

(Photos courtesy of W. A. Skroch, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.)

omy. One end of the film is buried at the beginning of the row to anchor it. As the tractor moves across the field, the plastic sheet is unrolled. The leading edge of the first sheet is buried with soil by a disk mounted on the tractor. Subsequent sheets are glued to the preceding sheet to form one continuous covering over the field. A rig such as the one described costs $6,200 and can be depreciated over 10 years. Three workers with one tractor rig can treat up to 5 acres (2 ha) in one day.

A less expensive rig buries both sides of the plastic sheet. No gluing is involved. A 5- to 12-foot (1.5- to 3.7-m) strip of the field is treated; the next strip is skipped. This procedure is repeated across the field. In a few days, when sufficient exposure time has lapsed, the plastic is removed and the untreated strips are treated. This rig costs $2,900, and the labor and time inputs are about equal to the former rig.

Other materials for field fumigation include 1.7 rolls of 10.5-foot-by-3,000-foot (3.2 m × 914 m), 1-mil (0.025-mm) VIF at $610 per acre ($1,507/ha) and 200 pounds of 50 percent methyl bromide plus 50 percent chloropicrin at $1,180 per acre ($2,915/ha). If the glue system is used, 5 gallons of glue are required per acre at a total cost of $140 per acre ($346/ha). Custom applicators can be contracted for a 3- to 5-acre (1.2- to 2.0-ha) plot at the rate of $2,200 to $2,500 per acre ($5,434 to $6,175/ha) by those who are not set up to apply the chemical themselves. Everything is included in the custom applicator price except two laborers to bury the ends of each plastic strip applied and the labor of removing the plastic after a few days of exposure.

Drip Application

Many vegetables and fruit are grown under the plasticulture system. In this system, beds of soil are pulled up in the field and covered with plastic film. Holes are cut in the plastic through which plants grow. A drip tube is buried in the soil under the cover for periodic application of liquid fertilizer. The drip tube can also be used to inject fumigants. Since some cut-flower crops are grown in this system, drip application of fumigants is advantageous. The common fumigant is a mixture of Telone and chloropicrin.

Steam for Field Beds

Difficulties encountered in the application of field fumigation involve rules for buffer zones and personal protective equipment. Buffer zones are required to ensure that gases do not transfer to adjacent properties. These zones can constitute a significant proportion of crop land. Training of application personnel, cost of respirator gear, and cartridge replacement add to the cost. The discomfort of long-sleeve shirts and long pants in the hot fields lowers labor efficiency. For these reasons and the rising cost of fumigants, more cost-effective means of field steam pasteurization are currently under investigation. More efficient steam boilers and permanently buried metal steam tubes are being tested. Although a few field-flower growers use steam today, many more are expected to use it in the near future.

Residue Test

Wet, heavy, or cold substrates are slow to release chemical fumigants upon aeration. A grower must be certain that the residue is below an injurious level before planting a crop. A simple lettuce test can determine this. The procedure is as follows:

1. Fill a few jars three-quarters full with treated substrate. The substrate should be at a moisture content for planting. Wet it if necessary.
2. Place wet, 1-inch (2.5-cm) squares of absorbent cotton on the substrate, and on each square of cotton place 10 to 15 lettuce seeds that have been presoaked in water for 30 minutes.

3. Seal the jars tightly as soon as possible, and place them at room temperature in an area where they receive daylight. (Some types of lettuce seed will not germinate in the dark.)
4. Prepare some other jars in the same manner, using untreated substrate as a control.

After two days, the seeds in the control jars should have germinated as well as those in the treated-substrate jars if the residue is down to a safe level. If the seeds fail to germinate in the treated-substrate jars, aerate the substrate longer. It will help to mix or rototill the substrate.

REINOCULATION

Root substrate pasteurization eradicates biological pests; it does not provide resistance to these pests. Growers must think through all of the operations in which they might introduce contaminated substrate to clean substrate.

Pots and flats are of first concern. If they have been used before, they contain substrate and possibly plant tissue that could be contaminated. They should be cleaned. Clay and wooden containers can be steamed along with root substrate. Because plastic pots will distort at high temperature, they (as well as clay and wooden containers) can be treated with chemical fumigants.

Tools are another source of disease inoculum. They should be periodically disinfected to prevent the spread of any disease that might be present in the range and certainly before using a recently pasteurized substrate. Greenhouse-supply firms sell disinfectants such as Green-Shield, Physan 20, and ZeroTol that can be used for spraying or dipping tools, plant containers, and spraying floors to destroy and remove fungi, bacteria, and algae. Household bleach diluted 1:9 with water serves well also, but it will break down in sunlight in a day or so. This recommendation refers to a bleach containing 5.25 percent sodium hypochlorite active ingredient; for a higher percent active ingredient, increase the dilution appropriately. All of these disinfectants also work well for plastic pots.

Another common source of contamination is the soil on the soles and heels of shoes. Placing one's foot on the side of a bench in the greenhouse is an efficient way to transfer inoculum. Visitors with an interest in plants have probably been in another greenhouse range or a garden, and the probability of their carrying contaminated soil is great. It should be a standard rule around the greenhouse that feet are to be kept off the benches. Some growers place a fiber mat in a shallow tray of disinfectant solution at the entry to their ranges so that everyone steps through it, disinfecting their shoes before entering. This is a particularly wise practice for a propagation greenhouse, where disease prevention is an even more serious matter.

Plastic watering systems become distorted when left under the cover during steam pasteurization. They are customarily removed or raised above the bench during pasteurization. They should be sprayed or dipped in one of the four disinfectants mentioned earlier for cleaning tools before they are placed back on the root substrate. In a small operation, these pipes may be wiped with a rag saturated with disinfectant. The thin tubes and weights used in automatic pot-watering systems should be dipped in a container of disinfectant. Wire and string supports for cut flowers should likewise be sterilized before they are reused on a recently pasteurized bench.

For pasteurization to be effective, the grower must think through all operations to identify and correct those that can cause reinoculation of the root substrate. Means exist to ensure a clean range. Where failure occurs, it is due to a lack of foresight.

SUMMARY

1. All greenhouse root substrates used for successive crops, such as cut flowers and vegetables, should be pasteurized at least once per year, and more often as required, to rid them of harmful disease organisms, nematodes, insects, and weed seed. All substrates containing soil need to be pasteurized before initial use. Soilless substrates used for a single crop are generally not pasteurized before initial use.
2. Numerous nonharmful microorganisms develop in root substrate. These can be beneficial by providing competition for harmful microorganisms, which might otherwise proliferate. For this reason, root substrates are pasteurized and not sterilized; that is, only some organisms are killed.
3. A root substrate may be pasteurized with steam by raising it to a temperature of 160°F (71°C) for 30 minutes.
4. Volatile chemicals are also used for pasteurizing root substrates in greenhouse ground beds, and the chemical pasteurization precludes the need for a steam boiler—an advantage for field growers. Methyl bromide has been the fumigant of choice but is being phased out due to its damage to the earth's ozone layer. At the moment, fumigants in use include methyl bromide, chloropicrin, methyl iodide, and a mixture of methyl bromide plus chloropicrin, all of which are applied by tractor. Additionally, a mixture of Telone and chloropicrin is applied through drip irrigation in plastic covered beds.
5. Both steam and chemical pasteurization require that the root substrate be loose and of a moisture content suitable for planting. Amendments such as peat moss, manure, and bark should be incorporated prior to pasteurization to prevent introducing diseases or pests.
6. Pasteurization can result in ammonium and manganese toxicities in certain situations. If the root substrate contains organic matter rich in nitrogen, such as manure, steam and chemical pasteurization can result in an excessive release of ammonium, particularly in the period of two to six weeks after pasteurization. Either these materials should be avoided, or an adjustment should be made in the watering practice to ensure adequate leaching of ammonium. Many soils contain large levels of manganese, most of which is unavailable. Steam pasteurization causes a conversion of unavailable manganese to an available form. A toxic level is sometimes reached. This is another reason for pasteurizing root substrate at a low temperature (160°F, 71°C) and for only the necessary length of time (30 minutes).
7. Pasteurization of root substrate is designed to eliminate harmful organisms. It does not protect against future infestation. Good sanitation practices must be employed to maintain clean conditions. Some considerations include disease-free seeds and plants, sterilization of containers and tools, a pesticide program, foot baths, a clean working area, sanitation outside the greenhouse, and proper control of temperature and humidity.

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Watering

Watering is the greenhouse operation that most frequently accounts for loss in crop quality. Taken at face value, it would appear to be the simplest operation. When performed correctly, it is simple and perhaps a bit boring. For this reason, the task is often mistakenly assigned to a less experienced employee. If this employee waters at the wrong times or uses an incorrect amount of water, the crop will be impaired. The original quality cannot be regained.

The decision of when to water should be made by the greenhouse manager. He or she should inspect every bench of plants at least twice daily and should supervise the watering operation when it is carried out by another employee. Actually, with the wide variety of inexpensive automatic watering systems available today, the range should be equipped with a system simple enough to permit the manager to program the actual watering while inspecting the range. The time spent checking water needs affords the manager a chance to further inspect plants for insects, disease, nutritional disorders, and any other problems. Success or failure is due not so much to the quantity of labor expended as to the correct timing of the various labor operations. It is of utmost importance that the greenhouse range be inspected daily by the most knowledgeable person and that work plans be altered according to his or her findings.

EFFECTS OF WATERING ON PLANTS

Underwatering

When water is not applied frequently enough, plants wilt, thus retarding photosynthesis and slowing growth. The elongation of young developing cells is reduced, resulting in smaller leaves, shorter stem internodes (the length of stem between leaves), and, in general, a hardened appearance to the plants. In more extreme cases, burns may begin on the margins of leaves and spread inward, affecting whole leaves. On plant species capable of leaf abscission, the leaves will drop off. Before the days of chemical height retardants, it was customary to control the height of some crops by allowing plants to wilt between waterings. Today, this practice is restricted primarily to bedding plants. Also, growers now rely

more on chemical height retardants or manipulation of the day-to-night temperature relationship. The risk of foliar injury from drying has brought about this change.

Overwatering

When water is applied a little too frequently, new growth may become large but soft as a result of high water content, and as a whole, plants tend to be taller. This situation is undesirable because some of these plants wilt easily under bright light or dry conditions and do not ship or last well. If water is supplied even more frequently, the oxygen content of the root substrate is reduced by the higher average water content in the pores, resulting in damage to the roots. A damaged root system cannot readily take up water or nutrients. This condition causes wilting, hardened growth, an overall stunting of the plants, and several nutrient-deficiency symptoms.

RULES OF WATERING

Rule 1: Use a Well-Drained Substrate

If the root substrate is not well drained and aerated, proper watering cannot be achieved. Either you will underwater to achieve aeration or you will provide the required water at the expense of aeration. In either case, poor plant quality will result. A well-drained substrate of high water-holding capacity is required for use in containers. This calls for coarse texture and a high degree of stable structure—in short, a formulated substrate, not field soil alone.

Rule 2: Water Thoroughly Each Time

Because substrates cannot be partially wetted, it is important to water all of the substrate in a container each time water is applied (Figure 1). Water applied to the root surface of the substrate enters the pores at the top and adheres to the particle surfaces making up the pore walls. Additional water causes the layer on the particle surfaces

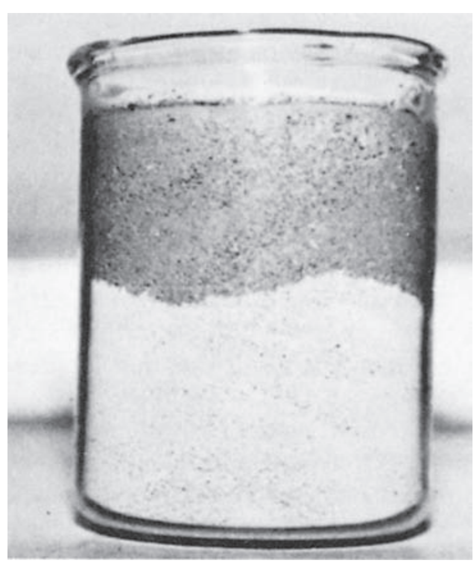


Figure 1
Only half the amount of water the soil in the beaker is capable of holding was applied. Instead of all the particles being partially wetted, those at the top are thoroughly wetted, while those at the bottom remain dry. This points out the fallacy of trying to partially water a root substrate.

to become thicker. Eventually, the layer of water becomes thick enough that any additional water is too far away from the particle surface to be held, and gravity pulls this additional water down to the next particle below. There, it is attracted to the particle surface, and as more water enters, the water layer on this particle grows thicker. This process keeps repeating itself until water finally reaches the particles at the bottom of the container. Additional water then flows through the substrate and out the bottom of the container.

If 6 ounces of water are required to water the root substrate in one pot and only 3 ounces of water are applied, the substrate in the top half of the pot will be thoroughly wetted while the substrate in the lower half will remain dry. Late in the afternoon or on Saturdays, there is always a temptation to water a crop partially to carry it over until more time is available for watering. From the preceding discussion, one can readily see the fallacy of doing this. The root substrate in the lower part of the pot or bench will not receive water.

In open cultural systems where water is applied to the top of the pot or bench and excess water drains from the bottom of the pot or bench, it is important to apply more water or fertilizer solution than the substrate can hold. Ten to 15 percent of the water applied to the top of the container should run out of the bottom. This is done to leach excessive fertilizers and nonfertilizer elements that might otherwise build up to toxic levels. Some fertilizers contain elements that are not used in large quantities by plants. As fertilizer is repeatedly applied to provide the elements needed in large quantity, these other elements accumulate. Recommendations in this paragraph apply to the open watering system option where leaching occurs. Alternatively, there are closed watering system options where no leaching occurs. Open and closed watering systems will be discussed in the "Watering Systems" section of this chapter.

As a general rule of thumb for soil-based substrates, $\frac{1}{15}$ gallon of water should be applied to each square foot of bench for each inch of root substrate depth. A typical bench 8 inches deep containing 7 inches of substrate should receive $\frac{7}{15}$ gallon of water, or in practical terms, ½ gallon of water per square foot. (Apply 1.1 L/m^2/cm of depth, or 20 L/m^2 to an 18-cm-deep bed.) A 6-inch (15-cm) azalea pot requires about 10 to 12 ounces (300 to 350 mL) of water. This rule applies to the application of nutrient solution as well as to water. These quantities of water should be checked out for each individual situation, since substrates vary in water-holding capacity. Larger or smaller quantities may be justified for various soilless substrates.

Rule 3: Water Just Before Moisture Stress Occurs

It is apparent from rule 2 that overwatering does not refer to the amount of water applied during a single application. Overwatering indicates that water is applied too frequently. When this is done, too much of the lifetime of the root is spent under conditions of minimum aeration, and as a result root development is suppressed.

Water should be applied just before the plant enters the early symptoms of water stress. For each plant, these signs are different. Some plants, such as chrysanthemum, take on a darker leaf color; others, such as begonia, exhibit a gray-green leaf color. By observing a crop, one can quickly learn the early warning signs of moisture stress. There are always individual plants that will run short of water ahead of the other plants and serve as an indication of impending water stress. It is also important to learn the color and feel of the root substrate associated with early moisture stress. Some crops, such as azalea, do not show signs of moisture stress until permanent damage has occurred to the roots. Judgment of when to water rests in this case entirely on substrate appearance, feel, and weight. Growers who measure substrate water content with tensiometers vary a little in the tension at which they apply water. This tension can range from 200 to 300 centimeters of water column (0.2 to 0.3 bars or 20 to 30 KPa).

There is an exception to the rule of watering just before stress occurs. The exception occurs in the pulse watering procedure that is covered later in this chapter under “Further Considerations.” An objective in that situation is to minimize or avoid leaching.

WATER QUALITY

It is very important to know the chemical content of water to be used in the greenhouse. Irrigation water should be tested any time a new source is established, whether it be from a well, river, pond, or municipal system. During the first two years, it is advisable to test the water source at least twice a year. It should be tested during a wet period and during a dry period. Introduction of large amounts of rain water into a surface water source or an aquifer servicing a well can result in a reduction of the chemical content of this water. Conversely, water impurity concentrations can increase during a drought. Once the water-quality pattern is established, water needs to be tested only every few years. Governmental and private laboratories that run substrate tests can usually analyze water.

Soluble Salt (EC)

An all-encompassing test in virtually all water analyses is the soluble-salt (EC) test (Table 1). Typically, this test is conducted with an electrical conductivity (EC) meter. This test measures all electrically charged salt ions dissolved in water, but does not measure noncharged dissolved molecules such as urea nitrogen. The meter probe has

Table 1
GUIDELINES FOR GREENHOUSE IRRIGATION WATER

Electrical conductivity (EC)	
0.75 mS/cm	Seedlings; maximum tolerable level
1.5 mS/cm	General crops; maximum tolerable level
pH[1]	
5.8–7.2	Acceptable
Alkalinity	
1.5 me/L (75 ppm $CaCO_3$ equivalent)	Caution
3.0 me/L (150 ppm $CaCO_3$ equivalent)	Troublesome
Hardness	
3.0 me/L (150 ppm $CaCO_3$ equivalent)	Caution—check the calcium-to-magnesium balance
Calcium and magnesium	
3 to 5 ppm calcium per 1 ppm magnesium	Tolerable

Specific elements (maximum tolerable levels)

Sodium	50 ppm	Zinc	0.3 ppm
Chloride	70 ppm	Copper	0.2 ppm
Chlorine	2 ppm (less in hydroponics)	Borate-B	0.5 ppm
Iron	4 ppm	Fluoride	0.5 ppm
Manganese	0.5 ppm	Lithium	0.5 ppm

[1]A pH level of 5.8 to 7.2 is easiest to handle. A much wider range can be successfully used, but with increasing difficulty as the pH level becomes lower or higher. A high pH level such as 7.3 is not a problem unless the water is highly alkaline (contains a high level of bicarbonate and carbonate). Thus, a high pH level is a warning to look at the alkalinity level, which in turn will indicate if corrective measures are needed.

two electrodes that are placed in the liquid sample to measure the conductance of electricity between them. The higher the salt content, the greater the flow of electrical current through the liquid sample. EC is measured in terms of mho/cm; the mho is a unit of EC and is the reciprocal of the ohm, a unit of electrical resistance. Since the conductivity is very low, it is recorded in fractions of a mho—thousandths of a mho in most cases (mho × 10^{-3}/cm), also called a millimho (mmho). Today, two other terms for EC measurement are popular: mS/cm and dS/m, which have the same value as a mmho/cm (1 mmho/cm = 1 mS/cm = 1 dS/m). Each laboratory will use only one term and will make available an interpretation chart. The upper acceptable EC level for water used for irrigating seedlings is 0.75 dS/m, and for older crops in general, it is 1.5 dS/m.

Occasionally, a well is drilled that yields water of low quality (containing quantities of impurities). The impurities may be sulfate in areas of old coal-mine shafts, sodium chloride (table salt) or sodium bicarbonate (baking soda) along coastal areas, calcium bicarbonate in areas of limestone deposits, and sodium in the alkaline areas found in arid parts of the world. Surface waters can contain fertilizer salts that have leached or drained from adjacent farms or landscapes.

Salts in water are transferred to the substrate during irrigation. There, these salts add to other salts derived from fertilizers and possibly from the breakdown of nitrogen-containing components of the substrate such as composts. High salt levels in the substrate are injurious to plants. Salt concentrations in the substrate solution and in the root cells determine to a large extent the flow of water between the two. Water flows in the direction of the higher salt concentration, which generally exists in the root cells. Thus, when the salt level in the substrate solution equals or exceeds the salt concentration in the root cells, water no longer moves into the root. Actually, water flow is determined by the solute concentrations. Solutes consist of the electrically charged ions that make up salts as well as neutral compounds that are dissolved in the solution such as urea nitrogen, sugars, amino acids, and organic acids. In substrate solution, salt makes up the majority of the solutes, thus the EC value is used as a representation of the solute concentration.

An excessive level of soluble salts in the root substrate is first seen as wilting of plants during bright times of the day, even though the root substrate is moist. Overall growth slows down, leading to compact plants. Roots die from the tips back, particularly in the drier zones of the root substrate. Leaves become necrotic, in some cases along the margin and in others as circular spots scattered across the leaf blade. Ultimately, deficiency symptoms of many nutrients occur as a result of acutely impaired nutrient uptake by the injured root system.

Alkalinity

Too much importance has been placed on water pH. It is a misconception that substrate pH is mainly under the control of water pH. The primary impact of water on substrate pH stems from water alkalinity. Suppose that two water sources exist, each with a pH of 7.4. If the first has an alkalinity level of 2 me/L and the second has a level of 6 me/L, the first will raise substrate pH very little, while the rise from the second will be unacceptably high. Judgment of the quality of these two water sources would have been 50 percent accurate on the basis of pH and 100 percent accurate based on alkalinity. A high water pH—that is, 7.2 or higher—should be merely a warning to look at the alkalinity level.

The alkalinity test has far-reaching implications. Alkalinity is a measure of the facility of water to raise pH. It is primarily a measure of the amount of carbonate plus bicarbonate in water. These are the active ingredients in liming materials used to raise substrate pH. Thus, applying alkaline water is equivalent to applying limestone.

Alkalinity is generally reported as milliequivalents per liter (me/L) of water or as parts per million (ppm) of equivalent calcium carbonate. One me/L of alkalinity is equal to 50 ppm of equivalent calcium carbonate. Precise upper critical water-alkalinity levels cannot be assigned. An excessive alkalinity level is one that causes the pH of the substrate to rise to an unacceptable height by the end of a crop. There are three crop situations that dictate the upper critical alkalinity level: the length of the crop period, the plant-to-substrate ratio, and the upper substrate pH level tolerated by the crop.

Water alkalinity causes substrate pH to rise gradually over time, as the cumulative quantity of bicarbonate plus carbonate increases with additional applications of water. A 3-week crop of marigolds could possibly tolerate an alkalinity level of 6 me/L, while a 12-week crop of chrysanthemums would not. During the short 3-week period of marigold growth, the substrate pH might rise only to a safe level of 6.8. On the other hand, the 12-week cultural period of the chrysanthemums could provide the time necessary for an unacceptable pH rise to 7.5.

The impact of the ratio of shoot mass to root substrate mass on the critical alkalinity level is best seen in plug seedling production. The roots of a plug seedling can be confined to a cell with as little as 0.1 in.^{3} (2 cc) of substrate. Yet the shoot of this seedling will be grown over six weeks to a large size greatly out of proportion to the substrate volume. The great cumulative volume of shoot transpiration throughout this period will demand an unusually large amount of water application per unit volume of substrate. If the irrigation water is alkaline, substrate pH will rise surprisingly fast because there is little substrate present to neutralize the bicarbonates and carbonates supplied in the water.

Finally, crops that need to be grown at low substrate pH levels are less tolerant of water alkalinity. Some examples are pansy, petunia, vinca, and snapdragon. These crops perform best at a pH level of 6.0 or lower; otherwise, iron and possibly boron deficiencies become a problem.

It is desirable for irrigation water to contain a low level of alkalinity, around 1.0 to 1.5 me/L, to counteract the acidifying effect of root respiration that releases carbon dioxide that ultimately becomes carbonic acid. Growers with less than this level of alkalinity usually experience declining substrate pH values during crop production.

Water-alkalinity guidelines can be found in Figure 2. Alkalinity levels up to 1.5 will probably not require any preventive action against substrate pH rise. Levels in the range of 1.5 to 3.0 might call for action. The cheapest action includes use of less limestone in the substrate and/or a shift to acid-reacting fertilizers. Most greenhouse substrates require limestone in their formulation. Therefore, less limestone can be used to compensate for the lime that will be applied in the alkaline water. The amount of limestone to use is that amount that achieves the minimum substrate pH

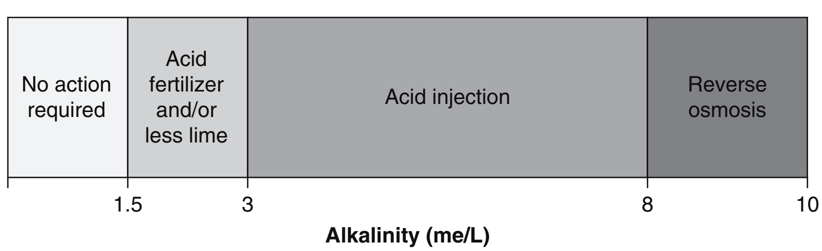


Figure 2
A graphic presentation of the steps to be taken in sequence for correcting high water-alkalinity problems as waters of increasing alkalinity are encountered.
(Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695–7609.)

requirement of the crop at the start of the crop, yet does not result in an excessive pH level at the end of the crop. Some plug seedling growers in areas of extremely alkaline water apply no limestone to their germination substrate, leaving the initial pH at about 4.5. By the time seedlings have germinated and developed a bit, bicarbonate in the irrigation water has raised the substrate pH to a safe level of 5.2 or higher. If the pH does not rise above 6.8 by the end of the seedling crop, no further costly measures are needed to combat the water alkalinity. Some fertilizers are basic (alkaline) in that they raise the substrate pH, while others are acidic. Fertilizer acidity/basicity can be used to manipulate moderate pH shifts in substrate. Use of an acidic fertilizer may be all that is required to counteract alkalinity in moderately alkaline water.

Often when the alkalinity level of water is 3.0 me/L or higher, it becomes necessary to take stronger action to prevent the substrate pH level from rising too high by the end of the crop. The next level of action in effectiveness and cost is injection of acid into the water (Figure 2). Bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) in water cause the substrate pH to rise because bicarbonate (equation 1) and carbonate (equation 2) combine with substrate acidity (H^+) to form carbonic acid (H_2CO_3), which then converts to water (H_2O) and carbon dioxide (CO_2):

$$HCO_3^- + H^+ \rightarrow H_2CO_3 \rightarrow H_2O + CO_2 \quad (1)$$

$$CO_3^{-2} + 2H^+ \rightarrow H_2CO_3 \rightarrow H_2O + CO_2 \quad (2)$$

In these processes, the acidity and the bicarbonate are consumed. Since pH is a measure of H^+ ions, the loss of H^+ ions in substrate results in a higher pH level. When acid is added to water, it dissociates to yield H^+, as in the case of nitric acid in equation 3. These H^+ ions consume much of the bicarbonate before it reaches the substrate through the same reaction seen in equation 1.

$$HNO_3 \rightarrow H^+ + NO_3^- \quad (3)$$

Water below pH 8.3 contains only bicarbonate, while water at or above pH 8.3 can contain bicarbonate plus carbonate.

Four types of acids are used for neutralizing alkalinity in irrigation water. The first three, purchased as liquids, are nitric, phosphoric, and sulfuric acids; the fourth is citric acid, which is purchased as a solid. Nitric acid, available in concentrations of 61.4 percent and 67 percent, and sulfuric acid in a concentration of 93 percent are dangerous to handle, but are often used in greenhouses. Phosphoric acid is available in 75 percent and 85 percent concentrations and is much safer to handle. Thirty-five percent sulfuric acid is popular among greenhouse growers due to its greater safety in handling and its low cost. This latter acid can be purchased at automotive-supply companies as battery acid.

The quantity of acid required depends on the initial alkalinity and pH of the water to be treated and the final desired pH or alkalinity level of the treated water. An alkalinity calculator is available on the World Wide Web for calculating the quantity of each of the four listed acids for any given situation. The Web address *floricultureinfo.com* opens up the North Carolina State University floriculture home page. There, one can click on floriculture software and download the alkalinity calculator or the plant growth regulator calculator. These calculators require an Excel software program and will run on Macintosh or IBM-compatible computers. The alkalinity calculator was used to determine the quantities of 35 percent sulfuric acid required to bring water of various initial alkalinity and pH levels to a final pH level of 5.8 (Table 2). Although other end points are sometimes desired, a final pH level of 5.8 works well for most crops. Equivalent quantities of other acids can easily be

Table 2
Quantities of 35 Percent Sulfuric Acid Required to Treat Alkalinity in Water of Various Initial pH and Alkalinity Levels When an End Point of pH 5.8 Is Desired[1]

	Initial Water Alkalinity (me/L)				
Initial pH	**2**	**4**	**6**	**8**	**10**
			fl oz Acid/100 gal		
7.2	2.15	4.30	6.45	8.60	10.75
7.4	2.18	4.37	6.55	8.73	10.91
7.6	2.20	4.41	6.61	8.82	11.02
7.8	2.22	4.44	6.65	8.87	11.09
8.0	2.23	4.45	6.68	8.91	11.13
8.2	2.23	4.47	6.70	8.96	11.17
8.4	2.24	4.48	6.72	8.96	11.20
8.6	2.25	4.49	6.74	8.98	11.23
8.8	2.25	4.51	6.76	9.01	11.27
9.0	2.26	4.53	6.79	9.05	11.32
9.2	2.28	4.55	6.83	9.11	11.39
9.4	2.30	4.59	6.89	9.18	11.48
9.6	2.32	4.64	6.96	9.29	11.61
			mL Acid/L		
7.2	0.168	0.336	0.504	0.672	0.840
7.4	0.171	0.341	0.512	0.682	0.853
7.6	0.172	0.344	0.517	0.689	0.861
7.8	0.173	0.346	0.520	0.693	0.866
8.0	0.174	0.348	0.522	0.693	0.870
8.2	0.175	0.349	0.524	0.698	0.873
8.4	0.175	0.350	0.525	0.700	0.875
8.6	0.175	0.351	0.526	0.702	0.877
8.8	0.176	0.352	0.528	0.704	0.880
9.0	0.177	0.354	0.530	0.707	0.884
9.2	0.178	0.356	0.534	0.712	0.889
9.4	0.179	0.359	0.538	0.718	0.897
9.6	0.181	0.363	0.544	0.725	0.907

[1]Equivalent quantities of other types of acid can be determined by multiplying values in the table by the following factors: 0.25 for 93 percent sulfuric acid, 0.67 for 61.4 percent nitric acid, 0.60 for 67 percent nitric acid, 0.72 for 75 percent phosphoric acid, and 0.59 for 85 percent phosphoric acid. Always add acid to water, not vice versa.

determined by multiplying values in Table 2 by factors presented in the footnote to Table 2.

Acid is introduced into the water stream in various ways. Growers with low-volume wells pump water into a large holding tank. Water is then pumped at a much higher flow rate from this tank to the crops during the few hours of the day when irrigation is required. In this situation, acid may be pumped directly from the drum in which it was purchased to the holding tank any time water is being supplied to the holding tank. The two pumps that separately deliver water and acid to the holding tank are activated by the same water level sensor in the holding tank. The proportion of acid delivered to the holding tank is controlled by adjusting the flow rate of the acid pump. Growers who pump directly from the water source (well, river, pond) to the irrigation lines can use a proportioner to meter acid into the water line. As water passes through the proportioner under the pressure of the pump, acid is drawn into

Table 3
CONCENTRATIONS (PPM) OF ESSENTIAL NUTRIENTS RESULTING FROM THE ADDITION OF 1 FL OZ OF VARIOUS ACIDS IN 100 GAL OF WATER AND FROM 1 ML IN 1 L OF WATER

Acid (%)	Nutrient	From 1 fl oz/100 gal (ppm)	From 1 mL/L (ppm)
Nitric acid (61.4)	Nitrate-N	14.6	187
Nitric acid (67)	Nitrate-N	16.3	208
Phosphoric acid (75)	Phosphate-P_2O_5	67.1	857
Phosphoric acid (85)	Phosphate-P_2O_5	81.8	1,045
Sulfuric acid (35)	Sulfate-S	11.3	145
Sulfuric acid (93)	Sulfate-S	45.1	578

the proportioner and mixed with water. Often the proportion of acid to water is lower than the range of the proportioner. In this case, diluted acid is used in the supply tank. Remember, it is imperative that acid be added to water during the dilution process and that it be done slowly. If water is added to acid, there is a great risk of acid splattering out of the solution onto the worker due to the evolution of heat. Be sure that acid-resistant pumps and proportioners are used.

It is important to determine the quantities of essential nutrients that are supplied along with various acids so that fertilizer rates can be reduced by these amounts. Nitrate nitrogen is supplied by nitric acid, phosphate phosphorus by phosphoric acid, and sulfate sulfur by sulfuric acid. The concentrations of each of these three nutrients that result from the use of 1 fluid ounce of acid in 100 gallons of water (and from 1 mL in 1 L of water) are presented in Table 3. Consider a grower who fertilizes a crop of bedding plants with fertilizer containing 100 ppm nitrate-N, 50 ppm phosphate-P_2O_5, and 100 ppm potassium-K_2O, and has water with an alkalinity level of 10 me/L and pH of 7.8. If this water is treated with nitric acid, it will contain 109 ppm nitrate-N, which is more than can be tolerated in the fertilizer program. If phosphoric acid is used, the contribution of phosphate-P_2O_5 will be 540 ppm, which is also more than is desired in the fertilization program. This leaves only sulfuric acid that can be used. Although it will supply 125 ppm sulfate-S, this is tolerable. Whenever it is necessary to supply more of one nutrient element than is desired in a fertilization program, it is generally best to supply sulfate or calcium. These nutrients have less solubility in the substrate, and the plant is able to restrict their uptake more than most other nutrients. This point, coupled with price and safety of handling, renders 35 percent sulfuric acid the preferred material for many growers. Calcium, magnesium, and sulfate ions have two electrical charges that greatly slow down their uptake by plants, whereas ions such as potassium, sodium, ammonium, nitrate, and chloride have one electrical charge that allows rapid root uptake.

Citric acid is a much more expensive acid to use than the previous three. However, it has a decided advantage in that it does not supply an essential nutrient to interfere with the fertilization program. Citric acid is often used for acidifying water used in fertilizer concentrates. In greenhouses, most fertilizer is dissolved into a concentrate and then injected into the water line through a proportioner. The concentrate is typically 50 to 200 times more concentrated than the fertilizer solution applied to the plants. Solubility of the concentrate diminishes with increasing pH. Phosphoric and sulfuric acids acidify water and thereby increase fertilizer solubility. However, part of the increased fertilizer solubility is lost due to the contribution of phosphate or sulfate, which reduces fertilizer solubility.

Conceivably, enough acid could be injected into water to combat any level of alkalinity. This is not true for greenhouse irrigation purposes. The carbonates and bicarbonates that constitute much of the alkalinity in water are negatively charged ions. Such ions must be accompanied by positively charged ions—that is, cations such as calcium, magnesium, or sodium. Thus, you might think of alkalinity in terms of calcium bicarbonate rather than just bicarbonate. Acids are added to alkaline water to supply hydrogen (H^+), which removes the bicarbonate as seen in equation 1. However, each acid contains anions such as nitrate (NO_3^-) in nitric acid or sulfate (SO_4^{-2}) in sulfuric acid. When bicarbonate is removed, a new salt forms to replace it. Just such a scenario is seen in equation 4, where alkalinity in water is assumed to be mainly calcium bicarbonate [$Ca(HCO_3)_2$] and is neutralized with nitric acid (HNO_3), thereby forming calcium nitrate [$Ca(NO_3)_2$] in the place of calcium bicarbonate.

$$Ca(HCO_3)_2 + 2HNO_3 \rightarrow 2H_2CO_3 + Ca(NO_3)_2 \tag{4}$$

$$2H_2CO_3 \rightarrow 2H_2O + 2CO_2$$

As we have just seen, the active ingredients in alkalinity are salts. Highly alkaline water usually has an undesirable high EC level. Since none of the measures listed thus far for combating alkalinity eliminate salt, there is a limit to using acid to treat alkalinity.

When alkalinity is around 8 me/L (see Figure 2), reverse osmosis (RO) might be necessary. This is a last resort because it is more expensive. The exact alkalinity level at which RO is required depends on the salt tolerance of the crop. In RO, water is forced through sufficiently fine filters to remove ions such as sodium, calcium, and bicarbonate. This system effectively removes alkalinity and salts. Since most greenhouses do not need RO, this is an expense that could considerably reduce a firm's competitiveness. It is very expedient to evaluate the quality of water at a prospective greenhouse site prior to establishing a business.

Hardness

The presence of high alkalinity in water immediately dictates the need for a hardness test. Hardness is a measure of the combined content of calcium and magnesium in water. Hardness is expressed as me/L of water or as ppm of equivalent calcium carbonate (limestone). As in the case of alkalinity, 1 me/L equals 50 ppm of equivalent calcium carbonate. When hardness exceeds 3 me/L, it is important to check the calcium and magnesium concentrations in irrigation water to determine if they are in proper balance. For each ppm of magnesium, a concentration of 3 to 5 ppm of calcium is safe. The exact limits of the magnesium-to-calcium ratio are unknown. If there is more calcium than this, it can block uptake of magnesium in the plant, causing a magnesium deficiency. This can occur even though the concentration of magnesium in the substrate would otherwise have been adequate. If the calcium level is lower than the 3–5 Ca:1 Mg ratio, the relatively high proportion of magnesium could block calcium uptake, causing a calcium deficiency.

Specific Elements

It is difficult to state upper critical levels for nitrate and ammoniacal nitrogen, phosphate, and potassium. Water concentrations up to the fertilizer concentrations needed for application with every irrigation could be acceptable. It is important to reduce the fertilizer concentration by the amount that is found in the irrigation water to prevent overapplication. Excesses of nitrogen and potassium are generally expressed as high-soluble-salt damage. These two nutrients contribute more to the salt level of fertilizer solutions than the remaining nutrients combined. The presence of high nitrogen levels in a water source generally indicates that surface water is getting into the water supply. The fear in this case is that human pathogens can be introduced with the surface water, especially if it originates from livestock or residential areas.

Upper critical water levels for sodium and chloride are commonly stated to be 50 and 70 ppm, respectively (see Table 1). These values are highly questionable. Sodium is not an essential nutrient, although a small concentration of a few parts per million has been found to be beneficial for carnation. Chloride is an essential micronutrient. The requirement for chloride is so low that the contaminant amount of chloride in water, substrate, and fertilizers is sufficient to meet plant needs. It would be best to apply no sodium or chloride in order to keep the EC level of water and fertilizer solutions as low as possible. However, for situations where these ions cannot be avoided, sensitive crops will tolerate only the stated limits, while others can tolerate much higher levels. High levels of sodium block uptake of potassium, ammonium, calcium, and magnesium in plants. When the sodium concentration in water is high—that is, 50 to 100 ppm—one should increase the application rates of potassium, calcium, and magnesium to bring these into balance with sodium so that their uptake is not impeded. Whenever sodium and chloride levels are high in water, one should observe the EC level because these ions contribute in large part to the total salt level in water.

Chlorine is quite different from chloride just discussed. Low concentrations of chlorine are injurious to plants. A chlorine concentration of 0.4 ppm can cause root-tip injury to some crops, including chrysanthemum and rose, when grown in hydroponic systems. Crops grown in solid substrates tolerate much higher chlorine levels in water than crops in hydroponic systems, because far less of the chlorine gets to the roots in substrate. Chlorine converts rapidly to chloride as it reacts with (oxidizes) organic matter in the substrate. Since the concentration of chlorine in water rarely exceeds 10 ppm, the low level of resulting chloride is insignificant. The quantity of chlorine added to municipal water varies. Also, the longer the water remains in the water mains, the lower the chlorine content becomes as it converts to chloride. Water drawn from a position near the end of a municipal water main, or water drawn on a rainy day when customers are using little water, will have been in the pipe system sufficiently long for the chlorine level to drop significantly. Typical levels of chlorine in municipal water are in the range of 1 to 2 ppm but can be as high as 10 ppm. A study of 23 species of foliage, flowering pot, and vegetable crops grown in root substrate by Frink and Bugbee (1987) revealed that growth was inhibited by 2 ppm chlorine in irrigation water in begonia and geranium; 8 ppm in pepper and tomato; 18 ppm in kalanchoe, lettuce, and tradescantia; 37 ppm in broccoli, marigold, and petunia; and 77 ppm in English ivy, Madagascar palm, and Swedish ivy. Bridgen (1986) reported that zinnia seedlings began to react to chlorine in irrigation water when it reached 7.6 ppm. Symptoms included shorter shoots, leaf curl, and veinal chlorosis on all leaves. Pot mums were not adversely affected until a concentration of 15.2 ppm chlorine was reached. The symptom was veinal chlorosis of leaves. It appears that less than 2 ppm chlorine is generally safe for crops in solid substrate. Chlorine can be purged from irrigation water by aerating it for a day or by passing it through a carbon filter.

It is difficult to state an upper critical concentration for the essential micronutrients in irrigation water. If the water source is applied to high-pH substrate, a high proportion of these nutrients will precipitate and not bother the plant. Tolerable concentrations of iron, manganese, zinc, copper, and borate in water become lower with lower substrate pH. Thus, toxicities are best treated by raising the substrate pH to the highest safe level. A good way to set upper limits for these nutrients is to identify the higher concentrations used in hydroponic solutions. Roots in hydroponic solutions are fully exposed to nutrients 24 hours a day throughout their entire crop period. Typical upper concentrations for these nutrients in hydroponic solutions are 4 ppm iron, 0.5 ppm manganese, 0.3 ppm zinc, 0.2 ppm copper, and 0.5 ppm borate-B (see Table 1). These levels should be safe in irrigation water. How much higher they can be is not clearly known except in the case of boron. A concentration of 1 ppm borate-B is generally toxic.

Iron can pose an additional problem. A concentration of 0.5 ppm, and sometimes lower, can result in the formation of a bluish-bronze sheen as well as brown deposits on plant foliage and brown staining of greenhouse glass or plastic. The bluish-bronze sheen is due to iron bacteria, while the brown stains are iron precipitate. Iron bacteria form a slimy substance that plugs submersible pumps in wells and forms a layer on plant foliage. Iron that has not been incorporated into bacteria turns a rust color upon oxidation and stains anything it contacts. Iron at the bottom of a well is typically in the reduced ferrous form that is soluble and fairly clear in color. When exposed to air in a water or mist system, oxygen causes the ferrous iron to be oxidized to ferric iron. This ferric form quickly turns rusty brown and precipitates as it combines with oxide, carbonate, etc., in the water.

There are three categories of corrective procedures for these iron problems. When water is drawn from ponds, it should be taken from a depth of 18 inches (45 cm) or lower, but not from the bottom of the pond. Iron bacteria reside on the water surface, while iron precipitate is located at the bottom of the pond. Ferrous iron in ponds can be converted to ferric iron that quickly precipitates and settles to the bottom of the pond. The first procedure involves aeration of water. This is accomplished by either passing the water through a fountain or forming waves on the pond surface with a pump. The second method of iron precipitation consists of chemical oxidation with chlorine and can be used for well or pond water. This procedure simultaneously kills the iron bacteria and oxidizes ferrous iron to ferric iron. Chlorine gas or liquid chlorine (16 percent sodium hypochlorite) is injected into water so that it is exposed to a minimum concentration of 0.5 ppm chlorine for one minute or longer. Free chlorine can be checked at the end of the irrigation line with a swimming pool test kit. The presence of pink color in the test indicates a concentration of 1 to 3 ppm chlorine, which is sufficient to kill bacteria. The third procedure involves injection of commercial water treatment formulations. These can include various combinations of a chelating agent to tie up iron, algaecides, bactericides, detergents, and stabilizing agents. Some of these products are designed to remove bacterial deposits and stains from plant foliage. See Bailey et al. (1999) for more instructions.

Fluoride causes injury to some crops. The 0.5 to 1 ppm concentration of fluoride that is added to many water supplies to reduce the incidence of tooth decay is injurious to some foliage plants. Plants that are highly sensitive to fluoride are as follows: *Chlorophytum* (spider plant), *Cordyline terminalis* (mainly the cultivar Baby Doll), and *Dracaena deremensis* (mainly the cultivars Janet Craig and Warneckii). Sensitive plants include *Dracaena fragens* (corn plant), *Maranta leuconeura erythroneura* (red nerve plant), *Maranta leuconeura kerchoviana* (prayer plant), *Spathiphyllum* (most species), *Yucca elephantipes* (spineless yucca), *Ctenanthe oppenheimiana*, *Ctenanthe amabilis*, and *Chamaedorea elegans*. Plants that are probably sensitive are *Chamaedorea sigfritzii*, *Aspidistra eleatior*, *Calathea insignis*, *Calathea makoyana*, *Dracaena marginata*, *Dracaena sanderana*, and *Pleomele thalioides*. It is interesting to note that most of the plants belong to the families Liliaceae and Marantaceae. For these crops, it is best to avoid fluoridated water. When fluoride is a problem, the pH level of root substrate can be raised to reduce the solubility of fluoride.

Lithium appears in some water supplies. At concentrations over 0.5 ppm, some plants can be injured. The symptoms of toxicity are chlorosis of the margins of older leaves, followed by necrosis.

Reverse Osmosis

Reverse osmosis (RO) as it is used in greenhouses refers to a system for cleaning irrigation water. The heart of the system is a filter through which water is forced under pressure. The filter is sufficiently fine to remove ions such as sodium, chloride, bicarbonate, boron, and iron in the water. Because pores in the filter are this small, they are easily plugged by particles or ions in the water that could precipitate on the filter. The filter and its maintenance can be costly if the system is not engineered properly. For this reason, particulate matter is removed prior to the RO filter. Irrigation waters differ vastly in the types of particles and precipitating ions, thus the physical and chemical treatments within the RO system are equally variable. For this reason, it is important to have a water analysis and confer with an RO applicator company prior to deciding on the need for and type of system. It is also advisable to get a second assessment from an alternative firm.

The pretreatment stage is an extremely important part of the system. If algae or pathogens are present, the water is pasteurized by one of several methods such as UV radiation, chlorine, or peroxyacetic acid as discussed later in this chapter under Water Pasteurization. Pretreatment often includes prefiltering of particulate matter such as sand, silt, clay, and ferric (iron) oxide precipitates. Simple in-line 100- to 400-micron filters may be all that is necessary. On the other hand, a multimedia turbidity filter may be required. The multimedia filter consists of a vessel containing a gradient of decreasing particle sizes from bottom upward consisting of materials such as gravel, sand, and garnet and finally topped with coarse anthracite coal. This filter is capable of removing particles down to 5 microns in diameter.

Some dissolved ions in irrigation water can precipitate within the system. Soluble ferric ions coming from the anaerobic depth of a well could oxidize to less soluble ferric ions as they come into contact with air in the system. The ferric ions rapidly precipitate as ferric oxide. This precipitate will plug the RO filter. Likewise, calcium and magnesium can form a scale with carbonate that can also plug the RO filter. During pretreatment, iron can be oxidized and the precipitate removed prior to the RO filter. Antiscaling dispersant chemicals can be added that prevent calcium and magnesium carbonate scale from forming by dispersing these ions in water so they cannot combine into a precipitate. Other potential precipitating ions can be kept apart by similar dispersing agents. Residual chlorine in city water or from chlorine pretreatment to destroy algae and pathogens damages the RO filter. This chlorine is removed prior to the RO filter by the addition of a chemical such as sodium metabisulfite.

Water, following pretreatment, is pumped through the RO filter. There is a significant input of electrical energy consumed by pumps in this step. Contaminants collected on the filters must be cleaned off periodically. This typically varies from annually to every three months depending on the level of contamination in the treated water and the extent of pretreatment. Chemicals used to clean the filters vary depending on the contaminants retained on the filters. For example, it could require a low pH cleaning solution for calcium carbonate scale or high pH for other contaminants. Filters have a life expectancy. They can last up to seven years, with three to five years being common.

Some firms involved in hydroponic production or tissue culture may treat all of the irrigation water used in the operation. Many other firms will treat a percentage of the irrigation water and blend this with untreated water to reduce the level of contaminants in the combined water to the acceptable level. Typically, RO membranes filter out 98 to 99 percent of contaminant ions. Higher-purity membranes are an option that will remove 99.6 percent of ions for specialty situations. Boron presents a special situation. Because of its small diameter, the standard filter removes about 50 to 60 percent of it. This is sufficient for moderate boron contamination levels. For high boron contamination levels, additional treatment of the water is required. An ion exchange resin may be used for this purpose.

Contaminants removed by RO are carried away in waste water. Seventy-five to 90 percent of water introduced into the RO system is cleaned and passes on for irrigation purposes. The remaining contaminant laden water does not present much of a problem. Its contaminant level is low relative to many surface waters. Some communities allow it to be added into streams and rivers. Other firms may run it into a dry well, whereas others will use it in the landscape.

WATERING SYSTEMS

Plant watering options in the greenhouse consist of hand application and automatic systems. Hand watering is exceedingly expensive. It should be restricted to "spot watering"—that is, watering a few select pots or areas that have dried sooner than others. Automatic watering systems have one of the fastest payback schedules of any automation, often less than one year. To illustrate this point, we will first consider the price of hand watering a bench 4 feet (1.22 m) wide by 100 feet (30.5 m) long and then compare this price later to those of four automatic systems for watering a bench of equal size. The price of materials in each system is based on minimum order rates, which maximize the cost. The water main to each bench is not calculated into the cost of each system. The labor of installation is not included either, but is quite minimal. A fair estimation of the time required to install an automatic system on one bench is four hours. Thus, the labor bill will be only about $69 at an hourly rate of $14 plus all benefits. (Benefits include two 15-minute coffee breaks per day, six holidays, five vacation days, five sick-leave days, unemployment insurance, worker's compensation, and social security, for a total of 23.5 percent of the hourly rate.) In all cases, the labor saved will pay for the automatic system in less than one year.

A bench area of 400 ft^2 (37 m^2) with a cut-flower crop requires 200 gallons (750 L) of water at each watering. The frequency of watering can range from once a week in the dark part of the winter to more than three times a week during the summer. Taking a conservative average of two times per week, the bench is watered 104 times in a year. At a water flow rate of 8 gpm (30 L/min), which is common for ¾-inch (19-mm) hose, 25 minutes is required to apply 200 gallons (750 L). For the whole year, 43.3 hours are spent watering one 4-foot-by-100-foot (1.22 m × 30 m) bench. At an hourly rate of $10 plus 23.5 percent in benefits, the cost is $535.

As we get into four other systems later, it will become apparent that this cost is too high. In addition to this deterrent to hand watering, there is a great risk of applying too little water or of waiting too long between waterings. Hand watering requires considerable time and is very boring. It is usually performed by inexperienced (lower-paid) employees, who may be tempted to speed up the job or put it off until another time. Automatic watering is rapid and easy and is performed by a manager, who is less tempted to submit to error. Where hand watering is practiced, a water breaker should be used on the end of the hose (Figure 3). Such a device breaks the force of the water, permitting a higher flow rate without washing the root substrate out of the bench or pot. It also lessens the risk of disrupting the structure of the substrate surface.

Figure 3
The device on the end of the hose is a water breaker. It reduces the force of water striking the root substrate by increasing the cross-sectional area through which it flows. Reduced water pressure minimizes the breakdown of the root substrate structure and the loss of substrate from containers.

Twelve automatic watering systems, six open and six closed, will be discussed next. In an *open system*, water or fertilizer solution is applied to the upper surface of the substrate in a bench or pot, and any excess liquid applied is allowed to drain from the bottom of the container to the environment. By contrast, a *closed system* is one in which water or fertilizer solution is applied either to the bottom or top of the substrate in a manner that allows for the unused liquid to be collected and reused. Closed systems are becoming more popular as one means for combating environmental contamination.

Open Watering Systems

Perimeter Watering for Cut-Flower Crops A perimeter watering system for cut-flower crops consists of a plastic pipe around the perimeter of a bench with nozzles that spray water over the substrate surface below the foliage (Figure 4). Either polyethylene or PVC pipe can be used. PVC pipe has the advantage of being very stationary, whereas polyethylene pipe tends to roll if it is not anchored firmly to the side of the bench. This causes nozzles to rise or fall from proper orientation to the substrate surface.

Nozzles are made of nylon or a hard plastic and are available to put out a spray arc of 180°, 90°, or 45°. For cut flowers other than roses in benches up to 42 inches (107 cm) wide and for rose benches up to 48 inches (122 cm) wide, the 180° nozzles are used and are spaced 30 inches (76 cm) apart. For cut flowers other than roses in benches 48 inches (122 cm) wide, 180° and 90° or 45° nozzles are alternated 20 inches (51 cm) apart. The 90° and 45° nozzles project water farther into a bed than the 180° nozzles do. Regardless of the types of nozzles used, they are staggered across the benches so that each nozzle projects out between two other nozzles on the opposite side. A hole is punched in the polyethylene pipe or drilled in the PVC pipe, and the threaded nozzle is then turned in with a wrench.

Perimeter watering systems with 180° nozzles require one water valve for benches up to 100 feet (30.5 m) in length. For benches over 100 feet (30.5 m) and

Figure 4
A perimeter watering system for cut-flower production in benches or beds. A polyethylene or PVC pipe carries water around the perimeter of the bed. Plastic or nylon nozzles screwed into the perimeter pipe spray water into the bed below the foliage.

up to 200 feet (61.0 m), a water main should be brought to the middle of a bench, and ¾-inch (19-mm) water valves should be installed on either side, one to service each half of the bench. This system applies 1/10 gpm of water per foot (1.25 L/min/m) of pipe. Where 180° and 90° or 45° nozzles are alternated, the length of a bench serviced by one water valve should not exceed 75 feet (23 m).

The cost of this perimeter watering system for a 4-foot-by-100-foot (1.22 m × 30 m) bench with alternating 180° and 90° nozzles is $112.73. This includes PVC pipe and two water valves. The cost breakdown is as follows:

2	¾-in. valves	$17.40
15	¾-in. PVC pipe fittings	7.50
210 ft	¾-in. PVC pipe	44.63
120	nozzles	43.20
		$112.73

Turbulent Twin-Wall for Cut-Flower Crops The Turbulent Twin-Wall hose system (Figure 5) is popular because long lengths of bench can be handled from a single header (over 200 ft, 61 m) and because this hose equalizes water pressure along the length of sloping benches (slopes up to 2 percent). The perimeter water system does not work well on sloping beds. Turbulent Twin-Wall hose, when flat in the roll, is 0.75 inch (1.9 cm) wide. It is made from black polyethylene plastic of thicknesses from 4 to 15 mil (0.10 to 0.38 mm), with most used for field crop application. For cut-flower application, the 10-mil (0.025-mm) thickness is most often used. Water outlet spacings are available at 2- to 24-inch (5- to 61-cm) intervals, with 2- or 4-inch (5- or 10-cm) intervals most popular for cut flowers. Water flow rates for the 2- and 4-inch-spacing tubes are 1.5 and 1.0 gpm per 100 feet of tube (5.7 and 3.8 L/min per 30.5 m), respectively. The recommended pressure for this system is 10 psi (70 kPa).

Turbulent Twin-Wall tubes are placed on the surface of the substrate from end to end in the bench. Individual hoses are spaced 8 inches (20 cm) across the bench. A cap is sold to seal the distant end of the hose. The inlet end of the hose is slipped

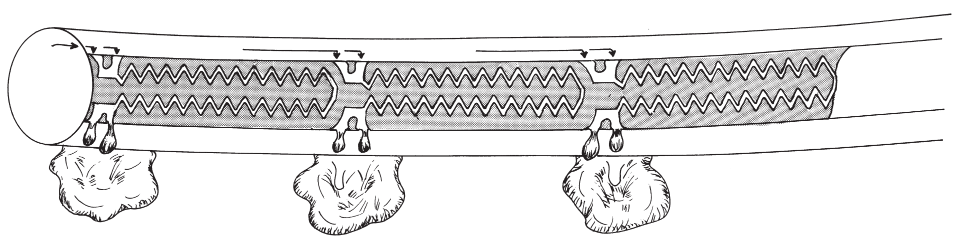


Figure 5
A cutaway view of a Turbulent Twin-Wall hose. Water enters the large tube and quickly runs the length of the bed. Water then moves through pores in the upper wall of the large tube into the small turbulent channel. Water in the turbulent channel moves along a serrated path that produces a turbulent flow. After flowing a short distance, water turns 180° and flows back to a point opposite to where it entered the turbulent channel. At this point, water drips out onto the root substrate. The turbulent flow helps prevent blockage from debris.

over a special pipe fitting, which is an integral part of a manifold designed to deliver water from a 0.75- or 0.5-inch (19- or 13-mm) supply line to each of the hoses in a given bench.

A Turbulent Twin-Wall hose system for a 4-foot-by-100-foot (1.22 m × 30 m) bench making use of six lengths of 10-mil (0.025-mm) hose with outlets every 2 inches (5 cm) and a ¾-inch (19-mm) plastic header with a valve costs $46.85. The cost breakdown is as follows:

600 ft	10-mil Twin-Wall drip hose	$21.50
1	Manifold	9.00
6	end closers	3.50
4	¾-in. PVC pipe fittings	2.00
10 ft	¾-in. PVC pipe	2.15
1	¾-in. valve	8.70
		$46.85

Tube Watering for Container Plants Tube watering has been the standard for automatic watering of potted plants. It is an open system. Water is carried to each pot by a thin polyethylene microtube (Figure 6). The tube is available in various inside diameters from different sources, including 0.036, 0.045, 0.050, 0.060, 0.075, and 0.076 inch (0.9, 1.1, 1.3, 1.5, 1.9, and 1.9 mm). The number of pots that can be watered from a single ¾-inch (19-mm) water main depends upon this inside diameter. The 0.036-, 0.050-, 0.060-, and 0.076-inch microtubes can handle 1,600, 900, 700, and 400 pots, respectively. The narrower-diameter microtubes are used for small pots, where the density is high in the bench and the water requirement per pot is low. This minimizes the expense of laying larger water lines. The 0.060-inch (1.5-mm) size is popular for 6-inch (15-cm) pots, and the 0.075- or 0.076-inch (1.9-mm) size is used for 2- to 5-gallon (7.5- to 18-L) containers for items such as poinsettia stock plants and foliage plants.

If the end of the microtube rests on the root substrate surface, there must be an emitter at its end in the pot. The weight of the emitter prevents it from being thrown from the pot when the water is turned on. The emitter further serves the purpose of breaking the force of water so that it does not dig a hole in the substrate. Usually, there is a baffle in the emitter that breaks the flow of water and permits it to trickle out. The emitter also prevents light substrate components from being drawn into the microtube and plugging it. When the water is turned off, suction often occurs, which

Figure 6
The tube system is used for automatic watering of potted plants. Water is carried the length of the bench in a plastic pipe generally located down the center. Each pot is connected to the central pipe by a separate small polyethylene tube. A weight is attached to the end of the tube in each pot to anchor the tube, break the force of water before it reaches the root substrate, and prevent substrate from being drawn into the tube when the water is shut off.

can draw particles into the microtube. Various types of emitters are sold. Most emitters are conical in shape and are made of noncorrosive metal. Alternative tubes are sold that do not have an emitter at the end. These have a short stake at the end that is about 3 to 4 inches (7.6 to 10.2 cm) long. The stake is inserted into the substrate in such a way that it holds the tube nearly horizontal above the substrate.

Some emitters are designed to be turned off when the pot is removed. This is accomplished in various ways, such as by inserting a rod in the opening or by simply pushing the emitter back against the microtube. The on–off-type emitters are particularly handy for overhead hanging baskets where a free stream of water could land on personnel or other plants where a basket has been removed.

When a coarse substrate is used in large pots, 2 gallon (7.5 L) and larger, it becomes difficult to wet all of the substrate in the pot. Water slowly flowing from a tube tends to channel down through the substrate in a conical shape, leaving much of the surface dry. In such situations, a spray-type water emitter can be used (Figure 7). Water is delivered at a greater flow rate and is sprayed out over the surface of the pot. This works well for plants that have little foliage at their base. Drip-ring emitters also serve the purpose of wetting multiple locations on the surface of a large pot (Figure 8). In this product, a polyethylene tubular ring is attached to the end of a microtube. Rings can vary in diameter from 4 to 10 inches (10 to 25 cm) to meet the requirements of various sizes of pots serviced. The tube comprising the ring has several pin-sized holes in it for water to exit.

Generally, water is provided along the bench by a ¾-inch (19-mm) polyethylene or PVC supply pipe. The latter lies straighter. Microtubes to each pot may be connected directly into holes punched or drilled into the supply pipe, which is usually run down the center of the bench from end to end. The microtube can be pushed into the hole directly, or a brass insert can be pressed into the hole first and the microtube

Figure 7
A Spray Tube water distributor. This method of water distribution is used in larger pots and in root substrate that is very porous, such as that used for orchids. Broad distribution of water over the surface of the pot reduces the problem of water channeling down through the root substrate.

Figure 8
A Dribble Ring water emitter for delivering water to large pots. Water is emitted from a series of small holes on the underside of the ring. This wets more of the substrate surface in a large pot than would be possible from a single emitting point.

inserted into it. The brass insert facilitates subsequent removal and replacement of microtubes. Plugs are available to fill holes left by removed microtubes. Microtube watering can be used for hanging baskets as well (Figure 9). A plastic water line is run along the length of a row of baskets. A separate thin polyethylene microtube connects each pot to the water line. Some growers install a galvanized water pipe and hang pots directly from it.

Each microtube must be the same length because the flow rate depends upon the length of the microtube. To cut down on the quantity of tubing, particularly in benches with numerous small pots, manifold systems are sold. Either the manifold is attached directly to the water-supply pipe on the bench, or it is supplied water through a large microtube from the water pipe. The manifold then supplies water to 8, 10, 20, or more microtubes, each running to an individual pot.

Figure 9
An automatic tube watering system for hanging baskets. Each pot is connected to the plastic water line above by a thin polyethylene tube.

Benches or beds that have a slope along their length create special problems. The water flow rate from tubes at the lower end of the bench is greater than at the higher end. When the pot at the low end is watered properly, the one at the high end is underwatered. Conversely, if the pot at the high end is watered properly, the pot at the low end is overwatered and leached. A second problem occurs when water is turned off and the residual water in the system drains out at the lower end of the bed. These problems can be solved with pressure-compensating emitters. These emitters contain a device such as a diaphragm that requires a minimum pressure to open, commonly 5 to 10 psi (35 to 70 kPa). Once opened, the flow rate remains constant, even at pressures up to 60 psi (414 kPa) in some models. An emitter is installed in the supply pipe at the beginning of each microtube. An added benefit from the pressure-compensating emitters is that the length of the microtube can be different for each row of pots across a bench without affecting the water output.

A microtube system of potted-plant watering for a 4-foot-by-100-foot (1.22 m × 30 m) bench costs $201.95. This includes a manual valve, a ¾-inch (19-mm) PVC water main along the length of the bench in the center, and 400 24-inch (61-cm) tubes with weights and brass inserts where each is connected directly to the water main. The cost breakdown is as follows:

100 ft	¾-inch PVC pipe	$21.25
400	24-in. 0.060 ID microtubes with weights	162.00
400	brass inserts	7.00
1	¾-in. valve	8.70
6	¾-in. PVC pipe fittings	3.00
		$201.95

Mat Watering for Container Plants Mat (capillary) watering offers a very good alternative for potted-plant growers who have different pot sizes in a given bench during the year (Figure 10). The tube system would require constant removal and addition of tubes to suit the changing pot densities from crop to crop. Mat watering is also beneficial to growers of small potted plants, where the number of tubes in a tube system would be cumbersome and it is best not to wet the foliage, as in a sprinkler system.

The mat watering system uses a fabric mat from 3⁄16 to ½ inch (5 to 13 mm) thick, which is kept constantly moist with water or fertilizer solution. Pots on the mat take up water or nutrient solution by capillarity through holes in the bottoms of the pots. Pots of any size can be placed on the mat at one time. No adjustment is needed

Figure 10
A mat (capillary) watering system for potted-plant crops. Water is applied to the mat several times a day through tubes such as Turbulent Twin-Wall that are spaced 2 feet (61 cm) apart. Water moves by capillarity from the mat into the root substrate in the pot and maintains a constant moisture content in the pot at all times. Fertilizer solution may likewise be applied through this system. Various types of mats are available.

for shifting pot sizes. Mat watering is an old system based on subirrigation. Years ago, sand was placed in a bench and kept moist. Pots were set in the sand, and water continuously rose by capillarity into the root substrate in the pots. This system maintains a constant moisture content in the pot and greatly reduces the labor of watering.

A number of mats are available, but to use them, benches should be level. A polyethylene sheet is placed on the level bottom of each bench. It is preferable, but not necessary, that it be black to reduce light in the mat and, thus, algal growth. A sheet 2 mil (0.05 mm) thick is sufficient since its only role is to serve as a water barrier. The mat is placed on the polyethylene sheet. Care should be taken to keep the edges of the mat level with the plane of the mat. If they are lower, they act as a wick, drawing water from the mat and dripping it to the ground. Mats can be cut with scissors, and more than one piece can be used to line a bench by butting the edges together. Various types of mats are used. Some are composed of reprocessed cloth, while others are composed of virgin synthetic fiber.

Algal buildup is a problem on all mats, but particularly those supplied with fertilizer solution. Algae is unsightly on the mat and on pots, it harbors insects, and it emits a foul odor upon drying. To prevent most algal growth, black perforated polyethylene (up to 14,000 perforations/ft^2, 150,000 perforations/m^2) is available alone or as a component of some mats. The perforated polyethylene lies on the mat, and the pots rest on the plastic. This film restricts light from the mat, which blocks algal growth, and is easy to wash. Roots do not penetrate the polyethylene film. The perforated film also reduces humidity within the plant canopy because its surface is dry except during the time when water is delivered to it.

Watering tubes such as Turbulent Twin-Wall can be used to deliver water to the mat. These tubes run the length of the bench and are placed 2 feet (61 cm) apart. Alternatively, suppliers of mats offer a water delivery system kit that includes the header, tubes, and end closures for the tubes. The mat should be kept moist at all times. Often, water or fertilizer application is required several times per day. A time-clock can be set to activate a solenoid water valve. Overwatering is not a problem because excess water simply drips from the edge of the mat to the floor. This is an open system because excess fluid is delivered to the mat and ends up in the environment.

Disease organisms can build up on mats. After being used for a crop in which disease has appeared, the mat should be sterilized with a disinfectant such as Agribrom, ZeroTol, or bleach (5.25 percent active ingredient). A 1:9 bleach-to-water solution can be sprinkled on, allowed to sit for 5 to 10 minutes, and then hosed off. Some mats can withstand steaming, which kills algae and pathogens.

Nutrient solutions applied to mats must be lower in concentration than those that would be applied to the top of the pot in a tube watering system. A good starting point is half the concentration used in a tube watering system. The more common problem encountered is a buildup of salts in the substrate. Water utilization generally exceeds nutrient uptake; thus, fertilizer salts concentrate, particularly at the top of the pot. This situation should be monitored through periodic soluble-salt tests. When it occurs, pots should be heavily watered one time from the top to leach the substrate.

Mats, drip tubes, and fittings can be purchased separately from greenhouse supply companies. Alternatively, a complete system, including mat, film plastic, drip tubes, and connectors, can be purchased for a 4-foot-by-100-foot (1.22 m × 30 m) bench for $475.00.

Overhead Sprinklers for Container Plants While the foliage on the majority of crops should be kept dry for disease-control purposes, a few crops do tolerate wet foliage. These few crops can most easily and cheaply be irrigated from overhead. Bedding plants, azalea liners, and some foliage plants are crops commonly watered from overhead.

A pipe is installed along the middle of a bed. Riser pipes are installed periodically to a height well above the final height of the crop. A total height of 2 feet (0.6 m) is sufficient for bedding-plant flats and 6 feet (1.8 m) for cut flowers. A nozzle is installed at the top of each riser. Nozzles vary from those that throw a 360° pattern continuously to types that rotate around a 360° circle. Nozzles with a 180° arc can be obtained for the ends of beds. The spray diameter of various nozzles can range up to 36 feet (11 m) or more. Dripless overhead sprinkler systems are also available.

Trays are sometimes placed under pots to collect water that would otherwise land on the ground between pots and be wasted (Figure 11). Each tray is square and meets the adjacent tray. In this way, nearly all water is intercepted. Each tray has a depression to accommodate the pot and is then angled upward from the pot toward

Figure 11
A plastic tray designed for collecting water applied by overhead sprinklers that would otherwise land between pots.

the tray perimeter. Drain holes are located in the tray, a short distance out from the pot, in the event that excessive water is inadvertently applied. Without the holes, the trays could hold enough unwanted water to keep the base of the soil ball excessively wet for a day or more. Water held in the reservoir below the holes is generally absorbed by substrate in the pot within an hour or two. The object is to turn off the sprinklers before water rises above the drain holes.

Boom Watering for Container Plants Boom waterers can function either as an open or as a closed system, and are used most often for the production of seedlings grown in plug trays. Plug trays are plastic trays that have width and length dimensions of approximately 12 by 24 inches (30 × 61 cm) and a depth of 0.5 to 1.5 inches (13 to 38 mm), and that contain from about 100 to 800 cells. Each seedling grows in its own individual cell. Watering precision is extremely important over the two- to eight-week production time of plug seedlings.

A boom watering system generally consists of a water-pipe boom that extends from one side of a greenhouse bay to the other (Figure 12). The pipe is fitted with nozzles that can spray either water or fertilizer solution down onto the crop. The boom is attached at its center point to a carriage that rides along rails, often suspended above the center walk of the greenhouse bay. In this way, the boom can pass from one end of the bay to the other. The boom is propelled by an electric motor. The quantity of water delivered per unit area of plants is adjusted by the speed at which the boom travels.

Often, each side of the water boom, right or left of its center point, is under separate control. In this way, one side of the greenhouse bay may be watered while the other side is not. In addition, the water boom can be turned on and off automatically as it passes over different blocks of plants on its way down the bay.

Most growers water when the crop approaches stress. They apply a sufficient quantity of water or fertilizer to cause 10 to 15 percent of the applied fluid to pass out the bottom of the trays. This is an open system. A few growers practice what is commonly called *zero-leach watering*. They water much more frequently during the day than the former group. Each time, a small quantity of water is applied by a fast-moving boom in order to replace only the water that has been utilized by the plants or has evaporated. No water leaches from the trays. This is a closed system. In the closed system, the concentration of fertilizer must be reduced to approximately half the concentration of the open system. While the fate of fertilizer in the open system can be leaching and plant uptake, only uptake occurs in the closed system.

Figure 12
A boom watering machine applying water to a crop of plug seedlings. The machine is contained within a carriage that travels along two overhead rails. Water may be automatically turned on or off in the right and left booms independently. Thus, individual crops may be skipped or watered as the boom travels the length of the greenhouse.

Closed Watering Systems

The next six watering systems are closed where excess fluid applied is recirculated. Fluid is delivered to the base of the container in the first five systems and to the top of the substrate in the last system. The first four systems are used for container plants in standard root substrates where the plant with its substrate is marketed. The last two systems are nutriculture systems used for cut flowers and vegetable fruit production because they lack a root substrate that can be marketed with the product. Nutriculture involves the culture of plants in an inert substrate such as water (hydroponics), gravel (gravelculture), sand (sandculture), rock wool, or air (aeroponics). An inert substrate is one that neither contributes nor alters the form of plant nutrients. Soil, peat moss, and bark are examples of noninert substrates that are both biologically and chemically active. These substrates contribute nutrients that are held on their negative exchange sites and others that are released during substrate weathering and decomposition. In addition, these substrates are handled in a manner such that large populations of microorganisms develop in them, which can change the form of applied nutrients (e.g., convert ammonium to nitrate). Inert substrates, such as rock wool or water in the nutrient film technique (NFT) system, afford much greater control over plant nutrition than is possible in today's noninert substrates.

Ebb-and-Flood Systems for Container Plants The ebb-and-flood system is basically a closed subirrigation system for potted plants and bedding plants (Figure 13). Pots or flats are grown in a level, watertight bench. Nutrient solution is pumped into the bench during a period of 10 minutes or less to a depth of about 0.75 to 1 inch (1.9 to 2.5 cm) and is held there for 10 to 15 minutes, or long enough for the solution to rise to the top of the root substrate in each pot by capillarity. The solution is then allowed to drain back to a storage tank, over a period of 10 minutes or less,

Figure 13
An ebb-and-flood bench for potted- and bedding-plant production. Nutrient solution enters through the plastic pipe in the foreground. Channels molded into the bottom of the watertight bench ensure rapid and even delivery of nutrient solution to the base of each pot. Solution is held at a depth of 0.75 to 1 inch (1.9 to 2.5 cm) for 10 to 15 minutes to allow time for it to move up through the substrate by capillarity. Then a valve below the bench (not shown) is opened and the solution drains back to a holding tank to be used again the next time plants require water.

where it is held until the next bench requires watering. Fertilizer is applied at each watering. The nutrient solution is tested, altered as required, and recycled for months. This closed system is for container-grown plants, and it eliminates nearly all effluent from the greenhouse. It is not a nutriculture (hydroponic) system in that conventional substrates and containers are used. Also, it is not necessary to provide all of the essential nutrients in the fertilizer solution as in nutriculture systems such as NFT and rock wool, which are discussed later in this section. Calcium and magnesium can be provided as dolomitic limestone, phosphorus as superphosphate, and micronutrients as a commercial mixture—all of which are mixed into the substrate prior to planting.

Benches are prefabricated primarily from plastic or fiberglass components in various widths of 4 to 6.5 feet (1.2 to 2.0 m) and a customary length of 39 inches (1 m). Bench components are cemented together to form the desired bench length. Ebb-and-flood benches can work well as movable (rolling) benches. The floor of the bench has channels molded into it to conduct nutrient solution to all parts of the bench before reaching the bottom of the pots and also to aid in drainage from the bench. The bench must be absolutely level for uniformity of watering and for complete emptying of the bench after watering. Many designs have leveling screws on the bench legs. Below the bench is a solution holding tank. The tank is covered to exclude dust and light and thus prevent algal growth. During watering, nutrient solution is pumped from this tank into the bench through a hole in the floor of the bench. After watering, solution returns to the tank through the same hole by way of a pressure-sensitive tee valve. A filter is built into the return line to remove debris such as plant tissue and substrate.

Pots with holes that extend up the sides work well. Pots with holes on the bottom work best only if there is a ridge on the bottom of the pot to elevate it off the bench floor. Situating the pot drainage hole off the floor of the bench permits thorough drainage of water from the pot when the bench is emptied. It also separates the root substrate in the pots from slight puddles that could remain in the bottom of the bench after emptying.

Generally, ebb-and-flood fertilizer concentrations are half the level used for the same crop when it is fertilized from the top of the pot, as in a tube watering system. The optimum concentration can vary. When a substrate is used that does not fully absorb water during subirrigation, higher concentrations of fertilizer are needed to compensate. Incomplete water absorption can be caused by using a substrate that is too coarse or by allowing it to dry too much between watering, so that it repels water. The use of a fine-textured substrate reduces the former problem, while the use of a wetting agent in the substrate reduces the latter problem.

During subirrigation, water and fertilizer move up through the pot to the top of the substrate, where water evaporates and leaves fertilizer behind to accumulate as salt. The accumulating salt levels are generally not a problem when the proper substrate is selected and thus permits the use of low fertilizer concentrations. If salts build up at the top of the pot, it is necessary to leach them down through the profile of the pot and out the bottom. This must be done thoroughly; otherwise, salts will be moved down into the root zone, where injury can occur. Leaching is accomplished by applying a large volume of water to the top of the pots. The resulting effluent is not collected in the holding tank but discarded.

Several zones of ebb-and-flood benches will often be fertilized in succession with the same solution. After a series of zones is fertilized, or at least once per week, the nutrient solution should be tested for pH and salt (EC) levels. If these levels have deviated, adjustments should be made. Generally, the fertilizer solution does not change. After entering the pots by capillarity, little (if any) fertilizer solution returns to the bench; thus, changes usually do not occur. Losses in volume of fertilizer solution returning to the holding tank are generally made up by adding more of the original fertilizer formulation through a fertilizer proportioner system. Some evaporation of water can occur from the fertilizer solution when it is in the benches. This will raise the salt concentration, which is determined by the EC meter. When this happens, additional water is added to lower the concentration to the desired level.

In more sophisticated systems, the solution is automatically tested in the holding tank after each zone is watered. Equipment commercially available to growers will automatically sample the fertilizer solution, analyze it, and make additions, including an acid if the pH is too high, a base such as potassium hydroxide if the pH is too low, fertilizer concentrates if the salt level is too low, and water if the salt level is too high.

Disease pathogens would appear to be a very formidable threat to an ebb-and-flood system, where solution contacting one pot will ultimately contact all other pots over and over for weeks to come. Years of experience have demonstrated that disease is not a problem with this system. However, one would be well advised to take preventive measures. Benches should be cleaned and sterilized between crops. Chlorine bleaches, ZeroTol (peroxyacetic acid), or hospital disinfectants work well. The disinfectant should be rinsed from the bench, plumbing, and tank after use. Care should be taken to use disease-free plants. During the crop production time, plant debris and any diseased plants should be removed from benches.

Fungicidal drenches can be applied to the top of pots in ebb-and-flood benches in the conventional manner. Growers will generally not allow the drench effluent from the bottom of the pots to return to the fertilizer holding tank, but rather will reroute it to waste. Although the feasibility of applying drench fungicides through subirrigation in the fertilizer solution has been demonstrated, this practice does not have label clearance. For this reason, it cannot be done. More research should be directed toward this objective because it would appear that lesser amounts of fungicide could ultimately be used. Also, this would be an excellent way of nearly eliminating the flow of fungicide to the environment. It would be contained in a closed system, where extensive degradation could occur. Should disease become a problem in an ebb-and-flood system, a grower could use one of the nine in-line pasteurization systems described later in this chapter under "Water Pasteurization."

The ebb-and-flood system is expensive, costing about \$7.50/ft^2 (\$80/m^2) of bench for a 1-acre (0.4-ha) installation. This cost includes all materials (benches, holding tank, pump, and plumbing) but not the cost of installation. Nevertheless, growers who have adopted this system find that it pays for itself in the following four ways:

1. Fertilizer effluent can nearly be eliminated, since the ebb-and-flood system is closed.
2. Less water and fertilizer are used. The exact amount saved depends on the amount that would normally be lost through leaching. For most greenhouses, this would probably be 30 to 40 percent.
3. The labor input is reduced because watering is automatically handled, and there is no need to install or remove microtubes before and after each crop.
4. It is easy to change from one pot size to another between crops. In a tube watering system, it would be necessary to change the density of tubes. However, it is important that all pots in a zone require the same watering frequency. Thus, the same species of plant, age of plant, and pot size are situated in a zone at the same time.

The disadvantage that goes along with an ebb-and-flood system is the high relative humidity (RH) that can build up in the canopy of plants. This situation can lead to condensation and ultimately to foliar diseases. Humidity rises because air is

Figure 14
A trough culture system for potted-plant production. Each trough is inclined so that nutrient solution pumped to the top flows down around the base of each pot in the trough and finally spills from the lower end into a collection gutter. The gutter returns the solution to a holding tank. The nutrient solution is recirculated sufficiently long to allow some of it to move throughout the substrate in each pot by capillarity. The unused solution is stored in a holding tank to be used the next time plants require water.
(Photo courtesy of D. A. Bailey, Dept. of Horticulture, Univ. of Georgia, Athens, GA 30602–7273.)

unable to circulate through the floor of the bench. To combat this problem, growers frequently place heating beneath their benches, which helps to dry the air in the plant canopy and sets up air currents during the heating season. It is likewise important to have an effective air movement system that will replace the moist air in the plant canopy resulting from plant transpiration with drier air. A final measure that can be taken is to apply fertilizer solution early in the day so that drying can occur long before the cooler hours of the evening.

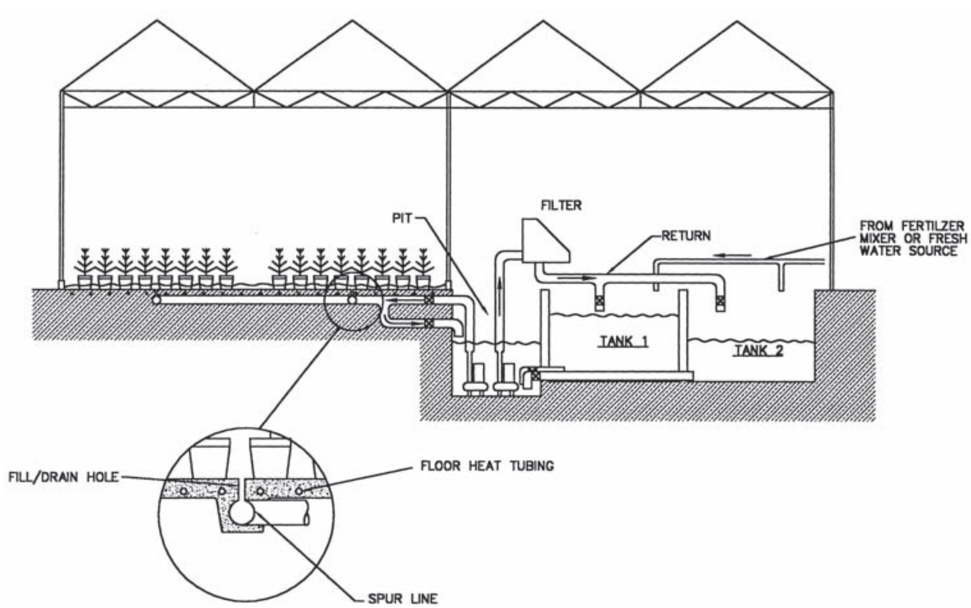
Trough Culture for Container Plants Trough culture is a variation of ebb-and-flood culture that is used for growing potted plants (Figure 14). Single rows of plants are grown in watertight troughs. Several troughs parallel to one another, with spaces between the troughs, constitute the equivalent of a bench. Troughs are sloped from end to end at a decline of 0.25 to 0.5 inch per 10 feet (2 to 4 mm/1 m). Nutrient solution is pumped to the high end, where it slowly trickles down by gravity to supply each pot along the way. At the low end of each trough, the solution drops into a single gutter, perpendicular to the troughs, which returns it to the holding tank. The length of time the solution is left recirculating is determined by how long it takes the solution to rise by capillarity to the top of the substrate in the pot. The same fertilizer solutions and methods of handling are used in trough culture as are used in ebb-and-flood systems.

The advantage of the trough over the ebb-and-flood system is the air circulation that occurs through the plant canopy. The space between troughs allows natural convection currents to move up through the bench platform and the plants. This results in drier plants and consequently less foliar disease.

Flood Floor System for Container Plants Flood floors work well for pot crops that have a low labor input once they are placed in the greenhouse. Bedding plants are grown to a lesser degree on flood floors. These crops respond well to a modification of the closed ebb-and-flood recirculating system. The floor is paved, with a lip around the edge and a drain in the center so that it can be flooded and drained in the same fashion as an ebb-and-flood bench (Figures 15 and 16). The advantages of any

Figure 15
Poinsettias growing in a flood floor system. Nutrient solution can be seen bubbling up from a line of holes in the floor along the center of the greenhouse bay. Solution enters the bottom of the pots and is drawn throughout the substrate by capillarity. Then the excess fluid returns through these same holes in the floor to a holding tank from where it can be reused.
(Photo courtesy of Green Link, LLC., P.O. Box 2118, Asheville, NC 28802–2118, Web: greenlink@msn.com.)

Figure 16
A schematic design of the mechanics for a flood floor system.
(Photo courtesy of Green Link, LLC., P.O. Box 2118, Asheville, NC 28802–2118, Web: greenlink@msn.com.)



floor system of production are the possibility of utilizing a greater portion of the floor for production and the ease of moving materials in and out by motorized equipment. The disadvantage of this system is the difficulty laborers have in bending over to work on crops. The flood floor system costs approximately \$10.00/ft^2 (\$107.60/m^2) of floor for labor and all materials, including the floor, plumbing, tanks, and controls.

Since the floor is much larger than a bench and it is difficult to construct an intricate pattern of channels in the floor for drainage, the floor is usually sloped from either side to a drain channel in the center. Slopes of 0.25 to 0.75 inch per 10 feet (2 to 6 mm/m) have been used. Individual zones should not be made larger than can be flooded in 10 minutes, or preferably in five minutes. Without channels in the floor, the pots at the highest point of the floor are the last to begin taking up fertilizer solution and the first to lose contact with the solution. The width of the greenhouse bay constitutes the width of the ebb-and-flood zone. The drain is at the center point of the bay and runs along the length of the greenhouse.

Hot-water heat pipes are installed in the floor of most ebb-and-flood systems to dry the floor rapidly after watering. This lowers humidity in the plant canopy and prevents condensation on the foliage. Some precautions must be taken for bedding plants. A heated concrete floor is slow to cool. Heat application in the concrete may have to be restricted after the first few weeks of growth to ensure that the floor cools before the heat of day occurs. If not, plants will grow too tall.

Float System for Tobacco and Some Vegetable Seedlings In the United States during 2009, 2.3 billion tobacco seedlings were produced to support 354,000 acres of field production. Ninety-five percent of these seedlings were produced in greenhouses on the float system (Figure 17).

Seeds are sown in polystyrene trays that contain from 200 to 392 cells. The most common trays for tobacco contain 200 cells. The trays are floated on pools of nutrient solution. Nutrient solution is absorbed by the substrate in each cell through a hole at the base of the cell. A constant moisture content is thereby established in the substrate. Trays are approximately 13 inches (33 cm) wide and 26 inches (66 cm) long. The pools are on the floor of the greenhouse and can consist of either a concrete floor with a concrete curb around its perimeter or a level earthen floor surrounded by a 2-inch-by-6-inch (5 cm × 15 cm) wooden frame, all of which is lined with 6-mil (0.15-mm) black polyethylene.

Figure 17
A float system for growing tobacco seedlings. Note the fertilizer solution ponds on the floor of either side of the greenhouse and the polystyrene trays of tobacco plants being removed for field planting.
(From W. D. Smith, Dept. of Crop Science, North Carolina State University, Raleigh, NC 27695–7620.)

The pool is filled with water to a depth of about 4 inches (10 cm), and sufficient fertilizer, typically 20-10-20 ($N-P_2O_5-K_2O$), is added to the water to establish a nitrogen concentration of 150 ppm. Trays are filled with soilless substrate, preferably without nitrogen, phosphorus, or potassium. Seeds are sown in the trays, then floated on the pool of solution. Some growers start the system with water only and add the fertilizer at seven days, when seeds have germinated. About four weeks after sowing, when the solution level has fallen to the point where an addition is required, water is added to the existing solution to restore the original level. At this time, sufficient fertilizer is added to increase the concentration of the total volume of solution by 100 ppm nitrogen. After this date, no further fertilizer additions are made. However, about once per week, water is added to maintain the original level. The total cropping time is typically 60 to 65 days.

NFT System for Cut Flowers and Vegetables The first nutriculture system to gain wide acceptance in greenhouse culture and to prove itself economically efficient was NFT. NFT is a form of hydroponics in which plants are grown in narrow, sloped channels (Figure 18). A thin film of recirculating nutrient solu-

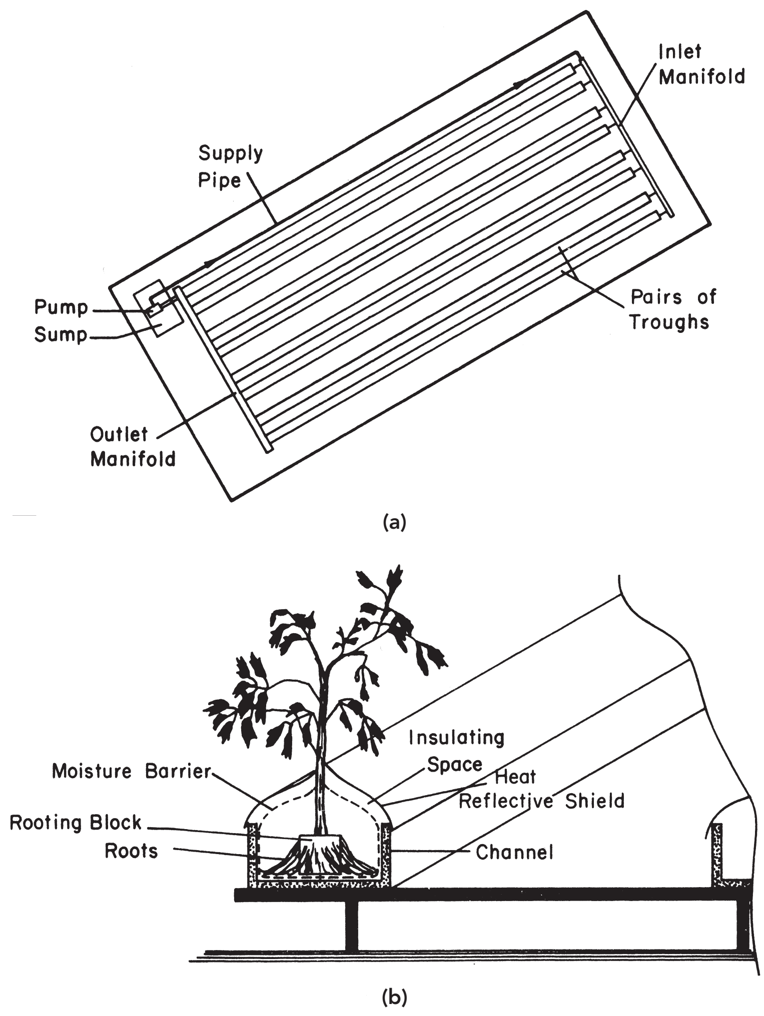


Figure 18

(a) The floor plan of one possible NFT system. Nutrient solution is pumped from the sump tank to an inlet manifold at the upper end of the NFT troughs. From there, the solution flows by gravity to an outlet manifold at the lower end of the troughs and finally back to the sump.
(b) A cross-sectional view of a trough showing plant placement and the arrangement of the film plastic moisture barrier and thermal barrier. The outer thermal barrier is optional.

tion flows through the roots in the channels. With NFT, unlike the classical hydroponic systems, aeration is not a problem because the nutrient solution is confined to a depth of ⅛ inch (3 mm). Commercial installations of NFT began in the early 1970s. Today, the majority of greenhouse lettuce is grown in the NFT system.

The most extensive development of NFT occurred in The Netherlands partly because of pasteurization problems. Greenhouses in The Netherlands have traditionally been heated with hot water, which is inappropriate for pasteurization; thus, methyl bromide was very popular. In the sandy soils of the concentrated greenhouse region known as the Westland, methyl bromide readily permeated the soil as well as the plastic walls of water pipes lying within these soils. Contaminated drinking water prompted a restriction in the dosage rate of methyl bromide and threatened its future use altogether. Without steam to fall back on, NFT became very attractive.

Cooper (1979) thoroughly outlined the NFT system in his book. The system begins with a channel, free of valleys and peaks, laid out on a 1 percent slope. The channel must be level across its width to ensure that the whole floor will be covered with nutrient solution. Such channels may be molded into a concrete floor or situated on raised platforms. For crops such as tomato and cucumber, a channel is typically about 9 inches (23 cm) wide and 2 inches (5 cm) high. It may be constructed from wood, plastic, metal, or concrete. Lettuce, chrysanthemum, snapdragon, and other cut flowers are more often grown in a bed fashioned from several closely spaced parallel channels (see Figure 18).

The channel needs to be watertight. Channels constructed from leaky materials are lined with a film plastic sufficiently large to cover the top of each channel, including the plant-propagation blocks. The film plastic should be 5 mil (0.13 mm) thick or thicker; otherwise, the plastic will adhere to the roots, which will cause it to ripple along the bottom of the channel. This, in turn, will force the solution to puddle in spots and to flow around roots in other places. Watertight channels, while not requiring a lining, do need a covering. This may be formed from a solid material or a film plastic.

Channel coverings serve to (1) prevent water loss through evaporation; (2) restrict light entry to prevent algal growth, which would remove nutrients and plug the system; and (3) help control root temperature. The outer surface of the covering should be white or silver to reduce heat absorption and to reflect light to the plants for better growth. Air inside a black channel would become hot enough to burn roots on warm, bright days. White plastic does not sufficiently restrict light; therefore, film plastic is sold with one (inner) surface black and the other surface white. In regions of temperature extremes, an insulated channel covering may be constructed by using two film plastic coverings with a dead-air space between them.

The nutrient solution is handled in a closed recirculating system. A tank, usually built into the floor, collects solution by gravity flow from the ends of the channels. Solution is pumped from the tank to a header pipe that runs perpendicular to the upper ends of the channels. Small tubes running from the header pipe supply each channel. The flow rate should be sufficient to maintain a nutrient film thickness of not more than ⅛ inch (3 mm) over the entire bottom surface of the channel. Greater depth will exclude oxygen from the roots. A flow rate of about 0.5 gpm (2 L/min) per channel is required. In some systems, the solution is constantly recirculated. Often in the United States, the solution is circulated for 10 minutes out of every 15 minutes to increase aeration of the roots. A considerable volume of water will be lost through transpiration, necessitating continual additions to the holding tank. This can be automatically handled by installing a float valve on a water inlet line in the tank.

Cooper (1979) suggests the following nutrient concentrations given in parts per million concentrations as ideal for NFT culture: N (200), P (60), K (300), Ca (170), Mg (50), S (67), Fe (12), Mn (2), Zn (0.1), Cu (0.1), B (0.3), and Mo (0.2). He has grown over 50 species of ornamental, fruit, and vegetable plants in this solution for three continuous years without problems. It is not necessary for a firm to formulate its own nutrient solution. Various companies sell NFT fertilizers. Generally, they come in two or three packages that must be added separately to the tank to prevent precipitation.

The solution is used for the duration of the crop before replacement. It is necessary to test the solution for pH and EC (soluble-salt) levels at least daily. The pH level should remain in the range of 5.8 to 6.5. When it decreases, potassium hydroxide is added; when it increases, sulfuric acid (battery acid) is added. Different fertilizer formulations will have different EC levels. For Cooper's solution, the level should start at 3 dS/m (3 mmho/cm). When it drops to 2 dS/m, the complete package of nutrients should be added in sufficient quantity to restore the level to 3 dS/m.

Computerized equipment is available that can automatically sample nutrient solution from the holding tank, analyze it for pH, EC, and individual nutrients, and make the appropriate additions of acid, base, or fertilizer. This equipment includes concentrate tanks of acid, base, and each individual fertilizer salt such as potassium nitrate and magnesium sulfate. The test results are processed in the computer to determine which nutrient salts and how much of each will be injected into the NFT solution. These additions are then automatically made. Concentrate from any individual tank or combination of tanks can be added to the single-strength nutrient tank in order to hold all nutrients in balance. The automated system allows the pH and nutrient concentrations of the solution to be maintained more precisely than by merely analyzing solutions once per day.

Plants to be set in an NFT system are propagated in containers such as blocks of rock wool or foam cubes, or in netlike pots containing soilless substrate. It is important that the propagation unit not contribute peat moss or other loose substances that will plug the system. A propagation area is set up for establishing plants under conditions more ideal to this stage. It also permits growing at high plant densities to cut overhead costs. Young plants are often grown in channels in the propagation area; however, plants within the channels as well as the channels themselves are placed much closer together than they are in the finishing greenhouse. When established plants are then moved to channels in the finishing greenhouse (Figure 19),

Figure 19
Carnations growing in an NFT system. Note header pipes running across the upper end of the troughs for delivering nutrient solution.

nutrient solution may meander along the plastic and miss some root blocks. This problem can be solved by placing sticks beneath the plastic just below each plant to form a dam for puddling water around each block. In a week or two, when roots develop across the channel, the sticks can be removed.

Advantages of NFT production include the following.

1. The NFT system eliminates the materials and labor costs for steam or methyl bromide pasteurization between crops, as well as the period of 10 to 14 days required for methyl bromide application and aeration. If the channel in which plants are grown is formed from film plastic, the plastic is gathered up with the crop and discarded, and new plastic is laid out. Permanent channels not lined with film plastic are rinsed with a sterilant such as bleach between crops.

2. NFT has the potential for conserving water and nutrients. The nutrient solution is recirculated in a mostly closed system where little evaporation occurs and excess water and nutrients are reused.

3. Recirculation of solution provides an excellent method for reducing nutrient and pesticide effluent from greenhouses.

4. NFT has the very attractive potential for automation. Formulation, testing, and adjustment of nutrient solutions can be handled at a central point, and even this can be done automatically. The solutions are mechanically delivered to the crop. Some of the heat may likewise be delivered in the nutrient solution. Heavy root substrates and the handling of them are eliminated.

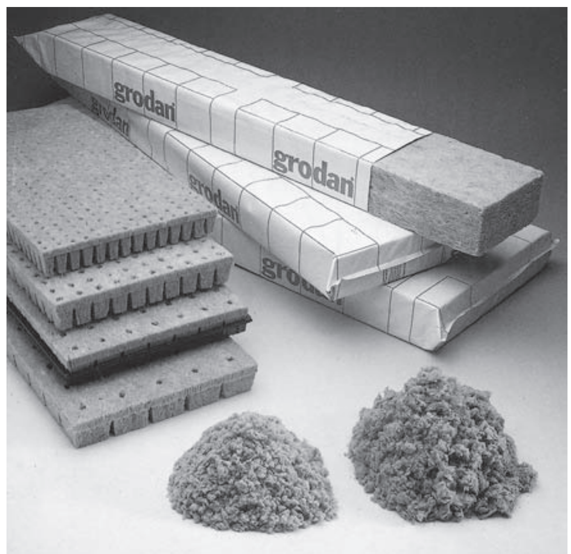
Rock Wool for Cut Flowers and Vegetables Rock wool culture was pioneered in Denmark during the late 1950s. By the early 1970s, horticultural rock wool was in production in Denmark. Today, nearly all greenhouse cucumber and tomato plants in Denmark are produced in rock wool. Rock wool appeared in the American market in the early 1980s. Crops grown in rock wool include the full range of greenhouse vegetables, carnation, chrysanthemum, gerbera, and rose.

Rock wool is produced by burning a mixture of coke, basalt, limestone, and possibly slag from iron production. At a 2,900°F (1,600°C) temperature in the furnace, the rock minerals melt. This liquid is tapped from the base of the furnace. A molten stream flows onto a high-speed rotor. Droplets thrown from the rotor enter an air stream where they lengthen and solidify into fibers as they cool. The fibers, while suspended in the cooling air stream, are sprayed with a binding agent and a surfactant to render them hydrophilic. The air stream carries the fibers and orients them into a single direction on a belt conveyor. The pad of fibers is then compressed between rollers to a specified density. Finally, the pad is cut into desired dimensions.

Insulation- and acoustical-grade rock wool is not suitable for plant growth. Horticultural-grade rock wool is formulated to a prescribed higher density to provide the air- and water-holding requirements of plants. Rock wool used in cubes for propagation and in slabs for finishing crops is, unlike industrial rock wool, treated with surfactants to improve water absorbance. Industrial rock wool repels water for heat insulation purposes. Horticultural rock wool contains about 3 percent solid and 97 percent pore space.

Rock wool is not biodegradable, but it does slowly weather. Slabs are often used for two years of cropping before disposal. Root tissue builds up in rock wool over time increasing its water-holding capacity and reducing its aeration. Initially, rock wool contains no significant quantity of soluble materials. However, fibers can contain calcium, magnesium, iron, manganese, copper, and zinc, and there is evidence that these can slowly be released for plant uptake (Rupp and Dudley, 1988). Since the cation exchange capacity is negligible, applied nutrients are not adsorbed. Nutrient availability is dictated by the nutrient solution applied. The pH of rock wool is between 7.0 and 8.5 (often 8.0), but is not buffered. It is important that the nutrient solution applied has a pH level in the range of 5.5 to 6.0. The pH level of the rock wool will adjust to the nutrient-solution pH level after one application.

Horticultural rock wool is available in 0.7- to 4-inch (18- to 100-mm) cubes with or without predrilled holes for propagation of seed or cuttings (Figure 20). The smaller cubes can be obtained unwrapped in blocks suitable for use in trays. Larger cubes are often wrapped on the vertical sides with polyethylene to prevent evaporation and spread of roots into adjacent cubes; these are sold in single-row strips. The 3- and 4-inch (76- and 100-mm) cubes can be obtained with a depression in the top of suitable size to insert smaller cubes into them for transplanting purposes. For purposes of finishing crops, slabs of rock wool are available. These can be obtained unwrapped or wrapped in white polyethylene. Slab widths can be 6, 8, 12, or 18 inches (15, 20, 30, or 46 cm), lengths can be 36 or 39 inches (91 or 100 cm), and



(a)

(b)

Figure 20

Various rock wool products used in the greenhouse. (a) Blocks of cells of various dimensions for propagation of seeds and cuttings, polyethylene-wrapped slabs of rock wool for supporting vegetable and cut-flower crops, and loose rock wool to be used as a component in root substrate for pots. (b) An individual propagation cell in which a seed or cutting would be propagated, a block with predrilled hole to accommodate the propagation cell, and a slab on which the block will ultimately be placed after plants have been grown for an interim period of time at close spacing in the block.

(Photos courtesy of Grodania A/S, Hovedgaden 483, 2640 Hedehusene, Denmark; distributed in North America by Agro Dynamics, 10 Alvin Ct., East Brunswick, NJ 08816.)

Figure 21
A tomato crop growing in a rock wool system. The 3-inch (7.6-cm) rock wool propagation cubes are sitting on rock wool slabs 6 inches (15 cm) wide by 3 inches (7.6 cm) deep. The slabs are wrapped in white polyethylene film. Nutrients and water are provided to the propagation cubes through plastic microtubes fed from PVC pipe running along the sides of the slabs.

the height is usually 3 inches (7.6 cm). Granulated rock wool is also available for potting substrate.

As in the case of NFT, plants can be propagated at a high density in small cubes in a specially regulated environment. They may then be transplanted into larger blocks and spaced out into a moderately high-density nursery area to cut down overhead costs. The large cubes are finally set on top of slabs for final production (Figure 21).

Evenness of the floor is not as important for rock wool culture as it is for NFT. Where there is a slope along the length of the bed, solution in individually wrapped slabs cannot drain from the high end to the low end of the bed. Narrow slabs are placed end to end in a double row for cucumber, tomato, and rose crops to form a bed (Figure 22). A space is generally left between the two rows for vegetables. For cut flowers, the wider slabs are used to line a bench. Ideally, for double-row culture, the floor should be level from end to end but sloped at a 2° angle to a drain between the two rows of the bed.

Cubes with individual plants are placed on top of the slabs at the desired final spacing for the crop involved. Roots penetrate into the slabs below the cubes in two to four days. During this period of adaptation, it is necessary to water the plants frequently. The additional height of the cube plus the slab causes the cube to drain to a lower water content than existed during nursing of the young plants. In temperate climates, slabs are covered with polyethylene. The cover may be omitted in tropical climates to allow for evaporative cooling of the root zone. When wrapped slabs are used, three drain holes must be cut along one side—the low side if the floor is sloped to a drain between double rows. A 1.5-inch (4-cm) slit is made starting one-quarter inch (6 mm) from the bottom of the side and extending upward at a 45° angle from the floor.

Nutrient solution is applied with each watering. Solutions used for NFT and other nutriculture systems are appropriate. Crops can require 3 to 10 applications per day. This frequency will vary with plant size and weather conditions. When only two or three plants are grown on a slab, as in the case of tomato or cucumber, nutrient solution is delivered to each cube through a microtube supplied from a plastic pipe

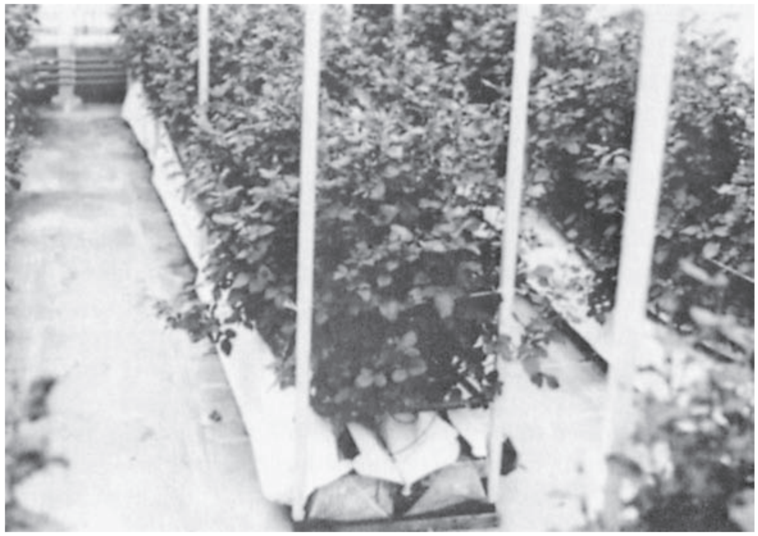


Figure 22
Roses growing in slabs of rock wool that are individually wrapped in polyethylene film and placed end to end. Nutrient solution is delivered from the black plastic pipes above the slabs through microtubes to individual plants.

running along the bed. This is not feasible when large numbers of cubes are grown on a slab. In this instance, three or four fertilizer emitters are placed directly on top of the slab. Traditional fertilizer injectors and water mains can be used to supply the plastic pipes.

Rock wool in a 6-inch (15-cm)-deep configuration can hold water in about 50 percent of its pore space. The distribution of water is unequal, with pores in the lower 1 inch (2.5 cm) holding nearly 100 percent water and those in the top 1 inch (2.5 cm) holding less than 10 percent. A 3-inch (7.6-cm)-deep slab will hold enough water to fill 77 percent of its pore space, leaving 23 percent of the pores open for aeration. It follows that the small cubes will have even less aeration. When seeds or cuttings of plants sensitive to oxygen stress are propagated in these cubes, it is advisable to place the cubes on a well-drained substance such as sand or perlite. This increases the effective depth of the cube and consequently its drainage and aeration.

Just as the nutrient solution in NFT systems is sometimes heated to keep the root zone warm, heat may be applied under rock wool slabs. A polystyrene board can be placed on the ground. It has a notch at the middle of its top side running along its length. A plastic hot-water pipe is placed in this notch. Rock wool is placed directly on the pipe. By warming the root zone, cooler air temperatures can be maintained in the greenhouse, which results in fuel savings.

The salt content of rock wool can be lowered for the next crop by applying only water during the last days of the previous crop. Old crops can be removed by twisting the cubes off the slab. Rock wool may be used for one year for cucumber and two years for tomato and floral crops less sensitive to oxygen stress. If the rock wool is to be used for a second year, it is advisable to pasteurize it. Most of the water can be removed prior to pasteurization by cutting off the water supply during the last days of the final crop. The slabs are then stacked and covered with a pasteurization cover, and steam is applied for 30 minutes. Methyl bromide may be used as well. It can be readily washed out of the rock wool after fumigation. Repeated use of rock wool results in collapse of its structure and a buildup of organic matter from roots with a resultant loss of aeration. Cucumber is very sensitive to this problem.

Advantages of rock wool production include the following.

1. ***Elimination of pasteurization.*** As in the case of NFT, pasteurization can be eliminated in rock wool culture, unless it is used for a second year.

2. ***Production efficiency.*** Rock wool is an excellent inert substrate for open-system nutriculture. This greatly reduces the chances for the spread of disease, since the nutrients are not recirculated. It is, however, possible to recirculate nutrient solution in a rock wool system. In this case, slabs are placed on a sloped, paved floor. Nutrient solution is collected at the low point and is handled in the same way as in NFT.

3. ***Reduced production space.*** Rock wool is light weight and self-contained, which allows movement of plants into different environments and densities in different stages for faster crop production and lower overhead cost. The light weight further permits growth of crops on movable benches. Both of these factors reduce the overhead costs of the crop by reducing average growing space.

GREENHOUSE WATER LINES

A greenhouse area of 20,000 ft^2 (1,860 m^2) requires a 2-inch (51-mm) water main that can accommodate a 50-gpm (190-L/min) flow rate. An area of 50,000 ft^2 (4,645 m^2) needs 3-inch (76-mm) mains for a flow rate of 125 gpm (473 L/min). Plastic (PVC) pipes are commonly used because they are cheaper and have less pressure drop due to friction than iron pipes. Mains can be installed underground or overhead. More commonly, they are placed overhead, which greatly reduces the cost of the system and facilitates subsequent repairs and alterations. Water in overhead mains, warmed by the sun, can become sufficiently hot to burn plants. In warm climates, and particularly in situations where water is not drawn often, it may be necessary to insulate these lines. Water mains are used for delivering fertilizer solutions as well as water to the crop. It will occasionally be necessary to switch from one fluid to the other.

Consider a greenhouse firm of 20,000 ft^2 (1,860 m^2) laid out in one block measuring 144 feet (44.0 m) wide and 139 feet (42.4 m) long. A roadway runs through the middle along the length of the greenhouse. Benches 6 feet (1.8 m) wide by 68 feet (21.0 m) long run out from either side of the roadway. Pot mums are grown in 6.5-inch (16.5-cm) azalea-type pots at a bench-space allotment of 1.25 ft^2 each (13.5 pots/m^2). There are 326 pots on each bench. Each requires 12 fluid ounces (350 mL) of water at each watering. Benches are grouped in sets of three, and each set is supplied with water through a single valve and manifold. Water or fertilizer is applied to 1,008 plants simultaneously. The best arrangement of water mains calls for two 2-inch (51-mm) mains running the length of the greenhouse, each perpendicular to the benches and running over the midpoint of each bench, for a total of about 350 feet (107 m) of 2-inch (51-mm) main pipe. Each linear foot of pipe holds 17.4 fluid ounces of water (1.7 L/m of pipe). The total main system holds 47.6 gallons (180 L). Assume that one day after a watering, an application of fertilizer must be applied. The fertilizer proportioner is turned on at the beginning of the water main. At the opposite end of the water main, the valve on a three-bench station is opened. Before fertilizer reaches plants in that station, 47.6 gallons (180 L) of water must be flushed from the lines onto the 1,008 pots. This provides 4.8 fluid ounces (142 mL) of water to each pot. Also, 1 fluid ounce (30 mL) of water is pushed out into each pot from the 0.75-inch (19-mm) supply pipes (2.44 fl oz/ft of pipe or 236 mL/m of pipe) located on the bench, for a total of 5.8 fluid ounces (171 mL). Of the 12 ounces (354 mL) of fluid supplied, only 6.2 ounces (183 mL) are fertilizer solution. After this station is fertilized, another station will be opened. This time 12 fluid ounces (354 mL) of fertilizer solution are applied.

Figure 23
A dual-main system suspended overhead at the midpoint and perpendicular to benches. One pipe carries water while the other carries fertilizer solution. Each main is connected to the water distribution system on the bench below through a manual valve. The manual valves could be replaced with solenoid valves, and these, in turn, could be controlled by two stations on a sequential timer.

A much worse situation occurs in a greenhouse area of 50,000 ft^2 (4,645 m^2) where 800 feet (244 m) of 3-inch (76-mm) main pipe are required. Each linear foot of pipe holds 39.1 fluid ounces (3.8 L/m) for a total of 244.4 gallons (924 L) in the whole system. The combined water in the main system and in the 0.75-inch (19-mm) pipes on the bench provide 12 fluid ounces (354 mL) of water to the first 2,840 pots supposedly fertilized. Therefore, 10 percent of the plants in the firm receive water rather than fertilizer.

The problem can be rectified by installing double mains, one for water and one for fertilizer (Figure 23). The appropriate valve is opened at each station, depending upon the need for water or fertilizer. A second answer calls for installing a solenoid water valve at the end of a single main system. In order to change from water to fertilizer, a fertilizer proportioner is turned on at the beginning of the water main, and the solenoid at the other end of the main is opened by a switch in the fertilizer room to allow water to be purged out of the main to waste. When the fertilizer solution reaches the end of the greenhouse main, the solenoid is closed. The time required to reach this point is predetermined.

The number of benches in one water station is determined by the size of a single planting of one crop species. It can be safely assumed that all plants in this unit will be watered and fertilized on a single schedule. Generally, from one to three of the benches described earlier would constitute a station.

Water is distributed along the bench from a microtube watering system through two 0.75-inch (19-mm) plastic pipes running the length of the bench. Water is supplied to the midpoint of each 0.75-inch (19-mm) pipe, rather than to the end, to minimize the pressure drop along the bench. A 0.75-inch (19-mm) pipe 70 feet (21.3 m) long supplied with water at one end can distribute water to 70 pots. The same length of pipe supplied with water at its midpoint can distribute water to 280 pots without an adverse differential in the amount of water delivered to each pot. These figures are based on 0.06-inch (1.5-mm)-inside-diameter microtubes 2 feet (61 cm) long. For further details on greenhouse water main systems, see Brumfield et al. (1981).

FURTHER CONSIDERATIONS

Effluent Reduction

Pulse Watering Construction of closed systems can be very costly. Modification of open systems, such as perimeter watering of cut flowers or tube watering of pot crops, is an attractive alternative because many components of the traditional system can be retained. Pulse watering is a modification of an open system and is designed to reduce consumption and effluent of water and nutrients. Benefits of pulse watering include lower usage of fertilizer and water and reduced runoff into the environment of nutrients and any pesticides that might be in the substrate. We have already described one pulse watering system—that is, zero runoff—in the “Boom Watering for Container Plants” section.

There are two main reasons that excesses of fertilizer and water are applied in many greenhouses. In times prior to governmental regulation of nutrient runoff from greenhouses, it was expedient to apply higher concentrations of fertilizer than were necessary to guard against deficiencies. The excess fertilizer was removed by applying 10 to 15 percent excess fluid at each application. Although wasteful, this system is in common use today because it is easier to administer than a more precise system in which the exact requirement of nutrients is met. The excess fluid applied is actually much greater in many greenhouses where a timeclock is not used for exact control. In these greenhouses, an extra minute of watering can easily occur and result in doubling or tripling of the amount of excess water applied. It is probably more common to see 40 to 50 percent excess fluid and, consequently, fertilizer applied in greenhouses. The second reason for excess application relates to the porosity of the root substrate used. If there are excessively large drainage pores in the substrate, water will quickly pass through and out the bottom without moving laterally to the dry, fine-textured substrate. To compensate, growers leave the water or fertilizer solution running longer to allow sufficient time for lateral movement of fluid. Excess fertilizer solution is lost during this time. Of course, partial solutions to these problems are to precisely time the application of water or fertilizer solution and to avoid substrates with too high a percolation rate.

Pulse watering goes a step further in reducing water or fertilizer application. Fertilizer solution is applied several times during a drying cycle rather than just once at the end of the drying cycle. However, less solution is applied each time, so that close to zero leaching occurs. The concentration of fertilizer must be lower—approximately half the concentration used in an open system. The exact concentration of fertilizer required can be gauged by EC tests of the substrate. When the salt level in the substrate becomes too high, it can be lowered by applying only water for a period to allow for plant uptake of the fertilizer. This concept is new to greenhouse firms. With time, various ways of implementing it will emerge.

Whole-Firm Recirculation Some firms, such as those in California, are faced with a zero tolerance of nitrate in the effluent water from their property. This, in effect, means there can be no runoff. One way of achieving this is to recirculate all water from the firm (Figure 24). Whole-firm recirculation is being done commercially (Skimina, 1986).

Plants in the greenhouse or the field are grown on a plastic-lined or paved surface. Water or nutrient solution is applied in the conventional manner to the top of the pot, flat, or bench if it is a cut-flower crop. Leachate passing out of the bottom of the container is caught on the greenhouse floor and flows to a lined ditch. A network of ditches from each growing area carries water to a set of settling ponds. Much of the sediment in the leachate settles out in these ponds. From these ponds, water is

Figure 24
An effluent water treatment system at Monrovia Nursery Co. in Azusa, California. Effluent from plant pots during watering or fertilization is channeled throughout the entire firm to a settling pond where large particles settle to the bottom. A coagulant is added to aggregate fine particles, and these are filtered. Chlorine is added to eliminate disease organisms. After testing, appropriate nutrients and/or water are added to the effluent to restore the desired fertilizer concentration and balance for subsequent application.

pumped to an equalization pond to better establish an average level of fertilizer in the leachate coming from the previous applications of water or fertilizer to the crops. A flocculant, such as alum (aluminum sulfate), is added to cause remaining, suspended solids to flocculate (gather together) so that they can settle out. Clear leachate is drawn from this pond above the sediment and is then injected with chlorine, which pasteurizes it to ensure that disease pathogens are not returned to the crop. Chlorine can also cause iron and manganese to precipitate. The leachate is filtered to remove any remaining solids that might otherwise have clogged small orifices in the watering system. The cleaned leachate is tested for pH level and individual nutrient concentrations. Acid or base is added to adjust the pH level, and water or individual nutrient concentrates are added as indicated by the tests. Since much of the water and some of the nutrients were used by the crop in the previous applications, new nutrient solution is made and added to restore the volume of the recycled leachate. This solution is held in a reservoir, from which it will be drawn when needed for the crop again. If only water is next required on the crop, clean water is used, and the leachate from it is captured in the same system just described.

Life Expectancy

It is difficult to assess a life expectancy for each watering system, and yet this must be done in order to give proper economic consideration to this form of automation. In general, it can be assumed that the more delicate parts of these systems, such as 8-mil (0.2-mm) polyethylene tubes and plastic nozzles, will last five to six years if properly maintained. The pipes, valves, and overhead metal nozzles can last considerably longer, at least 10 years, particularly if PVC is used.

Problems arise when particles are not strained from well or pond water. These particles accumulate in the smaller tubes and nozzles. A 150-mesh strainer should be used in all systems, even when city water is used. Metal fittings should be avoided after the filter to prevent clogging from rust. When river water is used, it is best to strain the water through a sand filter prior to the 150-mesh filter.

Sufficient light enters thin-walled white PVC pipe to permit algal growth, which can plug tubes and nozzles. To prevent this problem, pipes can be painted. The best color is aluminum since it restricts light and at the same time keeps the pipe cool. Water in black pipes that are not used continuously on summer days can become sufficiently hot to burn plants.

Water System Sterilization

The plastic components of automatic watering systems should not be steam sterilized. This process tends to reduce the life expectancy of the polyethylene components and to distort PVC pipe and plastic nozzles. Prior to steaming substrate in cut-flower beds, the flexible tubes should be rolled up, and the plastic pipe mains should be lifted above the bench and secured to the superstructure.

Once these components are removed, the watering system must be sterilized; otherwise, there is the risk of recontaminating the bench substrate with particles adhering to the watering system. A sponge or rag dipped in a pail of disinfectant such as bleach can be used to wipe pipes and nozzles. Disinfectants could also be proportioned into the water line and applied by hose. The flexible water tubes can be removed and soaked in a barrel of disinfectant.

The problem is not as great for potted-plant benches because there is no substrate to be pasteurized. These benches and the watering system may be hosed with a disinfectant.

Water Pasteurization

Some sources of irrigation water need to be cleaned and pasteurized prior to use. Municipal water is clean and generally does not require treatment. Well water usually requires only filtration to remove particulate matter. Occasionally, well water contains iron bacteria deriving its energy form iron. Iron bacteria form a slime that can plug pumps and water emitters. Pond and river water often contains algae that can plug water emitters and pathogens that can harm crops. Water recycled from crops requires filtration to remove particulate matter and pasteurization to reduce levels of algae and pathogens. Recycled water may consist of recirculating nutrient solution in closed NFT or rock wool systems, or leachate collected after passing through root substrate in pots or beds of plants.

Irrigation water is usually pasteurized rather than sterilized. If it were sterilized, all organisms would be killed. This would require large doses of treatment materials that would be too costly and might lead to high residual levels toxic to the crop. The process of pasteurization results in reduction of the levels of pathogens to acceptable levels with minimal destruction of nonpathogenic organisms. Nonpathogenic organisms present competition to pathogens, helping to hold them in check. Particularly troublesome water-borne pathogens transmitted in irrigation water include *Colletotrichum*, *Fusarium*, *Phytophthora*, *Pythium*, and *Ralstonia*.

Prior to treating water for pathogens, it is necessary to pretreat the water. Particulate material such as sand, silt, and soil particles should be filtered out. These materials, due to their size, can clog water emitters and cause excessive wear in pumps and fertilizer injectors. Organic materials such as peat moss, bark, algae, and biofilm also need to be filtered out. These materials can clog emitters, and equally important, they will react with many of the microbiocidal agents used against the pathogens. These microbiocidal agents indiscriminately attack and destroy inert organic matter along with pathogens. In doing so, these agents become inactive. Higher levels of agent are required with increasing amounts of organic matter in water. This raises the cost of the process and increases the risk of crop injury. Pond, river, and recirculated water from closed systems can vary widely in level of contamination. If water contains leaves, sticks, peat moss, bark, and other large materials, it should be passed through a coarse screen to remove these at stage one. Then, depending on the level of contamination and the requirement of the selected microbiological agent, this water should be passed through one or two additional stages of filtration. The common 200-mesh filter used in greenhouses removes particles down to 75-micron size, which is sufficient to remove sand, silt, clay, and aggregates of algae to prevent clogging of emitters. Water containing a large amount of suspended organic matter will require additional filtration. Three hundred- and 400-mesh filters will remove particles down to 50 and 35 microns in diameter, while paper or belt filters will remove particles down to 10 microns. Since installation and operation of pasteurization systems is an expensive proposition, growers should confer with companies that supply these specifications prior to installation.

Nine pasteurization systems used in greenhouses will be discussed next. Features to be considered when selecting one system include the following: What are the initial and operational expenses? Does it kill pathogens at one point in time or provide residual activity throughout the irrigation system? Can it be used for a "shock" treatment for one-time removal of a heavy buildup of biofilm, iron bacteria, or pathogens as well as a subsequent maintenance program? An irrigation line that has not been treated might contain an excessive level of organic matter. This system should be treated first with a shock treatment to get rid of the excess organic matter. Then, a maintenance program with a lower concentration of disinfectant can be employed. This will reduce the cost of pathogen control and reduce risk of crop injury. Materials used during the shock treatment are not applied to the crop for fear of toxicity. They are expelled to waste from the end of the irrigation line.

Five of the nine pasteurization systems destroy pathogenic microorganisms through oxidation. During the process of oxidation, organic compounds are broken down whether they are in inert organic matter or in living cells. When they are in living cells, these organisms die.

Hypochlorous Acid (sodium hypochlorite, calcium hypochlorite, chlorine gas) The first three systems use hypochlorous acid as the oxidizing agent. One of the three sources can be employed: sodium hypochlorite (liquid bleach), calcium hypochlorite (solid swimming pool disinfectant), or chlorine gas. These systems can be used for shock as well as maintenance treatment. Since the active products formed from these three chemical sources persist throughout the irrigation system, they provide residual control against microorganisms. Equipment is available for safely injecting each of these chemicals. All three chemicals form hypochlorous acid (HOCl) and hypochlorite (OCl^-) in water. These two end products are active oxidizing agents that destroy organic matter. Hypochlorous acid is the more effective of the two. It converts to hypochlorite as pH rises. Therefore, the optimum pH range for irrigation water into which these chemicals are added is 6.0 to 7.5. At pH 4.0 and below, a toxic gas is formed that should be avoided. The following equations show the chemistry of these compounds and their reaction with water to form hypochlorous acid. Sodium hypochlorite and calcium hypochlorite form hydroxide that elevates the water pH modestly. Chlorine gas forms hydrochloric acid that lowers water pH moderately.

$$\underset{\substack{\text{sodium}\\\text{hypochlorite}}}{NaOCl} + \underset{\text{water}}{H_2O} \leftrightarrow \underset{\text{sodium}}{Na^+} + \underset{\text{hydroxide}}{OH^-} + \underset{\substack{\text{hypochlorous}\\\text{acid}}}{HOCl}$$

$$\underset{\substack{\text{calcium}\\\text{hypochlorite}}}{Ca(OCl)_2} + \underset{\text{water}}{2H_2O} \leftrightarrow \underset{\text{calcium}}{Ca^{2+}} + \underset{\text{hydroxide}}{2OH^-} + \underset{\substack{\text{hypochlorous}\\\text{acid}}}{2HOCl}$$

$$\underset{\text{Chlorine gas}}{Cl_2} + \underset{\text{water}}{H_2O} \leftrightarrow \underset{\substack{\text{hypochlorous}\\\text{acid}}}{HOCl} + \underset{\substack{\text{hydrochloric}\\\text{acid}}}{HCl}$$

Hypochlorous acid, hypochlorite, and chlorine are collectively termed *free chlorine*. A level of 0.5 to 2 ppm free chlorine is required at the last emitter in the greenhouse irrigation line to control pathogens such as *Pythium* and *Phytophthora* during the maintenance program. If algae are all that has to be controlled, a free chlorine level of 0.25 ppm may be sufficient. Concentrations above 4 ppm for short-term exposure and 2 ppm for long-term exposure can be injurious to crops. Free chlorine can be measured with a meter selling for about $150 to $300. The meter should measure free chlorine and not total chlorine, since the latter includes some ineffective forms of chlorine. Color test-strip kits can also be used. The oxidation-reduction potential (ORP) meter is an alternative meter that sells for about $100 to $400. An ORP reading of 650 mV is desired for greenhouse irrigation water.

Free chlorine reacts with nearly all organic matter, whether peat moss or living cells. The oxidizing power (disinfectant property) of free chlorine diminishes as it reacts with organic matter. Thus, the concentration of free chlorine that must be injected into the irrigation water system must be increased in accord with increased levels of organic matter, regardless of whether it is nonliving matter, algae, biofilm, iron bacteria, or free microorganisms. It is important that a residual level of 0.5 to 2 ppm free chlorine persists at the end of the irrigation line so all plumbing and water is protected. Clean water may only require an injection level of 1 to 2 ppm, while contaminated water may require 6 ppm to achieve the desired residual level at the end of the line. Sodium hypochlorite and calcium hypochlorite are finally converted to sodium chloride and calcium chloride salts. These salts are ineffective against microorganisms and concentrations generated during water disinfection are usually harmless to crops.

Chlorine Dioxide Chlorine dioxide (ClO_2) is a stronger oxidizing agent, at equal concentration, then hypochlorous acid. It is effective over the pH range of 4 to 10. Chlorine dioxide has a neutral to slightly alkaline pH, thus it has little effect on irrigation water pH. Like hypochlorous acid, it has a residual activity. Chlorine dioxide can be used as a shock treatment and as a maintenance treatment. For shock treatment, the irrigation lines are filled with a solution of 20 to 50 ppm for 12 hours. The solution is then purged from the lines and the lines are flushed with water without any of these liquids going through the emitters to plants. Repeat application is sometimes required. A concentration of 0.25 ppm at the last emitters in the irrigation line is typically used for the maintenance program. Plants can be injured by concentrations of 1 to 2 ppm. For safety, plants should not be exposed to more than 0.25 ppm. Color test strips and meters can be used to measure concentrations. A reading of 650 on the ORP meter is desired. Chlorine dioxide can be used for sanitizing hard, nonporous surfaces such as benches, tools, equipment, containers, tanks, and evaporative cooling systems.

Chlorine dioxide gas is generated at the greenhouse site. Solid tablets or a packet of solid chemical reactants is placed in a tank of water. They dissolve in about 20 minutes, releasing chlorine dioxide gas that dissolves into the water. This stock solution is then injected into the water lines with a fertilizer injector. The set-up cost is much less than that of the hypochlorous acid systems, but the cost of the chemicals is higher. Chlorine dioxide works well in greenhouses where there is a high pathogen pressure.

Peracids (hydrogen peroxide) Hydrogen peroxide is an oxidizing agent that attacks organic matter including microorganisms in a similar fashion to the chlorine compounds. However, hydrogen peroxide is rapidly broken down and rendered ineffective by ultraviolet (UV) light. When organic acids are bonded to hydrogen peroxide to form peracids, the hydrogen peroxide becomes sufficiently resistant to UV light to give it a sufficiently long useful life to be used for greenhouse sanitation purposes. Not all of the hydrogen peroxide compound is bound to the acid. Some remains in solution in equilibrium with the peracid. The common acid used is acetic acid that forms peroxyacetic acid (PAA). Peracids are highly effective at water pH levels of 7.0 and below and remain suitably effective at pH 8.0. The pH level of peracid concentrates is around 1.9. This will lower the pH of irrigation water that can be an advantage for systems with high water alkalinity.

Peroxyacetic acid can be used for shock treatment of tanks and irrigation lines, for a low concentration maintenance program, for sanitation of greenhouse surfaces, and as a bactericidal and fungicidal application directly to plant foliage and roots. Peroxyacetic acid is sold as a liquid concentrate. Two products and their percentages of peroxyacetic acid are ZeroTol (2 percent) and SaniDate 12.0 (12 percent). These products also contain stabilizers that make them more resistant to UV degradation. Low levels of 1 to 1.2 ppm peroxyacetic acid can be used for continuous maintenance in the irrigation system. Test kits are available for monitoring the concentration. The ORP meter does not work for this chemical.

Ozone Ozone is another strong oxidizing agent. Like the other oxidizing agents, it can be used for shock as well as maintenance treatments. It has a residual effect, although not as long as the other oxidizers. Ozone generators are expensive, costing around $10,000, but are inexpensive to run. The principal continual expense is electricity since ozone is generated from air. Once generated, ozone is injected into water. It can be applied through a sprayer to sanitize hard surfaces such as floors. While effectiveness of ozone is not pH dependent, the length of time it persists in the water system decreases with increasing pH, particularly above pH 7. When ozone reacts with organic matter, it breaks down into harmless products. However, it is important to avoid ozone leaks from the generating equipment, since ozone itself is a harmful gas for people and plants.

Biofilm can be destroyed with a concentration of 0.2 ppm held in the lines for 30 minutes. A continual concentration of 0.01 to 0.05 ppm will control algae. Ozone concentration can be monitored with test kits and with an ORP meter. Plant symptoms of ozone toxicity begin with reduced growth, color changes, and progress to foliar stippling, mottled chlorosis, necrotic lesions, and patches of water-soaked tissue.

UV Radiation UV radiation effectively controls pathogens and algae in water. The UV-C range of wavelengths (100 to 280 nm) is effective, while UV-B (280 to 315 nm) and UV-A (315 to 380 nm) ranges are not. UV lamps emitting radiation in the 240 to 280 nanometer range are used for water disinfection. This range of UV radiation disrupts the genetic chemistry of the microorganisms rendering them unable to reproduce. It is effective against algae, fungi, bacteria, and viruses. The UV system offers no residual activity. Organisms are destroyed as they pass through the light beam but not further down the water stream. Thus, biofilm along the pipe system is not contacted and destroyed. For this reason, a second residual control system is recommended to go along with UV radiation. Ozone serves this residual purpose well.

The system uses UV lamps, very much in the shape of narrow fluorescent lamps, each contained inside a water-tight quartz sleeve to protect it and allow unfiltered emission of UV light. These tubes are contained inside and parallel to the length of a cylinder. Water flows through the cylinder, over the outside of the UV lamps. In this way, water passes within close proximity to the source of UV radiation. Suspended solids in the water will block the beam of radiation, leaving some water untreated. For this reason, it is very important to filter water before treatment. The maximum turbidity of water to be treated should be 2 nephelometric turbidity units (NTU), a common unit for turbidity. Lamps have a life expectancy of 10,000 hours.

Copper Ions Copper ions with their positive charges readily attach to microorganisms as well as organic matter. When attached, they destroy the organisms. A concentration of 0.5 to 1 ppm is effective against pathogens, while 1 to 2 ppm may be required for algae. Copper ions have a residual effect. Set-up equipment is expensive, starting around $5,000, but operational costs are low. This results in a moderately low long-term cost. Operational costs consist of electrical input and replacement of copper electrodes every year or two.

Copper ions are generated by passing an electrical current through copper metal electrodes. This converts solid metal copper atoms in the rod into soluble copper ions by removing electrons from the copper atoms. The ions pass by a magnetic coil to increase their activity. The concentration of free copper ions is dependent on water flow rate and water EC level. Thus, electrical input is under the control of a flow meter and EC sensor to maintain the desired concentration of copper ions. Equipment is available to treat from a few gallons to thousands of gallons per minute. Test kits are available for measuring free copper ion concentration. A test for total copper is inaccurate because it is the free ions that are active. Water pH should not be above 7 due to precipitation of copper ions that renders them inactive.

Although copper ions are less affected by organic matter than the other systems, it is still recommended to filter water before treatment. Copper concentrations in effluent water coming from crop production are well below the 1.3 ppm limit set for U.S. drinking standards.

Heat Treatment Equipment is available for heat pasteurization of nutrient solution while it is recirculating between the crop and the sump tank. The solution is heated to a temperature close to 212°F (100°C) in 30 seconds and held at this temperature for 10 to 30 seconds, after which it is cooled at an equally rapid pace. Much of the heat is passed on to subsequent solution entering the system.

Automation

Solenoid Water Valves It is perhaps best for small growers with one or two plastic greenhouses to use manual valves on the watering system. In this way, the expense of automation is avoided. The owner can quickly check the few benches of plants daily, and as needed, open the water valve, wait for watering to be completed, and then shut the valve on each bench. As a firm grows, it becomes better able to justify investment in automation. The increased number of water zones in the firm creates a time-consuming task of waiting for a large number of zones to be watered. This problem can be remedied by installing a solenoid water valve at the beginning of each water zone. The solenoid valve serves as an electric on-off valve. The whole set of solenoid valves can be controlled by a sequential-control instrument (Figure 25). Once activated, the sequential-control instrument will open and close any number of solenoid valves, one at a time, for any preset time, from 15 seconds to 30 minutes. The price of sequential controllers begins around $200 for 12 station systems and increases according to the features included and the number of stations activated. Up to 40 stations can be handled by one controller.

Sequential timers can result in considerable labor savings for large firms. Consider the time required for a manager to open valves, wait three to five minutes for water to be applied, and close valves on each of 40 water zones. With a sequential timer, the manager walks through the 40 zones, making a list of those that need watering. Then, he or she programs the sequential timer to apply water to those zones

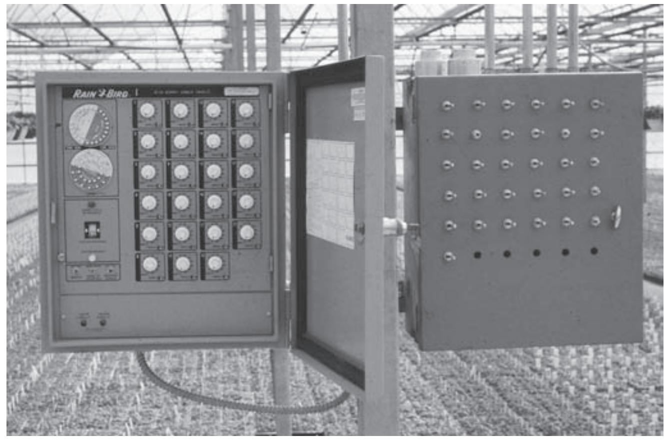


Figure 25
A sequential timer capable of watering 23 separate zones in a greenhouse individually.

and is thus free to perform other tasks. The cost savings are considerable since the person capable of making watering decisions should be one of the more experienced (higher-paid) employees.

Automated Water Decision A fixed interval cannot be set between waterings, thus timeclocks are not effective. Large plants as well as bright and warm conditions increase the frequency of drying, while small plants and cold or overcast conditions reduce it.

Sensors can be used to make the decision when to water. Commonly in Europe and occasionally in the United States, a solar energy sensor is used to determine the time to water. This instrument has a remote light-sensing mechanism that measures cumulative solar energy at the point in the greenhouse where the sensor is installed. A given level can be set on the instrument, and when it is reached, any electrical system plugged into it, such as a solenoid switch on the watering system, can be turned on. Alternatively, tensiometers are available that can be inserted into the substrate of a representative plant. When the tensiometer senses dry conditions in the substrate, it sends a signal that ultimately activates a solenoid valve to deliver water to the crop.

When such sensors are used in several water zones, the use of a computer is suggested to coordinate actions in these zones. Zones vary in water needs according to the species of plant and the stage of growth of the species. In the case of the solar sensor, the computer can be programmed to water each zone at a different cumulative quantity of solar energy, all based on one sensor. For the tensiometers, the computer can pass the signal on to the solenoid valves, ensure that one is activated at a time, and control the quantity of water that is delivered in accordance with the needs of the particular crop being watered.

The vapor pressure deficit (VPD) principle is used by some firms for making crop watering and propagation misting decisions. In this computer model, three measurements are made from which the rate of water loss from plants is predicted. These are leaf temperature, surrounding air temperature, and RH.

The principle on which the model operates is as follows. The rate of water movement from plant cells to the surrounding air is dependent upon the difference in water content (*water vapor pressure*) of the air that resides between cells within the plant and that of the air surrounding the plant. This difference in water vapor pressure is called *vapor pressure deficit*. Water vapor pressure of the air within the leaf is a function of temperature alone because the RH of this air is always 100 percent since cells continually lose water to this air. Water vapor pressure of the air surrounding the

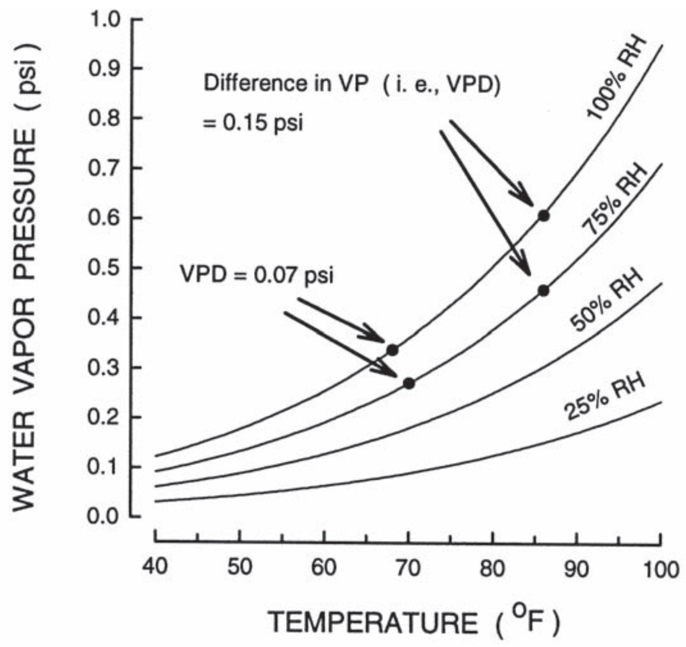


Figure 26

The interrelationship in air of temperature, relative humidity (RH), and water vapor pressure (VP). Illustrated in this graph are two examples of water vapor pressure difference (VPD) calculation. In the first daytime situation, air within the leaf is at 85°F and has an RH of 100 percent, while air outside the leaf is 85°F and has an RH of 75 percent. The graph indicates that the water vapor pressure of the air inside the leaf (85°F; 100 percent RH) is 0.60 psi, while the water vapor pressure of air outside the leaf (85°F; 75 percent RH) is 0.45 psi. The VPD is 0.15 psi (0.60 – 0.45 = 0.15). In the second nighttime example, the leaf is at a temperature of 68°F and has an RH of 100 percent, while the surrounding air is at 70°F with an RH of 75 percent. The water vapor pressures of internal leaf air (68°F; 100 percent RH) and surrounding air (70°F; 75 percent RH) are 0.36 psi and 0.29 psi, respectively, for a VPD of 0.07 psi.

leaf is a function of temperature and RH because both can vary widely. The temperatures of the leaves and the surrounding air must be measured separately because they are not always the same. Leaf temperature is generally lower than air temperature at night, unless a radiant heating system is used, in which case leaf temperature is higher than air temperature.

The graph in Figure 26 shows the relationships between temperature, RH, and water vapor pressure. If temperature and RH are known, water vapor pressure can be read from the graph. Illustrated in this graph are two examples of VPD calculation. In the first daytime situation, the air and leaf temperature are 85°F, and the air outside the leaf has an RH of 75 percent. From the graph, we see that the water vapor pressure of the air inside the leaf (85°F; 100 percent RH) is 0.60 psi, while the water vapor pressure of the air outside the leaf (85°F; 75 percent RH) is 0.45 psi. The VPD is 0.15 psi (0.60 – 0.45 = 0.15). In the second nighttime example, the leaf is at a temperature of 68°F, and the surrounding air is at 70°F with an RH of 75 percent. The water vapor pressures of internal leaf air (68°F; 100 percent RH) and surrounding air (70°F; 75 percent RH) are 0.36 psi and 0.29 psi, respectively, for a VPD of 0.07 psi.

The VPD watering and misting systems compute VPD values every 10 seconds and add these values to determine the cumulative VPD. The cumulative VPD at which irrigation should occur differs with stage of crop development and with crop. In the case of plant propagation, mist frequency is often decreased as roots develop. The grower must determine these cumulative VPD values through careful observation. These values are then entered into the system so that it will activate watering or misting each time this value is reached in the future.

The VPD system is sold as a package that includes the computer, software, and sensors. The sensor unit consists of an aspirated sensor box that is hung in the greenhouse. Within it are an air temperature sensor and an electronic, solid-state RH sensor. An additional sensor is located external to the aspirated box that simulates leaf temperature. Packages are available from $1,700 for an expandable system with 12 water control outputs, and range up to about $9,000 for a system with 64 outputs expandable to 512 outputs.

Economics

As one manufacturer states, "Automatic watering doesn't cost, it pays." This statement applies more to automatic watering than to most other systems of automation in the greenhouse. The automatic systems discussed range in materials-plus-installation costs from $116 to $544 compared to a labor cost of $535 for hand watering a 4-foot-by-100-foot (1.2 m × 30.5 m) bench for one year. The labor of operation throughout the year is negligible, since it simply entails opening and closing valves or programming a timer. It can be done by the manager during the rounds he or she would ordinarily make. In a large range, a sequential timer could ensure that this time is minimized. Taking all materials and labor into consideration, automatic systems can cost from far less to about the same during the first year as hand watering. With a payback of one year or less, it makes no sense to rely on hand watering.

Other factors make automatic watering a necessity for greenhouse operators. First, as already mentioned, the ease of watering better ensures that water will be applied when needed and in the quantity required. Second, automatic watering provides a means of applying water without wetting the foliage, which is very important for disease control, particularly in crops such as African violet, cyclamen, gloxinia, primula, Rieger begonia, and the lower foliage of cut-flower crops. Third, automatic watering systems provide the means through which liquid fertilizer can be automatically applied.

SUMMARY

1. Watering would appear at face value to be a boring, unimportant operation, but poor watering practices are probably the most common cause of poor greenhouse crops. Underwatering can have as deleterious an effect on crops as overwatering.

2. Proper watering depends upon three rules:
   - **a.** Use a well-drained substrate with good structure. This will allow for ample moisture retention along with good aeration, even immediately after application of water.
   - **b.** Water thoroughly each time. Substrates cannot be partially wetted. Water should be applied until it saturates all substrate in the container. (In open systems, where water is applied to the top of the substrate, 10 to 15 percent excess water is applied. In general, for soil-based substrates, water is applied at the rate of ½ gal/ft^2 [20 L/m^2] of bench, or 10 to 12 fluid ounces [300 to 350 mL] per 6.5-inch [16.5-cm] azalea-type pot. In closed systems, water is most frequently applied to the bottom of the substrate from where it is drawn up by capillarity.)
   - **c.** Water just before initial moisture stress occurs. This can be determined in most crops by subtle foliar symptoms such as texture, color, and turgidity changes. Some crops, such as azalea, do not show symptoms until root damage has occurred. Color, feel, and weight of the substrate are the cues for these crops.

3. Water quality is very important and is often overlooked. Total salt-content levels, alkalinity levels, the balance of calcium to magnesium, and levels of individual ions such as boron and fluoride can all have a serious bearing on crop success. The water source should be tested before a greenhouse is established. See Table 1 for water-quality guidelines.

4. Hand watering is too expensive in today's labor market. Numerous automatic watering systems exist for both cut-flower and potted-plant production. These systems can pay for themselves within a year. In addition to having an economic advantage over hand watering, automatic watering systems better guarantee that sufficient water will be applied on time because of the ease of application they offer. Automatic watering systems help to foster disease control by keeping foliage drier. These systems are also used for automated fertilizer application.

5. Water systems can be of the open type, in which water or nutrient solution is applied to the top of the root substrate and the excess drains from the bottom of the pot or bench to the environment, or they can be closed, in which no excess is released to the environment. Some typical open systems are perimeter watering and Turbulent Twin-Wall for cut flowers and tube, mat, overhead sprinkler, and boom watering for container plants. Closed systems include ebb-and-flood, trough culture, flood floor, and float for containerized plants as well as NFT and rock wool for cut flowers and vegetable fruit production. Fertilizer concentrations used in closed systems are usually about half those used in open systems.

6. Effluent runoff from open systems can be eliminated by the whole-firm recirculation system. Plants are grown in conventional containers and root substrate and conventional fertilizer solutions are applied to the surface of the substrate. Effluent from the bottom of the pots or beds throughout the entire firm is captured and directed to a single holding pond. The effluent is purged of suspended solids, pasteurized, tested, altered to correct the pH level and fertilizer concentrations, and then reused.

7. It is advisable to equip the greenhouse with dual water lines, one for water and the other for fertilizer. In this way, one can immediately switch from watering to fertilization or vice versa at any location in the greenhouse. It is also beneficial to control application of water or fertilizer solution by a sequential timer or a computer to eliminate the need for an employee to wait for each station of plants to be watered.

8. There are nine common systems in use for pasteurizing irrigation water and the plumbing system that delivers it to crops. These include sodium hypochlorite, calcium hypochlorite, chlorine gas, chlorine dioxide, peracids, ozone, UV radiation, copper ions, and heat. Considerations regarding which to use include initial and operational costs, whether they can be used for a shock treatment to purge residual microorganisms and organic matter in addition to a maintenance program, and whether they provide residual control of pathogens throughout the irrigation system beyond the point of introduction.

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Fertilization

Greenhouse fertilization has no equal in agriculture. Heavy plant growth is forced year-round under subtropical conditions. Root substrate volume is minimal by field standards and has no lower horizon, as in the field. In the field, the lower horizon catches leaching nutrients for subsequent plant uptake. As a result, nitrogen applications of 4,000 pounds are commonly applied to an acre of chrysanthemums in a year (3,600 kg/ha). Excessive levels and imbalances of fertilizer nutrients more often account for difficulties than deficiencies. Micronutrient deficiencies are a constant threat because of uptake antagonisms from other nutrients and possible occurrences of high substrate pH.

A typical plant is composed of about 90 percent water. The solid materials in the plant, commonly referred to as *dry weight*, are composed of 17 essential nutrient elements (Table 1) plus any of a number of nonessential elements that happen to be available in the root environment. Nearly 90 percent of the dry weight can be attributed to carbon, hydrogen, and oxygen—three essential elements that are not provided in a fertilization program but are obtained pursuant to other cultural procedures.

Carbon and oxygen are derived from carbon dioxide (CO_2) in the air, while oxygen and hydrogen are derived from water. Oxygen deficiency is usually a result of slow diffusion of air into the root substrate due to excessively high water content. Hydrogen deficiency is essentially nonexistent. Since only a small quantity of water is needed to provide hydrogen, water-stress injuries are usually related to factors other than hydrogen deficiency, such as reduction in photosynthesis caused by closing of stomates, by desiccation of cells, or by overheating of plant tissue due to insufficient transpiration.

The remaining 10 percent of the dry weight includes 14 essential elements. Two of these, chloride and nickel, are available in sufficient quantities in root substrate components or as contaminants in fertilizers to meet floral-crop needs. Thus, 12 elements must be applied in a fertilization program. These elements fall into two categories: (1) six macronutrients, which are present in the plant in large (macro) quantities, and (2) six micronutrients, which are present in small (micro) quantities.

Table 1
Essential Plant Nutrients, Related Chemical Symbols, Classification, and Typical Foliage Composition for Greenhouse Crops Expressed as a Percentage of the Leaf Dry Weight

Nutrient Element	Chemical Symbol	Classification	Typical Plant Content (% of Dry Weight)
Carbon	C	Nonfertilizer	41.0
Hydrogen	H	Nonfertilizer	6.0
Oxygen	O	Nonfertilizer	42.0
Nitrogen	N	Macronutrient, primary	4.0
Phosphorus	P	Macronutrient, primary	0.5
Potassium	K	Macronutrient, primary	4.0
Calcium	Ca	Macronutrient, secondary	1.0
Magnesium	Mg	Macronutrient, secondary	0.5
Sulfur	S	Macronutrient, secondary	0.5
Iron	Fe	Micronutrient	0.02
Manganese	Mn	Micronutrient	0.02
Zinc	Zn	Micronutrient	0.003
Copper	Cu	Micronutrient	0.001
Boron	B	Micronutrient	0.006
Molybdenum	Mo	Micronutrient	0.0002
Chloride	Cl	Micronutrient	0.1
Nickel	Ni	Micronutrient	0.0005

FERTILIZATION PROGRAMS

Until the middle of the 20th century, dry fertilizers such as dried blood, Milorganite, ammonium nitrate, muriate of potash, and superphosphate were applied monthly to the substrate surface in accordance with monthly soil tests. With the advent of automatic watering systems during the 1950s, it made sense to dissolve water-soluble fertilizer into the water during irrigation. In this way, a single investment provided automation for both water and fertilizer application.

Today, the standard practice is to dissolve high-analysis fertilizers into concentrated solutions. The concentrate is then proportioned, as needed, by means of a fertilizer injector into the greenhouse water line at the final concentration desired for crop application. This alleviates the need for a large tank to hold a single-strength solution. It also allows for proportioning the single concentrate out at different concentrations according to the requirements of various crops. Automatic watering systems connected to the greenhouse water line deliver the fertilizer solution to individual pots or to the soil surface in cut-flower or vegetable beds. Fertilizer is generally applied with each watering. (This practice is most common and is known as *fertigation.*) A smaller number of firms fertilize on a weekly basis but with higher concentrations of fertilizer.

Pre-Plant Fertilization

It is imperative that limestone is added to substrate prior to planting to set the desired pH level. Very few substrates have a naturally desirable pH level without limestone. Limestone can supply calcium and magnesium. While other nutrients are often mixed into substrate in a pre-plant fashion, their use is optional. The optional nutrients fall into four categories: phosphorus, sulfur, micronutrients, and nitrogen plus potassium.

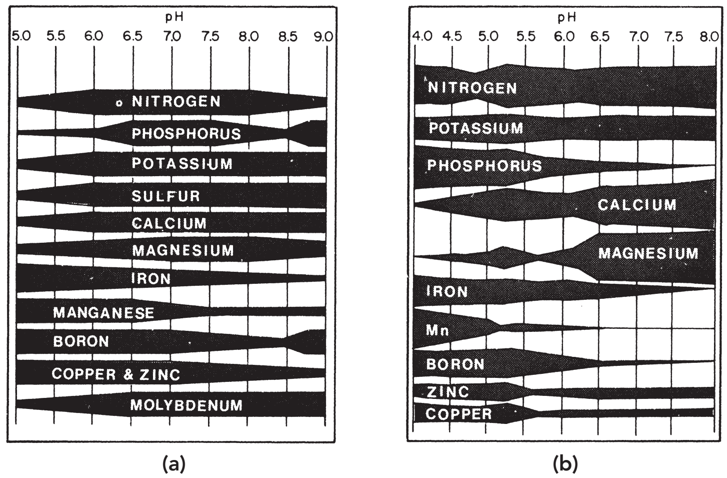

Figure 1
The influence of pH level on the availability of essential nutrients in (a) a mineral soil, and (b) a soilless root substrate containing sphagnum peat moss, composted pine bark, vermiculite, perlite, and sand.
(Photo a from Truog, 1948; photo b from Peterson, 1982.)

Limestone (Calcium and Magnesium) The generally desired pH ranges for most greenhouse crops are 6.2 to 6.8 for soil-based substrate and 5.4 to 6.6 for soilless substrate. Some crops, such as azalea and rhododendron, do well at lower levels, but very few require higher levels. Nutrient availability is controlled by the root substrate pH level, as illustrated in Figure 1. Low pH levels can result in excessive availability of iron, manganese, zinc, and copper; low availability of calcium and magnesium; increased leaching of phosphorus; and a higher sensitivity to high substrate levels of ammoniacal nitrogen (Figure 2). High pH levels, on the other hand, result in the tie-up of phosphorus, iron, manganese, zinc, copper, and boron. It is readily apparent from Figure 1 that the best compromise of nutrient availability lies in the pH range of 6.2 to 6.8 for soil-based substrate and in the range of 5.4 to 6.6 for soilless substrate. Soilless substrate pH levels up to 6.8 do not pose a great difficulty and may need to be accepted by growers with alkaline water. Higher-than-desired substrate pH levels dictate additional micronutrient application to compensate for their high pH tie-up. It is often stated in grower circles that more than half of nutritional problems are prevented when substrate pH is maintained properly.

A lower pH range is allowed in organic (soilless) substrate for two reasons. First, in organic substrate, there is less native iron, manganese, and aluminum to convert at low pH to a soluble form and thus become toxic or cause a phosphate tie-up. Second, higher quantities of calcium and/or magnesium are required in organic substrate to attain a given pH level; thus, a sufficient level of calcium and magnesium can be attained at a lower pH level.

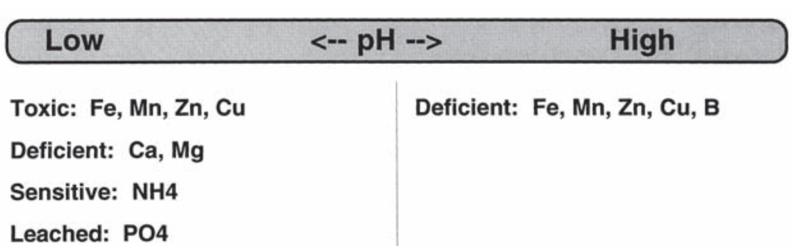

Figure 2
Nutrient disorders that occur as a consequence of excessively low or high substrate pH levels.

Most greenhouse root substrates tend to be acidic (low pH) due to the use of acidic amendments such as peat moss and pine bark. Agricultural limestone is used to raise the pH level.

Substrate pH cannot be treated in a singular fashion. Calcium and magnesium are intimately related to pH. Each factor that governs pH in greenhouse root substrates affects calcium and/or magnesium levels. The complicating issue here is that calcium and magnesium must be in balance. The ideal ratio of calcium to magnesium has not been precisely determined. Based on soil-test standards, a desirable range of ratios seems to extend from 3 to 5 ppm calcium for each 1 ppm magnesium in irrigation water as well as in the soil solution when determined by the saturated-paste procedure.

When calcium and magnesium are in balance in water, dolomitic limestone is the best material to use in the formulation of the substrate. The calcium-plus-magnesium content in the dolomitic limestone and in the irrigation water will ensure a proper balance throughout the crop. When magnesium is high relative to calcium in water, it is best to use calcitic limestone in the substrate. This will provide a large initial supply of calcium, which will help balance the excessive magnesium supplied throughout the crop in the irrigation water. If calcium is high relative to magnesium, one can use dolomitic limestone plus magnesium sulfate (Epsom salt) up to 1 lb/yd^3 (0.6 g/L) in the substrate. The extra magnesium supplied by Epsom salt will help balance subsequent excessive calcium derived from irrigation water. In all situations, it is important to monitor the nutrient status of the substrate with substrate tests to know when later adjustments in the calcium-to-magnesium ratio are required. It should be noted that injection of acid into irrigation water to reduce alkalinity does not lower the concentration of calcium and magnesium in that water.

Rates of addition vary between soil-based and soilless root substrate and are presented in Table 2. Depending on the initial pH level and the clay content, soil-based substrates can require from 0 to 10 pounds of dolomitic limestone per cubic yard (0 to 6 kg/m^3), while soilless substrates can typically require 5 to 10 pounds per cubic yard (3 to 6 kg/m^3). This is sufficient to provide the required calcium and magnesium as long as the pH level remains in the desired range. In general, 3 pounds of limestone per cubic yard (1.8 kg/m^3) of substrate will raise the pH about 0.3 to 0.5 units.

A bag of purchased limestone contains a range of particle sizes. The finer particles are known as *reactive limestone* because they dissolve rapidly to set the initial target pH of the substrate. The larger particles are known as *residual limestone* because they dissolve later to maintain the substrate pH. Maintenance of pH is necessary because plants continually acidify the substrate. Limestone recommendations generally refer to the agricultural grade. The finer pulverized, superfine, and micronized grades of limestone should not be used at the rates recommended for agricultural limestone. Most of the particles in these finer grades are in the reactive size category; thus, less of these limestones is required to reach the initial target pH. However, because these limestones have few particles in the larger residual category they do not maintain pH over time. When used at the rates given for agricultural limestone, the finer grades can raise the pH to levels of 7.5 and higher. Unfortunately, no national standard exists for the particle size distribution of agricultural limestone. North Carolina defines agricultural limestone by indicating that 90 percent will pass through a 20-mesh screen ($\frac{1}{20}$ or 0.05 in., 1.27 mm) and 35 percent will pass through a 100-mesh screen (0.01 in., 0.25 mm). Particles larger than 20 mesh dissolve slowly and are of little value during a typical greenhouse crop length. Each bag, regardless of the state, usually has the screen size indicated on it.

Table 2
NUTRIENT SOURCES COMMONLY ADDED TO ROOT SUBSTRATES DURING FORMULATION[1]

Nutrient Source	Rate per yd^3 (m^3) Soil-Based Substrates	Soilless Substrates
To Provide Calcium and Magnesium		
When a pH rise is desired:		
Dolomitic limestone	0–10 lb (0–6 kg)	5–10 lb (3–6 kg)
When no pH shift is desired:		
Gypsum for calcium	0–5 lb (0–3 kg)	0–5 lb (0–3 kg)
Epsom salt for magnesium	0–1 lb (0–0.6 kg)	0–1 lb (0–0.6 kg)
To Provide Phosphorus[2]		
Superphosphate (0-45-0)	1.5 lb (0.9 kg)	2.25 lb (1.3 kg)
To Provide Sulfur		
Gypsum (calcium sulfate)	1.5 lb (0.9 kg)	1.5 lb (0.9 kg)
To Provide Micronutrients: Iron, Manganese, Zinc, Copper, Boron, and Molybdenum		
Micromax	1–1.5 lb (0.6–0.9 kg)	1–1.5 lb (0.6–0.9 kg)
Pro-Max	1–1.5 lb (0.6–0.9 kg)	1–1.5 lb (0.6–0.9 kg)
F-555HF	3 oz (112 g)	3 oz (112 g)
To Provide Nitrogen and Potassium (optional)		
Calcium nitrate	1 lb (0.6 kg)	1 lb (0.6 kg)
Potassium nitrate	1 lb (0.6 kg)	1 lb (0.6 kg)

[1]Rates in this table are for crops other than seedlings. Only limestone is necessary in seedling substrates. Optional nutrient sources for seedling substrate include up to 1 lb (0.6 kg) each of superphosphate, gypsum, and calcium nitrate; no potassium nitrate; and the low end of the rate range for micronutrients.
[2]These are maximum rates designed to supply phosphorus for three to four months if pH is maintained in a desirable range for the crop and the leaching percentage is at or below 20 percent.

Neutral substrates can result when alkaline (high-pH) components such as hardwood bark are used along with acidic components such as peat moss or pine bark. Limestone is not used in these substrates due to the threat of excessively high pH. Such substrates should be tested. If the calcium or magnesium levels are low, these nutrients can be supplied by incorporating calcium sulfate (gypsum) or magnesium sulfate (Epsom salt) into the substrate during its formulation at rates up to 5 lb/yd^3 and 1 lb/yd^3 (3 kg/m^3 and 0.6 kg/m^3), respectively. These two salts do not affect the pH of substrates.

Sulfate for pH Reduction It is rare that a downward adjustment in substrate pH is required. Substrates most likely to require such correction are those that are alkaline-soil based. Insoluble elemental sulfur as well as soluble iron sulfate and aluminum sulfate can be used for this purpose. Quantities are presented in Table 3. The sulfates work immediately upon wetting to form sulfuric acid. The elemental sulfur must be microbially oxidized to sulfate before it turns into sulfuric acid and takes effect. Depending on temperature and substrate oxygen levels, this can take from a few to several weeks.

Phosphorus A pre-plant rate of 1.5 pounds treble superphosphate (0-45-0) per cubic yard (0.9 kg/m^3) is common for soil-based substrates and 2.25 pounds (1.35 kg/m^3) for soilless substrates (Table 2). These are the upper rates to be used to provide all of the phosphate for the entire crop length through the pre-plant application.

Complete fertilizers potentially contain the three primary macronutrients—nitrogen, phosphorus, and potassium—and are labeled with a numerical grade such

Table 3
QUANTITIES OF SULFUR, IRON SULFATE, OR ALUMINUM SULFATE NECESSARY TO LOWER THE pH LEVEL OF GREENHOUSE ROOT SUBSTRATE FROM VARIOUS LEVELS TO 5.0[1]

	Sulfur		Iron Sulfate or Aluminum Sulfate	
pH Change	lb/yd^3	kg/m^3	lb/yd^3	kg/m^3
8.0 to 5.0	3.5	2.1	8.75	5.2
7.5 to 5.0	3.25	1.9	7.75	4.6
7.0 to 5.0	2.5	1.5	6.5	3.9
6.5 to 5.0	2.0	1.2	5.25	3.1
6.0 to 5.0	1.5	0.9	3.75	2.2
5.5 to 5.0	0.75	0.5	2.0	1.2

[1]Adapted from Tayama (1966).

as 10-5-10. The first number indicates the percentage of elemental nitrogen (N), the second indicates the percentage of phosphate expressed in the oxide form (P_2O_5), and the third indicates the percentage of potassium, also expressed in the oxide form (K_2O). A very common fertilizer grade used in the greenhouse is 20-10-20.

Pre-plant phosphate will last for the length of the crop only when the leaching percentage is low, 20 percent or less, and when the substrate pH is held in the recommended ranges stated earlier. *Leaching percentage* refers to the percentage of the water or fertilizer applied to the top of the root substrate that passes out through the bottom of the substrate. If 10 fluid ounces are applied and 2 fluid ounces drain from the bottom of the pot, the leaching percentage is 20 percent. Phosphate is held in substrates mainly on clay particles. For this reason, a single pre-plant phosphate application can last a year or more in a soil-based substrate. Since soilless substrates rarely contain clay, phosphate rapidly leaches from these substrates. Leaching increases with increasing leaching percentage and with decreasing substrate pH. One should never depend on pre-plant phosphate to last for the entire crop length. Soil tests are necessary to determine if and when phosphate runs out. Subsequent post-plant applications of phosphate may be required.

When a grower intends to incorporate phosphate into the continuous liquid, post-plant fertilizer program, it is not necessary to incorporate pre-plant phosphate into the substrate. Post-plant phosphate is sufficient. However, some phosphate, less than the upper quantities previously recommended, is almost always incorporated into substrates as an insurance policy. The phosphate source is most often superphosphate, but it need not necessarily be. Commercial root substrate formulators more commonly spray water-soluble salts such as monoammonium phosphate onto the substrate prior to mixing to better ensure uniform distribution. Any of a number of calcium, potassium, or ammonium phosphate salts can be used dry or dissolved for the pre-plant phosphate source. The phosphate source in superphosphate is monobasic calcium phosphate and is water soluble.

Sulfur In the past, sulfur was incorporated into nearly all substrates through the application of single superphosphate (0-20-0). Although superphosphate was applied for its phosphate source, it supplied sulfur as well. Single superphosphate is approximately 50 percent gypsum (calcium sulfate). Single superphosphate is rarely available today and has been replaced by triple superphosphate (0-45-0), which does not contain gypsum.

When sulfur is desired, it can be supplied by incorporation of 1.5 pounds of gypsum into each cubic yard (0.9 kg/m^3) during substrate formulation (see Table 2). This is a moderately soluble salt that will generally leach from the substrate within a month. Yet, such an application can be effective because more sulfur than is required can accumulate in the early stages of plant growth. Later, the extra sulfur is translocated and utilized by newly forming plant tissue when substrate sulfur is low. Sulfur is a partially mobile nutrient in the plant. It is important to monitor sulfur in the plant tissue throughout crop production to ensure that the quantity taken up from the pre-plant application does not run out.

Micronutrients The preceding amendments—limestone, superphosphate, and gypsum—provide 4 of the 12 essential fertilizer nutrients. Six more—the micronutrients iron, manganese, zinc, copper, boron, and molybdenum—can be applied by one of three different strategies. A single application can be made with one of several commercial pre-plant micronutrient mixtures available for solid incorporation during root substrate formulation (Table 2). Some examples follow. Pro-Max (Frit Industries, Inc., Ozark, AL 36361-1589) and Micromax (The Scotts Co., Marysville, OH 43041) are mixtures of micronutrient salts. Frit-F-555HF trace element mix (Frit Industries, Inc., Ozark, AL 36361-1589) is a mixture of slowly soluble nutrients in oxide form. There are other pre-plant products in which micronutrients have been incorporated into a mix containing macronutrients, leaving only the possible need for limestone during formulation. Two products are Greencare 4-3-14 Soil Mix Charge (Greencare Fertilizers, Kankakee, IL 60901 www.blackmore.com/greencare.html) and Scotts 11-5-11 Uni Mix (The Scotts Co.). Barring adversely high pH levels, all of these micronutrient applications can last up to one year.

A second alternative strategy for micronutrient application involves a single liquid application after planting. CHEMEC (Plant Marvel Laboratories, Inc., Chicago Heights, IL 60411 www.plantmarvel.com), CHL-MIM (Frit Industries, Inc.), Microplex (Miller Chemical and Fertilizer Corp., Hanover, PA 17331) and Water-Soluble Micronutrient Blend (Greencare Fertilizers) contain chelated micronutrients. The latter product is also available in partially chelated or nonchelated form. STEM (The Scotts Co.) and Sol-Trace (Plant Marvel Laboratories, Inc.) contain micronutrient salts. These products generally provide micronutrients for three to four months.

The third alternative micronutrient application system calls for a low concentration of micronutrients to be applied along with each application of complete liquid fertilizer. Most commercially prepared complete fertilizers contain the six micronutrients. Growers who make their own fertilizers can purchase micronutrient packages to add into their complete fertilizer. Masterblend International LLC, 29400 Rt. 53, Elwood, IL 60421 (www.masterblend.com) contains chelated micronutrients. Other products listed earlier under the second strategy can be used at low rates toward this purpose, as indicated on their labels.

The quantity of micronutrients required for a crop depends in greatest measure on substrate pH. The requirement goes up with increasing pH. When pH is maintained in the recommended ranges—that is, 6.2 to 6.8 for soil-based and 5.4 to 6.6 for soilless substrates—any one of the three micronutrient strategies can be used alone. When the upper end of the desired pH range is encountered, a combination of two sources becomes necessary; for example, micronutrients may be added as a pre-plant addition in the substrate and as a component of the complete post-plant fertilizer. As pH increases further, it may become necessary to use a third micronutrient source such as a single soluble application. Micronutrient increases can even go a step further. Complete fertilizer formulations are available with standard or super-high levels of micronutrients. Those with super-high levels carry names such as "peat-lite special" and "plus" and are designed for soilless substrates. While standard fertilizers will typically supply about 0.25 ppm iron per 100 ppm nitrogen applied, the high micronutrient fertilizers will supply 0.5 to 1.0 ppm iron per 100 ppm nitrogen. The high micronutrient fertilizers also provide higher levels of the remaining micronutrients. Actually, the high micronutrient fertilizers can be looked upon as a fourth alternative for increasing the level of micronutrient addition to a crop.

If maintaining substrate pH in the recommended range makes supplying micronutrients so easy, why do so many firms operate at higher substrate pH levels? Some erroneously feel that soilless substrate pH should be the same as soil-based substrate—that is, above 6.0. Others agree with the lower recommended pH ranges but can't keep the levels down because of alkalinity in their water. It is more economical to allow the substrate pH to rise and then fight the high pH problem with increased micronutrient applications. Regardless of the micronutrient addition strategy used, the crop should be carefully monitored through foliar analysis to determine when upward or downward adjustments in micronutrient application are needed.

Nitrogen and Potassium The previous four categories of pre-plant nutrient addition are practiced by most growers. A fifth category is optional. A two-week supply of nitrogen and potassium can be provided by 1 pound each of calcium nitrate and potassium nitrate in 1 cubic yard of substrate (0.6 kg each/m^3) (Table 2). The pre-plant rate is kept low because a larger amount would raise the soluble salts to an excessive level in the substrate. When nitrogen and potassium are left out of the root substrate, seedlings or cuttings can be fertilized with a complete fertilizer on the day of planting. This practice will immediately establish sufficient levels of these nutrients. The problem of uniform mixing of potentially damaging fertilizers during root substrate formulation is thereby eliminated. Commercial substrates may be purchased with or without nitrogen, phosphorus, and potassium. Most contain these nutrients. More often, when these nutrients are included, growers use water at the first irrigation after planting and begin their fertilizer program at the second irrigation. However, other growers begin fertilization with the first irrigation, and generally do not experience toxicity problems.

Post-Plant Fertilization

Post-plant fertilizer is most often applied as a liquid and nearly always contains nitrogen and potassium or nitrogen, phosphate, and potassium. Application begins at planting or with the second irrigation.

Fifty or more complete greenhouse fertilizers are on the market, and a similar number of formulas are available for growers who make their own fertilizers. One can be intimidated when trying to decide which of these formulas to use. This need not be the case if nine simple decisions are made. The first two pertain to the concentration of fertilizer required, and the next seven provide the criteria for selecting the best fertilizer formula. These follow.

1. ***Frequency of Application*** Two frequencies of post-plant application are most common. The first, and most popular, is fertigation, in which fertilizer solution is applied at a dilute concentration during each irrigation. The second is a weekly application of a more concentrated fertilizer solution. In this latter program, fertilizer solution should not be applied precisely on every seventh day but rather should average a seven-day frequency over time. There will be times when the substrate has not sufficiently dried on the seventh day. To fertilize on that day would lead to excessively wet substrate and, consequently, insufficient aeration for the roots. The fertilization scheme for bedding plants is somewhat of a hybrid of the

Table 4
Quantities of a 20 Percent Nitrogen Fertilizer to Dissolve in 100 Gallons of Water and Resulting Nitrogen Concentrations Required for Fertigation and Weekly Application for Several Crops[1]

Crop	Concentration Category	Fertigation oz/100 gal	Fertigation ppm N (mg N/L)	Weekly oz/100 gal	Weekly ppm N (mg N/L)
Daffodil	None	—	—	—	—
Iris	None	—	—	—	—
Hyacinth	None	—	—	—	—
Tulip[2]	Very light	—	—	—	—
Snapdragon	Very light	6	90	16	240
Bedding plants	Very light	13.5	200	16	240
Elatior begonia	Very light	8.5	130	17	255
Azalea	Light	—	—	20	300
Gloxinia	Light	13.5	200	24	360
Rose	Moderate	10	150	32	480
Carnation	Moderate	13.5	200	32	480
Geranium	Moderate	13.5	200	32	480
Easter lily	Moderate	13.5	200	32	480
Chrysanthemum	Heavy	13.5	200	40	600
Poinsettia	Heavy	17	255	40	600

[1]Rates are for any fertilizer containing 20 percent nitrogen. Use one-third more if the fertilizer contains 15 percent nitrogen and one-fifth less if it contains 25 percent nitrogen. (1 oz 20 percent nitrogen fertilizer/100 gal = 15 ppm nitrogen.)
[2]As an insurance against nitrogen and calcium deficiencies, calcium nitrate should be applied at the rate of 32 oz/100 gal (2.4 g/L) at the start and at the midpoint of the growth-room stages and at the start of greenhouse forcing.

two systems. While a fertigation rate of 100 to 150 ppm nitrogen is applied when rapid growth is desired, there are many times when growth needs to be slower. When marketing is delayed due to cool or rainy weather, applications of fertilizer will be omitted as required to slow development of the crop.

Equal-quality crops can be grown under the fertigation and weekly schedules. The decision is based on labor considerations. In a small firm where a fertilizer injector and tank of fertilizer concentrate must be moved throughout the greenhouses and connected to one bench at a time, it is more convenient to fertilize weekly. In large firms where the fertilizer injector is plumbed into the main water line, it is easiest to fertilize at every irrigation. To do otherwise would require continuous switching of the system between fertilizer and water, purging of lines, and tedious record keeping.

2. ***Rate of Nitrogen*** Once the frequency of application is known, the concentration of nitrogen to apply should be established. This rate is based on the crop to be grown. Concentrations of nitrogen for weekly application are presented in Table 4 and range from 240 ppm to 600 ppm. Aside from the bulb crops listed in Table 4, all crops fit into one of four nitrogen-concentration categories. These categories and their nitrogen concentrations are as follows: very light, 240 ppm; light, 360 ppm; moderate, 480 ppm; and heavy, 600 ppm. Lower fertilizer concentrations are used when applied with each irrigation (Table 4). Many growers determine the concentration required by monitoring the substrate soluble salt level. The desired soluble salt concentration ranges for each of three categories of crops fertilized at each irrigation are presented in Table 5. Good starting points for nitrogen in the fertilizer for the light, medium, and heavy fertilized crop categories are 100 to 150 ppm, 175 to 225 ppm, and 250 to 300 ppm, respectively.

Table 5
Desirable Substrate EC Ranges That Indicate Proper Fertilization for Individual Actively Growing Greenhouse Crops[1]

No Additional Fertilizer Required

Amaryllis	
Crocus	
Narcissus	

Light
SME EC of 0.76 to 2.0 mS/cm
PourThru EC of 1.0 to 2.6 mS/cm

Aconitum	Coleus
African Violet	Cosmos
Ageratum	Cuttings (during rooting)
Anemone	Cyclamen
Anigozanthos	Freesia
Asclepias	Geranium (seed)
Aster	Gerbera
Astilbe	Gloxinia
Azalea	Impatiens
Balsam	Marigold
Begonia (fibrous)	New Guinea Impatiens
Begonia (Hiemalis)	Orchids
Begonia (Rex)	Pansy
Begonia (tuberous)	Plugs
Caladium	Primula
Calceolaria	Salvia
Calla Lily	Streptocarpus
Celosia	Snapdragon
Cineraria	Zinnia

Medium
SME EC of 1.5 to 3.0 mS/cm
PourThru EC of 2.0 to 3.5 mS/cm[1]

Alstroemeria	Kalanchoe
Alyssum	Larkspur
Bougainvillea	Lily, Asiatic, and Oriental
Calendula	Lily, Easter
Campanula	Lobelia
Cactus, Christmas	Morning Glory
Carnation	Onion
Cauliflower	Ornamental Kale
Centaurea	Ornamental Pepper
Cleome	Oxalis
Clerodendrum	Pepper
Crossandra	Petunia
Dahlia	Phlox
Dianthus	Platycodon
Dusty Miller	Portulaca
Exacum	Ranunculus
Geranium (cutting)	Rose
Hibiscus	Sunflower (potted)
Hydrangea	Tomato
Jerusalem Cherry	Verbena

Heavy
SME EC of 2.0 to 3.5 mS/cm
PourThru EC of 2.6 to 4.6 mS/cm

Chrysanthemum	
Poinsettia	
Vegetative Petunia	

[1]From Whipker et al. (2000). Separate values are presented for the SME (saturated media extract, also known as saturated paste) and the PourThru (or press) extract substrate tests. EC values in this table are based on programs in which fertilizer is applied with each irrigation.

Although common fertilizers in use today contain 20 percent nitrogen, such as 20-10-20, fertilizers with other nitrogen concentrations can be used equally well. When using fertilizers with 15 percent nitrogen, such as 15-0-15, 15-16-17, and 15-5-25, growers should use one-third more to achieve the same nitrogen concentration. If applying fertilizers with 25 percent nitrogen, they should use one-fifth less.

3. ***Proportion of Potassium (K_2O)*** The first criterion for selecting a fertilizer analysis is the amount of potassium needed relative to nitrogen. Most crops develop well on a fertilizer equally balanced in nitrogen and potassium-K_2O. Thus, fertilizers such as 20-10-20, 20-9-20, 20-0-20, 13-2-13, and 15-0-15 are among the most commonly used. There are a few exceptions (Table 6). Azalea develops best when the ratio is 3 parts nitrogen to 1 part potassium; 21-7-7 fertilizer is almost universally used for azalea. Elatior begonia grows faster and develops more side shoots when it is fertilized with a ratio of 2 parts nitrogen to 1 part potassium. The preference for nitrogen is slightly greater than potassium for foliage plants in general. The carnation requirement is quite different: A ratio of 1 part nitrogen to 1.5 parts potassium is favored. The greatest requirement for potassium is seen in cyclamen, where a

Table 6
THE BEST RATIOS OF NITROGEN-N TO POTASSIUM-K_2O FOR GREENHOUSE CROPS

N:K_2O					
3:1	2:1	1.5:1	1:1	1:1.5	1:2
Azalea	Begonia	Foliage plants	General crops	Carnation	Cyclamen

ratio of 1 part nitrogen to 2 parts potassium is best. A fertilizer such as 15-10-30 serves this crop well.

As time passes, the balance of nitrogen and potassium in the root substrate can change. Many fertilizer ratios are commercially available that can be used temporarily to reestablish the desired ratio.

4. ***Proportion of Phosphate-P_2O_5*** The second criterion for selecting a fertilizer analysis is the amount of phosphate required relative to nitrogen. When there is no pre-plant phosphate in the substrate, post-plant fertilizers containing half as much phosphate (expressed as P_2O_5) as nitrogen (N) will supply more than sufficient phosphate to meet greenhouse crop needs. This level is well met by fertilizers such as 20-10-20 and 20-9-20. In all probability, lower levels of phosphate will be used in the future, as greenhouse nutrient effluent is further reduced. The lowest level of fertilizer phosphate permissible is not clearly known. A light phosphorus deficiency is sometimes used to produce deep-green, compact plants, especially for seedlings and bedding plants. This is achieved by leaving phosphate out of the pre-plant addition and supplying 10 to 15 percent as much phosphate as nitrogen in the post-plant fertilizer. Fertilizer with a 13-2-13 analysis is a good example of such a fertilizer; here, the second number for P_2O_5 (2) is only 15 percent as large as the first number for nitrogen (13).

When pre-plant phosphate is supplied to soil-based substrates, post-plant phosphate can usually be omitted. However, when pre-plant phosphate is supplied to soilless substrates, it is important to conduct periodic soil tests to determine if and when leaching loss becomes sufficient to necessitate phosphate addition in the post-plant program.

5. ***Form of Nitrogen*** At this point, it would appear that an effective greenhouse fertilizer has been defined as a 2:1:2 ratio or a 20-10-20 analysis. This is true, except that the form of nitrogen has not been determined. There are three common water-soluble fertilizer forms of nitrogen: ammonium, urea, and nitrate. Selection of which to use is the third criterion for selecting a fertilizer analysis. Choice of nitrogen form is based on two effects of these forms: threat of ammonium toxicity and influence on root substrate pH. Before discussing each, it is important to realize that ammonium and urea have similar effects in each of these two considerations, while nitrate acts very differently. Urea is similar to ammonium because urea is split into ammonium and carbon dioxide in the root substrate by a urease enzyme from microorganisms or within the plant by plant urease. In either event, it is ultimately ammonium that is utilized in the plant.

Ammonium toxicity can occur when plants are supplied more nitrogen than the minimum required. Luxuriant nutrient uptake is the common situation in greenhouse crops. Plants can safely store vast quantities of nitrate, but not ammonium. To reduce the probability of ammonium toxicity, it is important to keep the proportion of total nitrogen in ammonium-plus-urea forms below a critical level. Unfortunately, the critical level varies. However, 40 percent of total nitrogen in ammonium-plus-urea forms would appear to be safe in nearly all situations. Symptoms of ammonium toxicity can be seen in Color plate 2.

Actually, all nitrogen could be in ammonium form if no extra nitrogen were supplied to the crop. In this case, all nitrogen would be assimilated by the plant into organic form and little or none stored as ammonium. The second factor controlling the proportion of nitrogen permissible in ammonium-plus-urea forms in fertilizer is the activity of nitrifying bacteria in the substrate. These bacteria convert ammonium to nitrate. The higher their activity, the higher the proportion of permissible fertilizer ammonium. Nitrifying bacteria are suppressed by cooler winter substrate temperatures, anaerobic conditions in overly wet substrate, and low substrate pH. The best pH for nitrifying bacteria is just above 7.0. Activity is acceptable at pH levels down to 6.0. At levels below 6.0, which often occur in soilless substrates, crops become very susceptible to ammonium toxicity.

During the early decades of liquid fertilizer injection in greenhouses, the most common fertilizer was 20-20-20. After 1970, when soilless substrates became well accepted, this fertilizer was replaced with 20-10-20. The reason was undoubtedly the shift from 70 percent of nitrogen in ammonium-plus-urea form in 20-20-20 to 40 percent in 20-10-20. Under the higher pH levels in soil-based substrates, ample quantities of ammonium were converted to nitrate, but this was not the case at the frequently lower pH levels in soilless substrates. The 50 percent reduction of phosphate in 20-10-20 was not a problem because the level in 20-20-20 was higher than needed.

Root substrate pH is the second effect of nitrogen to consider when deciding upon the form to use in a fertilizer. Generally speaking, ammonium and urea tend to lower the substrate pH, while nitrate tends to raise pH. The commercial fertilizers listed in Table 7 are arranged from the most acidic at the top to the most basic (alkaline) at the bottom. Note that the percentage of nitrogen in the ammonium-plus-urea forms tends to diminish from the top to the bottom of the table. Fourteen nutrient sources used for making fertilizers are listed in Table 8, along with the potential acidity or basicity of each.

Plants that grow well in highly acidic root media, such as azalea and rhododendron, develop best on a high proportion of ammonium nitrogen. It is interesting to note that when acid-tolerant plants such as azalea are grown at pH levels adversely low for them, nitrate becomes the preferred nitrogen form. This is fortuitous, since the use of nitrate raises the pH.

When positively charged ions (*cations*) such as ammonium, potassium, sodium, and magnesium are taken up by plants, positive hydrogen ions (H^+) are released. This release lowers the substrate pH. Conversely, when negative ions (*anions*) such as nitrate, phosphate, sulfate, or chloride are taken up, hydroxide (OH^-) is often released by the plant. Hydroxide release causes a rise in substrate pH by eliminating H^+, as seen in equation 1. Alternatively, anion uptake can be associated with the simultaneous uptake of a H^+ ion, in which case substrate pH rises due to the loss of H^+. Anion uptake may also be associated with release of a bicarbonate ion (HCO_3^-) from the root. Bicarbonate will also tie up a H^+ ion, causing a rise in substrate pH, as shown in equation 2. In all three responses to root uptake of an anion, the net effect is a loss of hydrogen ions (acidity) in the substrate.

$$OH^- + H^+ \rightarrow H_2O \tag{1}$$

$$HCO_3^- + H + \ \rightarrow H_2CO_3 \rightarrow H_2O + CO_2 \tag{2}$$

Since it is the relative uptake of all cations to all anions that determines substrate pH, nitrogen ions alone do not control pH. However, more nitrogen ions are

Table 7
A List of Several Commercially Available Fertilizers Along with the Percentage of Total Nitrogen in Ammonium-Plus-Urea Form, the Potential Acidity or Basicity of Each, and the Percentage of Calcium (Ca), Magnesium (Mg), and Sulfur (S) Wherever These Are 0.2 Percent or Greater

Fertilizer	NH_4[1] (%)	Potential Acidity[2]	Potential Basicity[3]	Ca (%)	Mg (%)	S (%)
21-7-7 (acid)	90	1,700				
21-7-7 (acid)	100	1,560		—	—	10.0
24-9-9	50	822		—	1.0	2.2
20-2-20	69	800				
20-18-18	73	710		—	—	1.4
24-7-15	58	612		—	1.0	1.3
20-18-20	69	610		—	—	1.0
20-20-20	69	583				
20-9-20	42	510		—	—	1.4
20-20-20	69	474				
16-17-17	44	440		—	0.9	1.3
20-10-20	40	422				
21-5-20	40	418				
20-10-20	38	393				
20-8-20	39	379		—	0.9	1.2
21-7-7 (neutral)	100	369				
15-15-15	52	261				
17-17-17	51	218				
15-16-17	47	215				
15-16-17	30	165				
20-5-30	56	153				
17-5-24	31	125		—	2.0	2.6
20-5-30	54	118		—	0.5	—
17-4-28	31	105		—	1.0	2.2
20-5-30	54	100				
15-11-29	43	91				
15-5-25	28	76		—	1.3	—
15-10-30	39	76				
20-0-20	25	40		5.0	—	—
21-0-20	48	15		6.0	—	—
20-0-20	69	0	0	6.7	0.2	—
16-4-12	38		73			
17-0-17	20		75	4.0	2.0	—
15-5-15	28		135	5.0	2.0	—
13-2-13	11		200	6.0	3.0	—
14-0-14	8		220	6.0	3.0	—
15-0-15	13		319	10.5	0.3	—
15.5-0-0 (calcium nitrate)	6		400	22.0	—	—
15-0-15	13		420	11.0	—	—
13-0-44 (potassium nitrate)	0		460			

[1]NH_4 (%) refers to the percentage of total nitrogen in ammonium-plus-urea form; the remaining nitrogen is nitrate.
[2]Pounds of calcium carbonate limestone required to neutralize the acidity caused by using 1 ton of the specified fertilizer (divide potential acidity or potential basicity values by 2 to convert to kg limestone per metric ton).
[3]Application of 1 ton of fertilizer has the effect of this many pounds of calcium carbonate limestone.

taken up than all other ions combined. Thus, the form of nitrogen supplied in a fertilization program tends to predict the pH effect. This is the reason the transition from ammonium-plus-urea at the top of Table 7 to nitrate at the bottom is not completely smooth. Urea has a similar effect to ammonium because urea is converted to ammonium in the substrate or in the plant prior to its assimilation.

Table 8
EFFECT OF VARIOUS NUTRIENT SOURCES ON THE pH LEVEL OF ROOT SUBSTRATE[1]

Source	Potential Acidity[2]	Potential Basicity[3]
Ammonium sulfate	2,200	
Urea	1,680	
Diammonium phosphate	1,400	
Ammonium nitrate	1,220	
Monoammonium phosphate	1,120	
Monopotassium phosphate[4]	0	0
Superphosphate	0	0
Potassium chloride	0	0
Potassium sulfate	0	0
Calcium nitrate		400
Dipotassium phosphate[4]		420
Potassium nitrate		520
Sodium nitrate		580
Magnesium nitrate[4]		670

[1]From Mortvedt and Sine (2002).
[2]Pounds of calcium carbonate limestone required to neutralize the acidity caused by using 1 ton of the specified fertilizer (divide potential acidity or potential basicity values by 2 to convert to kg limestone per metric ton).
[3]Application of 1 ton of fertilizer has the effect of this many pounds of calcium carbonate limestone.
[4]From manufacturer.

When a rapid decline in substrate pH is desired, a fertilizer such as 20-18-20, with a high potential acidity of 610 pounds of calcium carbonate equivalent (Table 7), can be used. Application of 1 ton of this fertilizer theoretically causes acidification that requires application of 610 pounds of calcium carbonate limestone to restore the original pH (305 kg/metric ton). Substrate pH decline would be much slower with a 15-16-17 fertilizer having a potential acidity of 165 pounds of calcium carbonate equivalent. Under extremely basic situations, growers will apply one or two applications of 21-7-7 azalea fertilizer with its potential acidity of 1,700 pounds of calcium carbonate equivalency (850 kg/metric ton). The 15-0-15 fertilizer with a potential basicity of 420 pounds of calcium carbonate equivalency will rapidly raise substrate pH. Application of 1 ton of this fertilizer is equivalent to the application of 420 pounds of calcium carbonate limestone (210 kg limestone/metric ton of fertilizer). These pH shifts are the result of plant uptake of fertilizer and not of the mere presence of fertilizer in the substrate.

In summary, a grower must consider the following factors when selecting the form of nitrogen to use in a fertilizer: First, if a decline in substrate pH is needed, acidic fertilizers should be used. Most, but not all, of these will have more than 20 percent nitrogen in the ammonium-plus-urea forms. Second, the total amount of nitrogen in the ammonium-plus-urea forms must not be excessive, generally 40 percent or less. Growers in northern climates will have to use a smaller proportion of ammoniacal nitrogen in the winter, due to their cooler soil temperatures, than those in warmer climates.

6. *Secondary Macronutrients* The fourth criterion for selecting a fertilizer analysis is its secondary macronutrient content. Many greenhouse fertilizers contain one or more of the secondary macronutrients (calcium, magnesium, and sulfur) (Table 7). If one or more of these nutrients become deficient during production of a crop, an easy way to restore the nutrients is to switch to a complete fertilizer that contains them. This points out once again the importance of monitoring the nutritional status of the crop through either soil testing or foliar analysis. As pointed out earlier, a decline in root substrate pH can result in loss of calcium and magnesium from the substrate. Fertilizers such as 15-5-15 (5 percent Ca, 2 percent Mg) and 13-2-13 (6 percent Ca, 3 percent Mg) contain both of these nutrients in balance. Use of either of these would raise the substrate level of both nutrients in proper proportion while continuing to provide the three primary macronutrients. If calcium is found to be low relative to magnesium, a 20-0-20 (5 percent Ca) fertilizer could be used to supply calcium without significant magnesium. Once the proper root substrate calcium-to-magnesium balance is restored, the 20-0-20 fertilizer could be discontinued and the previous fertilizer resumed. A shortage of sulfur could be corrected by switching to 20-9-20 (1.4 percent S) fertilizer. In all of these suggested corrective procedures, the 1:1 N-to-K_2O ratio and the nitrogen concentration remain constant.

7. ***Micronutrients*** The fifth criterion for selecting a fertilizer analysis is its micronutrient content. Most greenhouse fertilizers contain the six fertilizer micronutrients at "standard" concentrations. A few fertilizers are offered with no micronutrients, while several others are offered with higher-than-standard concentrations. This points out the need to read fertilizer labels. Availability of micronutrients is very high in substrates with a low pH level. In this situation, it might be best to have no micronutrients in the fertilizer if the root substrate has a micronutrient charge in it. At a very high substrate pH, micronutrients are tied up. In this situation, it might be best to have a fertilizer with a higher-than-standard concentration of micronutrients. The best test for the micronutrient status of a crop is foliar analysis. This further supports the necessity of having a crop nutrient monitoring system.

8. ***Finish Fertilization*** Nitrogen status at the end of the crop determines to a large degree the plants' post-production longevity and resistance to handling injuries. Plants stand up better to handling when nitrogen is low at the end of the crop. Nitrogen is generally reduced by reducing the total fertilization program. The specific steps to take depend on a soil analysis about two weeks before the end of the crop. If substrate analysis indicates that nitrogen is in the mid-to-high end of the optimum range, fertilization can be discontinued for the last two weeks of production. If nitrogen is in the low-to-mid end of the optimum range, fertilization can be cut in half for the last two weeks. This may be done by reducing the fertilizer concentration by half or by applying full-strength fertilizer at half the frequency. If nitrogen is found deficient, it would be best to continue fertilization up to the market date.

9. ***Daniels Soybean Extract Fertilizer*** A relatively recent addition to the greenhouse fertilizers occurred in 1997 with the introduction of Daniels 10-4-3 liquid fertilizer. The base for this fertilizer is derived from soybean seed. After roasting and crushing, oils are extracted from the seeds to yield high-value cooking (edible) oil as well as animal feed oils. The remaining material is divided into two fractions, solid material containing fiber and protein used for animal feed and oil seed extract. Oil seed extract is the water-soluble portion of the seeds. It contains minerals and the water-soluble compounds that include amino acids, organic acids, and sugars, among many other compounds. Unless converted to fertilizer, oil seed extract constitutes a disposal challenge requiring treatment to reduce carbon and nitrogen content by microbially volatizing these and ultimate discharge of remaining minerals, particularly P, into the environment. For fertilizer production purposes, additional inorganic nutrients are added to the oil seed extract to bring it to the guaranteed analysis. For this reason, it is not an organic fertilizer. Its final N composition includes 3.70 percent NH_4^+-N, 1.90 percent NO_3-N, 3.65 percent urea-N, and 0.75 percent organic N. This fertilizer could also be produced from other types of oil seeds such as sunflower,

corn, and canola. Environmental benefits of conversion of waste oil seed extract into fertilizer include less discharge of seed extract to the environment, less mining of phosphate and potassium minerals, and less natural gas burned to produce ammonia, the base nitrogen stock in most fertilizers.

Initially perceived problems associated with the fertilizer included the following. Could one unusual fertilizer analysis serve the requirements of a wide range of greenhouse crops? Would it provide sufficient potassium? Would its high proportion of ammoniacal and urea nitrogen lead to ammonium toxicity? Years of grower acceptance and extensive research at North Carolina State University and other institutions have shown that these concerns are not a problem.

Growers who have adopted this fertilizer indicate they have done so for reasons of ease of handling and for plant growth characteristics. Daniels is a liquid, which eliminates dissolving fertilizer. As a concentrate, it can be applied through fertilizer injectors without dilution. This single analysis is used for most crops. Plant characteristics include a tendency for compactness in the form of shorter stem internodes and lower tendency for rampant leaf expansion that can cause plants to out-grow containers such as plug trays, bedding plant flats, and container gardens. Deeper green foliage has been reported to often occur with the compactness. Earlier flowering of some species has been noted in research reports. Buffering of pH in the root substrate has also been reported. Additions of organic materials to substrate frequently results in pH buffering. This is thought to be due in part to increased cation exchange capacity resulting from the humic substances contributed by the organic matter. This would be one explanation for the resistance of Daniels fertilizer to ammonium toxicity, that is, more nitrifying bacteria at the higher pH level to convert ammonium to nitrate.

Although the reasons for Daniels fertilizer's effects on plant growth and substrate pH are not known, it would be reasonable to associate them with the impact of the fertilizer's biodegradable carbon content on substrate microorganisms. In theory, soluble carbon compounds, such as those in Daniels, would lead to a rapid proliferation of microbes. This would give it many traits of an organic fertilizer. Significant nitrogen would be assimilated along with carbon by the microbes, which should lower the nitrogen-to-potassium ratio, bringing it more in line with that of traditional fertilizers. This would also reduce the available level of ammoniacal nitrogen, explaining further the resistance to ammonium toxicity. Assimilated nitrogen would be rapidly released for plant uptake whenever the substrate nitrogen or carbon level declined. Under this condition, many microbes in the population would die and release their nutrients through the process of mineralization. Thus, the assimilated nitrogen would, in effect, be reserve nitrogen.

Daniels is generally applied at the same frequency and nitrogen rates as used with other water-soluble greenhouse fertilizers. When applying Daniels, one needs to have a fertilizer injector that has an adjustable proportion feature. The Daniels concentrate, which contains 120,000 ppm nitrogen (weight/weight basis), is drawn up directly by the fertilizer injector. Resulting nitrogen concentrations and associated EC values for dilution ratios of 200:1 to 500:1 are presented in Table 9. When additional compactness is required, a high concentration of Daniels, 500 to 600 ppm nitrogen, is applied as a spray or sprench in addition to the regular application program. *Sprench* is a term developed for greenhouse purposes from the words *spray* and *drench*. It describes a liquid application to plants that goes beyond covering all foliage with a spray to the point where excess fluid runs off the foliage into the substrate. While a spray would be applied with a spray nozzle or fog nozzle, a sprench is applied with a hose water breaker passed rapidly over the plants. This procedure for inducing compactness works well for plug seedlings, bedding plants, and finish potted crops. Plants are surprisingly resistant to salt injury from high concentrations of Daniels.

Table 9
Resulting Nitrogen Concentrations and EC Values for Dilutions of Daniels Fertilizer at Volume Ratios of 500:1 to 200:1

Injector Ratio	Nitrogen (ppm)	EC (dS/m)
500:1	240	0.90
400:1	300	1.13
342:1	350	1.29
300:1	400	1.50
240:1	500	1.88
200:1	600	2.26

In summary, Daniels, even with its odd analysis, has been found to be an effective fertilizer for the general range of greenhouse crops. Desirable characteristics of compactness, deeper green foliage, earlier flowering, and buffering of root substrate pH have been often associated with it.

Formulating Fertilizers

A greenhouse crop manager has to know the math for converting between parts per million (ppm) of a nutrient and its equivalent in ounces or pounds per 100 gallons of water (g/L) for two reasons. First, many fertilizer recommendations are given in ppm of a nutrient, such as 240 ppm nitrogen. This gives no direct information relative to how much fertilizer to dissolve in a given volume of water. If the recommendation were given as 2 pounds of 20-10-20 fertilizer per 100 gallons, there would be no problem.

The second need for fertilizer conversion math serves growers (fewer than half, and fewer as the years pass) who formulate their own fertilizer. These growers have a wider range of formulas available and save half or more of the purchase price of fertilizer. However, one should be aware that the cost of commercially prepared fertilizer constitutes only about 1 percent of greenhouse production costs. Formulating fertilizers is simple in concept. Most fertilizers are formulated from combinations of two or more of 10 nutrient sources. For example, 1 pound of potassium nitrate added to 1 pound of ammonium nitrate yields 2 pounds of 23-0-22 analysis fertilizer.

Three procedures are available to determine the amounts of fertilizer sources to dissolve in a given volume of water to achieve the nutrient concentrations in ppm in a given recommendation. These follow.

Rule of 75 The first method calls for determining the amount of fertilizer carrier needed by using equation 3:

$$\frac{\text{desired ppm}/75}{\text{decimal fraction of desired nutrient in nutrient source}} = \text{oz of nutrient source per 100 gal} \tag{3}$$

Let us assume that a recommendation calls for 200 ppm nitrogen and that we have a 20-10-20-analysis fertilizer available. Using equation 3, we divide 200 ppm by 75, which results in a value of 2.66. Then we divide this number by 0.20, which is the decimal fraction of nitrogen in the 20-10-20 fertilizer, to obtain a final answer of 13.33 ounces of 20-10-20 fertilizer per 100 gallons of water:

$$\frac{200/75}{0.20} = 13.33 \text{ oz}/100 \text{ gal}$$

Since this fertilizer also contains 10 percent phosphate-P_2O_5 and 20 percent potassium-K_2O, we end up with a final solution containing 200 ppm N + 100 ppm P_2O_5 + 200 ppm K_2O.

Assume now that we have potassium nitrate available and want 200 ppm potassium. This fertilizer source contains 13 percent nitrogen and 44 percent potassium-K_2O. Applying equation 3, we find that 6.1 ounces must be dissolved into each 100 gallons of water to yield a final concentration of 200 ppm potassium-K_2O:

$$\frac{200/75}{0.44} = 6.1 \text{ oz/100 gal}$$

We also obtain nitrogen from this fertilizer source, and it is important to know what quantity. Equation 4 is used to generate this information:

$$\begin{bmatrix} \text{oz of nutrient} \\ \text{source per 100 gal} \end{bmatrix} \times 75 \times \begin{bmatrix} \text{decimal fraction of} \\ \text{desired nutrient in} \\ \text{nutrient source} \end{bmatrix} = \begin{bmatrix} \text{ppm of desired} \\ \text{nutrient} \end{bmatrix} \quad (4)$$

Applying this equation to our problem, we find that the concentration of nitrogen in the final solution is 59.5 ppm:

$$6.1 \times 75 \times 0.13 = 59.5$$

Conversion Table The rule-of-75 equations can be cumbersome to use. A simplified alternative is to use Table 10. Consider formulating a fertilizer containing 200 ppm nitrogen-N, 100 ppm phosphate-P_2O_5, and 200 ppm potassium-K_2O from ammonium nitrate, potassium nitrate, and monoammonium phosphate. To use Table 10, we proceed as follows.

1. List the fertilizer sources to be used and the percentages of N, P_2O_5, and K_2O contained in each. (These percentages can be found in the first 10 entries in Table 11).

Ammonium nitrate (AN)	33-0-0
Potassium nitrate (PN)	13-0-44
Monoammonium phosphate (MAP)	12-62-0

2. Sketch a balance sheet as follows.

	oz/100 gal	N	P_2O_5	K_2O
Desired levels (ppm)		**200**	**100**	**200**
Potassium nitrate				
Monoammonium phosphate				
Ammonium nitrate				
Total (ppm)				

3. Select a fertilizer source that contains two desired nutrients. In this case, select potassium nitrate. Begin with the nutrient that is contained in this fertilizer source at the highest concentration. Since nitrogen is 13 percent and potassium is 44 percent, we will start with potassium. In Table 10, go to the column headed by 44. Read down the table until you come to 200 ppm. The value 197.6 is close enough. Stop at that point and read across that row to the extreme left entry, which is 6. This is the number of ounces of PN to dissolve in 100 gallons of water to achieve a fertilizer solution that contains 197.6 ppm potassium-K_2O.

Table 10

Conversion Table for ppm of Desired Nutrient to Ounces of Nutrient Source in 100 Gallons of Water (or g in 1 L) and Vice Versa[1]

	Percentage of Desired Nutrient in Nutrient Source																
	10	12	13	14	15	16	17	20	21	23	24	33	44	45	53	60	62
Oz Nutrient Source/ 100 Gal										ppm							
1	7.5	9	9.7	10.5	11.2	12.0	12.7	15.0	15.7	17.2	18.0	24.7	32.9	33.7	39.7	44.9	46.4
2	15.0	18	19.5	21.0	22.5	24.0	25.4	29.9	31.4	34.4	36.0	49.4	65.9	67.4	79.3	89.8	92.0
3	22.5	27	29.3	31.4	33.7	35.9	38.2	44.9	47.2	51.6	53.9	74.1	98.8	101.0	117.0	134.7	139.2
4	29.9	36	38.9	41.9	44.9	47.9	50.9	59.9	62.9	68.8	71.8	98.8	131.7	134.7	158.7	179.6	185.6
6	44.9	54	58.4	62.9	67.4	71.9	76.3	89.8	94.3	103.3	107.8	148.2	197.6	202.1	238.0	269.4	278.4
8	59.9	72	77.8	83.8	89.8	95.8	101.8	119.7	125.7	137.7	143.7	197.6	263.4	269.4	317.3	359.2	371.2
16	119.8	144	155.7	167.7	179.6	191.7	203.6	239.5	251.5	275.4	287.4	395.2	526.9	538.9	634.6	718.5	742.4
24	179.6	216	233.5	251.5	269.4	287.5	305.3	359.2	377.2	413.1	431.1	592.7	790.3	808.3	952.0	1,077.7	1,113.6
32	239.5	288	311.4	335.4	359.2	383.4	407.1	479.0	502.9	550.8	574.8	790.3	1,053.7	1,077.7	1,269.3	1,436.9	1,484.8
40	299.4	359	389.2	419.2	449.1	479.2	508.9	598.7	628.6	688.5	718.5	987.9	1,317.2	1,347.1	1,586.6	1,796.2	1,856.1
48	359.2	431	467.0	503.0	538.9	575.0	610.7	718.5	754.4	826.2	862.2	1,185.5	1,580.6	1,616.5	1,903.9	2,155.4	2,227.2
56	419.1	503	544.9	586.9	628.7	670.9	712.5	838.2	880.1	963.9	1,005.8	1,383.0	1,844.0	1,886.0	2,221.2	2,514.6	2,598.4
64	479.0	575	622.7	670.7	718.5	766.7	814.3	958.0	1,005.8	1,101.7	1,149.6	1,580.6	2,107.5	2,155.4	2,538.6	2,873.9	2,969.7
g Nutrient Source/L										ppm							
0.1	10	12	13	14	15	16	17	20	21	23	24	33	44	45	53	60	62
0.2	20	24	26	28	30	32	34	40	42	46	48	66	88	90	106	120	124
0.3	30	36	39	42	45	48	51	60	63	69	72	99	132	135	159	180	186
0.4	40	48	52	56	60	64	68	80	84	92	96	132	176	180	212	240	248
0.6	60	72	78	84	90	96	102	120	126	138	144	198	264	270	318	360	372
0.8	80	96	104	112	120	128	136	160	168	184	192	264	352	360	424	480	496
1.0	100	120	130	140	150	160	170	200	210	230	240	330	440	450	530	600	620
1.5	150	180	195	210	225	240	255	300	315	345	360	495	660	675	795	900	930
2.0	200	240	260	280	300	320	340	400	420	460	480	660	880	900	1,060	1,200	1,240
2.5	250	300	325	350	375	400	425	500	525	575	600	825	1,100	1,125	1,325	1,500	1,550
3.0	300	360	390	420	450	480	510	600	630	690	720	990	1,320	1,350	1,590	1,800	1,860
3.5	350	420	455	490	525	560	595	700	735	805	840	1,155	1,540	1,575	1,855	2,100	2,170
4.0	400	480	520	560	600	640	680	800	840	920	960	1,320	1,760	1,800	2,120	2,400	2,480

[1]Adapted from J. W. Love, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.

Table 11
AMOUNTS OF NUTRIENT SOURCES TO COMBINE IN MAKING VARIOUS FERTILIZER FORMULAS[1]

		Nutrient Sources[2]										
Fertilizer Name	Analysis	33-0-0	13-0-44	15.5-0-0	16-0-0	21-0-0	45-0-0	0-0-60	12-62-0	21-53-0	% of N as NH_4 + Urea	Reaction in Substrate[4]
Ammonium nitrate	33-0-0	x									50	A
Potassium nitrate	13-0-44		x								0	B
Calcium nitrate	15.5-0-0			x							6	B
Sodium nitrate	16-0-0				x						0	B
Ammonium sulfate	21-0-0					x					100	A
Urea	45-0-0						x				100	SA
Potassium chloride	0-0-60							x			—	N
Monoammonium phosphate	12-62-0								x		100	A
Diammonium phosphate[3]	21-53-0									x	100	SA
Magnesium nitrate	10-0-0										0	B
Chrysanthemum green	18-0-22	1	2			1					47	A
General summer	20-10-24	1					1	2		1	83	A
General low phosphate	21-4-20	7						4		1	55	A
General summer	21-17-20	1					2	3		3	90	A
General	17-6-27	4						4		1	57	A
UConn Mix	19-5-24		6	2			2		1		49	N
Editor's favorite	20-5-30		13				4			2	57	SA
20-20-20 substitute	20-20-22		4				1			3	67	SA
Starter and pink hydrangea	12-41-15		1						2		65	SA
Starter and pink hydrangea	17-35-16						1	4		10	100	SA
N-K only	16-0-24	2			1			2			40	SA
N-K only	20-0-30	1	2								28	SA
Blue hydrangea	13-0-22					2		1			100	VA
Blue hydrangea	15-0-15					3		1			100	VA
Acid	21-9-9	3	1			7		1		2	79	VA
Spring carnation	11-0-17				5			2			0	B
Winter nitrate	15-0-15		1	2							5	B
Winter potash	15-0-22		1	1							4	B
Lily substitute	16-4-12	1	4	6						1	22	N
High K	15-10-30		7	1						2	28	N

[1]Adapted from Koths et al. (1980).
[2]For names of nutrient sources, see the first nine entries in the Name column.
[3]Diammonium phosphate may be pelletized and coated. To dissolve, use very hot water and stir vigorously. Do not worry about sediment. Use crystalline potassium chloride if possible.
[4]B, basic; N, neutral; SA, slightly acid; A, acid; VA, very acid.

Now determine how much nitrogen you will receive from the use of this rate of PN. Start in the leftmost column with the value 6 oz/100 gal and read across to the right until you reach the column under 13 (the percentage of nitrogen in PN). The value you find is 58.4, which is the ppm concentration of nitrogen provided by this rate of PN. Enter the two concentration values, 58.4 ppm N and 197.6 ppm K_2O, and the quantity value, 6 oz/100 gal, into the balance sheet as follows.

Desired levels (ppm)	oz/100 gal	N 200	P_2O_5 100	K_2O 200
Potassium nitrate	6	58.4		197.6
Monoammonium phosphate				
Ammonium nitrate				
Total (ppm)				

4. Select the next fertilizer source that contains two desired nutrients and the nutrient in it that is in highest quantity. The source is monoammonium phosphate, and the nutrient is phosphate-P_2O_5. Read down the column in Table 10 headed by 62 (the percentage of P_2O_5 in MAP) until you come to the closest value to 100 ppm. The value is 92 ppm. Now read across that row to the extreme left entry, which is 2 oz/100 gal. Two ounces of MAP in 100 gallons will yield 92 ppm P_2O_5. However, we need 8 ppm more, or roughly 10 percent more; thus we need 2.2 oz/100 gal. This will give us 101.2 ppm P_2O_5. Determine the amount of nitrogen that is supplied by this concentration of MAP by starting in the leftmost column at the value 2 and reading across the row to the column headed by 12 (the percentage of nitrogen in MAP). The value you find is 18 ppm (nitrogen). Since you are actually dissolving 2.2 oz of MAP, you need to expand this nitrogen concentration value by 10 percent to 19.8 ppm. Enter these values into the balance sheet as follows.

Desired levels (ppm)	oz/100 gal	N 200	P_2O_5 100	K_2O 200
Potassium nitrate	6	58.4		197.6
Monoammonium phosphate	2.2	19.8	101.2	
Ammonium nitrate				
Total (ppm)				

5. We have already supplied 78.2 ppm nitrogen (58.4 from PN and 19.8 from MAP); thus, the concentration we still need to achieve our goal of 200 ppm is 121.8. This will be supplied by ammonium nitrate (33-0-0). Go to the column in Table 10 headed by 33 (the percentage of nitrogen in AN). The closest value to our desired 121.8 is 98.8. The reading at the left of that row tells us that 4 ounces of AN/100 gallons will yield a nitrogen concentration of 98.8 ppm. Note that the first entry in the column headed by 33 is 24.7 ppm and that this concentration is achieved by dissolving 1 ounce AN in 100 gallons. Therefore, we can use 5 ounces of AN/100 gallons to achieve a concentration of 123.5 ppm nitrogen (98.9 ppm from 4 oz AN + 24.7 ppm from 1 oz AN). This value is close enough to the 121.8 ppm we sought and should be added into the balance sheet. At this time, the concentrations in the balance sheet are summed. The resulting fertilizer solution contains nutrient concentrations close enough to the desired levels and can be achieved by dissolving 6 ounces of PN, 2.2 ounces of MAP, and 5 ounces of AN in 100 gallons of water.

Desired levels (ppm)	oz/100 gal	N 200	P_2O_5 100	K_2O 200
Potassium nitrate	6	58.4		197.6
Monoammonium phosphate	2.2	19.8	101.2	
Ammonium nitrate	5	123.5		
Total (ppm)		201.7	101.2	197.6

6. This table can be used for determining the quantity of a commercially prepared fertilizer to be dissolved in 100 gallons of water. A recommendation might call for supplying 240 ppm nitrogen from 20-10-20 fertilizer. One would find 239.5 ppm in the column in Table 10 headed by 20, the percentage of nitrogen in this fertilizer. The number in the extreme left column opposite this concentration indicates that 16 ounces of 20-10-20 fertilizer must be dissolved in 100 gallons of water.

Table of Fertilizer Formulas This is the third system for determining the quantity of nutrient source to use. The formulas for 20 fertilizers have already been calculated and are presented in Table 11. The first nine fertilizer entries are the individual nutrient sources from which the 20 subsequent fertilizer formulas are derived. For example, an 18-0-22 formula fertilizer can be formulated by blending together 1 pound of ammonium nitrate plus 2 pounds of potassium nitrate plus 1 pound of ammonium sulfate. This formulation was determined by locating the 18-0-22 formula in the Analysis column. Then, the three numbers 1, 2, and 1 were located in the row after this formula. Each of these three numbers was traced to the x above it and then to the nutrient source to the left of the x.

Different fertilizers are recommended in Table 11 for blue and pink hydrangea crops. Aluminum serves to regulate flower color in hydrangea. Copious quantities of aluminum exist in most soils. When the pH is low, much of the aluminum is available to the plant, and flowers are blue. When the pH is high, aluminum is rendered unavailable, and flowers are pink. High levels of phosphate also render aluminum unavailable. You will note that fertilizer formulations used for blue flowers are devoid of phosphate and are very acid, while those used for pink flowers contain large quantities of phosphate and are not very acid.

Additional formulations can be found in Table 12. Three commercially formulated complete fertilizers are listed first, followed by three "make-your-own"

Table 12

Quantities of Fertilizers or Nutrient Sources to Dissolve in 100 Gallons of Water to Make Solutions Containing Concentrations of 50 to 600 ppm Each of Nitrogen (N) and Potassium (K_2O)

Fertilizer	% NH_4 + urea	Concentration of N and K_2O 50	100	200	300	400	500	600
					oz/100 gal			
20-20-20[1]	70	3.3	6.7	13.3	20.0	26.7	33.4	40.0
15-15-15[1]	52	4.5	8.9	17.8	26.7	35.6	44.5	53.4
20-10-20[1]	40	3.3	6.7	13.3	20.0	26.7	33.4	40.0
Ammonium nitrate	36	1.4	2.9	5.7	8.6	11.4	14.3	17.1
+ potassium nitrate (23-0-23)		1.5	3.0	6.1	9.1	12.1	15.2	18.2
Calcium nitrate	4	3.0	6.0	12.0	18.0	24.0	30.0	36.0
+ potassium nitrate (15-0-15)		1.5	3.0	6.0	9.0	12.0	15.0	18.0
Ammonium nitrate	40	1.2	2.5	4.9	7.4	9.9	12.3	14.8
+ potassium nitrate		1.5	3.0	6.0	9.0	12.0	15.0	18.0
+ monoammonium phosphate (20-10-20)[1]		0.5	1.1	2.2	3.2	4.3	5.4	6.5

[1]These formulations also contain phosphate-P_2O_5 at equal to or half the concentration of nitrogen.

formulations. The percentage of total nitrogen in each fertilizer that is in ammonium (NH_4)-plus-urea form is given. Quantities to dissolve in 100 gallons of water to yield concentrations of 50 to 600 ppm each of nitrogen and potassium are also given.

While the make-your-own fertilizers do not contain micronutrients or dye, commercial preparations are available. They were discussed in the "Pre-Plant Fertilization" section, under "Micronutrients." One example is Compound 111 (The Scotts Co., Marysville, OH 46041), which is added at the rate of 1 pound per 40 pounds of macronutrient formulation.

Automated Fertilizer Application

The most expedient method for applying fertilizer is the automatic watering system present in most greenhouses. The fertilizer must be dissolved into a concentrated solution in order to conserve space in the mixing and holding tanks. This necessitates the use of a *fertilizer injector* (also known as a *proportioner*). This device mixes precise volumes of concentrated fertilizer solution and water together. By plumbing the proportioner into the main water line that serves the whole greenhouse range, all lines are made to carry a single-strength fertilizer solution. The proportioner is located either (1) on a bypass line so that either water or fertilizer solution can be obtained from the lines (Figure 3), or (2) on a second water main leading to the greenhouse such that one main in the greenhouse supplies water and the second main supplies fertilizer solution.

It is advisable, and in most states mandatory, that in a potable water system a backflow preventor be installed on any water-supply fixture that has an outlet that may be submerged (Figure 4). Such fixtures include fertilizer proportioners and hoses used to fill spray tanks or equipment washtubs. The backflow preventor stops back-siphoning of contaminated water into the water system in the event that a negative pressure (suction) develops. Nitrate, commonly supplied in fertilizers, is harmful to humans. Babies are particularly susceptible to low levels of nitrate. The World Health Organization standards for drinking water set the maximum acceptable concentration of nitrate (NO_3) at 23 ppm in Europe and at 45 ppm (10 ppm N) in the United States. Backflow preventors are not required when there is a gap equal to twice the diameter of the supply line between the water-supply line and the highest possible

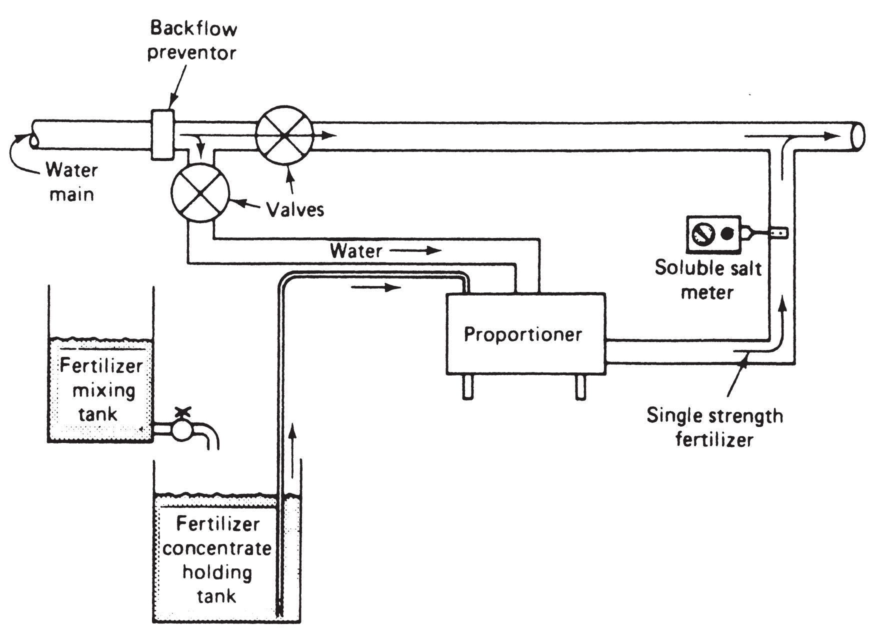

Figure 3
A typical arrangement of fertilizer mixing tank, holding tank, fertilizer proportioner, and soluble-salt (EC) meter along the main water line in a greenhouse range.

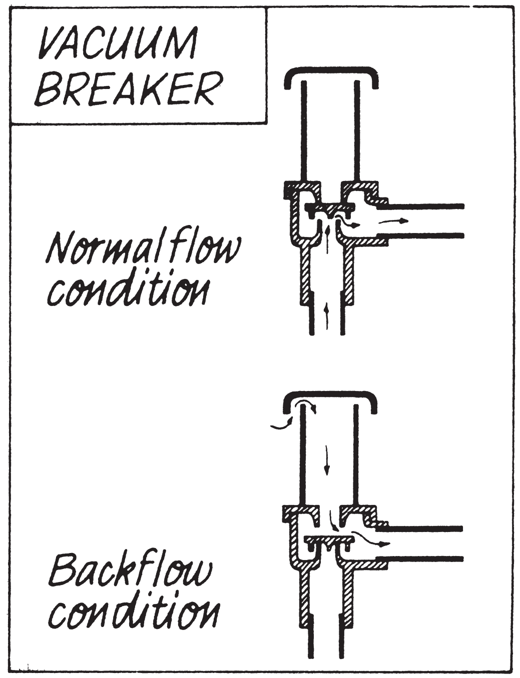

Figure 4
A backflow preventor in the open position, permitting normal flow of water (top). *When water pressure drops to a predetermined level, the check valve closes and shuts off the flow of water* (bottom). *At this point, air can enter the device, thus eliminating the negative pressure and any backflow of water.*
(From Aldrich and Bartok, Jr., 1994.)

level of water in a mixing tank receiving the water. In such a setup, it is not possible for contaminated water to enter the water-supply line.

Several types of proportioners (Figure 5) are used, depending upon the application. The five criteria to use in selecting the proportioner best suited for a given greenhouse application are as follows:

1. The ratio of fertilizer concentrate to water should be sufficiently high to keep the concentrate-tank volume needed for one complete fertilizer application down to a manageable size. For a small firm, a 1:16 ratio would be sufficient; for a large firm, it would not. The solubility of greenhouse fertilizers allows them to be concentrated up to about 200-fold. Ratios higher than 1:200 are rarely used. A ratio of 1:100 is most common.
2. An adjustable ratio is highly desirable. In this way, a single fertilizer concentrate can be applied at different concentrations to each of several plant species.
3. The flow rate of the proportioner determines the area of plants that can be fertilized at one time. An 8-gpm (30-L/min) flow rate will service only one ¾-inch (1.9-cm) pipe and, thus, only one bench of plants at a time. In a very large firm, it may be necessary to fertilize 10 or more benches at a time in order to finish the task in half a day.
4. The concentrate tank should have sufficient volume to allow the entire fertilization job to be completed with one batch of fertilizer concentrate. Larger firms purchase proportioners without a built-in concentrate tank. In this way, they provide their own tank of required size.
5. As soon as a firm is large enough to afford a dual-head proportioner, it should obtain one. Such a proportioner siphons simultaneously from two separate fertilizer concentrates. Calcium and/or magnesium can be supplied in one concentrate,

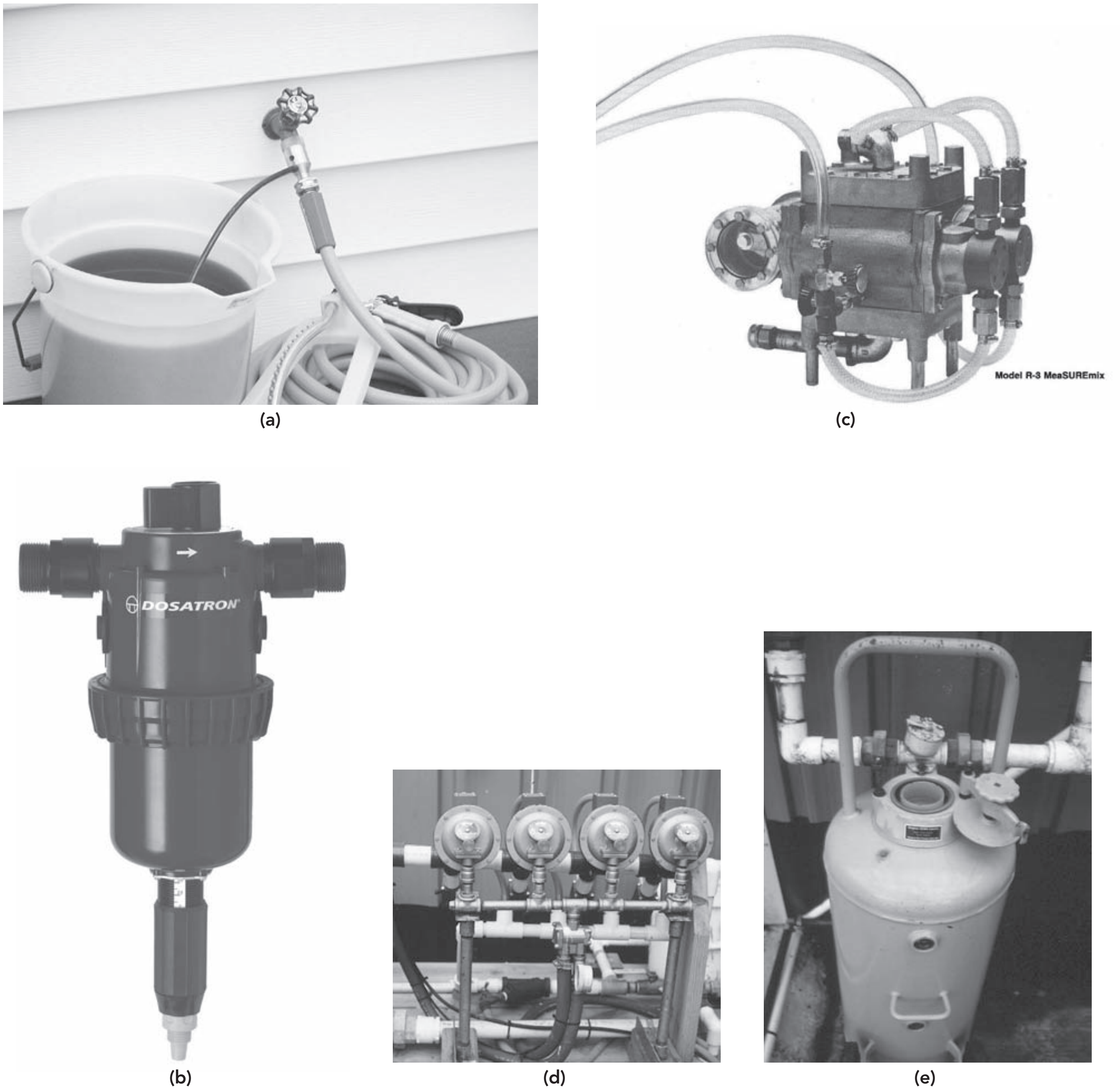

Figure 5

Five fertilizer proportioners typical of the many in use: (a) Hozon, (b) Dosatron, (c) Smith, (d) Anderson Ratio:Feeder, and (e) Gewa.

(Pictures courtesy of [a] Phytotronics, Inc., Web: www.phytotronics.com; [b] Dosatron, Web: www.dosatronusa.com; [c] Smith Precision Products Co., Web: www.smithpumps.com.)

while sulfate and/or phosphate may be supplied in the other. These nutrients are compatible in this case because they do not mix until after they are diluted to single strength. When either calcium or magnesium is added to phosphate, or calcium is added to sulfate in the concentrate tank, they are subject to precipitation.

Proportioners such as the Hozon and the Syfonex operate on the Venturi principle, whereby water passing at a high velocity through an orifice sets up suction in a line entering from the side. Fertilizer concentrate is drawn in through the side line. This type of proportioner is inexpensive and serves well in a small greenhouse, but is limited in application because of its fixed, narrow proportioning ratio of approximately 1:16. Where large volumes of fertilizer solution are needed, the concentrate tank would become prohibitively large. The ¾-inch (1.9-cm) thread size and 3-gpm (8-L/min) flow rate limit the area that can be fertilized at one time.

The Commander proportioner draws in fertilizer concentrate by means of a pump that is driven by water passing through it. It requires a much smaller concentrate volume with its fixed ratio of 1:128 (1 fl oz/gal), but it is limited to a ¾-inch (1.9-cm) thread size and 6.6-gpm (25-L/min) flow rate.

Fert-O-Ject and Smith Measuremix proportioners have factory-fixed ratios, including 1:100 or 1:200 for the Fert-O-Ject and 1:20 to greatly in excess of 1:200 for the Smith. They can be purchased to fit pipe sizes of up to 6 inches (15 cm). Their flow rates, which go up to 560 gpm (2,100 L/min) at a ratio of 1:200, permit simultaneous fertilization of many benches. These proportioners use the water-pumping principle to pick up fertilizer concentrate and do not have built-in concentrate tanks.

The Gewa proportioner adds versatility since its ratio is adjustable on-site from 1:15 to 1:350. This proportioner includes a concentrate tank available in 4-, 6-, 15-, and 26-gallon (15-, 20-, 57-, and 100-L) sizes and fits up to a 2-inch (5-cm) water line. The concentrate is contained in a rubber bag positioned inside an iron tank. Entering water builds up pressure between the rubber bag and the iron tank wall, thereby pressing concentrate out into the line. The ratio is set by moving a lever to the appropriate numbered setting. The number is determined by dividing 300 by the dilution factor desired. For a ratio of 1:100, 300 would be divided by 100 to achieve a setting of 3. The volume of concentrate is limited by the size of the built-in tank.

Anderson Ratio:Feeder proportioners are available in several models, each with on-site adjustable step ratios ranging from 1:80 to greater than 1:200. A flow rate of 450 gpm (1,700 L/min) is possible at a ratio of 1:200. Separate concentrate tanks are supplied by the grower.

Dosatron and Dosmatic proportioners may be adjusted on-site from a ratio of 1:50 to greater than 1:200. Flow rates extend up to 100 gpm (380 L/min) in pipe sizes up to 2 inches (5 cm). The concentrate tank is not a part of these proportioners.

Fertilizer proportioners may shift over time, resulting in higher- or lower-than-desired fertilizer concentrations. The fertilizer output concentration should be checked routinely. This may be done by measuring the volumes of concentrate taken up (input) and single-strength solution emitted (output) for a given length of time. The dilution factor of the proportioner is then calculated by dividing the output by the input.

The alternative procedure calls for measuring the electrical conductivity (EC) of the single-strength output solution. Most fertilizer sources are salts that conduct electricity. Thus, EC indicates the fertilizer concentration for any given fertilizer. Each fertilizer company supplies on the fertilizer bag or in its technical literature a table of EC values for each of its fertilizers (Table 13). One simply collects fertilizer solution from emitters at individual pots or from spray nozzles on cut-flower beds and measures the EC level with a meter available from most greenhouse-supply companies. The EC level of the irrigation water is then measured and subtracted from the fertilizer EC value to obtain the net EC contribution of the fertilizer solution. The fertilizer EC level should equal the one listed in the manufacturer's table for the concentration of fertilizer being applied. The EC values for a given fertilizer analysis, such as 20-0-20, may vary from company to company. This is reasonable since each company may use different nutrient sources to formulate this fertilizer. Also included in Table 13 are the EC values associated with five nutrient source salts commonly used by growers for formulating their own fertilizers.

To facilitate the measurement of fertilizer concentration, an EC meter should be installed in the plumbing downstream from the proportioner. The same meter

Table 13
Soluble Salt Conductivity (EC) Values in mmho/cm (dS/m) for Each 100 ppm Nitrogen from Several Peters® Fertilizers and Five Single-Salt Nutrient Sources[1]

Fertilizer	EC/100 ppm N	Fertilizer	EC/100 ppm N
21-5-20 Multi Purpose	0.63	17-3-17 Peat-Lite Neutral Cal-Mag	0.65
15-5-15 Cal-Mag Special	0.69	15-16-17 Peat-Lite Special	0.62
15-2-20 Pansy, Salvia, and Vinca	0.77	15-5-25 Peat-Lite Flowering Crop Sp	0.77
13-2-13 Plug and Bedding Plant Special	0.75	15-0-15 Peat-Lite Dark Weather Feed	0.71
21-7-7 Acid Special	0.52	10-30-20 Peat-Lite Plant Starter	0.86
20-20-20 General Purpose	0.41	Ammonium nitrate (34% N)	0.46
20-10-20 General Purpose	0.62	Calcium nitrate (15.5% N)	0.74
20-10-20 Peat-Lite Special	0.59	Ammonium sulfate (21% N)	0.90
20-2-20 Peat-Lite Low Phos Special	0.60	Potassium nitrate (14% N)	0.95
18-8-17 Peat-Lite High Mag Special	0.65	Epsom Salt (10% Mg)	0.75

[1]Adapted from The Scotts Company, LLC, Marysville, OH 43041, www.scottspro.com.

used for testing root substrate can be used, but the probe containing the electrodes is different. The probe is contained in a pipe fitting that is permanently plumbed into the water line. Each time the proportioner is turned on, the EC level of the solution coming from the proportioner should be checked.

Slow-Release Fertilizers

Many of the nutrient sources used in the early days of greenhouse culture were, in effect, slow-release fertilizers. They were mainly organic materials of plant and animal origin, which, upon degradation, slowly gave up their nutrient content to the soil. These were materials such as bone meal, seaweed, and fish. The residual component of limestone is in effect a slow-release fertilizer. Today, synthetically produced slow-release fertilizers have slow, sustained release patterns ranging from three months to several years. For greenhouse culture, the three-to-four-month release period is most popular. There are four common categories of these fertilizers. Some, when incorporated into the soil prior to planting, will provide all the necessary nitrogen, phosphorus, and potassium for the entire crop period, thus eliminating the need for a post-plant fertilization program. Others provide micronutrients in an equally effective manner. The four common categories are as follows:

1. Polymer-encapsulated fertilizers
2. Urea aldehydes
3. Sulfur-coated fertilizers
4. Chelated micronutrients

Slow-release fertilizers are in one sense a form of automation, since they eliminate the need for a continual input of labor into fertilization. These fertilizers are more efficient than water-soluble fertilizers in that a greater percentage of applied nutrients is utilized by the plant. Conversely, fewer nutrients leach from the root zone into the water table. This factor is important today as pollution guidelines and regulations are being enforced by government agencies. Although crops can be fertilized exclusively with slow-release fertilizers, many growers currently use these fertilizers in conjunction with a continual fertilization program merely as an insurance program against nutrient shortage. The reason for the limited use of slow-release fertilizers as the sole source of nitrogen and potassium is the fear of not being able to slow the rate of release, should it be necessary during the crop.

Polymer-Encapsulated Fertilizers One set of notable examples of polymer-encapsulated, slow-release fertilizers are the products under the trade name Osmocote®. They consist of polymer-coated spheres of dry, water-soluble fertilizers formulated from such carriers as potassium nitrate and ammonium sulfate. Particle diameters are about ⅛ inch (3 mm) or less.

These fertilizers can be mixed into root substrates prior to planting or top-dressed on the soil surface. Water vapor in the soil atmosphere penetrates the capsule wall. Once inside, the water vapor condenses on the fertilizer surface because the fertilizer lowers the vapor pressure. This reduces the moisture content of the atmosphere inside the capsule to a level lower than that in the moist soil atmosphere outside. As a result, water vapor continues to diffuse into the capsule in an attempt to equalize the moisture content of the atmosphere on both sides of the polymer film. Soon, sufficient water condenses inside to dissolve the fertilizer. As water continues to enter and pressure builds up inside, the walls of the capsule enlarge, which enlarges preexisting fissures through which the fertilizer solution passes to the soil solution, where it can be taken up by plant roots. The longevity of this process is controlled by the thickness of the multiple layer polymer coating.

Osmocote® is available for greenhouse fertilization in a variety of analyses that roughly encompass the ratios of 1-1-1 and 3-1-2. The release periods range from 3 to 4 months, which is suitable for most greenhouse crops, to 14 to 16 months for long-term crops such as carnation and rose. Listed in Table 14 are the various Osmocote® Classic and Osmocote® Plus controlled-release fertilizers. The Plus series contains micronutrients while the Classic does not. The Classic series is offered in Hi-Start and Lo-Start formulations that release more or less nutrients at the beginning of the crop than the Standard Classic formulations to meet specific crop needs. In addition to the formulations listed in the table, an Osmocote® Mini Prill is offered, in 19-6-10 (3–4-month) and 18-5-9 (5–6-month) analyses for use in small containers. Rates of incorporation for 14-14-14 Osmocote® Classic for low, medium, and high requirement plants expressed as pounds per cubic yard of substrate (kg/m^3) are 3.5 (2.1), 8.5 (5), and 13 (7.7), respectively.

Another product in the polymer-encapsulated category is Nutricote. It is also available under the trade name Florikan CRF (Florikan E.S.A. Corp., Sarasota, Florida, www.florikan.com). Again, it consists of a variety of solid, soluble fertilizers

Table 14
Analyses of Osmocote® Classic and Osmocote® Plus Controlled-Release Fertilizers Available for Various Release Periods and for Rapid or Slow Initial Release Rates[1]

	Osmocote® Classic			Osmocote® Plus		
Longevity	Hi-Start	Standard	Lo-Start	Hi-Start	Standard	Lo-Start
3–4 months		14-14-14 19-6-12			15-9-12	
5–6 months				16-9-12	15-9-12	
8–9 months	19-6-12	13-13-13 19-6-12	18-6-12	16-9-12	15-9-12	15-9-12
12–14 months	19-6-12	19-6-12	17-7-12	15-8-12	15-9-12	15-9-11
14–16 months		19-6-12	18-6-12			

[1]From The Scotts Co., Marysville, OH 43041; longevity was determined at a root substrate temperature of 70°F (21°C); when the product name includes the designation "Plus," it indicates that micronutrients are included; otherwise they are not.

Table 15
Rates in lb/yd³ (kg/m³) for Incorporation of Three of the Most Popular Formulations of Nutricote[1] into Greenhouse Root Substrates in Climatic Zones 6 to 8[2]

Release Type (days)[3]	Sensitive Crops		Medium-Feeding Crops		Heavy-Feeding Crops	
13-13-13						
70	2.5	(1.5)	5	(3.0)	8.5	(5.1)
100	3.5	(2.1)	7.5	(4.5)	12	(7.1)
140	5	(3.0)	9	(5.4)	13	(7.8)
180	6	(3.6)	11	(6.6)	17	(10.2)
270	8	(4.8)	13	(7.8)	21	(12.6)
360	11	(6.6)	15	(9.0)	25	(15.0)
14-14-14						
70	2.5	(2.4)	5	(5.4)	8.5	(8.3)
100	3.5	(3.0)	7.5	(7.1)	12	(11.9)
180	6	(7.1)	11	(11.9)	17	(16.6)
270	8	(9.5)	13	(14.2)	21	(19.0)
18-6-8						
70	2	(1.2)	4.5	(2.7)	7.5	(4.5)
100	3	(1.8)	6.5	(3.9)	11	(6.6)
140	4.5	(2.7)	8	(4.8)	11	(7.2)
180	6	(3.6)	10	(6.6)	14	(8.4)
270	8	(4.8)	12	(7.8)	20	(12.0)
360	11	(6.6)	15	(9.0)	21	(13.8)

[1]Also sold under the trade name Florikan CRF containing Nutricote.
[2]The Florikan company recommends incorporating magnesium sulfate (Epsom salt) into the root substrate at a rate of 3 to 5 lb/yd³ (1.8 to 3.0 kg/m³) to supply sulfur when using any of these products.
[3]Based on a root substrate temperature of 77°F (25°C).

coated with a polymer polyolefin resin. The resin can vary in composition to yield products with release periods of 70, 100, 140, 180, 270, or 360 days at a root-substrate temperature of 77°F (25°C). Many analyses are available, but the three most popular for floral crops are 13-13-13, 14-14-14, and 18-6-8 (see Table 15 for rates). The 14-14-14 formula does not contain micronutrients, while the other two do. Nutricoated calcium nitrate and magnesium sulfate (Epsom salt) are also available from Florikan. The Epsom salt product (22 percent Mg) is available in 100- to 360-day formulations and provides a convenient way for supplying magnesium or sulfate throughout a crop period from a single pre-plant application for crops such as poinsettia that have a continual need for magnesium. The calcium nitrate product (12-0-0 + 23 percent Ca) is available in 100- and 140-day formulations and serves well for crops, such as lily, that have a high calcium requirement. The Nutricote coating is different from the previous Osmocote® fertilizers in that it remains flexible after production. Water diffuses from the soil through a mazelike pattern of molecule-sized passages in the resin coating. Inside, fertilizer is dissolved and pressure builds up, causing fertilizer solution to flow out through the coating by reverse osmosis.

An important precaution for Osmocote® and Nutricote is that they should not be steam pasteurized. This could result in excessive nutrient release and ensue plant injury. The ammonium and nitrate forms of nitrogen in Osmocote and Nutricote are well balanced.

Urea Aldehydes Most notable in the urea aldehyde category is urea formaldehyde. This slow-release nitrogen-containing fertilizer is sold under several trade names, including Borden's 38, Ureaform, and Uramite. It contains 36 percent nitrogen and becomes available slowly, with about 65 percent released the first year, 25 percent the second year, and 10 percent the third year. This fertilizer has gained considerable prominence as a source of nitrogen for home lawns and golf courses. Much of urea formaldehyde exists in long chemical chains that cannot be taken up by plant roots. Once it is in the soil, microorganisms feed upon these chains, breaking them down into smaller pieces, some of which are urea. Urea is a form of nitrogen readily utilized by the plant. This breakdown process occurs slowly, over a long period of time.

A second urea aldehyde fertilizer that was used in the past in the nursery trade is IBDU (isobutylidene diurea). This urea aldehyde depends on chemical hydrolysis rather than microbial attack for the release of nitrogen.

Urea aldehydes have not been used extensively in greenhouse culture, except in mixed formulations, for two reasons. First, they provide only nitrogen, leaving the need for a potassium and phosphate source. Second, they provide nitrogen in the form of urea, which is ultimately converted to ammonium either in the substrate or in the plant. As discussed earlier, most greenhouse plants do not respond well to ammonium nitrogen exclusively. Urea formaldehyde is used by some azalea growers as a top dressing to guarantee against nitrogen deficiency because of the high requirement of this crop for nitrogen relative to potassium. It is used at the rate of 1 rounded teaspoon (5 g) per 6-inch (15-cm) pot at two-month intervals during periods of heavy growth. A continual fertilization program is used in addition to this application.

Sulfur-Coated Fertilizers Prills (small spheres) of various fertilizers, including urea, ammonium polyphosphate, triple superphosphate, potassium sulfate, and potassium chloride, are coated individually with a combination of sulfur, a waxlike sealant, and possibly a conditioner such as diatomaceous earth. Various combinations of these sulfur-coated materials are blended to yield a multitude of grades such as 13-13-13, 21-6-12, and 7-34-0. Release of nutrients is dependent upon soil microorganisms, which convert (oxidize) the insoluble elemental sulfur coating to soluble sulfate. When this happens, water enters the capsule and dissolves the fertilizer contained in it. The release period is typically three to four months, but coating alterations can extend the release period to one year. The sulfur-coated products have gained wide acceptance outdoors for turf and landscape uses. They were popular for nursery production but now have been mostly replaced by plastic encapsulated products. Their high sensitivity to temperature causes excessive release during high-temperature periods. Plastic encapsulated products are much less sensitive. Sulfur-coated fertilizers are not used to any extent in greenhouses because all of the nitrogen is ammonium and/or urea. While nitrates could theoretically be coated, they have not been because of the danger of explosion when the molten sulfur is sprayed on the prills of nitrate.

Chelated Micronutrients The word *chelate* is derived from a Greek word meaning "claw." It is appropriate because chelates are large, organic chemical structures that encircle and tightly hold the micronutrients iron, manganese, zinc, and copper. Plant roots can enhance release of micronutrients from the chelate. There is evidence that the chelating agents are absorbed, in addition to absorption of the micronutrients. When the substrate pH is higher than that desired for a specific crop, it contains high levels of hydroxide and possibly bicarbonates and carbonates that will precipitate iron, manganese, zinc, and copper. Precipitated nutrients are insoluble and unavailable to plants. Chelated micronutrients are protected from precipitation. However, micronutrients are slowly released from chelates, after which they can be precipitated if not intercepted by roots. The value of chelates lies in the low steady concentration of micronutrients released by them over a long period of time.

Roses were traditionally grown in a moderately acid substrate of pH 5.5 to 6.0. With time, it was learned that the benefit of the low pH level was the higher solubility of iron, a feature necessary for this poor accumulator of iron. Actually, the rose grows better at a higher pH level, provided sufficient iron is available. Today, iron is routinely applied in the chelated form at the rate of 1 lb/1,000 ft^2 (4.9 g/m^2) of bed at a frequency of about every three months. The alternative source of iron, iron sulfate, is much cheaper by weight. However, under adversely high pH conditions, it can be more expensive because it needs to be applied at a greater frequency than chelated iron. Iron sulfate rapidly releases iron into the soil solution, where it precipitates.

The chelated forms of iron, manganese, zinc, and copper are the most common forms used in premium greenhouse fertilizers. Most complete fertilizers with chelated micronutrients use the EDTA chelating agent, some use the stronger DTPA agent, while others use the even stronger EDDHA agent. The high solubility of chelates compared to alternative forms makes them very desirable to fertilizer formulators.

There is usually an advantage to using chelated iron when the substrate pH level is adversely high for the given crop. If the pH level is normal, the cheaper iron sulfate (ferrous sulfate) form serves well. However, chelated manganese, zinc, and copper do not show as great an advantage over the sulfate forms. Unless the soil pH is extremely high, the extra expense of the chelated forms of manganese, zinc, and copper is not usually warranted. Iron EDTA chelates are sold under the trade names Sequestrene Fe and Dissolzine E-FE-13; iron DTPA under the trade names Sequestrene 330, Sprint 330, and Dissolzine D-FE-11; and iron EDDHA under the trade names Sequestrene 138, Sprint 138, and Dissolzine Q-FE-6. As substrate pH becomes more adversely high, one needs to increase the strength of the chelate from EDTA to DTPA and finally EDDHA to keep an adequate level of iron available for plant growth.

NUTRITIONAL MONITORING AND DIAGNOSIS

Nutritional problems will develop even in the best of fertilization programs. The careful grower makes use of four systems for monitoring nutrient status. These systems are (1) water analysis, (2) visual diagnosis, (3) soil testing, and (4) foliar (leaf) analysis. Each test provides some information that is not provided by the others. Information from the four tests along with cultural records provides the basis for diagnosing nutritional status of a crop.

Visual Diagnosis

Visual diagnosis can be employed only after damage has occurred. Often, the damage is only partially reversible. Therefore, a grower should not rely on visual diagnosis as a routine measure of nutrient status. Each nutrient deficiency has several symptoms that are common to many crops. These symptoms are shown in Color plates 1 through 16. It should be noted that some crops will not develop these symptoms and many crops, in addition to these symptoms, will develop others. Only the more typical symptoms are presented here.

A few definitions will be of help. *Chlorosis* refers to a process whereby green chlorophyll is lost. The leaf tissue turns progressively lighter green and finally yellow. *Necrosis* refers to the death of cells and is manifested as various shades of brown. Interveinal chlorosis is chlorosis occurring between the veins (vascular tissue) of the leaf. The veins remain green in color. A *witch's broom* is a typical boron deficiency symptom because more boron is required for flower-bud formation than for vegetative-shoot development. When the plant reaches the stage of flower-bud formation, it aborts, giving rise to lateral vegetable shoots. These develop but, in turn, abort as flower buds are initiated. This process continues until a proliferation of developing shoots gives the appearance of a broom. *Strap leaves*, typical of calcium deficiency, are long, thin leaves having the appearance of a strap.

The more common symptoms in their order of occurrence for deficiencies and some frequent toxicities are as follows:

Nitrogen Deficiency (Color Plate 1)
The older leaves become uniformly chlorotic. After considerable time, older leaves become necrotic and drop off if abscission is possible for the species in question. Purple to red discoloration may develop in older leaves and stems as they turn chlorotic in some species, such as begonia, marigold, and pansy.

Ammonium Toxicity (Color Plate 2)
Older plants with floral buds: Margins of older leaves curl upward or downward, depending on the plant species. Older leaves develop chlorosis. The form of chlorosis is very variable and depends on the plant species. Necrosis follows chlorosis on the older leaves. Fewer roots form, and in advanced toxicities, root tips become necrotic, often with an orange-brown color.

Seedlings and bedding plants: Young leaves develop chlorosis, most often in an interveinal pattern, and margins curl up or down, depending on the species. Necrosis follows chlorosis, and root symptoms are similar to those described above for older plants.

Phosphorus Deficiency (Color Plate 3)
The plant becomes severely stunted, and at the same time the foliage becomes deeper green than normal. In some species, the older leaves develop purple coloration. Older leaves then develop chlorosis followed by necrosis. Roots become longer than normal when the deficiency is moderate.

Foliage plants: Older leaves may lose their sheen, becoming dull green followed by red, yellow, and blue pigments showing through the green, particularly on the undersides of the leaves along the veins. These symptoms spread across the leaf. Older leaves abscise if possible; otherwise, necrosis develops from the tip toward the base.

Potassium Deficiency (Color Plate 4)
The margins of older leaves become chlorotic, followed by an immediate necrosis. Similar necrotic spots may form across the blades of older leaves but more so toward the margin. Soon the older leaves become totally necrotic. Seedlings and young bedding plants, prior to the formation of chlorosis and necrosis on older foliage, are more compact and deeper green than normal. Some foliage plants develop oily spots on the undersides of older leaves that then become necrotic.

Calcium Deficiency (Color Plate 5)
Symptoms are expressed at the top of the plant. The edges of immature tissues become necrotic. Young leaves may develop variable patterns of chlorosis and distortion, such as dwarfing, straplike shape, or crinkling. Shoots stop growing.

Petals or flower stems may collapse. The edges of poinsettia bracts may burn. Roots are short, thickened, and lateral roots are short and dense.

Foliage plants: In addition to the above, the older leaves may become thick and brittle. In *Philodendron scandens* subspecies *oxycardium* and in *Epipremnum aureum*, calcium has symptoms of a mobile nutrient. Yellow spots occur in the basal half of older leaves. These spots enlarge into irregular yellow areas containing numerous scattered oil-soaked spots.

Magnesium Deficiency (Color Plate 6)

Older leaves develop interveinal chlorosis. In several species, pink, red, or purple pigmentation develop in the older leaves following the onset of chlorosis.

Foliage plants with pinnately (netted) veined leaves: Bronze-yellow chlorosis begins at the upper margin of older leaves, progressing downward along the veins, leaving a green V-shaped pattern at the top of the leaf. As chlorosis progresses down the leaf, a green V-shaped tissue remains at the bottom. Eventually, the tip and then the base become chlorotic. Necrosis follows chlorosis in the same pattern.

Sulfur Deficiency (Color Plate 7)

Foliage over the entire plant becomes uniformly chlorotic. Sometimes the symptoms tend to be more pronounced toward the top of the plant and other times toward the base of the plant. While symptoms on the individual leaf look like those of nitrogen deficiency, it is easy to distinguish sulfur deficiency from nitrogen deficiency because nitrogen deficiency begins in the lowest leaves while sulfur deficiency starts in all leaves simultaneously.

Iron Deficiency (Color Plate 8)

Interveinal chlorosis of young leaves is very typical of iron deficiency. Young leaves of seedlings sometimes develop general rather than interveinal chlorosis. In late stages, the leaf blade may lose nearly all pigment, taking on a white appearance and finally turning necrotic.

Iron Toxicity (Color Plate 9)

This disorder mainly affects African marigolds, seed geraniums, basil, cosmos, dahlia, nasturtium, pepper, strawflower, tomato, and zinnia. Marigolds develop bronzing on recently fully expanded leaves. The bronzing consists of numerous pinpoint spots that begin yellow and quickly turn bronze. Affected leaves become necrotic. Older leaves on the other crops develop numerous pinpoint necrotic spots across the blade that range in color from bronze to black, depending on the species. As the spots enlarge, they turn necrotic until the entire leaf dies.

Manganese Deficiency (Color Plate 10)

Manganese deficiency is often characterized by interveinal chlorosis of young leaves, sometimes followed by the formation of tan spots in the chlorotic areas between the veins. Initial chlorosis can also occur uniformly across the young leaf rather than in an interveinal pattern.

Manganese Toxicity (Color Plate 11)

Toxicity very often begins with interveinal chlorosis of young leaves due to iron deficiency caused by high manganese antagonism of iron uptake. Manganese toxicity takes the form of burning of the tips and margins of older leaves or formation of reddish-brown spots on older leaves. The spots are initially about

1/16 inch (1–2 mm) in diameter and are scattered over the leaf. Spots become more numerous and eventually coalesce into patches.

Zinc Deficiency (Color Plate 12)
Young leaves are very small, and internodes are short, sometimes giving the stem a rosette appearance. The young leaves are also chlorotic in varying patterns but tending toward interveinal. In kalanchoe, zinc deficiency can express itself as a fasciation (a flattened, highly branched stem). Seedlings develop chlorosis on young leaves followed by necrosis of nearly mature leaves just below.

Copper Deficiency (Color Plate 13)
Young leaves develop chlorosis in various patterns, often tending toward interveinal. Tips and lobes of these young leaves may retain green pigment longer than the rest of the leaf. Often there is a blue or gray cast to the green pigment. Margins of young leaves frequently roll upward. Necrosis suddenly appears on recently mature leaves and spreads rapidly, resembling desiccation. Flowers may be lighter in color and fewer.

Boron Deficiency (Color Plate 14)
Incomplete formation of flower parts such as fewer petals, small petals, sudden wilting or collapse of petals, and notches of tissue missing in flower stems, leaf petioles, or stems. Death of the bud, giving rise to branching followed by death of the new buds, eventually leading to a proliferation of shoots termed a *witch's broom*. Additional symptoms include short internodes; crinkling of young leaves; corking of young leaves, stems, and buds; thickening of young leaves; chlorosis of young leaves but not in any definite pattern; and roots short and thick with eventual death of root tips.

Additional symptoms in foliage plants can include brittle stems and leaves and necrotic spots (black and sunken) on stems just below nodes; nodal roots on vine plants may become thick and short and abscise, and vines may become highly curled at the nodes.

Boron Toxicity (Color Plate 15)
The margins of older leaves become necrotic with a characteristic reddish-brown color. Necrotic spots may also develop across the leaf blade, but tend to be concentrated at the margins.

Molybdenum Deficiency (Color Plate 16)
Symptoms apply to poinsettia, the only greenhouse floral crop molybdenum deficiency is known to affect. The margins of leaves at the middle of the plant become chlorotic, presenting a silhouette appearance, and then quickly necrotic. Symptoms spread up and down the plant. These leaves may also become misshapen, resembling a half-moon pattern with some crinkling.

Substrate Testing

Substrate testing offers unique information that is not available through visual diagnosis and foliar analysis, such as pH and soluble-salt levels and form of available nitrogen (i.e., nitrate versus ammonium). Only a portion of most nutrients in the soil is immediately available to a plant. Substrate-testing procedures give an estimate of the proportion of each nutrient that is available. One could say that substrate testing is predictive in that it estimates what will be taken up by the plant. Foliar analysis

Table 16
NUTRIENT CONCENTRATION (PPM) GUIDELINES FOR GREENHOUSE SUBSTRATE FROM MICHIGAN STATE UNIVERSITY FOR THE SATURATED-MEDIA EXTRACT (SATURATED-PASTE) METHOD[1] AND FROM THE OHIO STATE UNIVERSITY FOR THE SATURATED-PASTE EXTRACT METHOD[2] FOR CROPS IN GENERAL[3]

Interpretation	Nitrate-N	Phosphate-P	Potassium	Calcium	Magnesium
Michigan State University					
Low	0–39	0–2	0–59	0–79	0–29
Acceptable	40–99	3–5	60–149	80–199	30–69
Optimum	100–199	6–10	150–249	200+	70+
High	200–299	11–18	250–349	—	—
Very High	300+	19+	350+	—	—
The Ohio State University					
Extremely low	0–29	0–3.9	0–74	0–99	0–29
Very low	30–39	4.0–4.9	75–99	100–149	30–49
Low	40–59	5.0–5.9	100–149	150–199	50–69
Slightly low	60–99	6.0–7.9	150–174	200–249	70–79
Optimum	100–174	8.0–13.9	175–244	250–324	80–124
Slightly high	175–199	14.0–15.9	225–249	325–349	—
High	200–249	16.0–19.9	250–299	350–399	125–134
Very high	250–274	20.0–40.0	300–349	400–499	135–174
Excessively high	275–299	40.0+	350+	500+	175+

[1]From Warncke and Krauskopf (1983).
[2]From Peterson (1984).
[3]Values are listed in parts per million (ppm). Although ammoniacal nitrogen (NH_4-N) is not listed, generally accepted upper limits are 40 ppm for crops in general and 20 ppm for seedlings.

differs in that it provides a measurement of nutrients in the plant tissue that were taken up in the past. These two greatly different views work well together for diagnosing the nutritional status of a crop.

Each substrate-testing laboratory provides an interpretive chart of values for its tests. Even though two labs use the same test, their interpretive values may differ. This could be caused by subtle procedural differences within the test. Most labs use the saturated-paste, also known as saturated-media extract (SME), procedure for greenhouse substrates. Some macronutrient and micronutrient standards for the SME test are presented in Tables 16 and 17. Some labs use procedures designed for field crops and may or may not have standards for greenhouse crops.

Growers who use tests for which there are no standards should record and relate over the years their crop responses to fertilizer applications and substrate-test results. This procedure ultimately indicates to the grower the levels of each nutrient that should be maintained for best growth. Whether interpretive tables exist or not, a grower should take periodic substrate samples and keep a log book in which to record crop responses; substrate-testing and foliar analysis results; application dates of water, fertilizer, and pesticides; and other factors affecting growth. Quite often, it is necessary to adapt values in the interpretive table to individual situations. This can be accomplished through the logging procedure. Desirable sampling frequencies for crop categories include monthly for cut-flower and vegetable crops, twice monthly for 3–4-month pot crops, weekly for bedding-plant flats, and twice weekly for plug seedlings.

Table 17
Acceptable Ranges for Micronutrient Concentrations (ppm) for Greenhouse Substrate for the Saturated-Media Extract (Saturated-Paste) Method[1]

Micronutrient	Concentration (ppm)
Iron (Fe)	0.3 to 3.0
Manganese (Mn)	0.02 to 3.0
Zinc (Zn)	0.3 to 3.0
Copper (Cu)	0.001 to 0.5
Boron (B)	0.05 to 0.5
Molybdenum (Mo)	0.01 to 0.1

[1]Adapted from standards used by prominent commercial testing labs.

Periodic sampling facilitates identification of faulty samples, which might infrequently occur as a result of poor sampling procedure or an error in testing. Note in Figure 6 the March value for sample A, which is abnormally high. This value is an indication of a faulty sample. It also indicates the direction in which nutrient levels are changing in the root substrate. Note again in Figure 6 that the potassium levels in the root substrates represented by samples A and B in May are equal. If this level were desirable and May was the only month in which sampling was done, no action would be taken. Yet, from the series of sample results, it can be seen that in one substrate the level of potassium application should be diminished at this time, while in the other it should be increased so that imbalances do not occur the following month. Only sequential sampling will bear out these facts.

Test Meters Most substrate testing is performed by governmental and commercial laboratories. Growers can purchase equipment to test their own root substrates. Inexpensive pocket meters for testing pH and EC begin at about $50 each. These are accurate enough for substrate testing. Some more accurate portable meters that measure both pH and EC include the Economy pH/EC meter by Spectrum Technologies, Inc. (Figure 7a) and the Hanna Instruments model 9811 or 9813. These instruments cost between $180 and $260. Specific-nutrient tests, including tests for nitrate, potassium, and sodium, can be conducted with Cardy meters (Figure 7b and c),

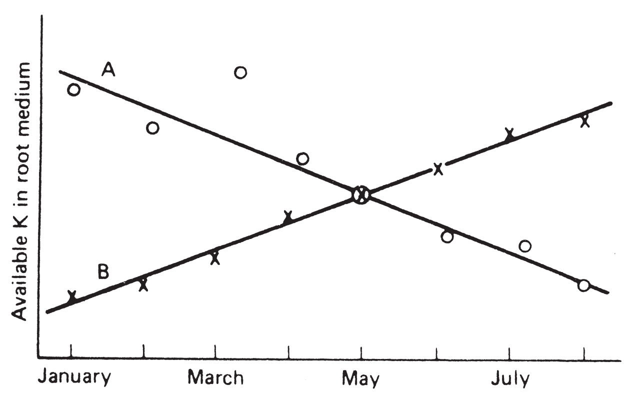

Figure 6
An illustration of the value of monthly soil sampling as opposed to a single sample date. Samples A and B drawn in May would indicate similar nutrient situations. This is erroneous, since the root substrate represented by sample A is decreasing in K level while that represented by sample B is increasing. These facts are borne out only by sequential sampling.

(a)

(b)

(c)

Figure 7
Meters frequently purchased by greenhouse firms for testing their root substrate. (a) Economy pH/EC meter, (b) Cardy Twin Nitrate meter, and (c) Cardy Potassium meter.
(Pictures courtesy of Spectrum Technologies, Inc., Web: www.specmeters.com.)

which are available at approximately $370 each. All of these tests can be run directly on a substrate extract in a matter of minutes. No chemical alterations of the soil extract are necessary. All of these meters are available from greenhouse-supply companies. Every greenhouse needs to have at least a pH and an EC meter. The pH level can give an estimate of the quantity of limestone to incorporate into substrate during its formulation. Later, during the crop, the pH level indicates the acidity or basicity level of fertilizer to use. The EC level indicates whether an inadequate, adequate, or excessive level of fertilizer exists in the root substrate. Larger firms with specific-nutrient Cardy meters will be able to determine the balance of nitrate and potassium in the substrate without waiting for soil test results to come back from the testing lab. This latter information is used to make adjustments in the fertilizer ratio.

Sampling Procedure An important decision in soil testing concerns the number of samples to be drawn. No set area can be assigned to a sample. To determine the boundaries of the area included in one sample, one should consider the origin of the substrate and its fertilization history. If two different substrates are used for a single crop, two substrate samples would be needed. Peat moss has different nutrient retention and pH-buffering capacities than pine bark. Coir coconut fiber differs even more from peat moss in pH level. Similar diversity could occur in a single substrate used for successive cut-flower crops. In a greenhouse containing one substrate, a snapdragon and a chrysanthemum crop might be replaced with chrysanthemums only. The new chrysanthemum crop would be growing in two nutritional zones due to carryover of nutrient and pH effects from the previous two crops. Thus, two samples would be required. Generally speaking, a substrate sample area could be as small as a single bench of plants and as large as several acres.

Other more subtle factors to consider in substrate testing will become recognizable as one becomes familiar with a greenhouse range. For example, a chrysanthemum grower experienced root injury, necrosis of leaf margins, and overall stunting of plants in specific sections of outdoor ground beds during rainy seasons. The problem was due to poor drainage in the low spots of the beds. Under this condition of low soil-oxygen content, an excessive proportion of the large manganese reserve of the substrate was converted to an available form and, in turn, resulted in manganese toxicity. The higher areas of the beds were sufficiently drained and aerated to prevent an excessive conversion of unavailable to available manganese. To identify this problem, it was necessary to recognize and sample the problem section only.

The customary volume of substrate submitted is 1 pint (500 cc). It is important that this sample is collected properly so that it is truly representative of the total area of crop sampled. A substrate-sampling tool such as the one shown in Figure 8

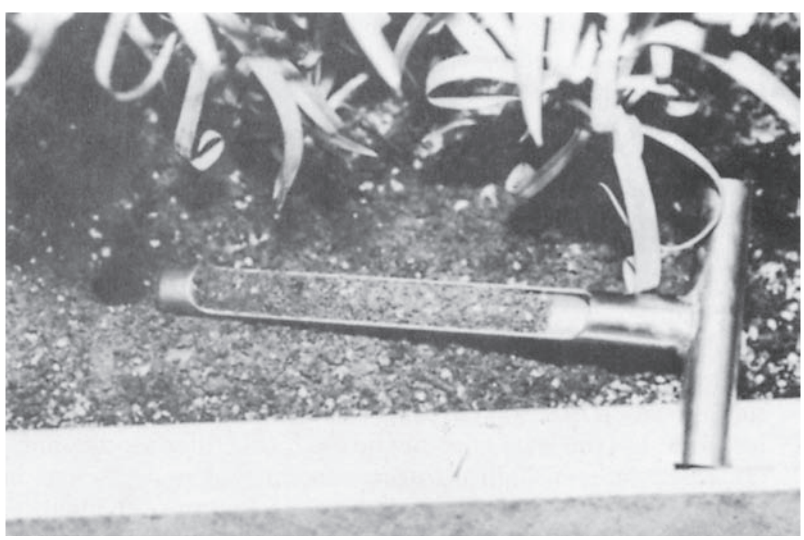

Figure 8
A sampling tool used for obtaining cores of substrate from pots or beds in greenhouses for substrate testing purposes. The side of the tube is cut away to permit removal of the substrate core.

should be used. The top 0.5 inch (1.3 cm) of substrate is scraped aside, and the substrate-sampling tube is then pressed into the substrate until it makes contact with the bottom of the pot or bench. In this way, the entire root zone is sampled. The top 0.5 inch (1.3 cm) is avoided because abnormal levels of fertilizer salts build up there as a result of water evaporation and also because roots rarely grow where there is rapid drying. At least 10 substrate cores should be taken for one sample. Some should be taken from the edge of the bench and others from the center, since drying conditions, which affect salt accumulation, differ in these locations. The 10 cores should be collected from all sectors of the sample area.

The substrate sample should be mailed to the testing laboratory without delay. If the substrate is wet enough to cause a breakdown of the package during shipment, it should be partially dried in the sun or on a warm surface, such as a boiler, prior to shipping. It is very important that information sheets supplied by the testing laboratory are completed and sent with the sample. This information aids in identifying problems and developing recommendations.

Substrate Extraction Procedures Greenhouse growers who have their own test equipment can use one of four substrate extraction methods. All four methods involve water extraction. In contrast, field crop soils are extracted with chemicals such as nitric acid, acetic acid, and ammonium acetate. The four greenhouse extraction procedures are the following:

1. The 1:2 extract method calls for placing one volume of dried substrate, compacted to the same density that it was in the pot or bench, into a watertight container such as a cup and then adding two volumes of water. The mixture is thoroughly stirred and allowed to sit for one to two hours. Then the substrate solution is squeezed from the slurry through cheesecloth. This extract can be used for pH and EC determinations only.
2. The saturated-paste extract, also known as the saturated-media extract, procedure calls for placing any volume of substrate in a watertight container. The substrate can be at any moisture level. Water is slowly added, with stirring, until the surface of the substrate just begins to glisten with free water. After 15 minutes, more water is added, with stirring if necessary, to return the substrate surface to a glistening state. After a total of one to two hours' contact between the water and the substrate, the soil solution is squeezed from the slurry through cheesecloth. This extract can be used for pH, EC, and specific-nutrient tests.
3. The PourThru method, originally developed by Wright at Virginia Polytechnic Institute and State University, Blacksburg, Virginia, for woody nursery crop substrate testing, has recently been adapted to floricultural crops by the Substrates Laboratory Group at North Carolina State University. PourThru extraction is the quickest of the procedures. The procedure is simple and starts with watering or fertilizing a crop. For fertigated crops, a fertilizer application is made, while for weekly fertilized crops, water is applied at the mid-point between successive fertilizations. One hour after fluid application, during which time the new fluid equilibrates with the substrate, pots (or a pack of cells from a bedding-plant flat) are placed over a saucer. Sufficient distilled water is poured over the substrate surface to cause 1.5 fluid ounces (50 mL) of substrate solution to be expelled from the pot (or pack of cells) into the saucer. This solution can be tested for pH, EC, and specific nutrients. Quantities of water to apply for various-sized pots are listed in Table 18. A minimum of five pots should be selected across a single crop, and the results of the five are averaged to get a reading for the crop. More detailed information is posted on the Web at the NCSU Floriculture site http://www.ces.ncsu.edu/depts/hort/floriculture/crop/crop_PTS.htm and at

Table 18
AMOUNT OF WATER TO APPLY TO VARIOUS CONTAINERS TO OBTAIN 50 mL (1.5 FL OZ) OF LEACHATE IN THE POURTHRU SUBSTRATE EXTRACTION PROCEDURE

	Water to Add[1]	
Container Size	Ounces	mL
4 in. (10 cm)	2.5	75
5 in. (13 cm)	2.5	75
6 in. (15 cm)	2.5	75
6.5 in. azalea (17 cm)	3.5	100
1 qt (1 L)	2.5	75
4 qt (3.8 L)	5.0	150
12 qt (11 L)	12.0	350
Flats—1 cell pack	2.0	50

[1]Containers should be brought to container capacity one hour before applying these amounts. These amounts are estimates. Actual amounts will vary depending on substrate type.

http://www.floricultureinfo.com. Standards developed for PourThru sampling relate to fertigated crops. Growers who fertilize weekly can start with these standards but will need to fine-tune them.

4. The press extraction method (PEM), developed at North Carolina State University, accomplishes the same end point for plug seedlings as the PourThru but is simpler and works well for small cells that exist in plug trays and high density flats. The crop is fertilized. After one hour, the plug tray is placed over a container, and the substrate in individual cells is pressed to cause substrate solution to be expelled. Several cells are pressed in each of at least five trays selected across the whole crop.

For all substrate extractions, it is best to use distilled water to prevent the addition of salts from low-quality water. Distilled water can be purchased at most grocery stores. The pH level will be modestly higher in the 1:2 extract and slightly higher in the saturated-paste extract compared to the PourThru and press extracts. pH is a measure of hydrogen ion concentration where lower concentrations give higher readings. The PourThru and press extracts are essentially unaltered substrate solution as the root experiences it. There is a moderate dilution of substrate solution in the saturated-paste extract and a large dilution in the 1:2 extract. Likewise, nutrient concentrations will decline from PourThru and press extracts to saturated-paste and finally 1:2 extracts due to water dilution. Each test must be interpreted with its own set of nutrient standards. There is a subjective step that must be carefully executed in the 1:2 and saturated-paste extractions. In the 1:2 procedure, the correct volume of substrate must be determined by compacting it to the same density that it was in the pot. In the saturated-paste extract, it is necessary to add the proper amount of water to just reach the glistening-paste state. For purposes of standardizing these steps, it is best to have a single individual run all of the extracts for a firm. The PourThru and press extractions do not have subjective steps.

Soluble Salts A valuable test provided only through soil testing is the measure of the soluble-salt (EC) level. Interpretation charts are presented in Table 19 for four EC test procedures. For more detailed EC recommendations by crop, refer back to Table 5.

Table 19
Interpretation of Soluble-Salt Levels[1]

Dilution[2] 1:2 Soil	Dilution[2] 1:2 Soilless	Dilution[2] 1:5 Soil	Saturated-Paste Extract Soil and Soilless	PourThru and Press	Interpretation
0–0.25	0–?	0–0.10	0–0.75	0–1.0	Insufficient nutrition
0.26–0.50	?–1.00	0.11–0.25	0.75–2	1.0–2.6	Low fertility unless applied with every watering
1.00		0.50	—	—	Maximum for planting seedlings or rooted cuttings
0.51–1.25	1.00–1.75	0.26–0.60	2–4	2.6–5.3	Good for most crops
1.26–1.75	1.76–2.25	0.61–0.80	—	—	Good for established crops
1.76–2.00	2.25–3.50	0.81–1.00	4–8	5.3–10	Danger area
Over 2.00	Over 3.50	Over 1.00	Over 8	Over 10	Usually injurious

[1]EC levels are expressed as mmho/cm, which is equivalent to mS/cm and to dS/m. For more detailed EC recommendations by crop, see Table 5.
[2]Some labs will report these values as mho × 10^{-5}/cm. (1 mmho/cm = 100 mho × 10^{-5}/cm).

Soluble salts come from various sources. Irrigation water can contain salts such as sodium, calcium, and magnesium bicarbonates, and sodium chloride. Soluble fertilizers are mainly soluble salts. Initially insoluble, slow-release fertilizers dissolve with time, releasing nutrients into the root substrate that are in themselves soluble salts. Thus, some soluble salt must be present to ensure a proper level of fertilizer, but the level must not be too high. It is interesting to note that the urea form of nitrogen is an electrically neutral soluble compound and not a salt composed of electrically charged ions. Therefore, urea is not sensed by EC meters. Other sources of salts may not be desirable. Organic matter of high nitrogen content that undergoes rapid decomposition can contribute considerable ammonium salts. Manure and highly decomposed peats may have sizeable nitrogen contents that are rapidly released through degradation in the root substrate as ammoniacal nitrogen. Ammoniacal nitrogen can quickly build up to a toxic level because its positive electrical charge causes it to be held in the root substrate.

Seedlings are more sensitive to high soluble-salt levels than are established plants. Established plants vary in their resistance to high soluble-salt levels. African violet and azalea are particularly sensitive and should not be grown in substrates with a level exceeding 1.5 mmho/cm on the saturated-paste test. Snapdragon is moderately sensitive and should be grown at levels below 2.5 mmho/cm on the saturated-paste test. Several houseplant crops are sensitive as well. There is probably no single upper critical EC level for each crop. Plants can adapt to high substrate salt levels by synthesizing soluble organic solutes in the root cells. These substances raise the solute content of the root high enough to counteract the rise in salt in the substrate solution. Thus, water continues to be attracted from the substrate to the root. Time is required for the formation of these solutes. A chrysanthemum plant that has been fertilized weekly with a 600-ppm fertilizer solution and is growing at a desirable substrate salt level would probably be injured if it were suddenly fertilized with a 1,200-ppm fertilizer solution. However, this same plant would not be injured if the 600-ppm nitrogen fertilizer solution were gradually raised in a series of fertilizer applications over a period of several weeks to 1,200-ppm nitrogen. This would afford time for the root solute concentration to gradually rise so that it exceeds at any given point in time the substrate salt concentration derived from the 1,200-ppm nitrogen application. Note that it is not just the concentration of charged ions but rather the combined concentration of charged ions plus dissolved compounds, whether neutral or charged, that determine the movement of water between substrate and root.

Aside from plant adaptation, the exact EC level at which injury occurs depends to a large degree on watering practices. If the root substrate is not permitted to dry, then a high salt content may be tolerated. When the substrate dries, the salts become more concentrated than indicated by the test, and injuries may result. Ordinarily, it is not wise to maintain root substrates at high moisture content, but between the time that a high salt level is identified and the cure is administered, it is expedient to do so.

Fortunately, soluble salts, as the name implies, are water-soluble and can be leached from root substrates. The standard corrective recommendation calls for application of 1 gallon of water per square foot (40 L/m^2) of root substrate for cut-flower and vegetable bench crops, a waiting period of a few hours, and then a second application of water at the rate of 0.5 gal/ft^2 (20 L/m^2) of root substrate surface. The waiting period gives the more slowly soluble salts time to dissolve. Pot crops are leached by first applying a heavy watering followed a couple of hours later by a second heavy watering.

Often, a root substrate with a soil base is adversely affected by the second application of water. The soil structure breaks down. This is particularly harmful in carnation and rose root substrates, where the crop is maintained for one, two, or five years without an opportunity to amend the root substrate. Researchers at the University of Connecticut have developed a more desirable procedure for leaching in these cases. Up to 5 gallons of water are supplied to each square foot (200 L/m^2) of root substrate in one application, preferably with a trickle-type irrigation system. This procedure utilizes more water but eliminates the destructive second application of water, when the substrate is excessively wet and subject to structural breakdown.

Foliar Analysis

Foliar analysis constitutes the fourth in the set of tests for determining the nutrient status of crops. Like soil testing, it is valuable because it can be used to assess a problem before damage occurs. In foliar analysis, representative leaves from a crop are analyzed to determine the quantities of essential, as well as potentially hazardous nonessential, elements the crop has taken up. The laboratory conducting the analysis compares the results to standards developed at many research institutions around the world and draws the necessary conclusions for the grower.

Foliar analysis works well because of the strong relationship between leaf composition and plant response, which is illustrated in Figure 9. Except in the zone of luxury consumption, where changes in leaf composition have no effect on growth, the nutrient content of the leaf can be used to predict the growth of the plant. It is fortunate that the zone of luxury consumption exists, because it lessens the chance of injury from overapplication of fertilizer.

Foliar analysis offers more accurate testing for all micronutrients than substrate testing. However, foliar analysis should be used in conjunction with substrate testing to give two different measurements of nutrient status. Just as one would not enter a serious medical operation without two independent assessments of the situation, one should not base the nutritional future of crops on one system of assessment.

The strength of substrate testing in combination with foliar analysis is shown by a situation that occurred in a carnation range some years ago in New York. The crop was growing slowly and showing symptoms of potassium deficiency. Contrary to this observation, a substrate test indicated that levels of nitrogen and potassium were high. Foliar analysis indicated that potassium was very deficient, while nitrogen was only moderately high. The combination of information led to the conclusion

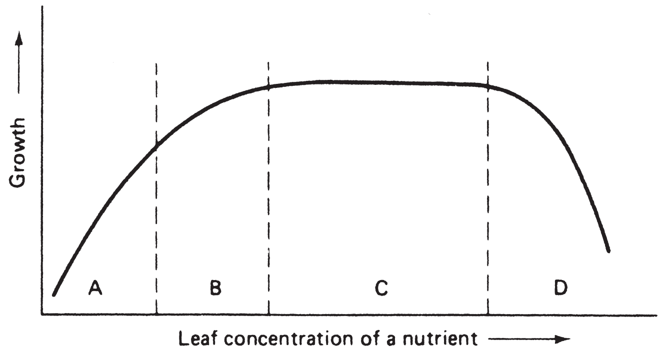

Figure 9
A nutrient calibration curve. When all other factors are adequate, the leaf content of an essential nutrient strongly affects growth. Little growth occurs at low concentrations of the nutrient, but with small additions of the deficient nutrient, large increases in growth occur (zone A). When the rate of growth comes closer to the optimum level, increases in the leaf content of the deficient nutrient bring about continually diminishing growth responses (zone B), until a point is reached beyond which no growth response is caused by increases in leaf concentration of the nutrient (zone C). This is the zone of luxury consumption. *Eventually, nutrient increases in the leaf reach a toxic level, resulting in decreases in growth and eventually in death (zone D).*

that potassium uptake was blocked by a high substrate-nitrogen level. This relationship is an antagonism that frequently occurs. The conclusion was verified when, four weeks after reducing the rate of 20-20-20 fertilizer application to half the previous level, the grower observed a twofold increase in the foliar level of potassium and the disappearance of potassium-deficiency symptoms.

Although there is an appropriate stage in each crop when foliar analysis should be applied, it is valuable to have a series of samples. This is accomplished by sampling a series of crops. For example, a pot mum grower who plants a crop each week could sample every fourth crop, each at the appropriate stage of development. This allows the grower to see trends in the fertilization program. The optimum level of nutrients in the foliage of each crop species is different, necessitating the taking of a different sample for each species. If one species is growing in two dissimilar substrates or has been fertilized in two different manners, two samples must be taken. It is important that the correct leaves are sampled, since the nutrient level in each is different from the rest. The age of the crop is also important because the nutrient levels in a leaf of a given stage of development will differ as the plant ages. The laboratory conducting the foliar analysis tests will provide a mailing envelope for the leaves, a set of instructions for collecting the proper leaves, and the appropriate stage of development in the crop when the sample should be taken.

Detailed sampling procedures exist for some crops such as rose and carnation. Rose plants are sampled by picking the two uppermost five-leaflet leaves on a stem whose flower calyx is cracking and whose color is just beginning to show. Thirty leaves with petioles attached should be collected. Carnation plants that have not yet been pinched are sampled by collecting the fourth and fifth leaf pairs up from the base of the stem (area A in Figure 10). Sampling continues in area A after pinching and until the resulting lateral shoots develop seven pairs of leaves. Then, the fifth or sixth leaf pairs are sampled on the new shoots (area B), counting the first pair of leaves to be separated for one-half the length of the leaves as the first leaf pair. Sampling continues in area B until a flower bud appears on this shoot. Then, sampling should be shifted to secondary lateral shoots, again using the fifth or sixth leaf

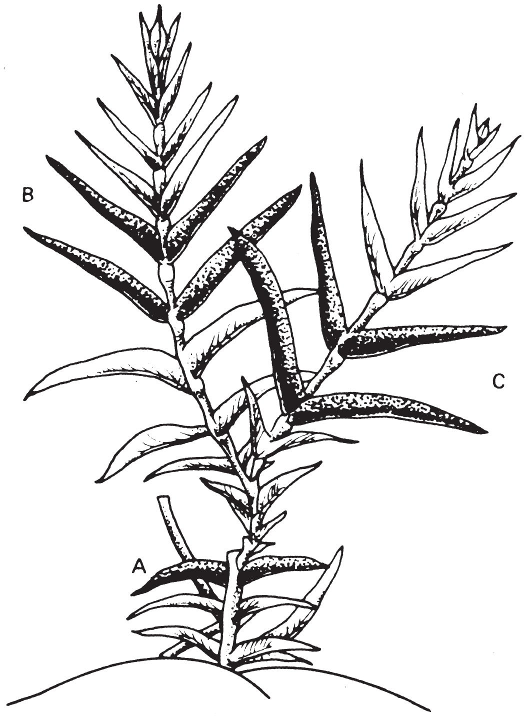

Figure 10
Leaf-sampling procedure for foliar analysis of carnation. As plants progress from a single shoot to secondary and tertiary shoots, shift sampling from position A through B to C.

pairs from the terminal end of the shoot (area C). When secondary lateral shoots develop flower buds, sampling is shifted to tertiary lateral shoots, and so on.

Chrysanthemums are typical of plants in general in that the youngest fully expanded leaves are sampled. These leaves are usually found on chrysanthemum plants about one-third of the distance down the stem from the top. Chrysanthemums are generally sampled five to six weeks after planting for a single-stem crop or five to six weeks after pinching for a pinched crop. The sample location has not been developed for most crops. For these, the youngest fully expanded leaves are sampled. These leaves are located about one-third of the distance down the lateral shoots and constitute the outer canopy of leaves.

Foliar analysis kits contain an information form similar to the one shown in Figure 11. This form permits laboratory personnel to gather the information necessary to enable them to draw conclusions and make nutritional recommendations. It is best to rinse leaves for one minute in deionized or distilled water, available in grocery stores. The leaves should be blotted dry, placed in the paper envelope provided by the testing lab, and mailed immediately. Leaves should not be placed in a plastic bag because they may rot during shipping. If distilled water is not available, leaves that are known to be free of fertilizer residues and soil can be shipped as is. Leaves contaminated with any nutrient-bearing material should be washed with the cleanest water available. The price for foliar analysis can range from \$6 to \$40 per sample. This charge is nominal, however, when compared to the total investment in a crop.

Considerable research has been conducted to determine the optimum levels of nutrients in foliage. Carefully developed standards exist for many florists' crops, and for other crops, good estimates have been developed from years of observation. Table 20 lists the minimum critical levels for several nutrients for some of the major crops. Concentrations below these levels are associated with deficiency. Macronutrient

MAILING ADDRESS PLANT ANALYSIS LABORATORY—DEPARTMENT OF HORTICULTURAL SCIENCE
N C STATE UNIVERSITY, RALEIGH.N C 27607

SAMPLE INFORMATION FOR FLORICULTURE CROPS		**LAB USE ONLY**
Name of Grower	County	Date Sample Received
Street Route	Date Sampled	Condition of Sample
City, State Zip Code	Grover Sample No	Grower II
Telephone No	Name of Crop	Country II
Identification of Field Sampled	Description of Sample Site:Which Field	Sample
		Date Analysis Received

SAMPLE INFORMATION

1. Name of crop _______________ 2. Variety _______________ 3. Date planted _______________
4. Date punched (if applicable) _____
5. This sample represents (a) an average condition __________ (b) a problem area ____________
   (c) a spotty or sporadic situation _____
6. Appearance or condition of plant and/or leaves ____
____
7. Location of sample on plant ____
____
8. Previous crop _______________ 9. What is your fertilization program for the crop represented by this sample?
   (List fertilizers used, rates, and frequency of application)
____
____
10. What amendments did you use during preparation of the soil mix in which this crop is growing (List such materials as dolomitic limestone, superphosphate, fritted trace elements and the rates used)
____
____

North Carolina State University Agricultural Experiments Station
and North Carolina Agricultural Extension Service, Cooperating

FARMER OR GROWER COPY

Figure 11
A typical information form to be completed by the grower and submitted to the foliar analysis laboratory as an aid in the interpretation of results.

standards vary sharply with each crop, whereas micronutrient standards remain rather constant for most crops. Macronutrients are expressed as a percentage of the dry weight of the leaf tissue analyzed. This would not be convenient for micronutrients, since they constitute only a small fraction of 1 percent; instead, micronutrients are measured in parts per million (ppm). The conversion from percent to ppm is simple: 1 percent equals 10,000 ppm. Excellent sources of standard tissue concentrations of nutrients for greenhouse crops can be found in Mills and Jones (1996).

Table 20
Minimum Critical Foliar Levels of Nutrients for Florists' Crops in General and for a Few Specific Crops[1]

Nutrient	General Crops	Rose	Carnation	Chrysanthemum	Poinsettia	Geranium	Rieger Begonia
N (%)	—	3.0	3.0	4.5	3.5	2.4	4.7
P (%)	0.3	0.2	0.45	0.3	0.2	0.3	0.2
K (%)	—	1.8	3.0	3.5	1.0	0.6	0.95
Ca (%)	—	1.0	1.0	1.0	0.5	0.8	0.5
Mg (%)	0.3	0.25	0.3	0.3	0.2	0.14	0.25
Fe (ppm)	50–60	—	—	—	—	—	—
Mn (ppm)	30	—	—	—	—	—	—
Zn (ppm)	20	—	—	—	—	—	—
Cu (ppm)	5	—	—	7	—	—	—
B (ppm)	25	—	—	—	—	—	14

[1]Concentrations above these are sufficient, while those below are associated with deficiency. Macronutrient standards are specific to each crop. Few micronutrient standards have been developed for specific crops. Fortunately, micronutrient standards do not vary much among crops.

Testing laboratories report their results on a form more or less similar to that reproduced in Figure 12. Generally, the numerical level of each nutrient is reported along with an indication of which of five categories each of the nutrient levels fits:

1. Deficient—showing deficiency symptoms
2. Low—hidden hunger
3. Sufficient
4. High—hidden toxicity
5. Very high—showing toxicity symptoms

Also included are recommended fertilization changes to correct any existent nutrient problems.

Nutritional Diagnosis

Interactions Before attempting to correct a nutrient deficiency, one should always be certain which nutrient is the cause of the problem. The carnation problem previously cited, in which potassium deficiency was induced by an excessive substrate-nitrogen level, is a good example. What first appeared to be a reasonable solution—to apply potassium fertilizer—would not have solved the problem; it might have led to an excessive soluble-salt level. The potassium deficiency was caused by an excessive level of nitrogen, and only a reduction of nitrogen in the soil corrected the deficiency. Such a relationship is known as an *antagonism*. Once the basic antagonisms are known, it is a simple matter to identify them in root substrate and foliar analysis reports.

The more common antagonisms are listed in Table 21. When a deficiency of one of the nutrients in the right column is identified, it should be determined whether an abnormally high level of the nutrient in the left column exists. If so, corrective action should involve reduction of the concentration of the nutrient in the left column. Note that some, but not all, of the nutrient antagonisms are reciprocal. For example, a high level of iron will reduce manganese uptake, and reciprocally, a high level of manganese will reduce iron uptake.

Putting It All Together: A Case Study The following case study illustrates how the monitoring tools, including visual symptoms, water-quality standards, root substrate standards, foliar analysis standards, and nutrient uptake antagonisms can be used in an integrated manner to diagnose a nutritional problem and identify its cause.

PLANT ANALYSIS REPORT

Name of Grower: Paul Nelson	County: Wake	Data Sample Received: 3-19-85
Street, Route: 29 Main St.	Data Sampled: 3-17-85	Condition of Sample: Good
City, State, Zip: Raleigh, N. C. 27607	Grower Sample #: 2	Grower #: 27
Telephone No.: 737-3132	Name of Crop: Cut Chrysanthemum	County #: 13
Identification of Field Sampled: III	Description of Sample Site (Within the Field):	Lab Sample #: 1971 Date Analysis Received: 3-26-85

COUNTY SAMPLE NUMBER	FARMER OR GROWER SAMPLE NUMBER	N %	P %	K %	Na %	Ca %	Mg %	Mn ppm	Fe ppm	S ppm	Cu ppm	Ma ppm	Zn ppm	Al ppm
	2	4.50	0.85	2.10	0.02	1.2	0.38	125	150	23	9	1	44	
RANGE														
DEFICIENT				X										
LOW										X				
SUFFICIENT		X			X	X	X	X	X		X	X	X	
HIGH			X											
EXCESS														

COMMENTS AND RECOMMENDATIONS.

1. Potassium is low. Apply potassium nitrate (13-0-44) for the next two weekly applications at the rate of 2 lbs. Per 100 gal.
2. Phosphorus is too high. After correcting the potassium problem use a 1-0-1 ratio fertilizer rather than the 1-1-1 you have been using.
3. Boron is approaching the deficiency level. Apply one ounce of borax per 100 sq. ft. of bench space one.

Mailing Address: Plant Analysis Laboratory, Department of Horticultural Science, N. C. State University, Raleigh, N. C. 27607 **FARMER OR GROWER COPY**
North Carolina State University Agricultural Experiment Station and North Carolina Agricultural Extension Service, Cooperating.

Figure 12
A typical foliar analysis report as received by the grower.

Table 21
COMMON ANTAGONISMS OCCURRING IN CROPS IN GENERAL[1]

Nutrient in Excess	Induced Deficiency
NH_4, K, Ca, Mg, or Na[2]	NH_4, K, Ca, or Mg
Ca or Mg	Mg or Ca
Ca	B
PO_4	Fe, Mn, Zn, or Cu
Fe, Mn, Zn, or Cu	Fe, Mn, Zn, or Cu

[1]High root substrate levels of any nutrient in the left column can bring about a deficiency of the nutrients opposite it in the right column.

Table 22
SURVEY RANGE OF ACCEPTABLE FOLIAR ANALYSIS CONCENTRATIONS FOR MATURE LEAVES OF PETUNIA[1]

	%		ppm
Nitrogen	3.85–7.60	Iron	84–168
Phosphorus	0.47–0.93	Manganese	44–177
Potassium	3.13–6.65	Zinc	33–85
Calcium	1.20–2.81	Copper	3–19
Magnesium	0.36–1.37	Boron	18–43
Sulfur	0.33–0.80	Molybdenum	0.19–0.46

[1]From Mills and Jones (1996).

The case study goes on to show how this information can be coupled with fertilization recommendations from the first two sections of this chapter and corrective procedures presented in the next section of this chapter to prescribe an immediate action to correct the problem in the current crop and to establish a plan for preventing the problem in future crops. For this case study, it is necessary to know the foliar analysis standards for petunia presented in Table 22.

CASE STUDY

Symptoms and Background A bedding-plant crop of petunias in flats was grown in a commercial soilless root substrate that was properly limed to pH 5.8. The crop was fertilized with 20-10-20 fertilizer at a concentration of 200 ppm nitrogen weekly. Four weeks after transplanting into flats, the lower foliage developed interveinal chlorosis.

Water Analysis

			(ppm)
pH	7.4 High	Phosphorus	0.8
Salt (EC) (dS/m)	1.4	Potassium	1.1
Alkalinity (me/L $CaCO_3$)*	4.1 High	Calcium** High	120 (6me/L)
Nitrate-N (ppm)	2.0	Magnesium***	6 (0.5me/L)
Ammoniacal-N (ppm)	0.1		

Substrate Analysis (Saturated media extract: macronutrients by Michigan State University; micronutrients by Fafard Analytical Lab.) (See Tables 16 and 17 and Figure 13.)

			(ppm)
pH	6.9 High	Calcium	430 High
Salt (EC) (dS/m)	2.2	Magnesium	75
	(ppm)	Fe****	0.9
Ammoniacal-N	7.0	Mn****	1.0
Nitrate-N	110	Zn****	0.4
Phosphorus	8	Cu****	0.2
Potassium	170	B****	0.2

Plant Analysis

	(%)		(ppm)
Nitrogen	4.1	Iron	85
Phosphorus	0.6	Manganese	49
Potassium	3.9	Zinc	40
Calcium	2.8	Copper	7
Magnesium	0.19 Low	Boron	34
Sulfur	0.4	Molybdenum	0.3

*50 ppm (mg/L) calcium carbonate = 1 milliequivalent (me)/L.
**20 ppm = 1 me/L.
***12 ppm = 1 me/L.
****These micronutrient levels are acceptable.

The Nutrient Disorder is Mg deficiency.

The Cause is a high substrate level of Ca-antagonized plant uptake of Mg (see Table 21). High substrate Ca came from water. If substrate Ca was not high, the substrate Mg level would have been sufficient.

Correction: Apply Mg as Epsom salt at 2 lb/100 gal (2.4 g/L) once (see Table 23).

Future Prevention: Compensate for water alkalinity with less limestone in substrate, acid fertilizers, or acid injection to avert excessive substrate pH rise and potential micronutrient deficiencies. Balance the high level of Ca supplied in water by applying (1) only dolomitic type limestone in substrate, (2) post-plant fertilizers that contain Mg, and (3) Epsom salt periodically as needed.

This case study illustrates the need for four sets of analytical data and the list of nutrient uptake antagonisms in Table 21 to thoroughly diagnose a nutritional problem and develop plans for its immediate correction and future prevention. The substrate test indicated adequate magnesium; thus it alone would have missed the magnesium deficiency problem. Visual symptoms and foliar analysis identified and confirmed magnesium deficiency. At this point, the need for an application of magnesium to cure the current problem was obvious. However, the cause was not identified, and thus development of a plan for prevention in future crops was not yet possible. Water analysis plus substrate analysis explained the cause of the problem (i.e., high calcium in water caused an excessively high substrate calcium level that blocked plant uptake of magnesium). Now it became obvious that future prevention could be accomplished by balancing the high quantity of calcium in irrigation water with magnesium from dolomitic limestone and fertilizers.

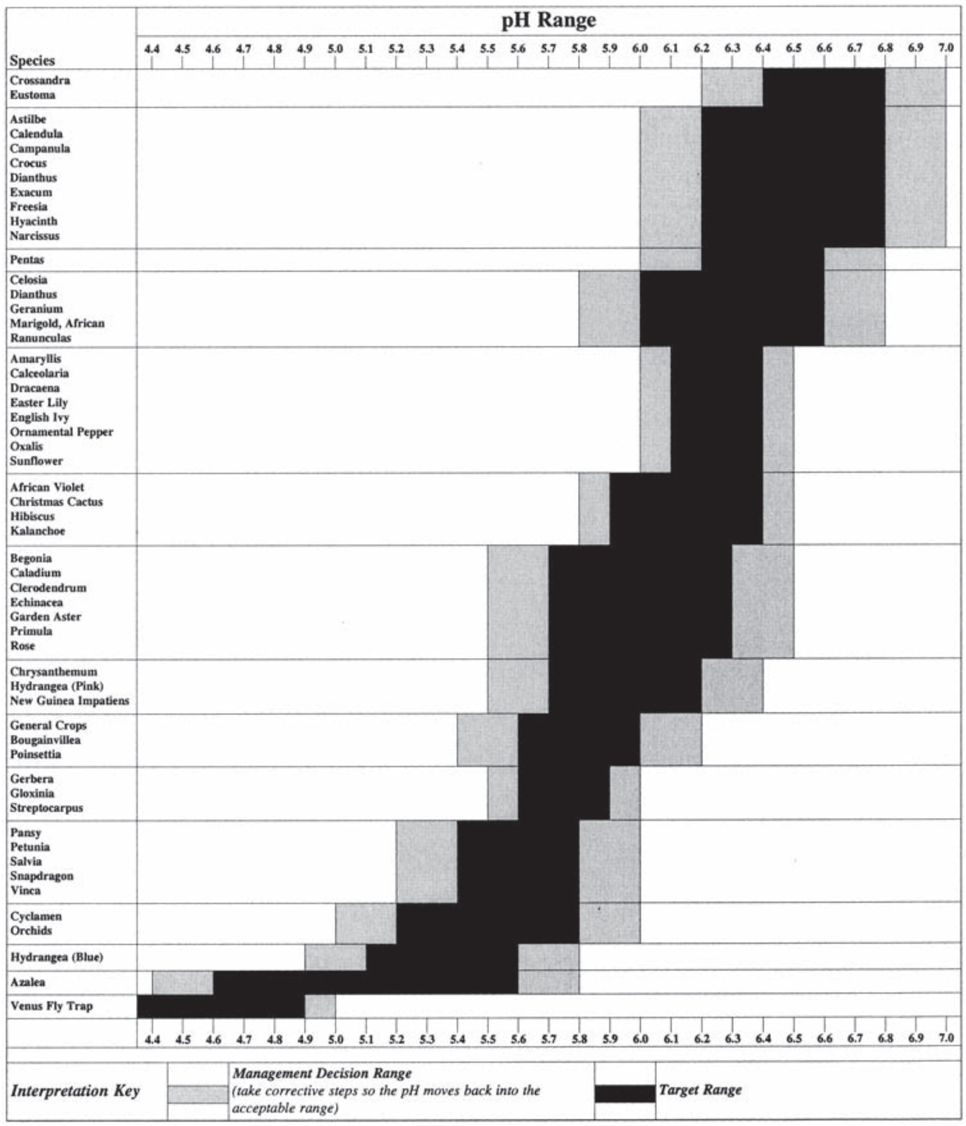

Figure 13
Suggested substrate pH ranges for specific greenhouse crops grown in soilless substrate.
(From Whipker et al., 2000.)

CORRECTIVE PROCEDURES

Essential Nutrients

Fertilization systems were recommended in the earlier part of this chapter. Under ideal conditions, these systems work well, but conditions are not always ideal. The optimum rate of fertilizer application relates to the rate of plant growth, which, in turn, can be adversely affected by inclement weather, a poor root substrate that does not drain well, over- or underwatering, a dirty greenhouse covering, nutrient tie-up by constituents of the root substrate, antagonisms by other nutrients, and many other factors. Some nutrients are affected more than others; thus, it is important not only to adjust the rate of fertilization but also to change the ratio of nutrients in the fertilizer. Occasionally, a single nutrient will go far enough out of balance that it alone must be applied. Nitrogen and potassium ratio adjustments can be accomplished

Table 23
FERTILIZER SOURCES AND RATES FOR CORRECTION OF VARIOUS NUTRIENT DEFICIENCIES

Deficient Nutrient	Fertilizer Source	Rate of Application[1] oz/100 gal	g/L
P	Switch to a complete fertilizer containing N-P-K for the continual program		
	or one application of diammonium phosphate or monopotassium phosphate	32	2.4
Ca	Switch part or all of the N source to calcium nitrate for a few weeks		
	or spray with 400 ppm Ca up to weekly from calcium nitrate	30	2.25
	or from calcium chloride (25% Ca)	20	1.5
Mg	Magnesium sulfate (Epsom salts)	32	2.4
S	Magnesium sulfate (Epsom salts)	32	2.4
	or switch N or K source to ammonium or potassium sulfate for a few weeks		
Fe	Iron chelate (DTPA)[2] or ferrous sulfate	4	0.3
	or foliar spray ferrous sulfate or DTPA iron chelate	4	0.3
Mn	Manganese sulfate	2	0.15
	or foliar spray manganese sulfate or manganese chelate	8	0.6
Zn	Zinc sulfate	2	0.15
	or zinc chelate	1	0.075
	or switch to the fungicide Zineb and spray at the recommended rate		
Cu	Copper sulfate	2	0.150
	or copper chelate	1	0.075
	or foliar spray tri-base copper sulfate	4	0.3
B	Borax	0.5	0.038
	or Solubor	0.25	0.019
Mo	For soil-based substrate, drench once with sodium or ammonium molybdate	0.027[3]	0.002
	For soilless substrate, drench once with sodium or ammonium molybdate	2.67	0.200
	or foliar spray sodium or ammonium molybdate with a spreader-sticker	2	0.150

[1]These corrective procedures are to be applied once. Subsequent applications should be made only after soil and foliar analysis tests indicate the need. All fertilizers are to be applied to the root substrate unless foliar spray is specified.
[2]The DTPA form of chelate is sold as Sprint 330, Sequestrene 330, and Dissolzine D-FE-11.
[3]Dissolve 1 oz sodium or ammonium molybdate in 40 fl oz of water. Use 1 fl oz of this stock solution in each 100 gal of final-strength fertilizer solution.

through alterations in the continual fertilizer formula. Corrective procedures for all nutrient deficiencies are listed in Table 23.

Phosphorus deficiency is uncommon but not altogether nonexistent. It can be corrected by switching to a complete fertilizer in which the P_2O_5 content is 50 percent or more of the N concentration, for example, 20-10-20. Calcium and magnesium deficiencies do not often occur where the root substrate pH level has been properly adjusted with dolomitic limestone. Poinsettia was traditionally—and in many cases still is—grown in an acid substrate to minimize the development of root-rot organisms. Calcium and magnesium deficiencies often occur under these conditions. The new cultivars of poinsettia are prone to magnesium deficiency even when the root substrate pH level is adjusted to the recommended range. Easter lily is very susceptible to calcium deficiency. The use of calcium nitrate as a nitrogen source in the complete fertilizer can solve these calcium problems. An application of 2 pounds of Epsom salt (magnesium sulfate) per 100 gallons (2.4 g/L) of water is used to solve either a magnesium or a sulfur deficiency. Sulfur deficiencies have become more prevalent in recent years in soilless substrates that do not contain single superphosphate or gypsum.

It is generally safe to apply a micronutrient mixture when symptoms of a single micronutrient deficiency occur and evidence indicates no other micronutrients are present in high quantity. If this information is not known, the status of all micronutrients should be determined by a foliar analysis test. If all micronutrients are present in moderate or low concentrations, a micronutrient mix can be applied. Otherwise, only the deficient nutrient or nutrients should be applied. In the event that foliar analysis is not possible, small plots may be tested with the suspected deficient nutrient. Then, the deficient nutrient alone should be applied. Micronutrient excesses can be far more troublesome than deficiencies because micronutrients are difficult and sometimes impossible to remove from root substrate.

Iron deficiency is common in azalea, bacopa, calibracoa, diascia, dianthus, gerbera, gloxinia, hydrangea, nemesia, petunia, rose, snapdragon, verbena, and vinca. It also readily occurs in crops grown in soilless substrates if iron has not been incorporated into the substrate. The symptoms of manganese deficiency are similar to those of iron deficiency. Fortunately, manganese deficiency is fairly rare in the greenhouse. Zinc deficiency is rare in greenhouse crops except in the case of kalanchoe (see Color plate 12).

Copper deficiency occurs in specific field soil types and thus follows geographical patterns. Soils of the southeastern United States are very prone to copper deficiency. The rose crop is an exception, in that the deficiency occurs almost universally. Copper deficiency is most prevalent in old, established rose substrates that are high in humus.

Boron deficiency is a problem with carnation, impatiens, gerbera, pansy, petunia, seed geranium, and snapdragon crops. The requirement for boron is similar in these and other crops, but the ability of these crops to take up boron is lower. Boron is readily taken up by chrysanthemum. When carnation or snapdragon crops follow a chrysanthemum crop, boron deficiency often occurs. The pink varieties of carnation are most prone.

Molybdenum deficiency often occurs in poinsettia but is practically nonexistent in other greenhouse crops.

Substrate pH

If any component in a fertilization program could be singled out as the most important, it would be root substrate pH. The best pH range for soil-based substrates is 6.2 to 6.8 while for soilless substrates it is 5.4 to 6.6. See Figure 13 for more precise pH recommendations for individual greenhouse crops. There are two groups of crops that require special attention. The iron-inefficient plants, sometimes referred to as the petunia group, do not readily take up iron from the substrate. At pH levels above 6.0 they typically develop iron deficiency. They should be grown in the pH range of 5.4 to 6.0. This group includes azalea, bacopa, calibracoa, diascia, dianthus, nemesia, pansy, petunia, rhododendron, snapdragon, verbena, and vinca. The iron-efficient plants, sometimes referred to as the geranium group, are overly efficient in taking up iron from the substrate. If grown below pH 6.0 they develop iron toxicity. They should be grown in the pH range of 6.0 to 6.6. This group includes seed and zonal geranium, lisianthus, marigold, and New Guinea impatiens.

Maintenance of substrate pH depends on three major factors: residual limestone, irrigation water alkalinity, and fertilizer acidity/basicity level. The amount of residual limestone contained in different batches of limestone used to formulate substrate varies and is not known. Large proportions of residual limestone will cause pH rises whereas low proportions can result in pH declines. Irrigation water can contain little alkalinity, which often causes substrate pH decline or large amounts leading to pH rise. Alkalinity is primarily due to bicarbonate, which when applied through irrigation water is equivalent to applying limestone. The desirable level of water alkalinity lies in the range of 40 to120 ppm, depending on the crop. The impact of fertilizer acidity or basicity has a sizeable impact on substrate pH, as discussed earlier in this chapter. Note in Table 24 that basic fertilizer is recommended when there is a low level of alkalinity in the irrigation water. One would think that acid fertilizer would be needed in this situation to counteract bicarbonate in the water and residual limestone that is undoubtedly in the liming material used in the substrate. Obviously, there is a fourth force affecting substrate pH. The fourth force is root respiration, which is releasing carbon dioxide, which converts into carbonic acid in the substrate. These four forces point out the need for routine testing of substrate for pH level to avoid adverse shifts. The following sections indicate the options available for correcting adversely low or high pH.

Raising Substrate pH When pH is only moderately low, switching to a more basic fertilizer generally solves the problem. For the general category of crops with an optimum pH range of 5.8 to 6.2, this action should be taken when pH falls below 5.8. When the pH decline is more severe, that is, when it falls below 5.4, a substrate drench with flowable limestone, potassium bicarbonate, or hydrated lime (calcium hydroxide) may be needed.

Flowable dolomitic limestone is available as a water suspension from greenhouse-supply companies. It is applied as a thorough watering to the crop at the rate of 1 to 2 quarts of flowable limestone per 100 gallons of water (2.5 and 5 mL/L). Many growers will apply this through a fertilizer injector. Clear water should be run through the injector after the limestone to minimize damage to the seals. Since the flowable limestone is a suspension, it is necessary to continually stir the concentrate while it is being applied to prevent settling. Quantities of flowable limestone to mix into 1 final gallon of concentrate for application through 1:15, 1:50, and 1:100 injectors are 9.6 ounces, 1 quart, and 2 quarts (75, 250, 500 mL/L) respectively to achieve a final rate of 2 quarts per 100 gal (5 mL/L). While some growers apply through the irrigation drippers, most hand-water through a water breaker at the end of the hose to avoid plugging of drippers. Limestone should be rinsed from foliage before it dries to prevent phytotoxicity and unsightly residues. A portion of flowable limestone is residual; thus pH will rise for a few days after application. If the target pH range is not reached within three days a second application may be made. A single application can bring about a pH rise of up to 1 unit. Flowable limestone supplies calcium and magnesium. This can be beneficial since excessively acidic substrate does not retain these nutrients very well. In situations where the complete fertilizer does not contain calcium and magnesium, flowable limestone restores them.

Table 24
TYPES OF FERTILIZER TO BE USED WITH IRRIGATION WATER OF DIFFERENT ALKALINITY LEVELS[1]

Water alkalinity		Fertilizer Calcium Carbonate Equivalency (lbs/ton)[2]	Fertilizer Examples
Me/L	ppm		
4–6	200–300	>500 acidic	20-20-20, 25-10-10
3–5	150–250	150–500 acidic	20-10-20, 21-5-20
1.2–2.4	60–120	150 acidic to 150 basic	17-5-17, 20-10-20 alternated with 14-0-14 or 15-0-15
0.6–1.2	30–60	>150 basic	13-2-13, 14-0-14

[1]Adapted from Argo and Fisher (2002).
[2]Divide lbs/ton by 2 to convert to kg calcium carbonate per metric ton.

Potassium bicarbonate offers the advantages of being water soluble and suitable for injection through the automatic water emitters. But, one should be aware that it does not supply calcium and magnesium. Also, potassium bicarbonate has no residual property to maintain pH over time, as does flowable limestone. Potassium bicarbonate is available from fertilizer and industrial chemical suppliers. The technical grade should be used. A rate of 2 pounds per 100 gallons is used (2.4 g/L) and can bring about a pH rise of up to 1 unit. Solution should be washed off any contacted foliage before it dries to avoid phytotoxicity. The 2-pound-per-100-gallon rate of potassium bicarbonate supplies 933 ppm of potassium (K). To reduce this level and restore the macronutrient balance in the substrate, the crop should be leached the following day with complete fertilizer. A basic fertilizer such as 13-2-13 would be desirable.

Recommendations exist for using hydrated lime (calcium hydroxide) for raising pH. One pound of hydrated lime is mixed into 3 to 5 gallons of water. The mixture is then allowed to stand until the insoluble portion has settled to the bottom of the container. The clear liquid is decanted from the solid and is applied through a 1:15 injector. This procedure yields a final concentration at the substrate of 1.33 to 2.22 lbs per 100 gallons (1.6 to 2.7 g/L). Hydrated lime supplies calcium but not magnesium unless a dolomitic hydrated lime is used. Hydrated lime is caustic to people and foliage. It should be rinsed from the foliage before it dries. Hydrated lime is not used as often as flowable limestone and potassium bicarbonate because its results are more erratic and it is more difficult to handle.

Lowering Substrate pH Substrate pH can be lowered by various methods. A moderate reduction can be achieved by switching to acidic fertilizer. More substantial corrections can be accomplished through drenches of iron sulfate, acids, or sulfur. Chronic pH rise caused by high water alkalinity can be counteracted with continuous injection of acid into the irrigation water.

Acidic Fertilizers. The first line of approach to countering substrate pH rise should be use of acidic fertilizers. Increasing degrees of alkalinity in substrate can be countered with acidic fertilizers of increasing calcium carbonate equivalent acidity levels such as 20-10-20 with 420 lbs acidity, 20-20-20 with 580 lbs acidity, 20-18-18 with 710 lbs acidity, and 21-7-7 (acid) with 1,700 lbs acidity. Although some of these fertilizers may not have the desired ratio of nutrients, they can be used for a short period of time to adjust pH. After correction, a fertilizer with appropriate nutrient ratio and acidity level can be used to hold the pH level. The impact of fertilizers on pH is dependent on plant uptake of the fertilizer. This pH adjustment system works well when there is a reasonable mass of plant material in the container and the plants are actively growing. Otherwise, the pH correction may be insufficient. If the residual component in the limestone or the alkalinity level of the irrigation water is unduly high, it will not be possible to correct pH through fertilizer selection. Then, drenches or acid injection will be required. Acidic fertilizers are typically high in ammoniacal nitrogen. These fertilizers should be avoided during periods of cold dark weather when the substrate temperature is low. Under these conditions, microbial conversion of ammonium to nitrate may be too slow to avoid ammonium toxicity.

Drenches. Drenches that can be used to restore substrate pH up to the desired level include iron sulfate, acids, and flowable sulfur. Once the pH level has been corrected the drenches are discontinued. At that point remedial or preventative action is taken to ensure that a future pH decline does not occur. This may include switching to a more basic fertilizer if fertilizer was the problem. If the problem stems from high water alkalinity, continuous injection of acid into the water system will control the problem.

One common drench is iron sulfate (ferrous sulfate), which is purchased as a water-soluble powder. It will effectively lower pH within a day. Iron sulfate is applied as a drench at the rate of 2 pounds per 100 gallons of water. This rate will burn flowers and some sensitive leaves. When iron sulfate contacts foliage, it is important that it is rinsed off before it dries. Flower spotting is a problem with flats of flowering bedding plants, where it is not possible to avoid contact. In this situation it is important to allow for sufficient time between application and sales to permit a new set of flowers to form. Do not use iron sulfate for lowering pH for the iron-efficient plants (the geranium group). These plants are sensitive to iron toxicity, which can occur from increased availability of iron as pH declines. Substrate pH should be checked a few days after application to determine if a repeat application is necessary. Iron sulfate does not have a residual effect. Iron sulfate powder used for pH adjustment is in the reduced form (ferrous sulfate) and has a bluish color. If it oxidizes to a yellowish-brown color it is no longer effective. When dissolved, iron sulfate should form a clear solution. If it is cloudy it has oxidized to the ferric sulfate form and is ineffective. The powder should be stored dry and in the dark to retard oxidation. Iron sulfate is not very soluble at a pH level of 7.0 and above. Acidification of water to 6.0 or below greatly aids solubility. Phosphoric acid should not be used because it reacts with the iron to form a precipitate of iron phosphate.

Mineral acid drenches can also be used for temporary substrate pH adjustment. When water pH is lowered to 4.5 all bicarbonate alkalinity is removed. Nitric, sulfuric, or phosphoric mineral acids or solid organic acid, such as Seplex-L, can be used. The weak organic acid is not so often used due to the large quantity needed. The pH 4.5 water is applied as a drench. It is safe for the crop and is used only until substrate pH returns to the desired range. Acid drenches have no residual effect. If there is a persistent pH raising force in the crop production system, such as high residual limestone or high water alkalinity, the high pH problem will return. This will necessitate continual acid injection. When a more drastic temporary pH adjustment is needed, irrigation water may be acidified to pH 1.5 to 2.0 and used as a drench. This water can be harmful to personnel and plant foliage. Thus, it should be handled with care and kept off foliage. When acid drenches are first run through water lines that have been used for fertilization, it is possible that precipitates in the lines will dissolve. This can release nutrients and particulate matter. It is advisable to flush these lines when the acid is first used. Whenever acid is diluted, it is imperative that acid is added to water rather than adding water to the acid. The latter will release a large quantity of heat, which can cause splashing of the acid mixture.

The flowable sulfur drench consists of a suspension of insoluble, elemental sulfur and is available from greenhouse-supply companies. Studies at the University of New Hampshire have shown that it takes effect over a period of four weeks or more. Its efficacy is dependent on substrate type and environmental conditions, which renders it somewhat unpredictable. Elemental sulfur does not leach from the substrate; thus an overdose cannot be corrected by leaching. For these reasons, flowable sulfur is not the preferred treatment for post-plant lowering of pH. Iron sulfate and aluminum sulfate have an immediate effect, within a day. Iron sulfate is the more desirable of the two since, unlike aluminum, it is an essential nutrient and is often deficient at high pH.

Acid Injection. Continuous injection of acid into the irrigation water is required when use of basic fertilizer will not correct a chronic problem of pH rise. Such a pH rise would be due to a factor such as an excessively high residual component in the limestone used to formulate the substrate or highly alkaline irrigation water. One should be aware that nitric, sulfuric, and phosphoric acids supply nitrate, sulfate, and phosphate, respectively. Fertilizer formulations should take this into account to avoid excessive application of one of these nutrients.

SUMMARY

1. Pre-plant fertilization. A greenhouse fertilization program consists of pre-plant and post-plant applications. The pre-plant portion must include liming material to set the correct pH level. Care is taken in selecting the liming material to achieve the proper calcium-to-magnesium ratio in the substrate. Pre-plant application of other nutrients is optional. However, most substrate does include the following. Soluble nitrogen and potassium is frequently applied in quantities sufficient to last up to two weeks. Phosphate may be applied as superphosphate or soluble phosphate salts and can last from a month to the full crop time, depending on substrate pH and leaching rate. Calcium, magnesium, and sulfur may be applied as gypsum (calcium sulfate) and Epsom salts (magnesium sulfate). These three nutrients may last throughout the crop period; however, they should be monitored through substrate and tissue testing. A package of six micronutrients can be supplied that will last for the length of the crop.
2. Design of the post-plant fertilization program includes eight important considerations.
   i. The post-plant fertilization program generally involves periodic application of nitrogen, phosphorus, and potassium with or without secondary macronutrients (calcium, magnesium, and sulfur) and micronutrients.
   ii. The most common frequency of application is with each irrigation (fertigation). Weekly application is less frequently selected.
   iii. The rate and ratio of nitrogen and potassium vary according to the crop. Crops in general respond well to a 1:1 nitrogen (N)-to-potassium (K_2O) ratio. A few crops require more or less potassium. Nitrogen concentrations applied to crops fertilized at each irrigation in an open system, where fertilizer is applied to the top of the substrate with excess leaching from the bottom of the pot, generally range from 100 to 300 ppm. Sub-irrigated crops are fertilized at about half that rate.
   iv. Phosphate, expressed as P_2O_5, applied at half the concentration of nitrogen is more than adequate to meet needs of most crops. Plant compactness can be achieved by omitting phosphate in the pre-plant program and applying it at 15 percent of the nitrogen level.
   v. The form of nitrogen is very important. Ammonium and urea nitrogen will cause ammonium toxicity if they accumulate in the substrate. Microbes convert urea to ammonium and then to nitrate, thereby preventing toxicity. Low temperature, pH, and oxygen levels in the substrate suppress these microorganisms. Uptake of ammonium and urea nitrogen leads to acidification of substrate, while uptake of nitrate nitrogen leads to a rise in pH. Fertilizers are classified according to their potential to raise or lower substrate pH. It is mainly the form of nitrogen in fertilizers that accounts for this effect.
   vi. Complete fertilizers may contain one or more of the secondary macronutrients, calcium, magnesium, and sulfur. One should be aware of the presence of these, as stated on the fertilizer bag label, and select the appropriate fertilizer according to the crop needs for these nutrients.
   vii. Either pre-plant micronutrients or micronutrients contained in post-plant soluble fertilizers are usually sufficient for a crop when substrate pH is in the recommended range. At higher pH levels it may be necessary to use both sources of micronutrients. At yet higher pH levels a third source may be necessary.
   viii. Many crops develop superior post-harvest qualities when fertilization is reduced during the last two weeks of production.
3. Greenhouse fertilizer is prepared as a 15-up-to-200-fold concentrate, to conserve tank space and reduce the labor of mixing, and then is diluted to single strength and metered into the greenhouse water line by a fertilizer injector. It is delivered to the bench or pots through the automatic watering system.
4. Post-plant nitrogen, phosphate, and potassium can be applied alternatively as a single pre-plant application of a dry slow-release fertilizer, which, depending on its formulation, can provide N-P-K for 3 to 14 months.

Different analyses and types of slow-release fertilizers are available, eliminating the need for any regular fertilization during the crop schedule. However, most growers provide only a portion of these nutrients as slow-release, leaving the rest to water-soluble fertilizers. In this way they can reduce the rate of fertilization by cutting back the liquid application.

5. Identification of nutritional disorders is as important as the fertilization program itself. Visual diagnosis of disorders can be effective, but unfortunately it depends upon the presence of an injury that may not be completely reversible.

6. Substrate testing is a valuable diagnostic tool in that it gives a measure of the root substrate pH and soluble-salt levels as well as a determination of the available levels of nutrients yet to be taken up.

7. Foliar analysis is an excellent diagnostic tool to be used in conjunction with substrate testing. Unlike substrate testing, it provides a view of the quantities of nutrients already taken up by the plant. All essential nutrients are included in foliar analysis tests.

8. Two of the most important nutritional tests are EC (soluble salts) and substrate pH. EC is used to assess the purity of irrigation water, the accuracy of fertilizer injectors, and whether the level of fertilizer application is appropriate. Substrate pH controls availability of most nutrients. The grower's tool chest of materials for raising pH should include a basic fertilizer such as 15-0-15 and flowable limestone or potassium bicarbonate, while for lowering pH, it should include an acidic fertilizer such as 21-7-7 or 20-10-20 and ferrous sulfate.

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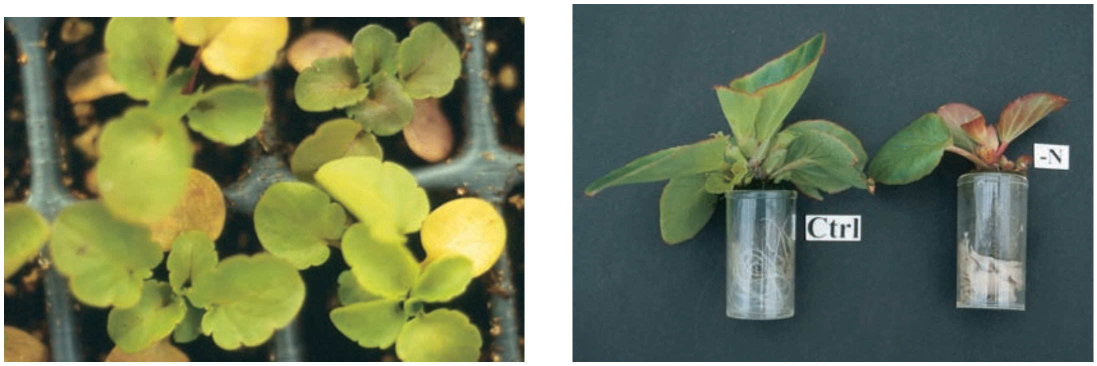


(a) (b)

Color Plate 1
Nitrogen deficiency. *Uniform chlorosis slowly progresses toward necrosis on lower leaves as in this (a) pansy seedling. Some species develop red pigmentation on lower leaves as in this (b) fibrous rooted begonia plant.*

(a) (b) (c)

Color Plate 2
Ammonium toxicity. *In older plants, symptoms progress from rolling of the margins of older leaves as in (a) gloxinia to irregular chlorosis and necrosis of older leaves and tip burn of roots seen in (b) chrysanthemum. In seedlings and young bedding plants symptoms tend to affect young rather than older leaves and chlorosis takes an interveinal form as in this (c) vinca plant where leaves are rolled up at the margin. Note that depending on plant species leaf margins may roll up or down.*

(a) (b)

Color Plate 3

Phosphorus deficiency. *Deficiency symptoms begin with stunted plants deeper green than normal as in this (a) sunflower plant. In some species purple pigment develops next, generally in older leaves, and more so on the under than the upper surface. In the late stage, seen here in (b) the pot chrysanthemum plant on the left, lower foliage develops chlorosis followed by necrosis.*

(a) (b)

Color Plate 4

Potassium deficiency. *Potassium typically starts as necrosis along the margins of older leaves as in this (a) dissected Elatior begonia. In a few species, necrosis may start as spots across the leaf lamina but most heavily situated along the margin as in this (b) fibrous rooted begonia. Seedlings and young bedding plants often become stunted and deeper green than normal prior to the formation of necrosis.*

(a) (b)

Color Plate 5
Calcium deficiency. *This deficiency most often starts with irregular chlorosis and distortion of young leaves as in (a) poinsettia and rapidly advances to necrosis as seen in (b) zinnia. In some plants necrosis may be the first visual symptom.*

(a) (b)

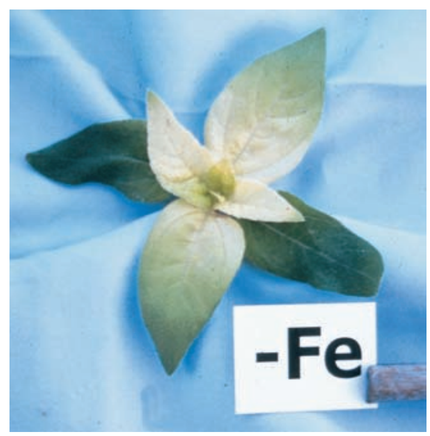
Color Plate 6
Magnesium deficiency. *Magnesium deficiency begins at the bottom of the plant as interveinal chlorosis of leaves and progresses up the plant as in (a) poinsettia and (b) sunflower.*

(a)

(b)

Color Plate 7
Sulfur deficiency. *Deficiency appears as uniform chlorosis of all leaves on the plant as seen in (a) petunia and (b) tomato.*

(a)



(b)

Color Plate 8
Iron deficiency. *Most often, deficiency begins as interveinal chlorosis on young leaves as in (a) poinsettia. As the deficiency advances, interveinal chlorosis gives way to uniform chlorosis across the leaf blade that progressively becomes lighter yellow and may finally turn white as in this (b) sunflower. In the final stage necrosis forms in the chlorotic areas.*

(a) (b)

Color Plate 9

Iron toxicity. *Low root medium pH fosters excessive uptake of iron and possibly manganese, copper, and zinc. Marigold and seed geranium are particularly susceptible. (a) Marigold exhibits bronze speckling, similar to spider mite damage, on the youngest fully expanded and lower leaves. (b) Iron toxicity appears on the older leaves of seed geranium as interveinal chlorosis, bronze speckling in the chlorotic areas, and necrosis of the leaf margins.*

(a) (b)

Color Plate 10

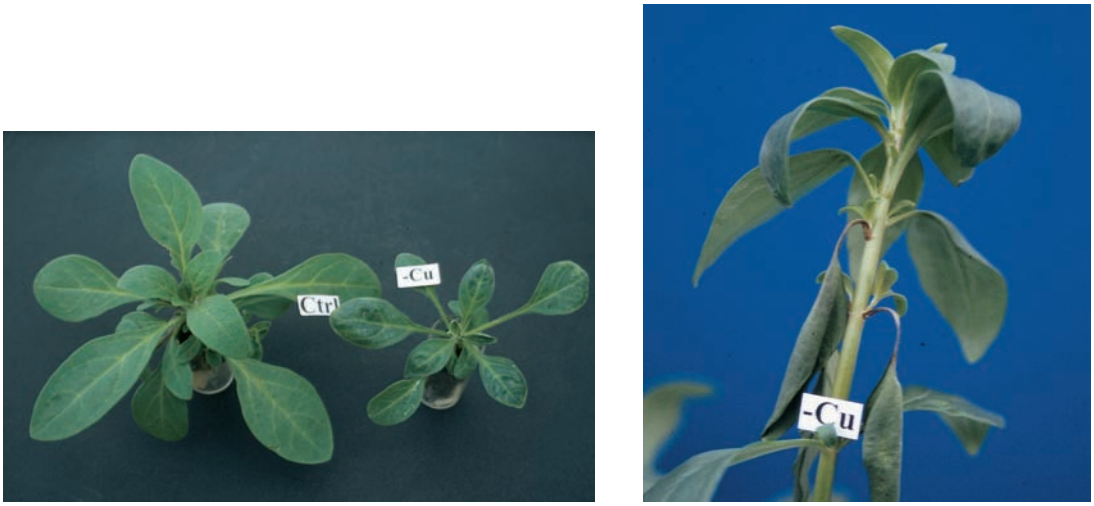
Manganese deficiency. *Symptoms of manganese deficiency start out similar to iron deficiency with interveinal or general chlorosis of young foliage as in (a) salvia. However, tan to gray spots often develop in the chlorotic areas as seen in (b) osteospermum. Eventually the tan spots become necrotic.*

Color Plate 11
Manganese toxicity. *Symptoms appear on lower leaves as either necrosis of the leaf tip or as purplish spots scattered across the leaf blade as in these Rhapis palm leaflets.*

(a)

(b)

Color Plate 12
Zinc deficiency. *Reduced leaf size, often called "little leaf disease," and shortened internodes are typical of zinc deficiency as seen in (a) the deficient carnation shoots on either side of a normal shoot. Irregular chlorosis of young foliage is also common as seen in the narrow chlorotic leaves of this (b) argyranthemum plant. An additional symptom often seen in seedlings and young plants is necrosis of recently expanded leaves just below the chlorotic youngest leaves. A few species, such as ornamental kale and snapdragon, develop red to purple pigment either along the margin or across leaf blades.*



(a) (b)

Color Plate 13
Copper deficiency. *The progression of symptoms includes deeper green foliage—particularly in seedlings, followed by rolling of the margins of young leaves as seen in (a) petunia, then chlorosis of young leaves sometimes in an interveinal pattern and other times without a pattern followed finally by sudden death of recently mature leaves below the previously affected leaves as seen in (b) snapdragon.*

(a) (b)

Color Plate 14
Boron deficiency. *(a) Sunflower with the early symptoms of boron deficiency including short internodes and distorted young leaves. (b) Elatior Begonia with subsequent symptoms including chlorosis, severely distorted young leaves, corking on the underside of leaves, notches of tissue missing in the stems and flower peduncle, and incomplete petal formation.*

Color Plate 15
Boron toxicity. *Symptoms appear on older leaves as a reddish-brown necrosis at the margins, as in this Elatior begonia leaf.*

Color Plate 16
Molybdenum deficiency. *This deficiency is rare in greenhouse crops except for poinsettia, where it is common. As pictured here, median poinsettia leaves develop a chlorotic margin that turns yellow and later necrotic. These symptoms spread inward, eventually killing the entire leaf.*

Plates 1a, b, 3a, 4b, 5b, 6b, 7a, b, 8b, 10a, b, 12b, 13a, b, and 14a are the result of a collaborative research program by Dharma Pitchay, Jamie Gibson, Brian Whipker, and Paul Nelson in the Department of Horticultural Science at North Carolina State University.

Carbon Dioxide Fertilization

ROLE OF CARBON

Carbon is an essential plant nutrient and is present in the plant in greater quantity than any other nutrient. About 40 percent of the dry matter of plants is composed of carbon. Plants obtain carbon from carbon dioxide (CO_2) gas in the air. For the most part, CO_2 gas diffuses through the stomatal openings in leaves when they are open. Once inside the leaf, carbon from CO_2 gas moves into the cells, where, in the presence of energy from the sun, it is used to make carbohydrates (sugars). The carbohydrates are translocated to various parts of the plant and transformed into other compounds needed for growth or maintenance of the plant. The process whereby CO_2 is utilized by the plant, known as *photosynthesis*, occurs in the green chloroplasts within cells. The process is summarized in the following equation:

$$CO_2 + \text{water} + \text{energy from sunlight} \rightarrow \text{carbohydrate} + \text{oxygen} \quad (1)$$

Air, on the average, contains slightly less than 0.04 volume percent (400 ppm) CO_2. The average level in 2009 was 387 ppm; the level of CO_2 in air outdoors can be 100 ppm higher in industrial areas where fuels are combusted. The carbon in fuels is converted to CO_2 during the process of combustion. Due to combustion and deforestation, the level of CO_2 has been increasing since around 1832 when ice core data showed a level of 284 ppm. The present rate of increase is about 2 ppm per year. The CO_2 level is also higher in areas such as swamps and riverbeds, where large quantities of plant material are decomposing. Microorganisms feeding upon plant or animal remains respire CO_2 gas, much as we humans do when we utilize plant- and animal-derived foods. This CO_2 gas is evolved through a process called *respiration*, which is summarized as follows for carbohydrates:

$$\text{carbohydrate} + \text{oxygen} \rightarrow CO_2 + \text{energy} + \text{water} \quad (2)$$

Respiration is the opposite of photosynthesis. It is a process that releases energy originally captured from sunlight in the process of photosynthesis. The energy released is used by the plant for various functions of growth, such as nutrient uptake.

A CO_2 level of 350 ppm is sufficient to support plant growth as we know it in the world today. Most plants, however, have the capacity to utilize greater concentrations of CO_2 and, in turn, attain more rapid growth. This genetic capability apparently stems back to earlier times in the development of plant life. Atmospheric concentrations of CO_2 were around 3,000 ppm 150 to 200 million years ago and 6,000 ppm around 400 to 600 million years ago.

CARBON DEFICIENCY

In the winter, greenhouses may be closed during the day to conserve heat. This situation may occur for several consecutive days during periods of inclement weather in the cooler temperate and frigid zones. During daylight hours, CO_2 is removed from the air by plants through the process of photosynthesis. The level continually drops in a closed greenhouse, and the rate of photosynthesis decreases until a point is reached at which growth stops.

It has been reported that an active sunflower leaf can consume the CO_2 in a column of air 8 feet (2.4 m) above it in an hour. Not all crops utilize CO_2 at this rate. However, in a matter of a few hours, the CO_2 level in a closed greenhouse can drop to the compensation point where growth stops. The actual level at which this happens varies for different greenhouse crops, but in general, it occurs at levels of 50 to 125 ppm CO_2. Carbon deficiency can occur for several days at a time, prolonging the culture time of the crop by the same number of days or reducing the quality of the crop. Deficiency of CO_2 can be even more pronounced inside the plant canopy. Circulation of air in the greenhouse can help alleviate this problem.

CARBON DIOXIDE INJECTION

Effects on Plants

During the 1960s, heavy research efforts were directed toward assessing the benefits and techniques of enriching greenhouse atmospheres with CO_2. Researchers were surprised to find that plant responses continued to increase as CO_2 levels were raised above the approximate 350-ppm level present in the atmosphere at that time. Levels of 2,000 ppm continued to evoke growth responses in some crops. Apparently, as previously stated, this stems back to the earlier adaptation of plants to higher CO_2 levels in primordial times.

For most greenhouse crops tested over a wide range of geographical latitudes, a response has been reported for increased CO_2 levels up to the range of 1,000 to 1,500 ppm. At levels of 1,500 ppm and greater, the results vary from a positive to a negative response. This is not surprising, since the level of CO_2 required for maximum photosynthesis is related to other factors that can control photosynthesis. Lettuce growing in the winter in England or The Netherlands at 50°N latitude will have a lower potential photosynthetic rate because of lower available sunlight than a crop in Spain or in the southern United States. A higher level of CO_2 will be required to support the higher photosynthetic rate in the brighter region. The first negative effect caused by high CO_2 is the gradual closing of stomates. This reduces the transpiration rate. With less evaporative cooling, the plant temperature rises. At higher CO_2 levels, around 1,500 ppm depending on the crop, lower yield as well as chlorosis (sometimes interveinal) and necrosis of lower leaves occurs. These symptoms resemble those of magnesium and potassium deficiencies. Upper threshold levels of CO_2 are crop specific—for example, 2,200 ppm for tomato, 1,500 for cucumber, and 1,200 for gerbera and chrysanthemum. In tomato, 2,200 resulted in reduced fruit set, while

3,200 ppm caused leaf damage. Tolerance to CO_2 concentration is dependent on light intensity. The threshold above which injury occurs falls with declining light intensity. Studies in The Netherlands, where light is often very limiting to growth, have shown negative effects beginning around 900 ppm and scorch occurring at 1,500 ppm. The commonly injected levels of CO_2 in greenhouses around the world today are 900 to 1,200 ppm. The principal of diminishing returns applies to CO_2 injection, in that the higher the CO_2 concentration, the lower the growth increase from each incremental increase in CO_2 level. Levels used in greenhouses are not harmful to humans. An exposure level up to 5,000 ppm (0.5 percent by volume) for an eight-hour workday is permitted by the U.S. Occupational Safety and Health Administration. Prolonged exposure to 10,000 ppm can cause drowsiness. Weight increases in lettuce of 31 percent have been reported from the use of 1,600 ppm CO_2. In other studies, this has translated into a 20 percent earlier harvest. A 48 percent increase in tomato production has been reported as a result of injection of 1,000 ppm CO_2. Injection of 1,000 ppm CO_2 in England has resulted in a 23 percent increase in cucumber fruit weight.

Specific effects from CO_2 injection on rose crops include a decrease in the number of blind shoots (shoots that fail to develop), increased stem length and weight, a greater number of petals, and a shorter cropping time in the winter. A test in Massachusetts (42°N latitude) showed a 53 percent increase in weight of roses cut when 1,000 ppm CO_2 was injected.

Chrysanthemum yields increase in the form of thicker stems and greater height when CO_2 is injected (Figure 1). Excessive stem lengths reduce the value of pot mums and, in the case of cut mums, are left behind in the bench when the flowers are cut. The increased height, however, can be translated into a reduction in the length of time required to flower the crop. Because the flower date is controlled by manipulating the length of day, it is possible to program chrysanthemums to flower up to two weeks earlier without a reduction in height when CO_2 is injected. This represents a considerable savings in production time, considering a normal crop time of 11 to 14 weeks.

Carnation yields have been increased up to 38 percent by CO_2 injection. The weight of flowers and the strength of stems have increased, and the time required for

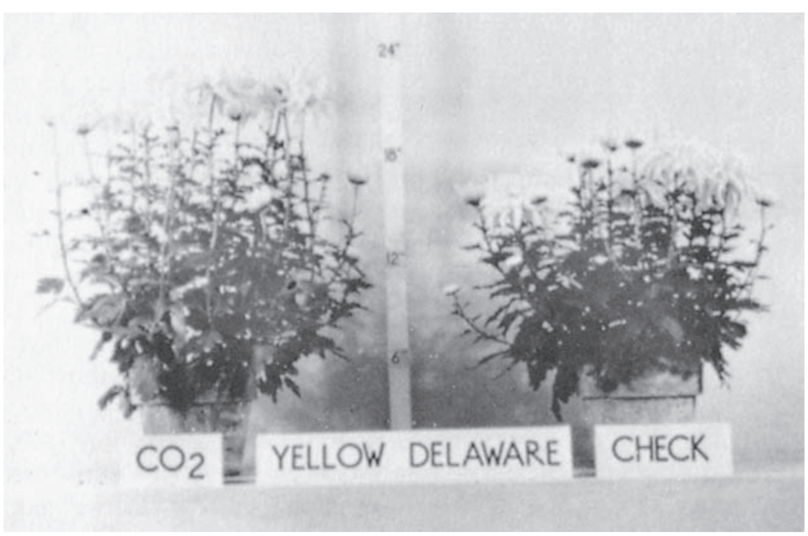


Figure 1
Dramatic increases in growth can be achieved by enriching the CO_2 level of the greenhouse atmosphere, as seen in these pot mums.

(Photo courtesy of R. A. Larson, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609.)

shoots to reach flowering has shortened by as much as two weeks. Equally beneficial effects have been obtained for carnation stock plants. Cuttings of greater quality and number have been produced, and the useful life of the stock plant has been increased as well.

CO_2 injection has had a variety of beneficial effects on a number of other crops. Fall crops of snapdragons were of better quality, while spring crops reportedly flowered 13 days early. Rooting of geranium cuttings was improved, and the height as well as the number of branches on subsequent plants was increased. Blindness was decreased in Dutch iris. The number, quality, and size of blooms on orchid plants were increased, as were poinsettia bract diameters. Other crops reported to benefit from CO_2 injection include African violet, *Campanula isophylla*, kalanchoe, and poinsettia.

Crop responses vary according to the extent to which elevated levels of CO_2 can be maintained. CO_2 levels drop appreciably when ventilators are open more than 2 inches (5 cm) and even more so when cooling fans are on. Our own studies, in which CO_2 was injected only when the ventilators were open less than 2 inches (5 cm), demonstrated that it was uneconomical for a number of crops in climatic zone 8 (Raleigh, North Carolina, at 35°N latitude) and points further south. There were too few hours when elevated CO_2 levels could be maintained.

Studies in England and The Netherlands have investigated summer injection of CO_2. When ventilators are open to more than 5 percent of their capacity or fans are on, the atmosphere is naturally enriched by incoming air to the ambient level of 384 ppm. When ventilators are open less than 5 percent, levels up to 1,000 ppm are set for the CO_2 injection equipment. Results indicate an economic advantage from injecting CO_2 during low-level ventilation. These procedures would work well for cooler locations above 40°N latitude where greenhouses are frequently opened and closed during the summer months. Growth can proceed only as fast as the growth supporting factor in lowest supply will permit. At a low photosynthesis limiting light intensity, there are maximum levels of temperature, fertilizer, and CO_2 that will allow for the low potential growth at that light intensity. When the light intensity is increased, temperature, fertilizer, and CO_2 inputs must be increased to meet the greater needs of growth at that higher light intensity. CO_2 can be injected when the light intensity is above 500 fc (5,380 lux) but is not economically feasible at lower intensities. Increased fertilizer application automatically happens for the grower applying fertilizer with each irrigation. As light intensity, temperature, CO_2, and consequent growth increase, evapotranspiration increases, thus more frequent fertilization occurs. When CO_2 is injected, daytime temperature should be increased. The magnitude of the increase is in the range of 5 to 10°F (3 to 6°C), depending on the crop and the extent of maximization of all other factors. Raising daytime temperatures for crops fertilized with CO_2 has generally been beneficial, while raising nighttime temperatures has not.

Method of Carbon Dioxide Injection

Since CO_2 injection is effective only during the daylight hours when photosynthesis occurs, it should be injected from sunrise until one hour before sunset. It should be injected only when the ventilation fans are off or, in the case of greenhouses cooled by ventilators, when the roof ventilators are open less than 2 inches (5 cm). CO_2 cannot be injected during the warm seasons, because greenhouse cooling generally coincides with daylight hours. Depending on the latitude where the greenhouse is located, the season for CO_2 injection will begin between late September and early November and extend to April or early May.

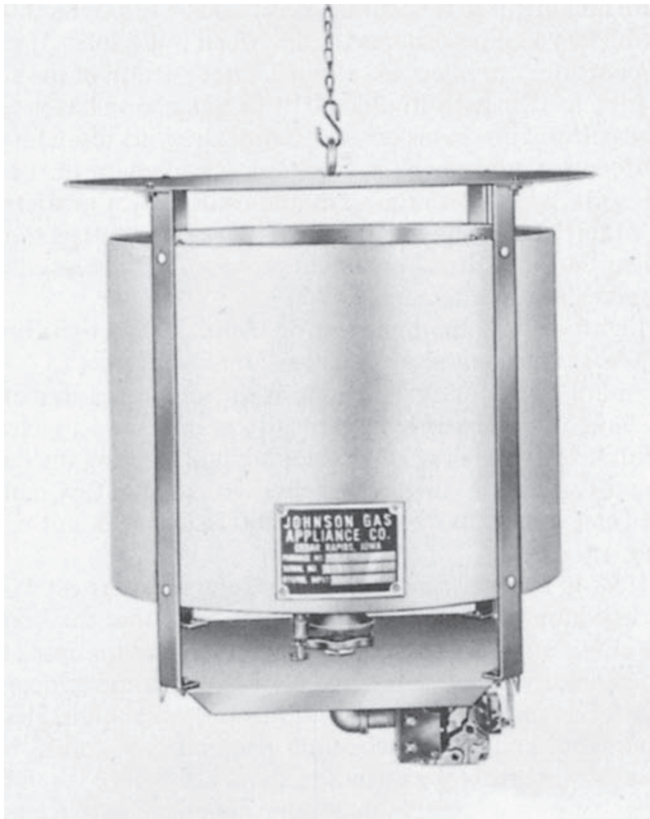


Figure 2
A CO_2 generator used for enriching the greenhouse atmosphere with CO_2 up to a level of 1,500 ppm in a 5,000-square-foot floor area for the purpose of increasing photosynthesis and growth.
(Picture courtesy of Johnson Gas Appliance Co., Cedar Rapids, IA 52405, Web: www.johnsongas.com.)

A few brands of CO_2 generators are popular today. One unit sells for about \$700 with a gas pressure gauge and a 24-volt solenoid valve (Figure 2). This unit provides 1,500 ppm CO_2 in a typical greenhouse of 5,000 ft^2 (465 m^2) floor area. It burns LP or natural gas. This generator has a burner range up to 60,000 Btu/hr (15,120 kcal/hr or 17,580 W); thus, it can consume 60 ft^3 (1.7 m^3) of natural gas per hour. A control package that automatically turns up to three units on at sunrise and off at sunset is available for \$160. CO_2 generators are hung above head height along the center of the greenhouse. Within each is a precisely calibrated burner with an open flame. Under conditions of complete combustion, gas is converted to CO_2 and water. CO_2 produced in some units rises out of the burner into the greenhouse atmosphere, where convection currents move the gas about the greenhouse. In other products, the CO_2 is positively displaced from the burner by a fan. Standard convection tube and horizontal airflow (HAF) systems serve well to circulate CO_2 in the greenhouse.

Gas consumed in the CO_2 generator must be of a high purity level, since any sulfur contained in it is converted to sulfur dioxide gas. Sulfur dioxide gas in concentrations over 0.5 ppm for four hours' exposure time can cause plant injury. When sulfur dioxide comes in contact with moisture on plant surfaces, it is converted to sulfurous acid and eventually to sulfuric acid. This burns the plant. The sulfur content of natural gas and propane should not exceed 0.02 percent by weight (Blom et al., 1984), while the sulfur content of kerosene should not exceed 0.06 percent (Hand, 1971).

Incomplete combustion will cause the formation of ethylene and carbon monoxide gases, which are injurious to a plant. Internodes on the plant become shortened, branching increases, and flowers become distorted and injured from ethylene. The upper limit of ethylene for plants is 0.05 ppm. Carbon monoxide is harmful to humans. It reduces the ability of blood to transport oxygen to the body's tissues. The upper average limit of carbon monoxide for humans is 50 ppm (American Conference of Government Industrial Hygienists, 1986), while the upper limit for instantaneous contact is 200 ppm. Therefore, only a burner designed for CO_2 production should be used inside a greenhouse, and it should be periodically calibrated. The burner should be kept clean and adjusted to a clear blue flame. The plumbing should be checked for gas leaks, since unburned fuel may be injurious to plants. Manufactured gases, and to a degree natural gas, can contain propylene and butylene, which are injurious to plants, causing symptoms similar to those caused by ethylene. The threshold for propylene, above which plant injury occurs, is 10 ppm (Hicklenton, 1988).

It is equally important to provide sufficient oxygen to support complete combustion of the fuel. In a film plastic greenhouse or a glass greenhouse located where it is prone to ice formation on the surface, an air inlet must be provided. The rule for heating systems applies here, where 1 square inch of opening is provided per 2,500 Btu of burner capacity per hour (1 cm^2 per 100 kcal/hr or per 733 W).

Considerable progress has been made since injection of CO_2 was commercialized in the early 1960s. The concept actually dates back to the earlier part of the 20th century, but it was not until commercial methods of application became available that extensive efforts were put forth to develop a system. Early research by Professor Holley at Colorado State University in the late 1950s, as well as work in The Netherlands and England, led to commercial systems using liquid CO_2 or dry ice, which is solid (frozen) CO_2. (See Hicklenton, 1988, for historical details.)

CO_2 gas under pressure becomes liquid. At a low temperature, it can be solidified into dry ice. In the early 1960s, liquid CO_2 tanks were installed at a greenhouse range and were serviced by CO_2 distributors. CO_2 gas formed above the liquid in these tanks and was carried by metal tubing to the greenhouses. A set of pressure-regulating valves reduced the pressure to a low level. Once in the greenhouse, the gas was distributed along the length of the greenhouse in a plastic tube 1/8 to 1/4 inch (3 to 6 mm) in diameter with needle holes every 12 inches (30 cm) along the length.

Liquid and solid CO_2 proved a more expensive source of CO_2 in the 1960s than the combustion of fuels. Burners were developed. Some early equipment was large and had to be located outside the greenhouse. The exhaust, essentially pure CO_2, was brought into the greenhouse through a duct and distributed along the length of the greenhouse through the conventional winter convection-tube ventilation system.

With time, smaller generators were developed and installed overhead in the greenhouse. These produced CO_2 in open-flame burners using kerosene, propane, or natural gas. Being simpler systems, they cost less to purchase. Depending upon the equipment purchased, they could handle greenhouse areas of 5,000 to 15,000 ft^2 (365 to 1,400 m^2). This generation of CO_2 generators is in common use today in the United States.

Partly because of recent shifts in fuel costs, larger greenhouse firms find it more economical to supply CO_2 from liquid CO_2 comparable to that of CO_2 generated from the combustion of fuel. A large consumption volume is necessary in order to negotiate an economical, steady source of liquid CO_2 from the supplier. Liquid CO_2 has the advantage of purity. Unlike CO_2 generation in burners, the use of liquid CO_2 releases no heat. Heat release can be an advantage during the winter but a disadvantage at the beginning and end of the CO_2 injection season.

A number of Dutch greenhouses generate CO_2 gas from their heating boilers for enrichment of the greenhouse atmosphere. When natural gas or propane is burned in the boiler, the resulting flue gas consists of CO_2 and water vapor. Oil-fired boilers are not used. The flue gas temperature is about 200°C (392°F), too hot to release into the greenhouse. It can be cooled to about 30°C (86°F) by mixing it with fresh air. However, this leaves all of the water in the mixture that will raise the relative humidity in the greenhouse by a few percent. Also, an efficient boiler can transfer about 85 percent of heat to the greenhouse heating water leaving 15 percent in the flue gas. Much of this remaining heat would be lost when fresh air is mixed with it. The better alternative is to pass the flue gas through a condenser. The condenser contains a heat exchanger that extracts heat by transferring it to hot water that can be used for heating the greenhouse. This renders the boiler more efficient for heating purposes. The flue gas temperature is reduced to 40°C (104°F), which is safe for injection into the greenhouse, and 70 percent of the water is removed from the gas before injection into the greenhouse. At the beginning and end of the CO_2 injection season when heat is not required during the day, this heat can be stored in a hot water tank until night when it is needed for heating. Boilers should be routinely calibrated to avoid incomplete combustion that generates carbon monoxide and ethylene.

The cooled flue gas is generally delivered to the greenhouses through PVC pipes that can range in diameter up to 12 inches (30 cm) or more, depending on the size of the greenhouse to be supplied, under pressure generated by a fan at the heat exchanger. Inside greenhouses with tall plants such as rose, tomato, cucumber, or pepper, the CO_2 gas is distributed through a flexible, perforated polyethylene tube of approximately 1.5 inch (4 cm) diameter that runs along the base of plants in each bed. In a potted-plant or bedding-plant greenhouse, CO_2 is distributed through a flexible, perforated polyethylene tube running overhead along the length of the greenhouse. Released CO_2 is picked up by the HAF system and distributed evenly throughout the greenhouse.

Measurement and Control of Carbon Dioxide Levels

The simpler forms of CO_2 injection control use either a timeclock or a light sensor to turn the CO_2 generator on in the morning and off in the evening. During the day, the CO_2 generator is automatically turned off when the ventilating fans are on. In the event of roof ventilation, mechanical switches are installed on the ventilators to allow the CO_2 generator to operate only when the vents are open less than 2 inches (5 cm).

When controlled by simple on-off switches, CO_2 generators will not have the same net effect in all greenhouses. The CO_2 level will be lower in glass greenhouses, where air leaks exist, than in film plastic greenhouses. In order to adjust the fuel pressure on some generators to compensate for this variation, it is important to know what level is being maintained in the greenhouse atmosphere.

The current, more sophisticated generation of CO_2-control systems is based on CO_2 sensors. These sensors continually monitor the CO_2 level in the greenhouse. The signal from the sensor is used to control the CO_2 generator so that a constant CO_2 level can be maintained. CO_2 sensors are in the price range of $2,700. However, one sensor can be connected through a multiplexer to 10 greenhouses by sampling tubes, through which air is drawn by a pump. Typically, air is sampled and tested for one minute from each greenhouse. Information from the single sensor is received by a computer, which in turn controls CO_2 generators in each greenhouse.

Current computer systems can program the daily on and off times to coordinate with the changing day length of the season. It is a simple matter for these systems to further coordinate injection of CO_2 with ventilation events. This control ensures that the full advantage of CO_2 enrichment is realized and that no unneeded CO_2 is used.

There is computer software that can receive inputs from photosynthetically active radiation (PAR) light, temperature, and CO_2 sensors for the purpose of optimizing these three factors in accord with any predetermined set point such as temperature. This results in conservation of CO_2 when no enrichment is needed or during periods when a lower-than-standard level of enrichment is required. On the other hand, it ensures that yield, as a function of CO_2 enrichment, is always optimized. The next step needed is an economic model that takes into account the costs of inputs such as CO_2, heat, and light and balances these against economic returns from associated yield increases. A marriage of growth and economic models will guard against seeking yield increases when the cost of the increase is greater than the return. At the same time, it will make it possible to identify and set the yield levels that generate maximum profit.

ECONOMICS OF CARBON DIOXIDE INJECTION

In cool climates, it is common to inject CO_2 for an average of five hours per day over a six-month period (900 hours). At an output of 60,000 Btu/hr (15,120 kcal/hr or 6.3 MJ/hr), this amounts to 54 million Btu or 540 therms (100,000 Btu/therm) of natural gas per burner. Since one burner handles about 5,000 ft^2 (464.7 m^2) of greenhouse, the natural-gas consumption is 0.108 therm/ft^2 (29,300 kcal or 11.4 MJ/m^2) of greenhouse area per year. At the current price of \$0.75 per therm, this carries a fuel cost of \$0.08/ft^2 (\$0.87/m^2) of greenhouse area per year. Depreciation of the equipment adds very little to the cost of injecting CO_2. The higher yields and shorter production time of crops more than justify the costs.

Professor Koths at the University of Connecticut points out an additional benefit from CO_2 injection. Many crops are grown at a 5°F (3°C) warmer daytime temperature when CO_2 is injected. The greenhouse acts as a solar collector. Heat is stored in the greenhouse structure, soil, plants, and benches. At night, the extra heat resulting from the higher daytime temperature is released. This conserves heating fuel and thereby pays part of the cost of CO_2 injection.

SUMMARY

1. Carbon, an essential plant nutrient, is supplied as CO_2 gas in the atmosphere. A concentration of 387 ppm is present in the atmosphere.
2. CO_2 is used during daylight hours in the process of photosynthesis. When the greenhouse is closed on cold winter days, the CO_2 concentration in the air inside the greenhouse can be lowered in a few hours to a level at which the rate of carbohydrate produced in photosynthesis equals the rate of carbohydrate breakdown through respiration. Net growth ceases at this point, delaying the crop or reducing quality.
3. CO_2 is often added to the greenhouse atmosphere during daylight hours of months when the greenhouse is not continuously ventilated. Common methods of addition today are (1) burning of LP gas or natural gas in special burners inside the greenhouse, (2) release of gas from liquid CO_2, or (3) release of flue gas from specialized heating boilers.
4. Reestablishment of a normal level of CO_2 (about 350 ppm) results in dramatic growth responses. Interestingly, further increases in CO_2 concentration up to 1,500 ppm or higher induce even greater growth responses. Concentrations of 900 to 1,200 ppm are the levels generally established in the greenhouse.

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Light and Temperature

Light and temperature interactively affect many aspects of growth and development of our crops. The optimal level of one depends on the existing level of the other. While flowering may be controlled singularly by the characteristics of light or temperature, often it is an interactive combination of the two that is important.

LIGHT

Light has four important characteristics for plant growth and development. These are *quality*, *intensity*, *daily light integral* (DLI) (the sum of light received in a day), and *daily duration*. Light quality describes the wavelengths (colors) of light. Different wavelengths of light trigger different processes in plant development. Intensity is important because rate of photosynthesis and growth increase up to an optimum intensity level and then decrease at higher levels. DLI is the product of intensity and the number of hours of light in a day. When the light intensity is reached for maximum rate of photosynthesis, cumulative photosynthesis can be increased further by extending the hours of light irradiance in the day. Light duration is important because the ratio of light to darkness each day controls processes such as flowering and form of growth in many plants. This is known as *photoperiodism*.

Light Quality

One classification of light is its wavelength, usually measured in nanometers (nm). This classification is referred to as light quality. The earth's atmosphere filters out the very short and long wavelengths of radiation from the sun. About 99 percent of the light transmitted through the atmosphere is in the wavelength range of 300 (ultraviolet [UV]) to 3,000 (infrared [IR]) nm.

There are three classifications of UV light (Figure 1). UV-C extends from 100 to 280 nm and fortunately is not transmitted through the atmosphere because it is harmful to humans and plants. It is generated by lamps in commerce to sterilize water, foods, and other materials. UV-B is between the wavelengths of 280 and 315 nm and is known to us for its skin-burning effect in people. UV-B is sensed by the UV-B photoreceptor pigment and results in harder plants. These plants have slower growth,

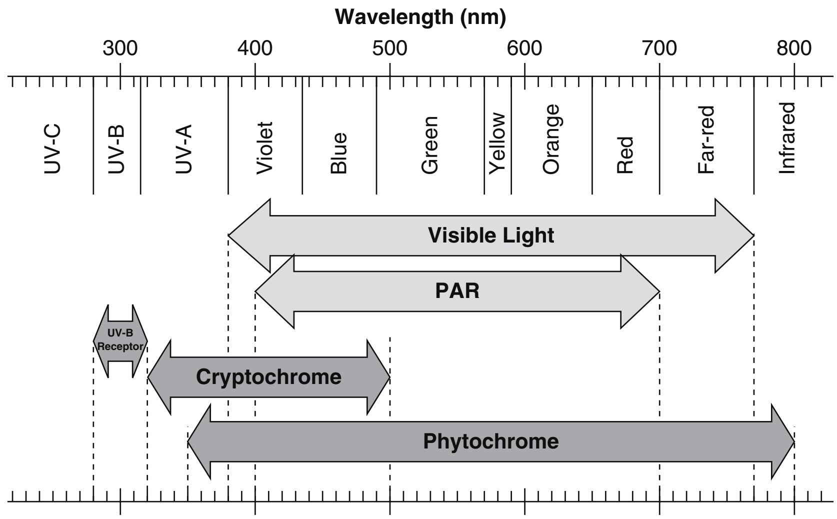

Figure 1
The plant active portion of the spectrum of electromagnetic radiation from 280 nm (UV-B radiation) to 800 nm (infrared radiation). Visible light extends from 380 to 770 nm, while photosynthetically active radiation (PAR) is primarily in the 400 to 700 nm range. The three groups of photoreceptors, UV-B receptors, cryptochrome, and phytochrome, are active in the ranges of 280 to 320 nm, 320 to 500 nm, and 350 to 800 nm, respectively.
(Illustration by Kay Jeong, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695.)

more branching, shorter internodes, less leaf expansion, thicker leaves, thicker cuticles, and more anthocyanin (red) pigment for protection against UV light. Glass blocks UV-B transmission, whereas plastic does not. UV-A ranges from 315 to 380 nm and is sensed, along with violet and blue light, by the cryptochrome photoreceptor pigments. UV-A light stimulates anthocyanin pigment, activates phenolic compounds that repel insects and fungi, activates a DNA repair system, and triggers orientation of leaves and stems toward light (*phototropism*). About 5 percent of transmitted solar radiation is in the UV-A plus UV-B range. When plants are grown in the absence of UV light, tumor-like growth known as *intumescence* occurs.

The human eye can see light in the wavelength range of 380 to 770 nm with greatest sensitivity at 555 nm (yellow-green) and least sensitivity at the extreme ends of the range (violet and far red). The effective range of wavelengths used in photosynthesis is narrower at 400 to 700 nm. This range is termed *photosynthetically active radiation* (PAR). The whole range of PAR wavelengths is utilized in photosynthesis. Common light meters measure intensity of light across the wider visible spectrum. For crop production purposes, a different light meter that measures the PAR (400 to 700 nm) range of wavelengths should be used. There are many developmental processes in the plant that are triggered by various light wavelengths in the range of 320 to 800 nm (UV-A to IR). Wavelengths above 770 nm comprise IR radiation. These wavelengths provide much of the heat from the sun. About 50 percent of the radiation reaching the earth's surface is in the 720 to 3,000 nm range.

Light Quality for Growth (photosynthesis) PAR light constitutes a source of energy for plants. Light energy, carbon dioxide (CO_2), and water all enter into the process of photosynthesis through which carbohydrates are formed:

$$CO_2 + \text{water} + \text{light energy} \longrightarrow \text{carbohydrate} + \text{oxygen} \qquad (1)$$

Considerable energy is required to reduce the carbon that is combined with oxygen in CO_2 gas to the state in which it exists in the carbohydrate. The light energy thus utilized is trapped in the carbohydrate. Later, the carbohydrate can be translocated (moved) from the green stem and leaf cells, where photosynthesis occurs, to all other parts of the plant. The carbohydrate can be converted into all other organic compounds needed in the plant. Amino acids may be formed and then combined into protein chains. Fats may be formed from carbohydrates. From all these compounds, other compounds arise, such as cellulose for cell walls, pectin to cement the walls together, hormones to regulate growth, and DNA to constitute chromosomes. The sun's energy is passed along in all of these compounds. These processes result in growth of the plant, which can be detected as an increase in dry matter.

Energy must be liberated at times to power other processes in the plant. The uptake of nutrients, formation of proteins, division of cells, maintenance of membranes, and several other processes require an input of energy. This energy is obtained when compounds formed as a direct or indirect result of photosynthesis are broken down in very much the reverse process of photosynthesis. This is the process of respiration:

$$\text{carbohydrate} + \text{oxygen} \longrightarrow CO_2 + \text{water} + \text{energy} \qquad (2)$$

Respiration occurs in all living organisms at all times. It is temperature dependent, increasing with increases in temperature. When animals eat plants, they obtain energy from the compounds they ingest. This energy was originally derived from light through photosynthesis. It can be released from these compounds by the animals through respiration. The same holds true for humans when they eat animal or plant tissue. Thus, we see that most living organisms are ultimately dependent upon light energy.

Wavelengths of light above and below the 400 to 700 nm PAR range are used in photosynthesis (Figure 2). However, their contribution is insignificant. Energy from all wavelengths within the PAR spectrum is used in photosynthesis. Within the spectrum, there are peaks of activity in the blue (440 nm) and red (620 and 670 nm) regions where light is most efficiently used in photosynthesis. Studies using filters, and more recently light-emitting diode (LED) lights, to provide single colors for

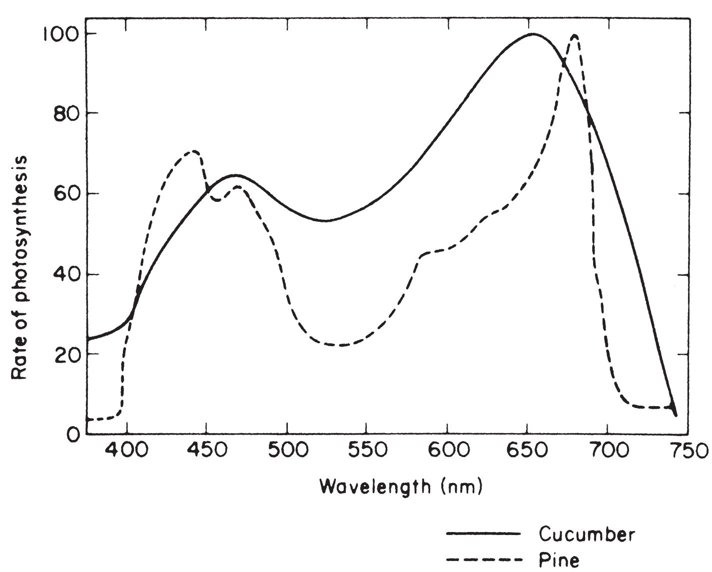

Figure 2
Rates of photosynthetic activity occurring under different qualities of light between the ultraviolet wavelength of 350 nm and the far-red wavelength of 750 nm.
(From Electricity Council, 1972.)

plant growth have shown that plants can be grown with red light alone but growth is suboptimal and developmental defects occur. When growing without ambient sunlight for the full spectrum of colors, it is necessary to provide UV-A, blue, green, and red light.

Light Quality for Plant Development In addition to light-driven photosynthesis for plant growth, light controls the form of growth, a group of processes known as *photomorphogenesis*. Wavelengths of radiation between 320 and 800 nm trigger many known and undoubtedly many yet-to-be-discovered plant processes. We have already introduced the UV-B photoreceptor pigment stimulated by radiation in the 280 to 320 nm range. In response to UV-B light, these photoreceptors caused hardening of plants, increased branching, shorter internodes, increased anthocyanin, closing of stomates, and several other reactions. The cryptochrome photoreceptors operate in the 320 to 500 nm UV-A-to-blue range of radiation (Figure 1). Reactions caused by this range of radiation include shorter internodes, shorter leaf petioles, thicker leaves, darker green foliage, increased anthocyanin, opening of stomates, and movement of stems and leaves toward light known as *phototropism*.

Phytochromes make up a third major group of photoreceptors. These respond to radiation in the 350 to 800 nm range. Best known of these is the red/far-red class of phytochromes. Responses to these include, among others, shade avoidance, apical dominance, flowering, formation of storage tissue such as tubers, diurnal leaf orientation to or away from light, and stomatal opening and closure. This phytochrome (P) exists in two forms: P_{fr} the active form and P_r the inactive form. Far-red light, with a maximum absorption at 730 nm, rapidly deactivates P by changing active P_{fr} to inactive P_r. Placing the plant in darkness will also cause P_{fr} to change to P_r, but this conversion proceeds slowly. Conversely, when a plant is exposed to red light, with maximum absorption around 660 nm, P is activated by a rapid conversion of inactive P_r to active P_{fr}. Some actions triggered by P_{fr} (formed by red light or long sunlight days) include the following:

1. short internodes and large leaves
2. thicker cuticles
3. increased branching
4. inhibition of flowering in short-day plants
5. flowering in long-day plants
6. germination in light-requiring seeds
7. opening of stomates

Both red and far-red light are supplied by the sun and most lamps. Therefore, P_{fr} and P_r exist together in plants. Ratios of red/far-red light reported for various sources of light by Spaargaren (2001) are as follows: 7 for fluorescent lamps (Phillips TL-D/33); 2.7 for high-pressure sodium (HPS) lamps (SON-T plus); 1.15 for sunshine during bright sunny weather; and 0.72 for incandescent lamps.

A good example of the impact of the balance of these two forms of P is seen in shade avoidance. Seedlings produced in plug trays that contain 288 or more plants and bedding plants produced in flats that can contain 36 or 48 plants present a serious shade avoidance problem. As these plants form successive layers of leaves, the upper leaves shade the lower leaves. The upper layer of leaves absorb 85 to 90 percent of PAR light striking them, including red light, as an energy source for photosynthesis. They absorb little far-red light. The small amount of PAR light remaining and most of the far-red light is reflected or transmitted to lower leaves in the canopy. Therefore, leaves inside the canopy are exposed to a high level of far-red but low level of red light. Consequently, the ratio of P_r/P_{fr} is high in the inner canopy leaves resulting in a low level of P_{fr}. These plants respond with longer stem internodes, smaller leaf area, and reduced branching (see aforementioned list of P_{fr} effects). This change in plant form is called shade avoidance. It maximizes penetration of light into the canopy and allows the plant to compete with surrounding plants for light by growing taller than them.

Shade avoidance increases success of the plant but reduces commercial value of the crop. It can be overcome commercially by maximizing light penetration into the greenhouse, spacing plants further apart, and providing supplemental lighting. However, incandescent lamps should not be used for this supplemental lighting because they emit a high level of far-red light relative to red light that results in a low level of P_{fr}. The low level of P_{fr} allows stems to elongate. Fluorescent and HPS lamps are a better choice for supplemental lighting due to their lower levels of far-red emission. These lamps result in a higher level of P_{fr}, thus less stem elongation. When available light cannot be increased, costly chemical plant growth regulators are applied.

A very serious shade avoidance problem is experienced by cut-rose growers. Successive flushes of roses are harvested from plants that are kept in production for five or more years. Each flush of rose stems shades the base of the stems below from which new shoots arise for the next flush of roses. For the reason discussed earlier for seedlings and bedding plants, a low level of P_{fr} exists deep in the canopy where auxiliary buds must develop to produce the new stems. Without adequate P_{fr}, new lateral shoots do not form. Results from a rose study reported a red/far-red ratio of 1.23 at the top of the canopy, while in the canopy 28 inches (70 cm) below, it was only 0.13. One technique used to increase light penetration into the canopy involves bending the remaining stem over to a 90° angle after flowers have been harvested from it. This preserves the remaining leaves for photosynthesis while opening up the lower stem to full light exposure.

Germination of seeds that require light is also under control of the red/far-red class of phytochrome photoreceptors in the seed. When the level of P_{fr} sensed is low, germination is inhibited. This is the situation when too little red light is reaching the seed. It could indicate that the seed is buried too deep in the soil or there is a heavy canopy of foliage above the seed. In either event, the food reserve in the seed will be insufficient to develop the plant to the point where it can reach sufficient sunlight to achieve adequate photosynthesis in time to sustain itself. Seed suppliers indicate which seeds require light. Other seeds can be indifferent to light or darkness or can have an absolute requirement for darkness. Thus, seeds may need to be either buried or placed on the surface of germination substrate during propagation.

Photoperiodism is a classic example of the role of the red/far-red phytochromes. Photoperiodism is the response of an organism to the relative day/night lengths in the daily cycle. A high level of P_{fr} generated under a large exposure to red light occurring during long days triggers a number of responses. Some of these responses include the inhibition of flowering in short-day plants, flowering in long-day plants, and suppression of tuber formation in dahlia. Photoperiodism will be discussed in greater length in a subsequent section in this chapter.

Light Intensity

When the factors of CO_2 level, temperature, and water are optimized for photosynthesis, an optimum light intensity can be determined. If the light intensity is diminished, photosynthesis (and growth) slows down. If higher-than-optimal light intensities are provided, growth again slows down because the chloroplasts are injured. Plants become chlorotic, and in severe cases, necrotic. Chloroplasts are the organelles within green cells in which photosynthesis occurs.

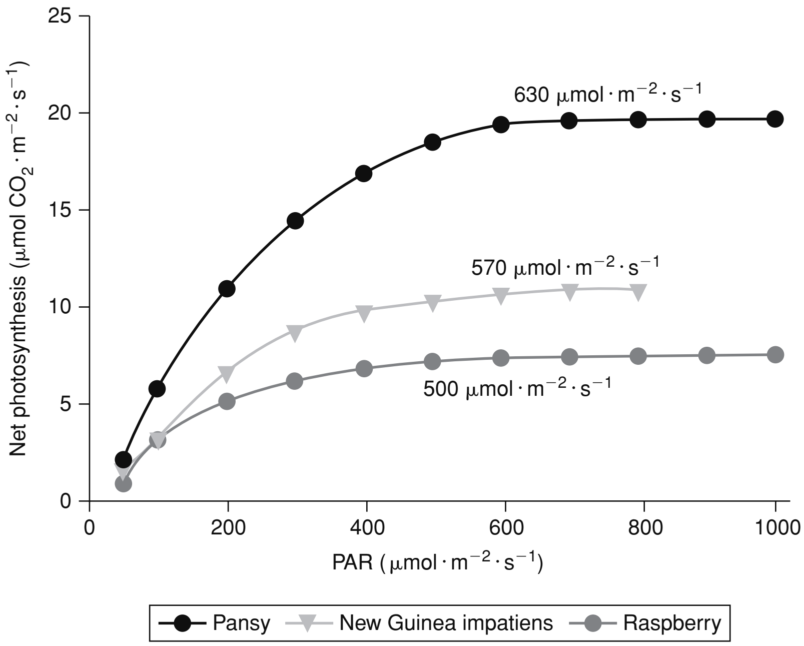

Figure 3
The relationship between photosynthetically active radiation (PAR) light intensity and rate of photosynthesis showing light saturation at 500, 570, and 630 μmol·m^{-2}·s^{-1} intensities in raspberry, New Guinea impatiens 'Prepona Pure Beauty,' and pansy 'Crystal Bowl Yellow,' respectively.
(Graph courtesy of Erwin et al., 2003.)

Greenhouses are subjected to light intensities as high as 10,000 foot-candles (fc) (108 klux; 2,000 μmol·m^{-2}·s^{-1}) on clear summer days. Since 65 percent or less of ambient light enters the greenhouse, crops in the Northern Hemisphere can be subjected to intensities of 6,500 fc (70 klux) in June to 300 fc (3.2 klux) in December. For most crops, neither condition is ideal. Most greenhouse crops become light-saturated (i.e., photosynthesis does not increase at higher light intensities) between 2,500 and 3,000 fc (500 and 600 μmol·m^{-2}·s^{-1}) when supplemental CO_2 is not supplied (Figure 3). Foliage plants saturate at 1,000 to 1,500 fc (200 to 300 μmol·m^{-2}·s^{-1}), while rose and tomato plants saturate at 5,000 to 7,500 fc (1,000 to 1,500 μmol·m^{-2}·s^{-1}). Of course, this is assuming that all leaves are exposed to this light-saturating intensity, which is rarely the case. Upper leaves cast shadows on lower leaves, thus reducing the light intensity at the lower leaves. As illustrated in Figure 4, an individual leaf at the top of the plant often saturates at 3,000 fc (32.3 klux), while the leaves within

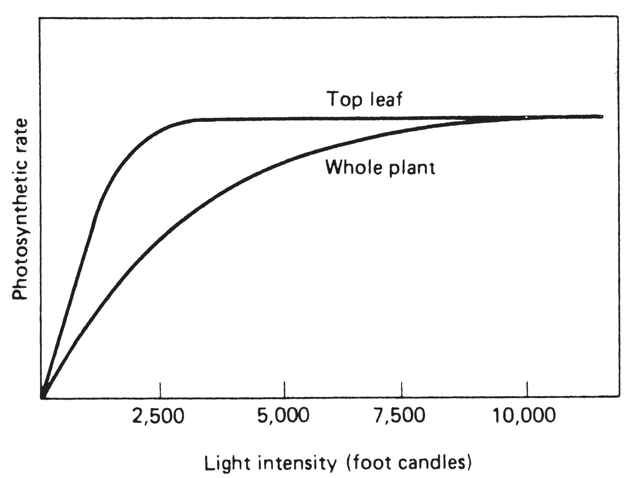

Figure 4
The effect of light intensity on the rate of photosynthesis of a single leaf at the top of a plant and of the whole plant. While the single leaf reaches its maximum rate of photosynthesis at 3,000 fc (32.3 klux), an intensity of 10,000 fc (108 klux) might be required for the whole plant in order to raise the light intensity within the leaf canopy to 3,000 fc (32.3 klux).

the canopy may not reach light saturation until the plant is exposed to 10,000 fc (108.0 klux). Depending on the canopy density, which differs from crop to crop, two to four times as much light can be required at the top to saturate inner canopy leaves. It is generally not advisable to supply this much light because of supplemental lighting cost, extra cooling requirement, and injury to upper leaves and flowers.

Rose and carnation plants grow well under full summer light intensities. Poinsettia foliage is deeper green if the greenhouse is shaded about 40 to 45 percent from mid-spring to mid-fall. This is a good level of shade for most crops. In addition to shading crops to prevent chloroplast suppression, crops such as chrysanthemum and geranium are shaded to prevent petal burn; high light intensity is believed to raise the temperature of the petal tissue to an injurious level. Other crops require even more shading. Foliage plants are burned at light intensities over 2,000 to 3,000 fc (21.5 to 32.3 klux), and African violet loses chlorophyll at intensities of 1,500 fc (16.1 klux) and higher. The optimum light intensity for African violets is near 1,000 fc (10.8 klux). Thus, it is apparent that the light-intensity requirements of photosynthesis vary considerably from crop to crop.

Overhead hanging baskets present a unique challenge for light intensity. Many growers capitalize on overhead hanging baskets to achieve an equivalent 100 percent use of floor space. Growers have recently revisited the wisdom of doing this. Some have decided to stop, while others have reduced the density of overhead pots. A study by Faust at Clemson University showed that overhead hanging baskets containing mature plants spaced at a density of one per square yard (one per 0.84 m^2) intercepted about 21 percent of light entering the greenhouse. Because baskets are generally spaced closer within rows than between rows, it is best to orient the rows from north to south. This allows the shadows to move across the plants below.

Maximizing Light Intensity Low light is the main limiting factor for growth in greenhouses during the winter in temperate climates. It is important to ensure the highest light intensity possible during the dark portion of the year, from mid-fall through early spring, for all crops except the low-light group already mentioned. In this way, growth is maximized.

Greenhouse Design. Maximization of light begins in the planning stage of the greenhouse range. The simpler the frame and the farther apart the sash bars, the greater the light intensity inside. A very significant stride forward was made when all-metal greenhouses were popularized in the 1950s. Because of the strength of the metal members of these greenhouses, compared to wood, fewer sash bars were required to support the heavy weight of the glass. As glass widths increased from the original 16 inches (40 cm) to 24, 30, 36, and even 72 inches (61, 76, 91, and 183 cm) in some cases today, the number of sash bars has been reduced to about one-quarter of the original number.

Frame simplicity is particularly important in film plastic greenhouses. The wooden-frame plastic greenhouses (which have almost entirely passed out of the picture now) required very massive frames that greatly reduced interior light intensity. It is very important to keep the wood of such structures painted white so that it reflects light into the greenhouse rather than absorbing it. The same is true of wooden sash bars on glass greenhouses. They should be painted every other year on the outside and about every five years (or as needed) on the inside. The pipe-frame Quonset and all-metal gutter-connected plastic greenhouses, with their minimal frames, are very good in terms of maximizing light intensity.

The importance of greenhouse design can be seen in light-transmission figures presented by Professor Holley of Colorado State University. The frame blocks 10 percent of the sunlight, the sash bars another 5 percent, and the glass another 7 percent.

Actually, the 78 percent light-transmission figure for this overall greenhouse is unusually high. Figures near 65 percent are common. Other factors that further decrease the transmission level are (1) overhead equipment such as automatic shading, heating and cooling systems, plumbing, and plant supports and (2) the geographical orientation of the greenhouse.

The covering material is another consideration. Tempered glass typically used today transmits 90 percent of the light impinging on it, while low-iron glass transmits up to 93 percent. Only a modest amount of low-iron glass is used due to its higher price. When used, it is for high-light-requiring crops, such as rose and vegetables. The double-layer polyethylene covering is very popular because of a 40 percent savings in heating energy compared to single coverings of glass or polyethylene. However, similar savings can be achieved in a single-layer glass greenhouse when a thermal screen is used within it at night. The single glass layer transmits 90 percent of light, while the double-layer polyethylene cover transmits only 78 percent of light.

Clean Covering. Many greenhouses are shaded during the summer to reduce light intensity. A residue of shade may still remain in winter. In addition, dust accumulates on the covering. These deposits reduce light intensity; 20 percent reductions commonly occur. Dirty coverings should be washed as the dark season approaches (usually in October or November in the Northern Hemisphere). Commercial cleaning products are available through greenhouse-supply companies. Some can be used on glass, rigid plastic, and film plastic. Sometimes the inside of the covering becomes dirty as well and may require application of a commercial cleaning material. Benches containing plants should be covered with plastic film during interior cleaning.

Plant Spacing. Plants tend to proliferate within a bench until the available light energy is fully utilized. In other words, an equal amount of dry matter will be produced in a bench whether plants such as chrysanthemum are spaced on 5- or 7-inch (13- or 18-cm) centers. In the former case, smaller stems and blooms are produced. The size and quality of product desired will dictate the proper plant spacing.

Generally, a greater amount of space per plant is provided in the winter than in the summer because of less available light. Catalogs provided by suppliers of plant material indicate the proper spacing for various seasons of the year. It is best to follow their recommendations.

Some growers of cut flowers have found it best to leave an open space along the center of the bench from end to end, as pictured in Figure 5. This permits light to enter the center of the bench where it would normally be darkest. There is a resultant increase in overall quality. In this system, the same number of plants are used in a bench; they are simply spaced closer together to compensate for the open space in the center.

Reducing Light Intensity The need for reducing light intensity, particularly from mid-spring to early fall, has already been pointed out. Two shade materials may be used: (1) a shading compound sprayed on the exterior of the greenhouse or (2) a shade screen (curtain) installed externally over the greenhouse or inside the greenhouse above head height. The shading material may be fixed for the season or retractable minute by minute. The most effective systems are those that are retractable and exterior to the greenhouse. Exterior screens prevent light from entering the greenhouse. When light is absorbed by interior components of the greenhouse, it warms them and makes the job of cooling more difficult.

Growers who use the spray method see three advantages. It is initially less expensive, although annual application and removal is probably more expensive in the long run; it is applicable to all covering materials and shapes of greenhouses;

Figure 5
A winter planting arrangement for chrysanthemum that allows for a space along the center of the bench to increase light intensity at that point and thereby improve quality.

and being on the outside of the greenhouse, it reflects light before entering the greenhouse. Commercial shading compounds can be purchased from florist-supply companies. In the recent past, some growers made their own shading material by mixing white latex paint with water. One part paint in 10 parts water provides a very heavy shade, while one part paint in 15 to 20 parts water provides a standard shade. The shading compound can be applied from the ground by means of a pesticide sprayer. In some large operations, it is sprayed on from the air by a helicopter. Most of the shading compound will wear off by early fall. If it does not, it needs to be washed off.

There are serious disadvantages to using the spray method. It is not possible to apply a carefully prescribed percentage of shading. The level of shading decreases with time. The degree of shading cannot be changed to coincide with hourly changes in solar radiation. This last point is very serious because the light barrier is still in place when the light intensity is low on cloudy days and early in the morning or late in the afternoon on all days. Thus, periods of inadequate light intensity occur, causing reduced growth and delayed crops.

Shade screens offer the best method for cooling. They may be installed in a horizontal plane exterior to the greenhouses a short distance above the peaks of the greenhouse (Figure 6). Or, they can be installed on the roofs of the greenhouses. These alternatives are used more frequently in tropical and subtropical climates where snow damage is not an issue. In either case, it is advisable to have a system where the screen can be retracted and extended as dictated by solar conditions. The advantage of the external screen is the interception of light, thus heat, prior to entry into the greenhouse.

Screens in temperate climates are generally installed inside the greenhouse. The covering/uncovering direction can move either gutter to gutter or truss to truss. Aside from that, in truss-to-truss configurations, the shape of the installation can be flat,

Figure 6
A retractable sunscreen situated in a horizontal position above the greenhouse roofs.
(Picture courtesy of Ludvig Svensson, Inc., Web: www.ludvigsvensson.com.)

Figure 7
A combination sun shade and thermal screen arranged in a flat configuration beneath gutters and pulled from truss to truss.
(Picture courtesy of Ludvig Svensson, Inc., Web: www.ludvigsvensson.com.)

below the gutter level (Figure 7) (most common and least expensive), or follow the peak shape in what is called slope-flat-slope configuration (Figure 8). This slope flat slope is used in houses with wider spans to allow space underneath the screen installation for other greenhouse equipment such as lamps, horizontal airflow fans, watering booms, and basket hanging systems. The advantage of having internal systems is lower cost, greater heat energy conservation, and protection of the screen and mechanism against full wind and precipitation exposure. The disadvantage is buildup of heat in the attic space above the screen. For this reason, it is advisable to ventilate this space. As with the outside screens, it is important to have a mechanism that allows the screen to be retracted and extended as needed. Growers who install the screens in

Figure 8
A photoperiodic screen in the slope-flat-slope arrangement pulled from truss to truss to control flowering during the summer and for retaining heat during the winter at White's Nursery in Chesapeake, Virginia.

a fixed manner for the season face the same problems associated with shading compound sprays.

It is difficult to select the characteristics of shade screens without getting into the other dual and even triple roles they play in the greenhouse. In addition to reducing light intensity, screens are used to diffuse light entering the greenhouse, conserve heat energy during the heating season, and increase the length of the dark period for photoperiodic crops. The composition of the screen must vary according to the role or combination of roles served.

Greenhouse screens commonly consist of strips of clear plastic, white plastic, or aluminum foil laminated onto plastic. These strips are knitted together with a yarn, often polyester. The strips are narrow, around 5⁄32 inch (4 mm) wide. The plastic is often polyester due to its strength and resistance to radiant heat transmission. Strips may touch each other across the entire screen in which case it is called a closed screen. Actually, there is an unperceivable space between strips that permits water vapor to pass up through the screen or liquid water to drain down through it. This keeps the humidity lower under the screen and prevents accumulation of condensate from collecting on the screen and damaging it. Closed screens are best for heat retention. When strips of plastic are occasionally omitted in the screen leaving open strips, it is said to be an open screen. Open screens readily allow air to pass through the screen. This is important in passively cooled greenhouses that rely on open roofs or ventilators for cooling.

Growers of nonphotoperiodic crops generally want a single screen that can be used to reduce sunlight during summer and retain heat during winter nights. A wide range of shade percentages is available including 15 to 85 percent. This is achieved by varying the ratio of clear or white strips to opaque aluminum strips. The heat retention property of the screens that use aluminum foils for shading increases with increasing degrees of shading provided. Thus, the properties of this dual purpose screen are dictated by the level of shade needed for the crops grown. For ornamental crops in general, a shade level of 40 to 45 percent is most common. Many foliage plants require heavier shade, up to 80 percent. Strips of aluminum laminated on plastic are used in the screen to reflect incoming light away from the crop to create shade. Vegetable crops for fruit production in the greenhouse, such as tomato and cucumber, require very high light intensity. For these crops, it is better to diffuse the entering light rather than to reflect it out of the greenhouse. This brings up the second role of screens, light diffusion.

Figure 9
A sunscreen in a partially open position would be applied in a passively cooled greenhouse to allow hot interior air to escape.
(Picture courtesy of Ludvig Svensson, Inc., Web: www.ludvigsvensson.com.)

Higher levels of light can be tolerated by crops when it is diffused compared to direct rays radiating on the plants. Diffusion of light spreads it out more uniformly throughout the greenhouse. For the same amount of light entering the greenhouse, the intensity is lower at the top of the plant so its tissue is cooler and chlorophyll is less likely to be injured. Simultaneously, more light is present on the normally shaded sides of beds and within the plant canopy. This factor as well as the facility to grow plants at higher light intensities results in improved growth. Strips of white plastic are used in the screen to diffuse light that is transmitted through these strips.

The closed screens work best for fan-and-pad cooled greenhouses because of their superior heat retention at night. Open screens are used in passively cooled open roof or ventilator greenhouses. The open screen allows hot air to rise up through the screen and out through the roof or ventilator while still providing sufficient shade. Alternatively, closed screens can be used in passively cooled greenhouses. These screens must be left partially open during days when cooling is required so the open area of the screens at least equals the ventilator opening (Figure 9). Since direct light enters through the openings, the openings must run north to south. This causes the bands of full sunlight to pass across the crop as the day passes. This closed screen option would be selected by growers faced with greater heating needs. The open screen option would best suit growers in climates where cooling is proportionately more important than heating. Both screens can be used to retain heat, but the closed screen is much more effective. The use of multiple screens is growing, especially with high-value crops. Multiple screens are usually installed to cover in opposing directions. This assumes that at least one of the screens is of closed, energy conserving, construction and must be ventilated around in naturally ventilated greenhouses. The opposing direction of covering/uncovering allows for the bottom screen to shade the opening left when ventilating around the top screen, and vice versa.

Growers of photoperiodic crops need to be able to block out light to provide longer nights for control of flowering. Screens for this purpose have a black underside to absorb light. Typically 99.9 percent of light is blocked. The outer side of the screen may be black, white, or aluminum. White or aluminum is common on the outer side. This reflects light in the late afternoon and early morning when the screen is still pulled over the plants. The reflective surface keeps plants under the screen cooler. Temperature under a black outer surface can become high enough to cause heat delay to the crop. The photoperiodic blackout screen is also used as a heat retention screen at night. It cannot function as a shade or diffusion screen. For these purposes, a second screen is needed. Heat retention and blackout screens should be installed on the four vertical walls as well as overhead. If warm air escapes from the plant zone up the walls into the gable, it will set up a current that will draw more warm air from under the screen up into the gable defeating much of the purpose of the screen. For heat retention and light exclusion, a screen box must be created around the crop.

Modern greenhouses have computerized equipment to draw shade screens across the greenhouse in response to photocells. In this way, screening is applied only during the hours when it is needed. The same apparatus used for drawing shade screens in the daytime during the bright months can be used for drawing heat retention and photoperiodic blackout screens in the evenings. Manual operation of screens would require constant vigilance seven days a week, which is out of the question. Computers responding to signals from photocells and clocks easily handle the task. Black or dark green porous saran screens are sometimes used for shade screening in greenhouses. These convert much incoming light into heat, reducing their effectiveness, and are not highly effective for heat retention during the heating season. They are good materials to use on shade houses where frost is not a threat.

Supplemental Lighting During the dark seasons of the year, light intensity is below optimum for most crops in most greenhouse production areas of the world. While the previously discussed methods for maximizing light intensity help, they do not completely solve the problem. The growth of affected crops is erratically slow because of day-to-day variations in weather conditions, and final quality is reduced. There is an increase in blindness (failure of shoots to develop) on crops such as rose and orchid. The size (grade) of cut flowers is smaller, stems are thinner, and plants can be adversely tall. This situation can be rectified by using supplemental lighting in the greenhouse to increase the rate of photosynthesis.

Lamp Types. Reports of using electric lamps for growing plants go back 150 years to a reference in 1861 (Wheeler et al., 2008). Carbon arc lamps that used carbon rods and an open arc were apparently the first electric lamps used for growing plants. A broad spectrum of bluish light was emitted by these lamps. These lamps required frequent replacement of carbon rods and presented dangers from high UV light radiation and exhaust emissions. Yet, they were tested for plant growth into the 1940s. In the 1920s and 1930s, incandescent filament lamps (Mazdas) became the commonly used lamp for growth-chamber research facilities. These lamps could last 3,000 hours when used continuously. Fluorescent lamps, developed in the 1930s, offered improved effectiveness for plant growth. These provided a broader spectrum of wavelengths compared to the red and far-red-biased incandescent lamp, had a higher electrical efficiency, and had a longer life expectancy. Fluorescent lamps were developed from the late 1800s vintage low-pressure discharge mercury vapor lamps by adding phosphors to them. A variant of the low-pressure mercury lamp was the low-pressure sodium (LPS) lamp developed around 1900. High-pressure mercury lamps were developed in the 1930s, and later in the 1950s and 1960s, metal-halide and HPS lamps were developed.

Lamps used in production greenhouses over the past half century fall into three groups: (1) incandescent, (2) fluorescent, and (3) high-intensity-discharge (high-pressure mercury, metal-halide, LPS, and HPS). Light emissions typical of each type can be seen in Figure 10.

Incandescent (tungsten-filament) lamps (Figure 10a) are generally not used for supplemental lighting because of excessive heat, poor light quality, and low efficiency. In order to avoid excess heat, the light intensity must be kept too low. For most plants, the high proportion of far-red light emitted causes tall, soft growth due to elongated internodes and leaf petioles as well as enlarged leaf area. These lamps are

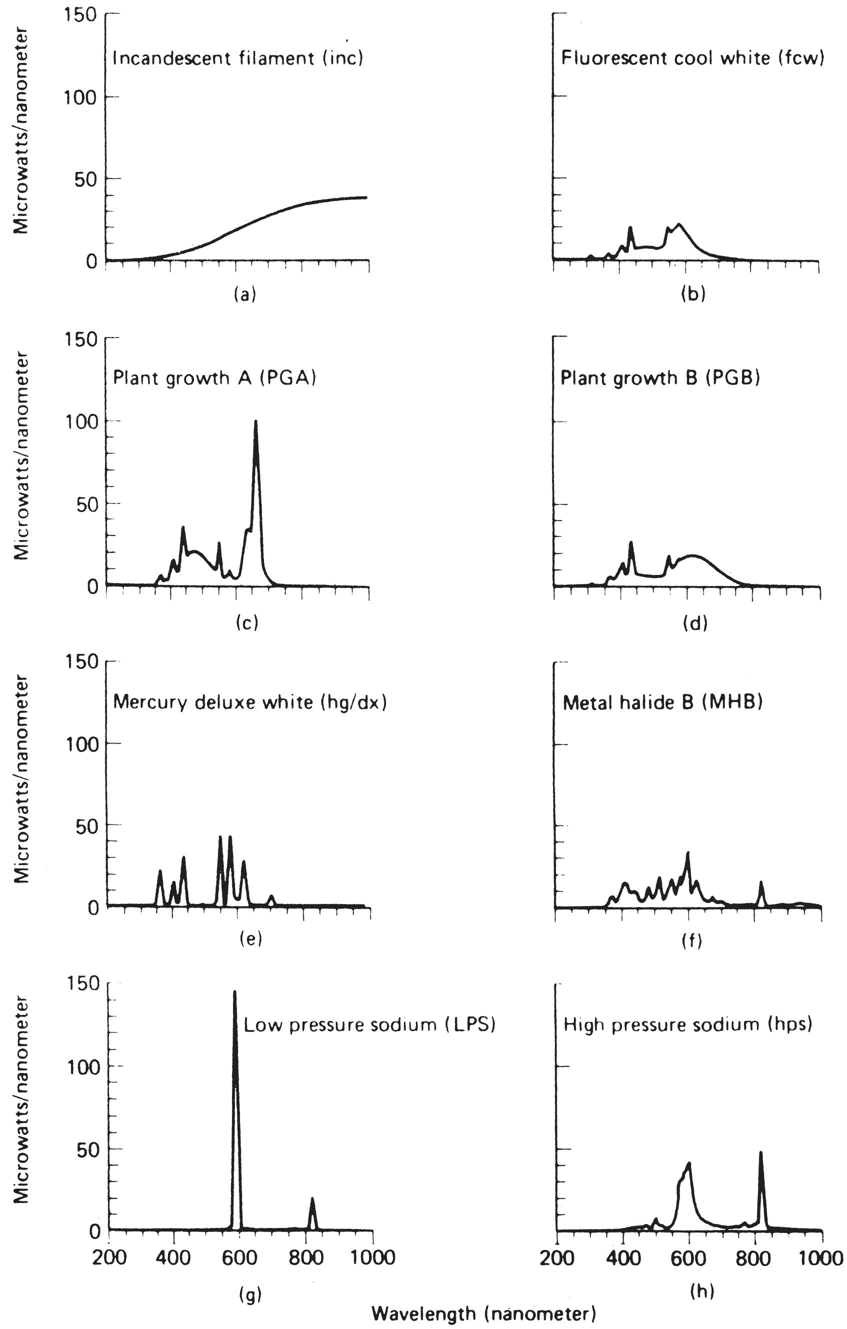

Figure 10
The spectrum of light emissions measured as radiant power per lumen from eight types of lamps considered for use in greenhouses.
(Adapted from Campbell et al., 1975.)

also very inefficient, converting only 7 percent of the electrical energy consumed into light energy. Much of the energy is converted into heat, which at times is of value and at other times is a detriment. While incandescent lamps are of little value for supplemental lighting, they have until recently been the lamp of choice for photoperiodic lighting (which will be discussed later in this chapter). For this application, a low level of light (10 fc, 108 lux) is applied for a short duration in the middle of the night during the darker months of the year.

Fluorescent lamps are the most common lamps used in germination chambers and over small germination areas in the greenhouse. (This application will be discussed later in the "Germination Chambers" section.) Although research has shown fluorescent lamps to be effective for enhancing growth in the greenhouse as a whole, they are rarely used for this application. The low power (wattage) of the lamps increases the number needed and, consequently, the total cost of fixtures and wiring required to do the job; also, the larger number of fixtures increases the area of shadows cast on the crop.

Among the more efficient of the fluorescent lamps are the cool white and warm white tube types. These lamps convert 20 percent of electrical energy consumed by them and the ballast to visible-light energy and have similar spectral-light emissions. Cool white lamps (Figure 10b) are perhaps the most commonly used fluorescent lamps for plant growth. Light emitted tends to predominate in the blue region. A number of other fluorescent lamps with special phosphors are used for emitting a spectrum of wavelengths more in line with the requirements of photosynthesis. These are categorized into two groups: plant growth A (Figure 10c) includes the earlier lamps with enhanced radiation in the red range, while plant growth B (Figure 10d) includes the later generation of lamps with extended spectral emission beyond 700 nm. The plant growth fluorescent lamps are used more for home plant shelves than by commercial growers. Their plant growth benefit is small compared to their higher cost.

High-intensity-discharge (HID) lamps are the preferred lamps for finishing crops in greenhouses today. High-pressure mercury-type HID lamps (Figure 10e) were once more common. These lamps were mostly replaced by metal-halide lamps and, more recently, by HPS-type HID lamps. Light emissions from high-pressure mercury lamps are somewhat similar to those from fluorescent tubes. Model MBFR/U (formerly popular in Europe) has fluorescent powder on the inner surface of the glass bulb, which converts much UV light to visible wavelengths, particularly red. This feature makes the lamp more desirable for plant growth and increases its efficiency to 13 percent of the electrical energy input into the lamp and ballast. Similar American lamps are the Mercury Clear and Mercury Deluxe White models (Figure 10e), which are often seen along roadways. These lamps are available in sizes up to 1,000 W. They have been used for up to 10,000 hours, at which point they still had 70 percent of their original output.

High-pressure metal-halide–type HID lamps (Figure 10f) were also at one time more commonly used in Europe than in the United States. These lamps are available in sizes up to 2,000 W and can convert 20 percent of total electrical input energy into light in the 400- to 700-nm band. These lamps cost more than high-pressure mercury lamps, have a shorter life, and lose their output level faster, but they more efficiently utilize electricity.

LPS-type HID lamps (Figure 10g), available in 35-, 55-, 135-, and 180-W sizes, were popular for a while. As refinements came along in the metal-halide and HPS lamps, LPS lamps lost popularity in the greenhouse. LPS lamps are the most efficient, with 27 percent of the electrical input into the lamp and ballast being converted to visible radiation. These lamps have a life expectancy of 18,000 hours.

LPS lamps emit most of their light in a narrow band around 589 nm. Because little light is emitted in the 700- to 850-nm range, there are adverse effects on some crops when these lamps are the only source of light. In tests of African violet, lettuce, and petunia grown under LPS lamps only, the plants developed pale green foliage. Lettuce plants were smaller in comparison to plants under both LPS and incandescent lamps. If 10 percent of the total light is supplied from incandescent lights or from natural daylight, the problem is averted. Lettuce plants grown under LPS lamps in northern Europe developed strap leaves. This problem does not occur in the United States, where winter light intensities are higher and days are longer. The problem is believed to be caused by low levels of blue light. These problems are not encountered with HPS lamps because of the broader spectrum of light emitted.

Reasons given in the greenhouse industry for not using LPS lamps include their bulky reflectors, which cast shadows, and the higher cost of purchasing and installing the large number of LPS lamps required relative to HPS lamps.

The majority of lamps being installed in greenhouses today worldwide are HPS-type HID lamps (Figure 11). They are cheaper to purchase and operate. The light-emission spectrum predominates more in the higher wavelengths, with a peak at 589 nm (yellow) (Figure 10h). The light-emission spectrum extends beyond the visible range (400 to 700 nm) into the 700- to 850-nm range. Radiation in this latter range is required for stem elongation, increased fresh weight, and early flowering of most plants. HPS lamps are very efficient, converting 25 percent of the electrical input into the lamp and ballast into visible radiation. Suitable models of HPS lamps

(a) (b) (c)

Figure 11

(a) A high-pressure sodium (HPS) light assembly including lamp, reflector, and ballast designed exclusively for greenhouse installation. Unlike the light assemblies sold for other commercial applications, the reflector pictured here maximizes uniformity of light intensity across the plant zone. (b) Night scene inside a greenhouse with HPS lights. (c) Exterior of greenhouse with HPS lights on at night.

(Pictures courtesy of P.L. Light Systems Canada, Inc., Web: www.pllight.com.)

for greenhouse use are available in 400-, 600-, 750-, and 1,000-W sizes. The life expectancy of HPS lamps can be as much as 24,000 hours.

LED Lighting. The first LED developed in the 1920s emitted a nonvisible wavelength of light. In 1962, a visible wavelength–emitting LED was produced. Since the mid-1980s, studies involving the use of LEDs for plant growth have shown them to be effective. The next generation of lighting for plant growth in germination chambers, controlled environment growth chambers, and tissue culture rooms will undoubtedly be LEDs. Their potential in greenhouses is being explored. Currently, their high cost prohibits use in greenhouse applications. However, price is rapidly declining with continuing development and mass production for applications such as vehicle headlights and taillights, bill boards, street lights, traffic lights, and general home and industrial lighting.

In an LED, electricity flows across the junction of a diode. As it does, light is emitted from the junction. The wavelength (color) of the light depends on the type of material and impurities used to make the junction. The wavelength of light can be set between 250 nm (UV-C) and 1,000 nm (IR). Colors available today include UV-C, UV-B, UV-A, blue, green, yellow, orange, red, far-red, and IR. White is also available, but it is a blue LED coated with a phosphor that renders it less efficient than the others. LEDs are not a lamp. They are more similar to a computer chip. An individual LED may use only a few milliwatts of electrical power and emit little light for plant purposes. They are more often composited into *arrays* of many LEDs. The array can be in any shape and use 100 W or more. Vertical arrays of 1 inch (2.5 cm) width and 1 foot (30 cm) or more length have been studied within canopies of plants. Planar arrays of any dimension can be assembled to light growth chambers and greenhouses.

LEDs have numerous advantages over current lighting. Their efficiency of conversion of electrical energy to light is similar to HID lamps and much higher than incandescent and fluorescent lamps. They are resistant to breakage since they do not have a glass envelope. LEDs operate at a cool touch temperature, reducing the threat of skin burn. The life of LEDs defined as the time to 70 percent of initial light output is about 50,000 hours. This is about twice the expectancy of the currently popular HPS lamps. They do not contain mercury-like fluorescent lamps. They do not have a ballast to take up space or require replacement. The life of an LED is not shortened by turning it on and off, as is the case with all light lamps. Light turns on and off instantly without a warm up or cool down period. Harmful UV light is not emitted unless it is added for a purpose.

Unlike all other light lamps, very little heat is radiated in the light beam of an LED. Most heat is released from the back of the fixture where it can be conducted away in an air stream or in chilled water. Due to the small size of LED arrays and low heat radiation in the light beam, they can be placed close to plant surfaces. Since light intensity diminishes in proportion to the square of the distance from source to irradiated surface, this allows for a much greater percentage of generated light to be intercepted by plants than from all other lamps. In comparison with HID and LED sources in controlled environment growth rooms, about one-third as much electrical energy was consumed by the LEDs to achieve the same light intensity. Much of this was attributed to closer proximity of light source to plant afforded by the LEDs. It has been possible in growth chambers to raise light intensity at the leaf surface to that received from full sunlight at noon in the summer with only a 3°F (1.5°C) rise in leaf temperature.

The specialized reflectors that are used with HID lamps in greenhouses are not needed with LEDs. These reflectors are ineffective because light from the LED is already directional. The standard lenses supplied with LEDs direct light in a single direction to the plant. This is a decided environmental advantage since unwanted release of light to the sky is avoided. Light pollution in parts of The Netherlands has brought about laws to limit the night hours when lights can be turned on in greenhouses.

LEDs are solid-state devices that are easily controlled by computer. This level of control opens up control possibilities never experienced before. Light intensity can be ramped up in the morning and down in the evening to conform to sunrise and sunset with no wear and tear on the lights. The spectrum of light colors can also be varied in accordance with the shifting spectrum that occurs with the natural passing of day. UV light can be eliminated or added as desired. The red-to-far-red light ratio can be fully controlled. This control over light wavelength is possible by designing array boards containing several LEDs, each emitting different wavelengths of light with each color controlled separately. Multiple array boards in a greenhouse could be individually turned on and off as plants are added and removed to eliminate lighting unused space.

Commercial Application. Supplemental lighting is modestly related to geographical area with more light applied in the darker latitudes. It is more strongly related to the crops grown. The heaviest use is in propagation of both seeds and cuttings. Young plants tend to respond more dramatically than older plants. Stock plants for cutting production are also commonly lighted. Vegetables produced for their fruit in greenhouses, including tomato, cucumber, and lettuce, most often receive supplemental light. A modest number of growers also use supplemental lighting for various ornamental finish crops and special situations such as timing gloxinia crops for Christmas.

Common supplemental light intensities are 400 to 450 fc (4.3 to 4.8 klux) for finishing potted ornamental crops and 600 to 650 fc (6.5 to 7.0 klux) for seed and cutting propagation. Supplemental lighting levels for vegetable fruit production have been increasing in recent years and currently range from 1,000 to 1,500 fc (10.8 to 16.1 klux).

It costs about \$3.00/ft^2 (\$32.25/m^2) of greenhouse floor to purchase and install an HPS system. The price of a 600-W lamp and fixture, including ballast, is around \$225. The price of wire and installation is about \$125 per lamp. For a rough estimate, one 600-W lamp will provide light intensities of 400, 600, and 1,000 fc (4.3, 6.5, and 10.8 klux) over plant area of 185, 124, and 74 ft^2 (17.2, 11.5, and 6.9 m^2), respectively. A second cost to consider is the consumption of electricity. Lamps of 400-, 600-, 750-, and 1,000-W sizes consume 465, 675, 840, and 1,100 W of energy per hour, respectively.

The various suppliers of lamps determine for growers the precise number, height, and spacing of lamps according to the desired light intensity and the configuration of the greenhouse. Growers can get a rough approximation of the number of lamps required for an installation as follows. Determine the floor area that can be serviced by a lamp by dividing the number of lumens of light supplied to the crop by the lamp by the desired number of foot-candles of supplemental light. The number of lumens of light received by the crop depends on the brand of the lamp. Reflector design is a principal factor in determining this level of irradiation efficiency. For 400-, 600-, 750-, and 1,000-W lamps with total radiation values of 50,000, 90,000, 105,000, and 127,000 lumens, consider the useful radiation to be 38,000, 74,100, 95,000, and 110,000 lumens. Dividing the useful radiation by the desired crop-level light intensity gives the effective crop area that can be lighted by one lamp. For example, one 600-W lamp will supply 400 fc of light over a 185 ft^2 crop area (74,100 lumens ÷ 400 fc = 185 ft^2). In the recent past, the 400-W lamps were used almost exclusively because better uniformity in light intensity across plants could be achieved with this size of lamp within the confines of the low greenhouse. Because of the increased height of greenhouse gutters, the 600-W lamps are now more popular. The 1,000-W lamps are used in tall greenhouses and for high-light-requiring crops such as tomato and cucumber.

Equally important to the lamp is the fixture that holds it and reflects the light to the plant area. Special horticultural fixtures are used. They are designed to spread the light in a square pattern as broadly and as uniformly as possible and with a minimum size of fixture, to reduce shading. Lamps designed for other industrial purposes direct a much lower percentage of their light toward the crop. Specialty designs include a reflector for lamps hung over an aisle to minimize the light in the aisle and direct it toward the two adjacent beds instead. Likewise, reflectors are available for use along the sides and ends of greenhouses to direct light into the greenhouse that would otherwise strike the wall.

The acceptable number of hours of beneficial light per day varies across crops. A few crops can benefit from 24 hours of light per day. These include lettuce, cucumber, sweet pepper, begonia, chrysanthemum, and *Ficus benjamina*. Most crops require some minimal length of darkness. For these crops, absence of darkness results in chlorosis, necrosis, and disruption of the closing mechanism of stomates resulting in shorter postharvest life. Crops receiving supplemental lighting are generally given a light period of 14 to 18 hours. This includes the time when the lamps are on as well as any part of the day when it is bright enough to turn the lamps off. Generally, the lamps are turned off when the natural light intensity exceeds a set point, often twice the intensity provided by the supplemental lamps. The yield benefit of extending the 18 hours of light to 24 hours is small for many crops. A daily light duration of 16 to 18 hours works well for vegetables. Growers in darker climates may extend the period of light to 20 hours. The decision of lighting duration is based on the return gained for the investment. Some cultivars of cut rose can tolerate 24 hours of light, while others do not. Many rose growers see a disadvantage to applying 24 hours of light because, during the night, blooms develop beyond the desired stage for cutting in the morning when the work crew arrives. Lighting roses for 18 hours speeds up flower development to the point at which successive harvests can be made for the four dates of maximum profit: Christmas, Valentine's Day, Easter (if it falls on the right date), and Mother's Day. In addition, a 50 percent or better increase in yield can be obtained.

Plant response to supplemental light is greatest in the young-plant stage, beginning with the first true leaves, and diminishes with time. This is fortuitous because plants can be grown at a higher density when they are young, and thus it is possible to light a relatively small area of the greenhouse. A good example would be bedding plants, which are often lighted when they are in plug trays, where there can be as many as 648 seedlings per tray. Much more light would be required later, when these seedlings are transplanted into flats similar in size to the plug trays but holding only one-tenth or fewer plants.

Tomato seedlings in flats or soil blocks are often lighted starting at the time of germination for a period of two to three weeks at an intensity of 465 fc (5.0 klux). In some cases, light is applied for 12 hours per day, enabling the lighting arrangement to be drawn on tracks to a second batch of seedlings each day. The switching of lights occurs at midnight and noon. In this way, each batch of seedlings can be exposed to a 16-hour day length, since an additional 4 hours of daylight will be obtained when they are not under the lights. "Five-week-old" plants can be produced in less than half that time with this method.

Cucumber seedlings for greenhouse fruit production benefit from supplemental light intensities of 280 to 465 fc (3.0 to 5.0 klux) from November to February in the Northern Hemisphere. Lettuce seedlings produced for growing in the greenhouse can require from two weeks in the summer to eight weeks in the winter to produce under natural light in England. If they are lighted at 700 fc (7.5 klux), they can be produced in 11 days in the winter.

Some pot chrysanthemum growers set up two zones for producing this crop. In the first zone, plants are spaced tightly and are provided a warmer temperature, elevated CO_2, and supplemental lighting. The plant is most responsive to all of these environmental factors in the early stages. Thus, the higher costs of providing this environment can be confined to a short period when the crop occupies minimal space.

Germination Chambers Germination chambers are used for producing seedlings (Figure 12). They may be constructed in the headhouse, in a barn, or in the greenhouse. Many materials can be used for construction, including waterproof plywood. The chamber should be well insulated with a material such as polyurethane board and have a moisture-tight barrier on the inside.

Shelves may be built inside in tiers, up to 2 feet (61 cm) apart, although they can be as close as 9 inches (23 cm). The space between shelves should be sufficient to permit a minimum space of 6 inches (15 cm) between the fluorescent lamps and the top of the plants when low-energy, 40- to 75-W lamps are used. If 8-foot (244 cm) long, high-energy 215-W lamps are used, the shelves should be 2 feet (61 cm) apart. Attached to the bottom of the shelf above are the lamps. Fluorescent lamps are best for growth rooms because of the uniform light intensity they emit over a wide area and the low heat level they emit. High-intensity lamps would be difficult to use in such close proximity to the plants, although LPS lamps are used in some chambers.

Figure 12
A growth room for starting seedlings. Plants are grown on tiered shelves to conserve space. Light is supplied entirely by fluorescent lamps above each shelf.
(Photo courtesy of George J. Ball, Inc., W. Chicago, IL 60185.)

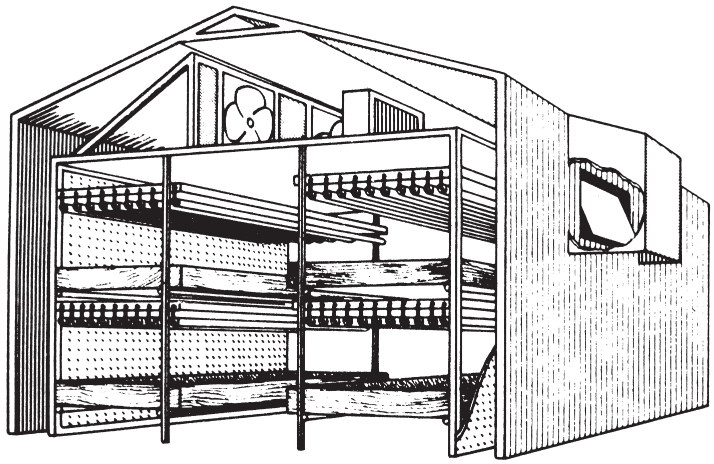

Figure 13
Arrangement of benches, fluorescent tubes, air circulation system, heater, and ventilator in a six-bench growing room.
(From Electricity Council, 1972.)

Cool white fluorescent lamps are commonly used. LED array strips have just come on the market that are very appropriate for this application.

A light intensity of 500 to 1,400 fc (5.4 to 15.0 klux) is used, depending on the crop. Light intensities of 500, 750, and 1,400 fc (5.4, 8.1, and 15.0 klux) can be provided by 8-foot (244-cm)-long, 125-W lamps installed 2 feet (61 cm) above the shelf at horizontal spacings of 8.9, 6.0, and 3.2 inches (22.6, 15.2, and 8.1 cm), respectively. A sheet of aluminum foil or a coat of aluminum paint should be provided above the tubes to maximize the light intensity below them, even when reflectorized tubes are used.

Light is generally applied for 16 hours per day; however, some crops, such as many of the bedding plants and lettuce, will respond to 24 hours of illumination. During the illumination period, the temperature is held between 70° and 80°F (21° and 27°C), depending on the type of seed being germinated.

The lamps will provide most of the heat needed. Only during exceptionally cold periods is it necessary to provide supplemental heat. A thermostatically controlled heater can be installed for this purpose. The greatest requirement regarding temperature is maintaining a uniform temperature. Hot and cold spots will form if the air within the room is not circulated. The two walls running the length of the room should be constructed of perforated material such as pegboard. The pegboard should be set 6 to 8 inches (15 to 20 cm) in from the outer wall of the room to provide a chamber for air movement behind the pegboard (Figure 13). A false ceiling provides a chamber overhead that is connected to the wall chambers. A fan is placed overhead that will cause air to be drawn in one wall and expelled through the other, thus setting up an airflow pattern across the growth room. The heater can be installed in the space over the ceiling in front of the fan. Should the room become too hot, a thermostatically activated motorized ventilator is used in the air duct behind the wall or over the ceiling. For very fine details of growth room designs, see Mastalerz (1985).

Daily Light Integral

The DLI is the total sum of light received in a day. Light can be visualized as traveling in a stream of particles called photons. DLI is measured in terms of moles of light photons impinging on a square meter of receptive surface per day ($mol \cdot m^{-2} \cdot d^{-1}$). Since this is a complicated term, it will be simplified in this text to "moles/day." Each photon of light can activate one molecule of chlorophyll in the process of photosynthesis. A mole of light contains 6.022×10^{23} (602,200,000,000,000,000,000,000) photons. DLI gives a good assessment of cumulative photosynthesis (growth) that can

Table 1
THE OPTIMUM DAILY LIGHT INTERVALS FOR THE FOUR LIGHT REQUIREMENT CATEGORIES OF GREENHOUSE PLANTS

Light Requirement Category	DLI (moles/day)
Low light (shade) plants	5–10
Medium light plants	10–20
High light plants	20–30
Very high light plants	30–50

occur during a day. Light intensity, on the other hand, relates to the rate of photosynthesis at the moment it is measured. It tells us little about how much photosynthesis will occur throughout the day because cloud cover can change minute to minute. However, it is important to know light intensity because below a threshold for each crop, growth is inadequate, while above a given level, injury can occur to the crop. Intensity is also used to develop specifications for a supplemental light system.

The required DLI inside the greenhouse to achieve satisfactory growth for various categories of greenhouse plants are given in Table 1. Low-light-requiring plants such as African violet, phalaenopsis orchids, ferns, spathiphyllum, and many green plants require only 5 to 10 moles/day, while very high-light-requiring plants such as rose, carnation, alstroemeria, pepper, and tomato require 30 to 50 moles/day. For most greenhouse crops, the medium light category, the target DLI inside greenhouses in northern climates during the winter is 10 to 12 moles/day. More precise DLI requirements for quality production levels of 86 crops are presented in Figure 14.

The average outdoor DLI ranges from 5 to 10 moles/day in December across the northern contiguous United States to 55 to 60 moles/day across the southwestern United States in May through July (Figure 15). Since only 50 to 65 percent of light is transmitted into the greenhouse, the average inside DLI can range from 3 to 40 moles/day from December to June. Average DLI and light-intensity levels measured inside greenhouses in Naaldwijk, The Netherlands, at 52°N latitude are presented in Table 2. DLI levels ranged from 2.3 moles/day in December to 24.5 moles/day in June, while intensity levels varied from 437 to 2,148 fc (4.7 to 23.1 klux; 84 to 413 $\mu mol \cdot m^{-2} \cdot s^{-1}$) between December and June.

Obviously, many medium- and high-light-requiring crops benefit from supplemental lighting, particularly during the winter. To get an idea of the amount of light that can be supplied by supplemental light, consider a program calling for a daily light period of 18 hours. It would be reasonable to expect that the ambient sunlight would be adequate for 6 of these hours leaving 12 hours of supplemental lighting. If intensities of 400, 600, 1,000, and 1,500 fc (4.3, 6.5, 10.8, and 16.1 klux) were applied for these 12 hours, DLI increases of 2.3, 3.4, 5.7, and 8.5 moles/day would be achieved. While these additions may not be very significant or cost effective in the summer, they can be very beneficial in the winter when the DLI is low. Astute growers, particularly those of vegetable fruit, test the relationship between DLI level and economic return. DLI can be increased by extending hours of lighting or by installing a higher density of lamps with new additions of greenhouses. Economic return can be realized through shorter production time, increased yield, or improved quality.

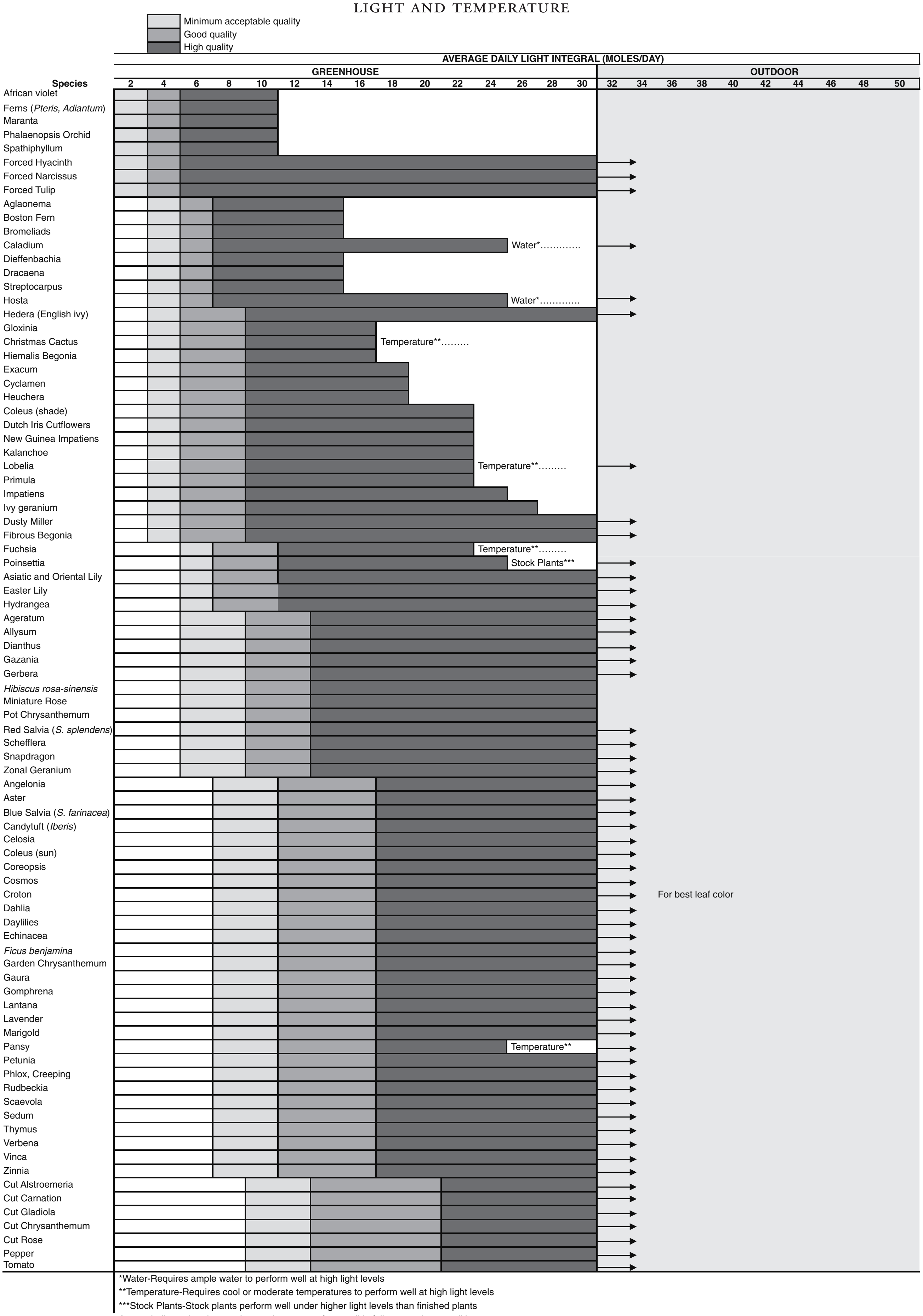

Figure 14

Daily light integrals (DLIs) required for achieving minimum acceptable, good, and high quality growth for 86 types of plants.

(Picture courtesy of James Faust, Clemson University; Faust, 2003.)

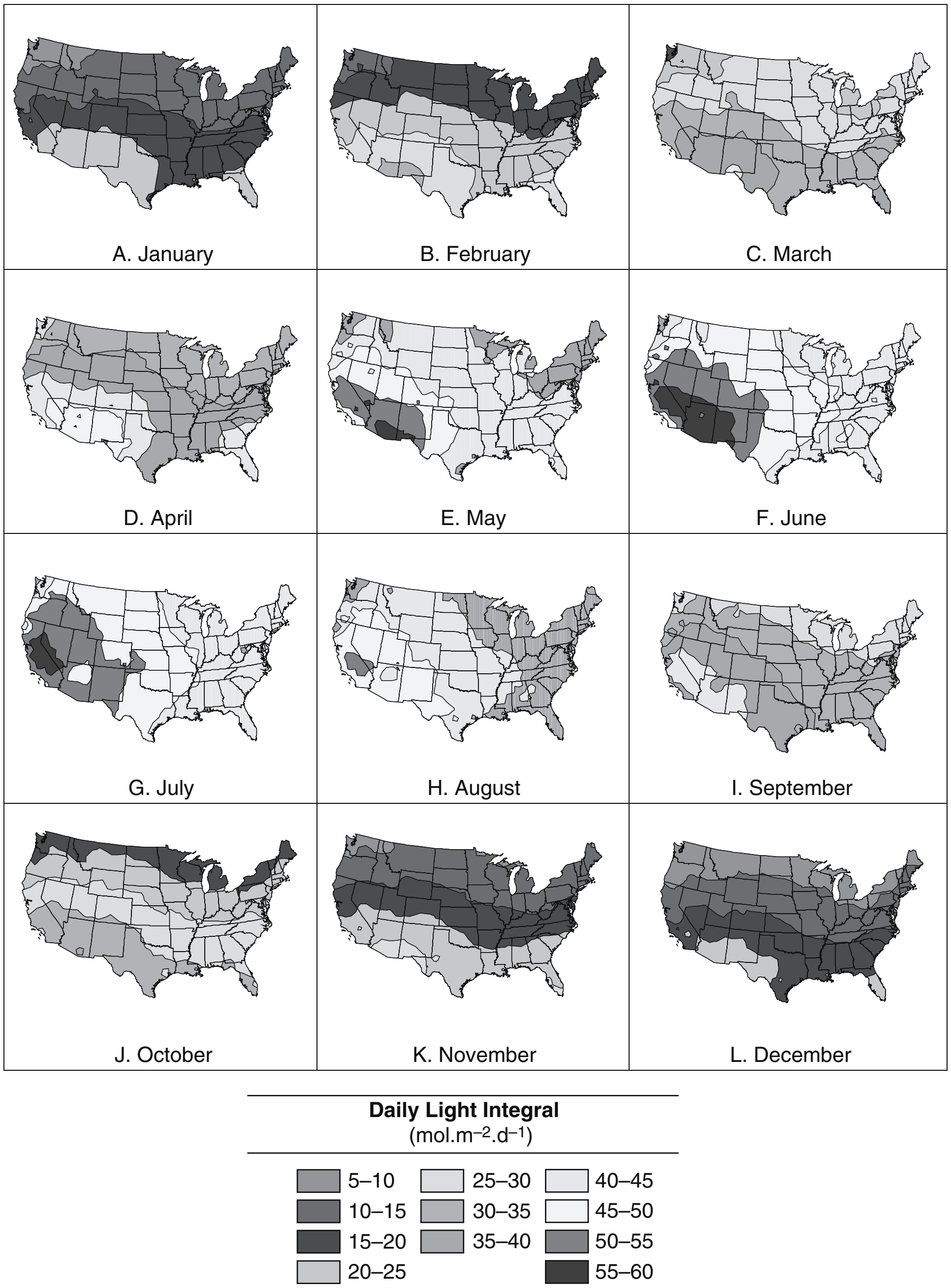

Figure 15
The monthly average outdoor daily light integral (DLI) ($mol{\cdot}m^{-2}{\cdot}d^{-1}$) across the contiguous United States based on 30 years of solar radiation data from 237 sites.

(Picture courtesy of James Faust, Clemson University; Korczynski et al., 2002.)

Table 2
AVERAGE DAILY LIGHT INTERVALS AND LIGHT INTENSITIES INSIDE GREENHOUSES WITH 60 PERCENT TRANSMISSION IN NAALDWIJK, THE NETHERLANDS, AT 52°N LATITUDE[1]

		Light Intensity		
Month	DLI (moles/day)	$\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$	fc	klux
December	2.3	84	437	4.7
March	10.6	256	1,331	14.3
June	24.5	413	2,148	23.1
September	13.3	297	1,544	16.6

[1]From Moe (1993).

It is easy to calculate the DLI value for lighting systems using the following equations.

$$\text{fc} \times 0.00047 \times \text{hours of light} = \text{moles/day}$$
$$\text{klux} \times 0.0436 \times \text{hours of light} = \text{moles/day}$$

Application of 1,000 fc (10.76 klux) for one hour would supply 0.47 moles/day (1,000 fc $\times$ 0.00047 $\times$ 1 hr $=$ 0.47 moles/day).

Light, Flowering, and the Juvenile Growth Stage Plant development begins with a juvenile phase followed by the adult phase. In the juvenile phase, plants are not responsive to flowering stimuli, while in the adult phase they can respond to a stimulus and flower. Length of the juvenile phase tends to parallel length of the life cycle of the species. The juvenile phase is commonly one to two weeks for annuals (bedding plants), four months for many herbaceous perennials, and years for long-lived trees such as oak and beech. Visual discernment of the two phases is possible in a few plants. Snapdragon leaves are arranged oppositely in the juvenile phase and alternately in the adult phase. Foliage of eucalyptus trees has a different form in the two phases. Unfortunately, most greenhouse plants lack distinguishing features. For these plants, the phase shift is identified by the number of leaves. The adult phase begins at about 3 to 4 leaves for annuals and 14 leaves for herbaceous perennials.

Environmental factors affect the time required to reach the adult phase. Increasing temperature up to the optimal level for growth hastens the time without changing the number of leaves required. The DLI also has an effect, but in a very different way. In this respect, plants can be classified as *irradiance indifferent plants* or *facultative irradiance plants*. Facultative irradiance plants respond to increasing DLI by flowering earlier, developmentally. In these plants, the number of leaves formed before the first flower is reduced. The maximum reduction in flowering time generally occurs when the DLI reaches 12 to 14 moles/day. For irradiance indifferent plants, the number of required leaves before phase shift is not changed with increasing DLI. There may be some hastening of flowering, but it is mostly related to increased leaf temperature caused mainly by IR light emitted by the light source. Close to one-third of bedding plants are facultative irradiance plants. Facultative irradiance plants occur within all photoperiodic groups. A few examples are snapdragon, *Centranthus macrosiphon*, *Cleome hasslerana* 'Rose Queen,' *Hibiscus moscheutos*, *Lavatera trimestris* 'Silver Cup,' *Lineraria maroccana*, and *Salvia farinacea* 'Strata.'

Light Duration

Now we look at the fourth and last aspect of light: its duration and how that affects photoperiodism. Living organisms are innately aware of rhythmic forces in their environment. Fiddler crabs at Cape Cod, Massachusetts, like any other of their species in the world, feed when the tide is low. It is then that food is trapped in small pools in which they can maneuver. When the tide comes in, it is time to sleep. If these crabs are placed in a tank of seawater in the darkness on Cape Cod, they will continue to feed when the tide goes out and sleep when it comes in on the beaches outside the tank. Upon being moved to Chicago, they eventually change their feeding time to the time when the tide would be low if there were an ocean in Chicago. Clearly, the crab is responding to the gravitational forces of the moon, which regulate the tides.

Plants and animals respond to many such rhythmic forces. The rate of metabolism of an earthworm has predictable peaks and valleys in accordance with the lunar month and the 24-hour solar day. Japanese industries have gone so far as to plot efficient and inefficient days in the lives of some of their key employees. What emerges

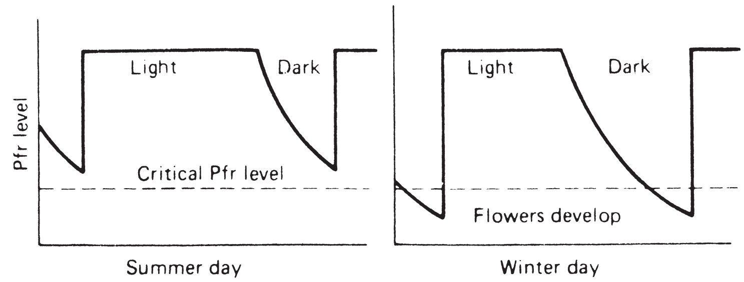

Figure 16
The effects of a summer and winter day–night cycle on the P_{fr} phytochrome level in a plant. P_{fr} quickly builds up in the light period and slowly diminishes in the dark period. A long-night plant will flower only when the P_{fr} level falls below the critical level, as shown, for the long winter night.

(Adapted from Electricity Council, 1973.)

from these data is a recognizable rhythm, such that one can be assured that on certain days an individual will perform at peak potential while on other days it might be better that he or she is not at work.

There is a mechanism in plants that tracks time. It is highly precise and can discern a five-minute difference within a 24-hour cycle. It is called *photoperiodism* because it is locked into the 24-hour solar day and is based upon the light–dark cycle. Photoperiodism is the response of a plant to the day–night cycle. Response can mean many things, including rosette growth versus bolting in lettuce, bulb formation versus leaf and stem formation in onion, tuber formation in dahlia, flowering of chrysanthemum, downward flagging of leaves of bean, a change in the shape of newly forming leaves, red pigmentation in bracts (leaves) of poinsettia, and the formation of plantlets along the margins of leaves of *Kalanchoe daigremontiana*.

As discussed earlier, the red/far-red class of phytochrome is rapidly activated to the active P_{fr} form in daylight or under supplemental light and is slowly deactivated to P_r in darkness. Levels of P_{fr} expected under summer and winter conditions in the Northern Hemisphere are illustrated in Figure 16. The important point is that the P_{fr} form is rapidly produced in the light, and the P_r form is slowly produced in the dark. The P_{fr} form is the active form that controls the photoperiodic response. It inhibits flowering in short-day plants and promotes flowering in long-day plants. During the summer when nights are short, the level of P_{fr} in a short-day plant such as chrysanthemum does not become low enough to permit flowering. During a long winter night, the level of P_{fr} does become low enough to permit flowering.

Photoperiodic Categories Plants can be classified into five common and two unusual photoperiodic categories. The common categories are obligate short day, obligate long day, day neutral, facultative short day, and facultative long day. The uncommon categories include intermediate day and ambiphotoperiodic. These categories will be discussed next in this order. In each case where there is a response of the plant to the day–night cycle, it is the night length that is controlling the process. Photoperiodic responses of 135 floral taxa are listed in Table 3.

Obligate short-day plants are those that undergo a response, such as flowering, only when the night length becomes longer than a critical length, that is, when the days are short. Poinsettias require approximately 11 hours and 40 minutes of darkness to flower. This length of night occurs in the latter part of September in the Northern Hemisphere. Prior to September 15, since the nights are too short to afford this dark period, plants grow vegetatively. In the latter part of September and on later dates, the nights are long enough; thus, the poinsettia buds change from vegetative buds that form leaves and stems to reproductive buds that form flower

Table 3
PHOTOPERIODIC (PHOTO) AND IRRADIANCE (IRRAD) CLASSIFICATIONS FOR 135 TAXA OF FLORAL CROPS[1]

Species	Photo	Irrad
Ageratum houstonianum L. 'Blue Danube'	FLDP	II
Alcea rosea	?LDP	—
Amaranthus hybridus L.'Pygmy Torch'	DNP	II
Ammi majus L.	OLDP	II
Anethum graveolens L. 'Mammoth'	OLDP	II
Anigozanthos flavidus	FLDP	—
Anigozanthos manglesii	FSDP	—
Anigozanthos pulcherrimus Hook.	DNP	—
Anigozanthos rufus Labill.	DNP	—
Anisodontea × hypomandarum K. Presl.	FLDP	—
Antirrhinum majus L.	FLDP	FI
Asclepias curassavica L.	DNP	FI
Asclepias tuberosa L.	OLDP	—
Asperula arvensis L. 'Blue Mist'	OLDP	II
Begonia × hiemalis Fotsch	O/FSDP	—
Begonia tuberhybrida	OLDP	—
Begonia semperflorens	DNP	FI
Bougainvillea spp.	FSDP	FI
Calceolaria herbeohybrida	FLDP	—
Calendula officinalis 'Calypso Orange'	FLDP	II
Callistephus chinensis L.	FLDP	—
Carpanthea pomerdiana L. 'Golden Carpet'	DNP	II
Catananche caerulea L. Per. 'Blue'	OLDP	FI
Celosia plumose L. 'Flamingo Feather Purple'	OSDP	II
Centaurea cyanus L. 'Blue Boy'	OLDP	II
Centranthus macrosiphon Boiss	DNP	FI
Cleome hasslerana Chodat 'Pink Queen'	FLDP	II
Cleome hasslerana Chodat 'Rose Queen'	DNP	FI
Clerodendrum thomsoniae	DNP	—
Clerodendrum × speciosum	DNP	—
Coleus spp.	?SDP	—
Cobaea scandens Cav.	DNP	II
Convolvulus tricolor L. 'Blue Enchantment'	DNP	FI
Cosmos bipinnatus Cav. Ann. 'Diablo'	FSDP	II
Cosmos bipinnatus Cav. Ann. 'Sensation White'	FSDP	FI
Cosmos sulphureus Cav.	OSDP	—
Collinsia heterophylla Buist	FLDP	II
Crossandra infundibuliformis L.	DNP	—
Cucumis sativus H.	DNP	—
Cyclamen persicum Mill.	DNP	FI
Dendranthema × grandiflorum	FSDP	—
Dianthus barbatus L.	DNP	—
Dianthus chinensis L. 'Ideal Cherry Picotee'	FLDP	II
Dimorphotheca sinuate DC. 'Mixed Colors'	DNP	II
Dolichos lablab L.	OSDP	II
Eschscholzia californica Cham. 'Sundew'	FLDP	II
Euphorbia pulcherrima Willd. Ex Klotzsch	OSDP	—
Exacum affine Balf. F.	DNP	—
Fusia × hybrid	OLDP	—
Fusia 'Gartenmeister'	DNP	—
Gazania rigens L. 'Daybreak Red Stripe'	OLDP	FI
Gomphrena globosa L. 'Bicolor Rose'	FSDP	II
Gypsophila spp.	?LDP	—
Hatoria gaertneri Reg.	OSDP	—
Helianthus annus L. 'Vanilla Ice'	FLDP	II
Helipterum roseum Hook.	OLDP	II
Hibiscus cisplatinus	DNP	—
Hibiscus laevis	OLDP	—
Hibiscus moschuetos	OLDP	FI
Hibiscus radiatus	OSDP	—
Hibiscus rosa-sinensis L.	DNP	—
Hibiscus trionum	FLDP	—
Impatiens balsamina	DNP	—
Impatiens hawker Bull.	DNP	—
Impatiens wallerana Hook.f.	DNP	—
Ipomoea × multifida Shinn. 'Scarlet'	FSDP	II
Ipomopsis rubra Wherry 'Hummingbird Mix'	OLDP	II
Kalanchoe blossfeldiana Poellin	OSDP	—
Lathyrus odoratus L. 'Royal White'	OLDP	FI
Lavatera trimestris L. 'Silver Cup'	OLDP	FI
Legousia speculum-veneris Chaix	OLDP	II
Leonotis menthaefolia R. Br.	DNP	—
Leptosiphon hybrida	OLDP	II
Lilium spp.	FLDP	—
Limnanthes douglasii R. Br.	OLDP	FI
Limonium sinuata Mill. 'Fortress Deep Rose'	FLDP	II
Limonium sinuata Mill. 'Heavenly Blue'	FLDP	II
Linaria maroccana Hook.f.	FLDP	FI
Linum perenne L.	OLDP	FI
Lobelia erinus L. 'Crystal Palace'	OLDP	II
Lobularia maritima	DNP	—
Lycopersicon esculentum Mill.	DNP	II
Matthiola longipetala Venten. 'Starlight	DNP	II
Sensation'	OLDP	II
Mimulus × hybridus L. 'Magic'	OSDP	II
Mina lobata Cerv.	OLDP	FI
Mirabilis jalapa L.	DNP	II
Nemophila maculate Benth. 'Pennie Black'	DNP	FI
Nemophila menziesii Hook & Arn.	DNP	II
Nicotiana alata Link & Otto 'Domino White'	OLDP	II
Nigella damascene L. 'Miss Jekyll'	OLDP	FI
Oenothera pallida Lindl. 'Wedding Bells'	DNP	FI
Origanum vulgare L.	DNP	—
Oxypetalum caerulea D. Don 'Blue Star'	FLDP	FI

(continued)

Table 3
PHOTOPERIODIC (PHOTO) AND IRRADIANCE (IRRAD) CLASSIFICATIONS FOR 135 TAXA OF FLORAL CROPS (CONTINUED)[1]

Species	Photo	Irrad	Species	Photo	Irrad
Pelargonium × domesticum L. H. Bail.	DNP	—	*Schlumbergera truncata* Haw.	OLDP	—
Pelargonium × hortorum L. H. Bail.	DNP	—	*Silene armeria* L. 'Elektra'	DNP	—
Pelargonium peltatum L.	?SDP	—	*Sinningia speciosa* Lodd.	SDP	FI
Perilla frutescens	FLDP	—	*Solidago* L. spp.	DNP	—
Petunia × hybrida	OLDP	II	*Streptocarpus × hybridus* Voss.	FSDP	—
Petunia × hybrida 'Purple Wave'	DNP	II	*Streptocarpus nobilis* Clarke	FSDP	—
Phacelia campanularia A. Gray.	FLDP	—	*Tagetes erecta* L.	DNP	—
Phacelia tanacetifolia Benth.	FSDP	II	*Tagetes patula* L.	FSDP	II
Pharbitis nil	OLDP	—	*Tagetes tenuifolia* Cav.	DNP	II
Polemonium viscosum Nutt.	OSDP	—	*Thunbergia alata* Bojer	FLDP	FI
Primula malacoides Franch	DNP	FI	*Tithonia rotundifolia* Mill. 'Fiesta Del Sol'	FSDP	II
Primula obconica Hance	DNP	—	*Tithonia rotundifolia* Mill. 'Sundance'	DNP	—
Primula × polyantha	OSDP	FI	*Verbascum phoeniceum* L.	?LDP	II
Rhododendron spp.	DNP	FI	*Verbena × hybrida*	FLDP	II
Rosa × hybrida spp.	DNP	—	*Viguiera multiflora* S. F. Blake	F/OLDP	FI
Saintpaulia ionantha Wendl.	?LDP	FI	*Viola tricolor* L.	FLDP	—
Salpiglossus sinuata	FLDP	II	*Viola × wittrockiana* Gams.	DNP	—
Salvia farinacea 'Strata'	FLDP	II	*Zea mays* H.	DNP	II
Salvia splendens F. Sellow 'Vista Red'	FSDP	—	*Zinnia angustifolia* Kurth.	FSDP	II
Sanvitalia procumbens Lam.	?LDP	II	*Zinnia elegans* Jacq. 'Exquisite Pink'	FSDP	
Scabiosa caucasia	OSDP	FI	*Zinnia elegans* Jacq. 'Peter Pan Scarlet'		

[1]From Erwin et al. (2003). Photoperiodic classifications are as follows: FSDP (facultative short-day plant); FLDP (facultative long-day plant); OSDP (obligate short-day plant); OLDP (obligate long-day plant); DNP (day-neutral plant). Irradiance classifications are as follows: FI (facultative irradiance response: supplemental irradiance hastened induction developmentally); II (irradiance indifferent response: increasing irradiance did not hasten flowering developmentally).

parts. Of course, several weeks must pass before these flower parts become large enough to be seen. Azalea, chrysanthemum, kalanchoe, and Lorraine and Rieger begonia are all short-day plants in terms of the flowering response. Tuber formation in dahlia and tuberous begonia is a short-day response. There are only a few common obligate short-day bedding plants. These include celosia, hyacinth bean vine, mina vine, and African marigold.

Obligate long-day plants undergo a response only when the nights are shorter than a critical length, that is, the days are long. Aster develops tall stems and initiates flower buds under long days and forms a rosette type of growth under short days. Long-day conditions prevent tuber formation in dahlia and tuberous begonia and thereby encourage flowering. Long days increase the height of Easter lily. Plantlets form along the margins of some bryophyllum leaves under long-day conditions. Most bedding plants are obligate long-day plants. A few common obligate long-day bedding plants are strawflower, bachelor's button, California poppy, gazania, lavatera, flax, lobelia, rudbeckia, and silene.

Day-neutral plants, such as rose, do not respond to the relative length of the light and dark periods. Other forces determine when a response will occur in these plants. Some require a certain level of maturity before they flower, while others must accumulate a specific quantity of solar energy. Some cultivars of chrysanthemum as well as Matthiola incana (stock), calceolaria, and cineraria initiate flower buds when a sufficient length of time at a cool temperature has passed. Calceolaria and cineraria will flower after four to six weeks at 50°F (10°C). In terms of the length of the night and these particular responses, these are all day-neutral plants.

Table 4
CRITICAL NIGHT LENGTH FOR THE CHRYSANTHEMUM CULTIVAR "ENCORE" AT EACH OF THREE NIGHT TEMPERATURES

°F	Night Temperature (°C)	Critical Night Length (hours)
50	10	10.25
60	16	9.5
80	27	8.75

Some plants will flower at any night length but do so faster at a particular night length. Carnation will flower at any night length, but flowers fastest under long-day conditions. Rieger begonia will flower at any night length, but flowers fastest under short-day conditions. These are called *facultative long-day* and *facultative short-day* plants, respectively.

The first uncommon category of photoperiodic plants is intermediate day. These are plants that will flower only when the night length is intermediate, not too long nor too short. The second category is ambiphotoperiodic. These dual day-length plants require short days and long days in a sequence. Very few crops belong to these categories (Thomas and Vince-Prue, 1997).

The critical night length is not any set figure. It is different for each plant species and can be different for cultivars within a species. Take as an example the single species of chrysanthemum classified as *Dendranthema* × *grandiflorum* (Ramat.) Kitamura. The hardy garden varieties can have a critical night length of 8 hours, while many greenhouse-forcing varieties have a critical night length of 9.5 hours. Since a night length of 9 hours is below the critical length for the greenhouse varieties, they remain vegetative. Since 9 hours is more than the critical length for the garden varieties, they initiate flower buds and proceed to flower. Kalanchoe has a critical night length of about 11.5 hours; poinsettia, about 11 hours and 40 minutes. Flowering occurs in each case at night lengths greater than these critical lengths.

The critical night length is also dependent upon temperature. The night temperature is more important than the day temperature. Table 4 shows the effect of night temperature on the critical night length of the chrysanthemum cultivar "Encore." As the night temperature goes up, the critical night length gets shorter. Thus, it is clear that a garden chrysanthemum will initiate flower buds sooner during a hot summer than during a cold summer.

The flowering response occurs in the shoot tip. Complete flower induction takes three to four weeks for most photoperiodic plants. For African marigold, a short-day plant, only two weeks is required. After the flowering phase has been induced, it remains fairly stable. If a fully induced plant is moved to nonfloral inductive conditions, it will continue to flower. A cutting taken from an adult flowering plant will develop into a flowering plant even if the new plant is under noninductive conditions for flowering. On the other hand, if a flowering mother plant is placed under noninductive conditions, a new shoot arising on this plant will produce a nonflowering plant.

Methods of Photoperiodic Control Day-length control for the greenhouse chrysanthemum is typical of short-day crops as a whole. Chrysanthemum is grown for an initial period under long-day conditions to develop a plant of suitable size that will support large blooms and tall stems; then the plants are grown under short-day conditions to induce flower-bud initiation and subsequent development. Long-day crops would need to receive the same short-night and long-night treatments but in the reverse order. The following short-night and long-night treatment sections will apply to all photoperiodic crops in the Northern Hemisphere. In the Southern Hemisphere, one simply interchanges summer and winter.

Short-Night Treatment. If the required short-night stage occurs during the summer, there is no need to do anything but grow the plants under the natural long days. However, one should realize that the length of night perceived by plants can be shorter than the time from sunset to sunrise. It can be reduced by 30 to 40 minutes due to twilight that occurs at each end of the day, particularly if the weather is clear. If the crop is planted during the winter when nights are long, it will then be necessary to shorten the dark period by turning lights on during the night. Lights may be turned on in the late afternoon to extend the day into the evening, or they may be turned on during the middle of the night to break the dark period. Fewer hours of lighting are required if the dark period is interrupted in the middle of the night, and this procedure is commonly used. The light break in the middle of the night quickly restores the P_{fr} phytochrome level, and since neither of the two dark periods before or after the light break is very long, the P_{fr} level does not diminish sufficiently to permit flowering.

Since the dark period in the Northern Hemisphere becomes longer as December 21 approaches, the number of hours of supplemental light required increases. The number of hours of light to apply for any given month at 40°N latitude is presented in Table 5. A word of caution is needed here: The night length and, consequently, the amount of light to apply depend upon the latitude at which the greenhouse is located on the earth. The shortest night of the year occurs around June 21 for the Northern Hemisphere. On this day, the dark period is 12 hours long near the equator, while no darkness occurs at the North Pole. Thus, the farther north one is located, the shorter the night is. The longest night of the year occurs around December 21. There are 24 hours of darkness at the North Pole on this day and 12 hours of darkness near the equator. In this case, the farther north one goes, the longer the night is. Northern latitudes have shorter summer nights and longer winter nights than points farther south. The light period near the equator is always 12 hours long. All places in the world reach a midway point around March 21 and September 21, at the vernal and autumnal equinoxes when the light period is 12 hours everywhere. These relationships can be seen in Figure 17. Rather than keep up with this complexity of day-length change, many growers simply apply four hours of light from 10 P.M. to 2 A.M. in any month when short nights are required.

Incandescent lamps have been the lamp of choice for extending the day or reducing the night length because a large percentage of the light emitted is in the red zone, which is required to convert phytochrome to P_{fr}. The required light intensity is

Table 5
Duration of Light to Apply During Night for Different Months to Ensure Short-Night Conditions at a Latitude of 40°N

Month	Hours of Light
June–July	0
May and August	2
March–April and September–October	3
November and February	4

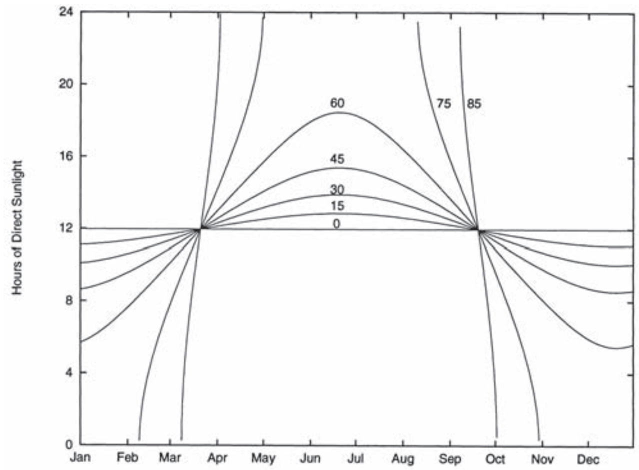

Figure 17

The daily length of direct sunlight received at northern latitudes of 0°, 15°, 30°, 45°, 60°, 75°, and 85° throughout the year. At the North Pole (90°N latitude), vertical lines would exist at the vernal and autumnal equinoxes (approximately March 21 and September 21), indicating a shift from 0 to 24 hours of direct sunlight or vice versa on these days.

very low, and most plants respond to 1 to 2 fc (11 to 22 lux). However, a minimum intensity of 10 fc (108 lux) should be provided to avoid any failure. The most important parts of the plant to illuminate are the recently mature leaves.

To provide the required intensity of light for a 4-foot (1.2-m)-wide bed, one string of 60-W bulbs 4 feet (1.2 m) apart should be installed not more than 5 feet (1.5 m) above the soil along the middle of the bed. Two beds can be lighted by installing a row of 100-W bulbs 6 feet (1.8 m) apart and not more than 6 feet (1.8 m) above the soil between the beds. Larger incandescent floodlight bulbs can be installed along the center ridge of the greenhouse to light the entire width. A minimum of 1 W is required for each square foot of ground lighted (10.8 W/m^2). Occasionally, the larger lights are installed in clusters to reduce the cost of wiring.

The cost of lighting a crop can be reduced by *flash lighting* (cyclic lighting). As little as one second of light at 10 fc (108 lux), every five seconds will keep phytochrome in the P_{fr} form and cause some chrysanthemum cultivars to remain vegetative. This frequency requires heavy-duty switches; thus, longer light cycles are generally used.

If the standard program calls for four hours of light in the middle of the night, from perhaps 10 P.M. to 2 A.M., one can divide this duration into 30-minute periods and apply light for 20 percent of each period. In this way, one would apply light for 6 minutes out of every 30 minutes between 10 P.M. and 2 A.M. Shorter cycles will work as well, as long as light is applied 20 percent of the time. It is essential that a minimum light intensity of 10 fc (108 lux) is applied in this system.

A greenhouse range using cyclic lighting could be divided into five zones, and all could receive their light requirement during one four-hour period. This would reduce the consumption of electricity by 70 to 75 percent and would permit the use of lighter main wiring, which would reduce the initial wiring cost.

Currently, many growers are switching to an HPS lamp system to save electrical energy. In the commercial unit offered today, a 400- or 600-W HPS lamp is held in a fixed position, while a reflector above it rotates back and forth to cast the light beam from one end of the greenhouse to the other (Figure 18). A 400-W fixture mounted 12 to 14 feet (3.7 to 4.3 m) above plants can provide sufficient light for a 30-foot-by-90-foot (9 m × 28 m) greenhouse.

Figure 18
A Beam flicker photoperiodic lamp. The assembly consists of a fixed HPS lamp with a parabolic reflector above it that rotates back and forth to cast the light beam from one end of the greenhouse to the other. An optional diffuser below the lamp provides for more even light distribution.
(Picture provided by Hydrofarm Greenhouse Lighting, Web: www.growlights.com.)

Long-Night Treatment. When the required long-night treatment occurs during the winter, no action is required since the nights are naturally long enough. When this stage of growth occurs in the summer, however, it is necessary to pull an opaque screen over the plants in late afternoon and off again in the morning. These screens typically reduce light transmission to less than 0.1 percent. Light pollution under the screen can cause flower delay or abortion and can originate with the sun and moon but also street lights, headlights, security or work space lighting. Sealing transition points between vertical and horizontal cloths is important. When considering light transmission through or around a screen, evaluate the light transmission during a relevant time of day. Light levels during the middle of the day are at the peak and a good time to make an evaluation but will result in higher levels than those found during hours when the cloth will actually be deployed.

Black sateen (cotton) cloth blocks light well but absorbs heat and is subject to rot where it touches a wet floor. Polyester cloth is effective, resistant to rot, and can have a laminated aluminum upper surface for heat and light reflection. Black polyethylene is used by a few growers but has the problems of heat buildup, tearing easily, and bunching up into a large bundle when retracted. Tears in any cover should be immediately repaired to prevent light leaks. Wherever light leaks in, plants will develop incomplete or hollow flower buds called *crown buds*.

Fourteen to fifteen hours of dark are commonly applied from 5 P.M. to 7 or 8 A.M. Some crops with a shorter dark period requirement can be shaded from 7 P.M. to 7 A.M. Heat buildup under the screen needs to be avoided because it can cause flower delay or bud abortion. Photoperiodic blackout screens ideally have a black underside to absorb light reflected within the greenhouse interior and a white or aluminized outer side to reflect light and thereby keep the temperature lower beneath them. A white underside can be used if the blackout screens double as energy screens during part of the year when daylight extension or supplemental lighting may be used. The reflective underside increases light distribution back to the crop from the lights under the screen. To further reduce heat buildup, some growers have arranged shade on the

Figure 19
Manual pulling of black cloth in the early evening during the summer to establish long-night conditions for photoperiodic control of flowering. The light bulbs are used during the middle of winter nights to give a short-night effect.
(Photo courtesy of J. W. Love, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695–7609.)

exhaust fan wall in a way that it is possible to operate the fan-and-pad cooling system, pulling the cool air beneath the cover. The intake pads and hoods over the exhaust fans block light entry.

This prevents excess buildup of heat, which can occur even at 7 P.M. in the summer. It is necessary to continue pulling the screen until color shows in the buds. Beyond that time, it need not be applied. The screen should be applied every day of the week. For each day that is skipped every week, a chrysanthemum crop will flower a day or so later.

The expenditure in labor to manually pull black cloth over frames, as pictured in Figure 19, is considerable and frequently requires labor after work hours. Larger growers use power-operated shading. Some make this apparatus themselves. An electric motor turns a pipe shaft along one side of the greenhouse. Cables attached to the shaft run across the greenhouse to a shaft on the other side and back again. Cloth is attached to the cables, enabling it to be drawn across the greenhouse and back again.

A number of commercial systems are available for automatically pulling photoperiodic shade fabric as well as thermal blankets and sunscreens (see the "Reducing Light Intensity" section earlier in this chapter). The same fabric used for heat retention during winter nights may be used for photoperiodic shading in the summer. The cost of automatic shading systems might seem high, but the advantages easily sell these systems. At the flip of a switch or a computer signal, acres of greenhouse can be covered in a few minutes, eliminating hours of manual labor. This savings occurs twice a day.

TEMPERATURE

We have already taken a long look at heat in terms of providing it in the greenhouse, removing it from the greenhouse, and controlling it at the desired level. Now we look at its influence on crops. Temperature is a measure of the level of heat present. All crops have a temperature range in which they can grow. Below this range, processes necessary for life stop; ice forms within the tissue, tying up water necessary for life processes; and cells are possibly punctured by ice crystals. At the upper extreme, enzymes become inactive, and again, processes essential to life stop.

Temperature Requirements for Crops

All biochemical reactions in the plant are controlled by enzymes. Enzymes are heat sensitive. The rate of reactions controlled by them often doubles or triples each time the temperature is increased by 18°F (10°C), until an optimum temperature is reached. Further increases in temperature begin to suppress the reaction until it stops.

Numerous biochemical reactions are involved in the process of photosynthesis. These all have the net effect of building carbohydrate and storing energy. Photosynthesis occurs during the daylight hours because of its dependence on light. Another extensive set of biochemical reactions is involved in the overall process of respiration. The net effect is a breakdown of carbohydrate and a release of energy. Respiration occurs in all living cells at all times.

When photosynthesis exceeds respiration, net growth occurs. When they equal each other, net growth stops. If respiration exceeds photosynthesis, the plant declines in vigor and will eventually die. To ensure that photosynthesis exceeds respiration, plants are grown in cool temperatures at night to keep the respiration rate down and in warm temperatures by day to enhance photosynthesis.

As a general rule, greenhouse crops are grown at a day temperature 5° to 10°F (3° to 6°C) higher than the night temperature on cloudy days and 15°F (8°C) higher on clear days. With CO_2 enrichment, the day temperatures may be an additional 5°F (3°C) higher. The night temperature of greenhouse crops is generally in the range of 45° to 70°F (7° to 21°C). Primula, *Matthiola incana*, and calceolaria grow best at 45°F (7°C); carnation and cineraria, at 50°F (10°C); rose, at 60°F (16°C); chrysanthemum and poinsettia, at 62° to 64°F (17° to 18°C); and African violet, at 70° to 72°F (21° to 22°C).

For most greenhouse crops, the rate of plant development increases with increasing day temperature up to a peak at 76° to 80°F (24° to 27°C). Above 74° to 76°F (23° to 27°C), the rate of increase becomes slow, while above 82° to 84°F (28° to 29°C) rate of development decreases with further increase in temperature.

It is plant temperature and not air temperature that controls growth. We indirectly set target air temperatures in our thermostats for the purpose of achieving desired plant temperatures. However, the relationship between air and plant temperature is not constant. During the day when sunlight strikes a leaf, IR radiation in this light warms the leaf to as much as 8°F (4°C) above the air temperature. Coupled with hot weather, this increase can injure chlorophyll, slow growth, burn flowers and foliage, and increase the demand for cooling energy. Sunscreening is applied to avoid the problem. On overcast days, the plant-to-air differential is much lower. At night, plant temperatures are lower than air temperatures because moisture is evaporating from the plant tissue, which lowers its temperature. The problem of air-to-plant temperature difference can be magnified by placement of heat in the greenhouse. Heat rises. Therefore, in-floor or under bench pipes warm the root substrate and plant canopy more than overhead pipes or unit heaters. This helps to counteract the low plant temperatures at night and on overcast days, which, in turn, leads to better growth. Root substrate temperature can also be higher or lower than air temperature. When sun shines on the substrate surface or pot wall, the temperature can be higher than the surrounding air. When in the shade or at night, substrate temperature can be lower than surrounding air due to water evaporation. Again, sunscreening by day and in-floor or under bench heating at night counteract much of this differential.

Seed germination presents a special case for temperature requirements. The majority of greenhouse seed crops germinate best in a constant day and night substrate temperature range of 72° to 74°F (22° to 23°C). For specific germination requirements of temperature, light, and moisture, see the *Ball Culture Guide* by Nau (1999). The temperature sensor controlling heat should be inserted in the substrate because evaporation can cause the substrate temperature to be 3° to 5°F (1.7° to 2.8°C) lower than air temperature. Substrate temperatures over 78°F (26°C) can inhibit germination in many crops. This can occur when full sunlight warms the substrate. This should not be a problem because light intensities over 200 fc (2.2 klux; 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$) should be avoided during the three days following seed coat cracking for best germination results.

Temperature Interrelationships

A rule by F. F. Blackman, in essence, states that the rate of any process that is governed by two or more factors will be limited by the factor in least supply. Photosynthesis is a good case in point. It is dependent upon heat, light, CO_2, and other factors. On cloudy days, it is futile to raise the temperature more than 5° to 10°F (3° to 6°C) above the night temperature because the low light intensity will limit the rate of photosynthesis, and any additional heat applied will be without beneficial effect. On bright days, light does not limit photosynthesis; thus, if the temperature is not raised, heat may become the limiting factor for photosynthesis. Even on dark days, the rate of photosynthesis will increase with CO_2 enrichment of the greenhouse atmosphere.

Light intensity is higher in the summer than in the winter, and photosynthetic rates can be expected to be higher in the summer. This is very fortunate, since it calls for higher daytime temperatures in the summer than in the winter to prevent heat from becoming the limiting factor. Cooling fans can be set at a higher temperature in the summer—as high as 80° to 85°F (27° to 29°C)—which saves considerable electrical energy.

Blackman's law is well illustrated in the curves of Figure 20. In the lowest curve, the rate of photosynthesis began to plateau at about 3,800 fc (40,000 lux), regardless of whether the temperature was at 68° or 86°F. The 300-ppm (0.03 percent) level of CO_2 became a limiting factor at that point. When the temperature was held at 68°F and the CO_2 level was increased to 1,300 ppm (0.13 percent), the rate of photosynthesis increased. Then the 68°F temperature became the limiting factor, because the increase in temperature to 86°F at the same 1,300-ppm CO_2 level brought about another increase in photosynthesis.

This interaction of CO_2, light intensity, and temperature is reminiscent of observations that increases in the CO_2 level in the greenhouse brought about beneficial effects from raising the daytime temperature above that normally maintained for many crops. When CO_2 is eliminated as a limiting factor for photosynthesis, a daytime temperature increase of 5°F (3°C) can often be profitable.

One must be careful when determining how high to raise the temperature, because it affects processes in addition to photosynthesis. Generally, higher temperature results in faster growth, but with it a reduction in quality can occur. Longer stems, thinner stems, and smaller flowers may occur. Quality and quantity must always be weighed in making such a decision. In the previous discussion about raising the temperature 5°F (3°C) along with increasing the CO_2 level, no adverse loss in quality is expected.

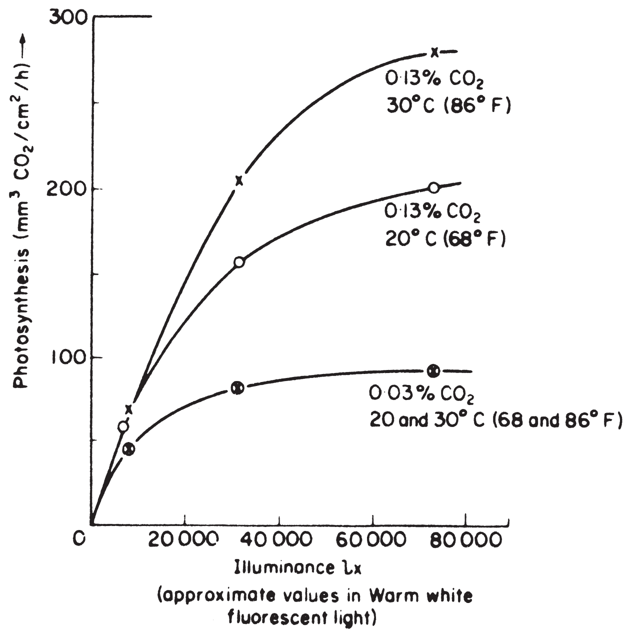

Figure 20
Effects of CO_2 concentration, light intensity, and leaf temperature on photosynthesis in cucumber.
(From Gaastra, 1962.)

DIF—The Day-to-Night Temperature Relationship

Effects of daytime temperatures versus nighttime temperatures on the growth and flowering of floral crops have been reported for some time (Cathey, 1954; Cockshull et al., 1981; Parups, 1978; Parups and Butler, 1982). More recently, scientists at Michigan State University, including Drs. Heins, Karlsson, Erwin, and Berghage, have uncovered a practical relationship between plant height and the day-to-night temperature differential. They gave the acronym *DIF* to this temperature differential. DIF refers to the differential obtained when one subtracts the night temperature from the day temperature:

$$\text{DIF} = \text{day temperature} - \text{night temperature} \tag{3}$$

The DIF values are +10, 0, and −10 for day and night temperature combinations of 70° and 60°F, 65° and 65°F, and 60° and 70°F, respectively. The information that follows is drawn from the work of this Michigan State University team.

Height Control by DIF Plant height can be controlled by DIF. A shift from a positive DIF toward a zero DIF results in a large reduction in height (Figure 21). While height continues to decline as the DIF value is shifted from zero to negative values, it is of smaller magnitude. Two underlying relationships are involved. Plant height can be decreased by decreasing the day temperature and also by increasing the night temperature. Conversely, plant height is increased by increases in day temperature as well as by decreases in night temperature. The effect is upon the length of stem internodes rather than the number of leaves. Controlling plant height by altering DIF is being used commercially on a wide range of crops. Large responses have been achieved in Asiatic lily, Celosia, chrysanthemum, dianthus, Easter lily, fuchsia, geranium, gerbera, hypoestes, impatiens, Oriental lily, petunia, poinsettia, portulaca, rose, salvia, snap bean, snapdragon, sweet corn, tomato, and watermelon. Small or no response has been obtained in aster, French marigold, hyacinth, narcissus, platycodon, squash, and tulip. DIF provides an effective means for controlling height because a shift in growth can be seen within one to two days of a shift in DIF.

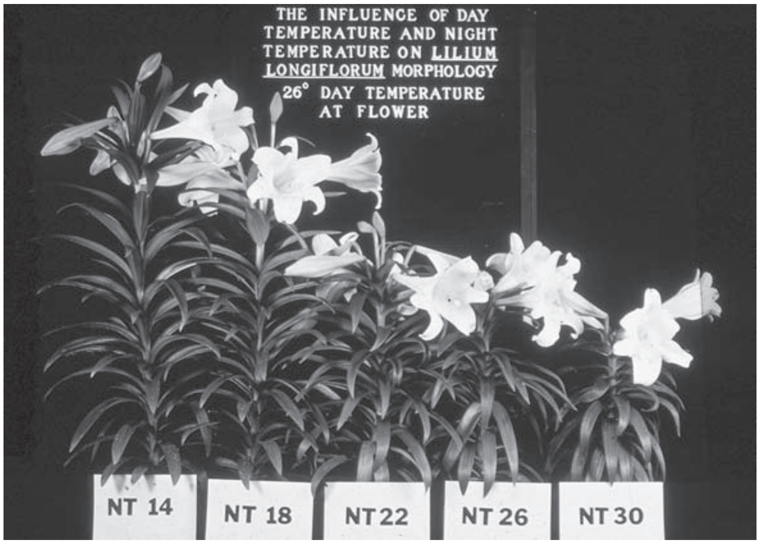

Figure 21
The effect of decreasing DIF values (from left to right) on decreasing final Easter lily height. For all five plants, the day temperature was 26°C (79°F), but the night temperatures were 14°, 18°, 22°, 26°, and 30°C (57°, 64°, 72°, 79°, and 86°F). From left to right, the DIF values were 12°, 8°, 4°, 0°, and – 4°C (29°, 22°, 16°, 7°, and 0°F).
(From Heins and Erwin, 1990.)

Controlling plant height through environmental modification rather than by chemical height retardants is particularly attractive in this era when all synthetic chemicals are under scrutiny. A second plus is the cost savings realized by reducing and, in many cases, dropping the use of chemical height retardants.

Flowering Time The rate of growth and maturation of plants is generally temperature dependent. Fortunately, it is the 24-hour temperature average and not just the day or night temperature alone that usually controls the rate of development. Because of this, tall, intermediate, or short plants may be produced for the same flowering date by reducing the DIF values in such a way that the daily average temperature remains constant. The +10, 0, and −10 DIF values referred to earlier all have the same average daily temperature of 65°F if the day and night lengths are taken to be the same length. The day–night temperature combinations were 70°F/60°F, 65°F/65°F, and 60°F/70°F. Each combination has an average of 65°F; thus, these three DIF values offer a choice of three heights of plants for the same market date. Remember, it is the average day–night temperature that drives the rate of growth while it is the DIF that drives plant height.

Two factors limit the range of temperatures that can be selected for developing a value of DIF. Each crop plant has a unique temperature-to-growth relationship, as shown in Figure 22. Temperatures may be selected within the linear range of the curve (the straight dashed line) and up to the optimum temperature (50° to 80°F in this curve). Higher and lower temperatures should not be selected, because unacceptably low growth rates occur at these temperatures. Both the timing and the quality of the crop could be jeopardized. The temperature range for "warm" crops, including hibiscus and poinsettia, is 50° to 80°F (10° to 27°C). The range for crops tolerant of cool temperatures, such as chrysanthemum, Easter lily, and petunia, is 40° to 80°F (4° to 27°C).

The second limit to the range of temperatures available for selection is the temperature requirement for flower initiation and development. At a night temperature

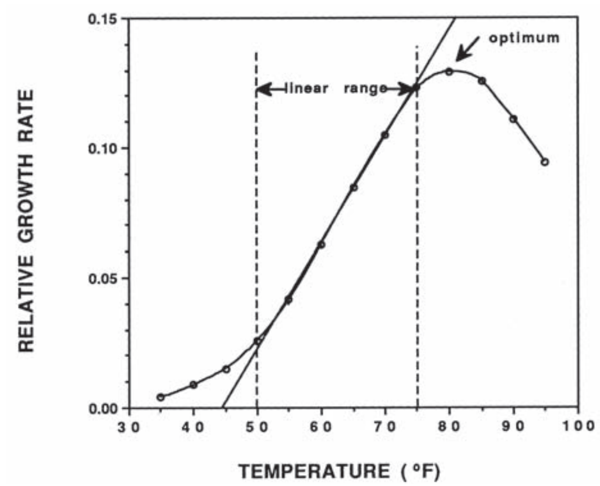

Figure 22
Hypothetical effect of temperature on relative growth rate. A straight line has been superimposed on the curve to show the range of linear response, which lies between 50° and 75°F (10° and 24°C). Most processes in the plant have a similar relationship with temperature.

of 73°F (23°C), poinsettia flower development is inhibited. While day temperatures may be higher, night temperatures may not exceed this level. Night temperatures above 72° to 75°F (22° to 24°C) can cause heat delay in flowering of chrysanthemums. It may be necessary to raise night temperatures to 75°F (24°C) to slow height development in Easter lily, but one pays a price in increased flower abortion at temperatures above 70°F (21°C). Such temperature sensitivities are greatest at the time of flower initiation and the early stages of flower-bud development. Once flower buds are visible, the plant is much less sensitive to heat delay. Higher night temperatures can be attempted at these times to achieve large negative DIF values when plants are excessively tall.

Side Effects The lower the DIF value, particularly in the negative range, the greater the chance of chlorosis of leaves. Chlorosis occurs on young, immature leaves. If the low DIF treatment is applied correctly, normal green color will return as these affected leaves mature. Chlorosis becomes a permanent problem when the plant is treated at too early an age. Plug seedlings treated during the first week have only immature leaves; thus, the whole plant turns completely chlorotic, and growth of the plant is severely reduced. Such stunting is not later corrected. Depending on species, a DIF value lower than –2 to –3 should not be applied to plug seedlings during the first one to three weeks.

A second side effect of very low DIF treatments is downward curling of leaves. This problem is particularly pronounced on Easter lily. If the curled leaves are not mature, they will uncurl when returned to a normal positive DIF value.

Implementation of DIF in Warm Seasons There is little difficulty in lowering the day temperature in northern locations during the winter. Later in the spring, and even in the winter in warm climates, it may appear impossible to do so. Low DIF effects can still be produced by lowering the day temperature for the first two hours of the day immediately after sunrise. This is based on the fact that the greatest rate of internode elongation occurs during the night, with a maximum peak at sunrise. Greater height suppression of Easter lily was achieved by applying a negative DIF only during the two hours after sunrise than by applying negative DIF for seven hours beginning two hours after sunrise and ending at sunset.

It is important that the temperature be at the lower setting as soon as the shift from dark to light occurs. For a hot-water heating system, this means the thermostat should be set lower perhaps 45 minutes before sunrise to allow sufficient time for the system to cool. The thermostat could be set lower 15 minutes before sunrise for faster-reacting heating systems, such as unit heaters.

Graphical Tracking The day-to-day implementation of DIF to control height is best handled through *graphical tracking* (Carlson and Heins, 1990; Heins and Erwin, 1989). A good example of such a graph for Easter lily can be seen in Figure 23. In this case, lilies were grown in a 6-inch (15-cm) standard pot having a height of 6 inches (15 cm). The final plant-plus-pot height desired was in the range of 22 to 24 inches (56 to 61 cm). Based on previous experience, the plant was expected to double in height after the point of visible bud. Thus, for the date of emergence, the height was plotted as 6 inches (15 cm) (the height of the pot), and at market stage, it was plotted as 22 to 24 inches (56 to 61 cm). Typically, the Easter lily is at half its final height at the first point of visible flower bud. For the date of visible flower bud, minimum and maximum heights were plotted as 14 and 15 inches (36 and 38 cm) (half the final plant height plus the 6-inch, 15-cm pot height). Growth between each of these pairs of dates proceeds in a straight line; thus, points were connected by straight lines to form the minimum and maximum height curves. Twice a week, the grower measured the height of the plants and plotted the results on the graph. On January 27, plants were too tall and a −10°F (−5°C) DIF treatment was applied (53°F day/63°F night, 12°/17°C). By February 10, plant height gain had been suppressed to where it was at the minimum acceptable level. DIF was increased to +9°F (5°C) and resulted in an increase in the rate of height rise. On three subsequent dates, further adjustments in DIF were made. In the end, the crop reached a desired height without the use of chemical growth regulators.

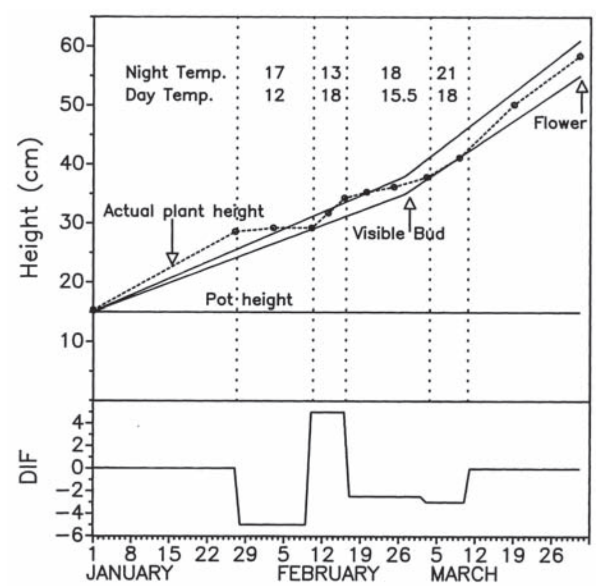

Figure 23

Graphical tracking plot for Easter lily. Solid curves depict the range of desired heights for various dates (the tracking window). The dashed line shows the actual measured heights of a commercial crop in which DIF was used to control height. Day and night temperatures applied to the commercial crop are shown in °C. Temperature conversions for 12°, 13°, 15.5°, 17°, 18°, and 21°C are 54°, 55°, 60°, 63°, 64°, and 70°F, respectively. The actual DIF values applied are given in °C in the curve at the bottom of the figure.

(From Heins and Erwin, 1989.)

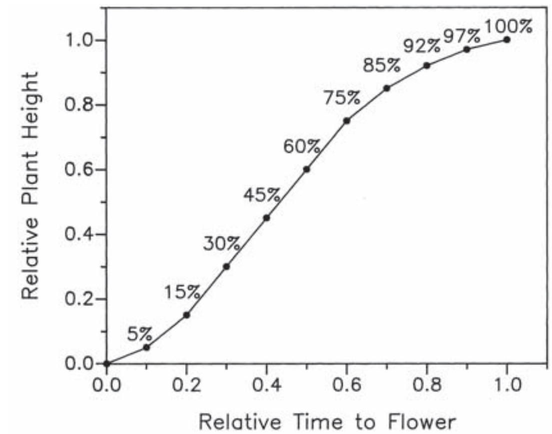

Figure 24
Growth curve for chrysanthemum and poinsettia beginning at the date of pinch and ending at market date.
(From Carlson and Heins, 1990.)

Unlike Easter lily, growth of chrysanthemum and poinsettia proceeds in a sigmoidal curve fashion, as shown by Figure 24 (Carlson and Heins, 1990). In this curve, the percentage of final plant height (not including the pot height) is plotted on the vertical axis against the relative time to flower on the horizontal axis. Relative time to flower is used because different cultivars of mums and poinsettias can require a different number of weeks to flower. If the crop requires 10 weeks to flower, its relative time to flower after five weeks of growth will be 0.5 (50 percent). The relative time to flower begins at the date of pinch. To develop a theoretical tracking curve for chrysanthemum or poinsettia, the final plant height desired is selected. Based on the percentages in Figure 24, the height the crop should be at each week is determined, and these heights are plotted on the vertical axis of a graph against weeks of growth on the horizontal axis. Then the actual height of the crop is measured twice a week and plotted on the same graph as the theoretically computed height curve. When actual crop height differs from the theoretical height, the DIF value is altered to bring the crop back into line.

Computer Control Each year, the need for an environmental computer to monitor and control the greenhouse environment becomes more critical to making a profit. Implementation of height control through DIF is a good example. DIF plans can be handled through thermostats and manual settings. However, increases in the number of crop zones requiring different DIF values and complications brought on by warm-weather restriction of low day temperatures to the first two hours of the day make it nearly impossible to handle the task manually. Greenhouse computer software currently includes DIF control. Computerized control is the most efficient way to go. Such systems can calculate the average daily temperature needed for controlling the date of crop maturity. In the future, growth curves will probably be available in computer software for all crops. These programs take over temperature control of the greenhouse. The crop manager simply enters into the program the dates of planting, pinching, and harvesting; the final desired height; and biweekly height measurements. The computer does the rest, and with less labor input as well as greater conservation of heating and cooling energy.

Subconventional Temperature Production

Heating fuel is a costly input into crop production. Sometimes, depending on a crop's tolerance of lower than conventional temperatures, the heating cost can be reduced by lowering the production temperature. *Cold-tolerant crops*, as categorized by Faust, lend

Table 6
COLD-TOLERANT AND COLD-SENSITIVE FLORICULTURE CROPS[1]

Cold-Tolerant		Cold-Sensitive	
Ageratum	French marigold	African violet	Hibiscus
Allysum	Geranium	Allysum	Impatiens
Bacopa	Nemesia	Catharanthus (vinca)	New Guinea impatiens
Calibrachoa	Pansy	Begonia	Orchids (Phalaenopsis)
Chrysanthemum	Petunia	Salvia (blue & red)	Pennisetum (purple-leaf)
Cineraria	Snapdragon	Caladium	Poinsettia
Cyclamen	Verbena (vegetative)	Canna	Tropical foliage
Diascia		Celosia	

[1]From Faust (2009).

themselves well to low production temperatures. Although the optimum temperature for these crops may be 70°F (21°C) or higher, they will grow and flower well at 40° to 60°F (4° to 16°C). *Cold-sensitive crops* do not develop at temperatures below 50° to 55°F (10° to 13°C). They will develop at temperatures below 60° to 65°F (16° to 18°C), but at unacceptably low rates. Representative crops in these two categories can be seen in Table 6.

The advantages generally associated with growing cold-tolerant crops at a lower temperature than customarily recommended temperature include fuel savings, thicker and stronger stems and foliage, height reduction, less plant growth regulator application due to shorter height, less pesticide application due to longer life cycles of insects such as thrips, whiteflies, and mites, and deeper flower colors. The disadvantages can be delayed flowering and intensification of white flower color to cream. Even though prolonged production time increases the period for heating and overhead costs, the overall cost of production is reduced in several cases.

Although poinsettia is classified as a cold-sensitive crop, economic analysis has shown it to be profitable to grow some cultivars at lower temperatures. This system works for poinsettias because they are available in early, mid, and late flowering cultivar categories that require, depending on the cultivar, 7.5 to 8.5, 8.5 to 9, and 9 to 9.5 weeks from floral initiation to market date, respectively. When early cultivars are grown at an average day–night temperature of 62° to 65°F (17° to 18°C), rather than 70°F (21°C) beginning around mid-October when flower color appears, they mature two to three weeks later in the late market season.

Plant propagation companies are testing existing plant material and are breeding for new crops that profitably respond to lower temperatures. It is important to keep up with academic and commercial information in print and at grower conferences to realize the economic advantage of this technology.

SUMMARY

1. There are four properties of light, quality (color, wavelength), intensity, DLI, and daily duration, that influence plant growth and development. Light quality regulates the developmental forms of plants. Receptors including the UV-B receptor, cryptochrome, and phytochrome control many factors such as internodal length, leaf thickness, pigmentation, and branching. Light intensity drives photosynthesis, the process that fixes carbon from CO_2 into carbohydrates and ultimately all the organic compounds of the plant. A relatively high intensity in the PAR energy spectrum range of 400 to 700 nm is required. The DLI takes light intensity one step further by summing the amount

of light received on 1 square meter of surface during one day. Depending on the light requirement, the optimum level for crops can range from 6 to 22 moles/m^2/day. The ambient DLI levels outside in the United States throughout the year can range from 5 to 60 moles/m^2/day. Light duration controls processes such as vegetative versus floral development, rosette versus elongated stem form, and tuber formation.

2. Light is often a limiting factor to photosynthesis and growth during the winter in northern latitudes. In order to maximize interior light intensity, single greenhouses can be oriented with the ridge east to west, and ridge-and-furrow greenhouses with the ridge north to south. The greenhouse covering should be washed when it becomes dirty. Plants should be spaced farther apart in the winter to increase the amount of light per plant.

3. Supplemental lighting during the daylight hours to enhance photosynthesis is highly effective. The economics, however, bear scrutiny. There are situations of high-density plantings, such as rooting and seedling beds and the production of young plants, where it is most profitable. HPS lamps are most commonly used today. LED lamps are making an entry into the greenhouse industry and show promise as a more efficient source of light.

4. A number of seedling producers construct growth rooms. Plants are grown on tiered shelves with a bank of fluorescent or LED lights above each shelf. This is the sole source of light for photosynthesis. A growth room can be better insulated than a greenhouse. Often, the heat from the lamps is sufficient to meet the heat requirement of the room.

5. The most common aspect of light duration is photoperiodism, which is the response of an organism to the day–night cycle. The relative length of the light and dark periods governs a number of responses, including flowering, leaf shape, stem elongation, bulb formation, and pigmentation. In terms of flowering, short-day plants are those that initiate and develop flower buds when the night is longer than a critical length. Conversely, long-day plants are those that initiate and develop flower buds when the night is shorter than a critical length. The critical night length varies among plant species and even among cultivars within a species. Not all plants are photoperiodic. Those that do not respond to the day–night cycle are day-neutral plants.

6. Long nights are established in the greenhouse during the summer by covering the plants with an opaque screen in the early evening (about 7 P.M.) and removing it in the morning (7 or 8 A.M.). The cover should be capable of reducing the light intensity beneath to 2 fc (22 lux) when the outside intensity is 5,000 fc (53.8 klux). Automatic equipment is available for this operation. Short-night conditions can be established in the winter by providing 10 fc (108 lux) of illumination for a period of one to four hours during the middle of the night.

7. Phytochrome (P) is the receptor pigment in young tissue that responds to the light–dark cycle. The P_{fr} form of phytochrome rapidly builds up during the light period and is slowly converted to the P_r form during the dark period. The P_{fr} form is the active form that inhibits flowering in short-day plants and promotes flowering in long-day plants. A long night is required to lower the level of P_{fr} phytochrome to the point at which flowering can occur in a short-day plant.

8. Heat is a form of energy and a factor essential to growth. Deleterious effects result from levels that are too high or too low. Heat is just one factor governing growth. The rate of growth is limited by the factor in shortest supply. It is not always economically feasible to optimize all factors affecting growth in a greenhouse; thus, the best temperature for a crop will depend upon the following factors:

- **a.** Light is often limiting in the winter. On low-light-intensity (cloudy) days, a day temperature 5° to 10°F (3° to 6°C) above the night temperature is maintained; on brighter winter days, a day temperature 15°F (8°C) higher than the night temperature is beneficial to growth. Although even higher temperatures would not be beneficial to growth in the winter, they are beneficial in the summer when light intensity is higher and not limiting to growth.
- **b.** The CO_2 level inside greenhouses often limits growth. When it is raised, growth increases to a point at which previously adequate temperatures become the limiting factor. A 5°F (3°C) rise in day temperature is often beneficial when the greenhouse atmosphere is enriched with CO_2.

9. Plant height can be controlled by adjusting the day-to-night temperature ratio. The term DIF refers to the temperature difference obtained by subtracting the night temperature from the day temperature. The rate of stem internode elongation is increased by increases in day temperatures and by decreases in night temperatures. Therefore, when DIF is highly positive (day temperatures are much higher than night temperatures), plants become tall. Large reductions in plant height are achieved by reducing DIF from positive to zero values; further, but more modest, growth reductions are obtained by continuing to reduce DIF to negative values. The concept of DIF works best when plants are young and their rate of growth is rapid.

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Regulation of Plant Growth

Brian E. Whipker
North Carolina State University

Mike R. Evans
University of Arkansas

Quality standards dictate that containerized plants should be proportional to the container in which they are grown. Elongated or excessively tall plants are considered to be of lower quality (Figure 1). Excessively tall plants easily fall over, which makes irrigation difficult, and they are also difficult to ship and for consumers to handle. Growers must be prepared to prevent excessive stem elongation (stretching) because undesirable stretching can be a production reality. Growth must be managed and growers have a number of excellent tools, both nonchemical methods and chemical plant growth retardants (one type of plant growth regulator [PGR]), to control excessive stretch. Used together, they can be used to manage plant growth and produce well-proportioned and compact plants.

NONCHEMICAL GROWTH CONTROL

Although chemical plant growth retardants are commonly used to control height in greenhouse crops, there are nonchemical methods for reducing plant height, producing more compact plants, and "holding" crops until the desired shipping date. In some situations, nonchemical methods might be the only means available for creating shorter and stronger plants or holding crops. Knowing how the growing environment and cultural practices affect plant growth will help greenhouse operators control a crop's growth, and the ability to manage these nonchemical control options will aid in avoiding excessive growth.

Water Stress

Allowing plants to dry between irrigation cycles (and suffering mild water stress without being allowed to dry to the permanent wilting point) reduces plant height and "toughens" the plants (by making shoots and auxiliary branches stronger).

Figure 1
Excessive stretch of plant growth results in lower plant quality. Growth control must be managed with cultural or chemical means in order for growers to produce an acceptable crop.

The difficulty in using this method to control plant height is that subjecting the crop to too great of a water stress can also result in negative responses such as flower-bud abortion, reduced growth, leaf abscission, and reduced plant quality. However, as a general rule, subjecting plants to mild water stress (just as the plants begin to show a slight amount of wilting) can be used to toughen plants and slow growth when plants need to be held for a later shipping date. Impatiens and tomatoes are two common crops in which water stress is utilized for height control. However, water stress may cause premature bolting if used with crops such as cauliflower and broccoli.

Nutritional Stress

Nutritional stress can also be used to control excessive plant height. Shorter plants can be grown by limiting the amount of nitrogen in the constant liquid fertilization program to 50 ppm. Plant height can also be controlled by restricting phosphorus fertilization (Figure 2). By limiting phosphorus application, internode elongation can be reduced. However, as with using other stresses to control plant height, applying the correct amount of stress without causing undesirable effects can be difficult. A general recommendation to control plant height is to not exceed 5 ppm phosphorus, as P_2O_5 (2.2 ppm P), in the constant liquid fertilization program.

Light

Higher light levels tend to limit plant elongation, thus resulting in shorter plants. Low light levels caused by late spacing of the crop, crowding, too many hanging baskets overhead, or greenhouse glazings with low light transmission (due to dirt, age, or unnecessary shading) can lead to excessively tall plants (Figure 3). Therefore, greenhouse managers need to maintain light levels that are optimal for the crops being grown.

Figure 2
Growth control can also be achieved culturally. Phosphorus fertilization is a primary factor in stimulating plant stretch. These ipomea plants were grown without added phosphorus, which resulted in more compact plants (right) with more intense coloration as compared with the complete fertilizer.

Figure 3
Plant spacing or plant growth regulator applications should occur before the leaf canopy touches. Lower light levels in the interior of the bench results in a greater degree of plant stretch as seen here with this cross-section view of a row of New Guinea impatiens.

Root Restriction

Another possible option to control excessive plant height is root restriction by utilizing small containers. This method will limit the amount of plant growth, but irrigation frequency of the crop will likely increase. The primary mechanism by which small containers reduce plant height is that the container holds a smaller volume of substrate. Therefore, the container will hold less water and fertilizer than a larger

Figure 4
Mechanical trimming (pruning) is a quick method of controlling plant growth and increasing branching of plants.

container and plants will tend to experience nutritional and water stresses more frequently than plants grown in larger containers with larger volumes of substrate.

Pinching

Pinching (also pruning or sheering) can be used to increase branching, improve the shape of the plant, and decrease the height of the plant (Figure 4). However, labor costs of pinching and the potential delay in flowering that may occur may make this method of height control an economically unfeasible option.

Thigmotropic Responses

Thigmotropic responses are plant responses to physical stresses (i.e., touch). Shaking, rubbing, or blowing air across plants has been shown to reduce plant height and reduce internode length. In some cases, rubbing or blowing air is being used to toughen vegetable transplants. The difficulty with these methods has been how to effectively apply the treatment (i.e., rubbing) over a large crop without damaging it.

DIF and DROP

A commonly used nonchemical method of height control is temperature manipulation (Figure 5). Growing plants at lower night temperatures reduces growth and elongation. However, temperature may be used in a more precise method to specifically control internode length (and thus stem elongation and plant height). This method of height control is referred to as DIF (for *difference*).

DIF refers to the difference between the day and night temperatures. The DIF is determined by subtracting the night temperature from the day temperature. A positive DIF occurs when the day temperature is greater than the night temperature. A negative DIF occurs when the night temperature is greater than the day temperature. A zero DIF occurs when the temperatures are the same.

Plants grown under a positive DIF are usually taller than plants grown at a zero DIF, and plants grown under a zero DIF are taller and have longer internodes than plants grown under a negative DIF. As the DIF becomes more negative, plants tend

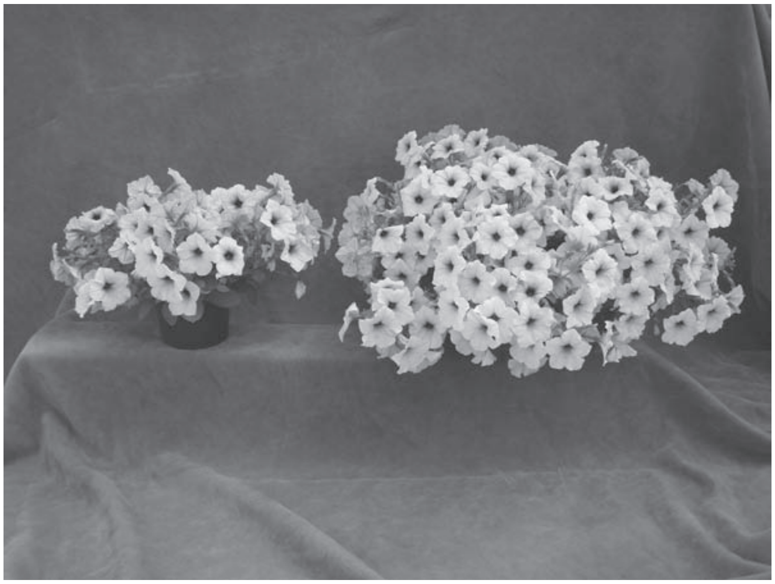

Figure 5
Growing plants at cooler temperatures helps to control growth. The petunia plant at the left was grown at 10°F (5.5°C) cooler temperatures than the plant at the right, thus resulting in more compact growth.

to become shorter. There are some undesirable effects when the DIF is too negative (i.e., chlorosis in lilies). Usually, a –10 DIF has been found to be optimal for controlling plant height.

A problem with maintaining temperatures higher at night than in the day is that of increased heating costs. However, it has been found that the first two hours in the morning is when the DIF is most effective. Therefore, lowering the temperature below the night temperature (creating a negative DIF) for two hours at sunrise is just as effective at reducing plant height and internode length as is maintaining a negative DIF throughout the night. This practice is commonly referred to as DROP.

CHEMICAL GROWTH CONTROL OF HEIGHT

The most common growth regulators used in greenhouse crop production are the plant growth retardants. Quality standards dictate that most container-grown greenhouse crops be compact, have short internodes, have a height proportionate to the container they are grown in, and have strong stems. Although short or dwarf cultivars exist for many greenhouse crop species, chemicals that further reduce plant height and increase the compactness and strength of the plant are often required. Growth regulators may also be used to slow growth or hold plant material in the greenhouse.

Plant growth is influenced by the class of plant “hormone” called *gibberellins* (GAs), which influence cell elongation. If synthetically produced GAs are applied to a plant, it will become tall and spindly. In contrast, if GA production in the plant is reduced, it will be shorter and stronger with thicker stems and smaller leaves. Therefore, most of the commercially available growth retardants function by inhibiting GA synthesis. There are a number of commercial growth retardants used in greenhouse crop production. Each label has specific recommended dose ranges, recommendations, and precautions (Table 1).

Table 1
COMPARISON OF ATTRIBUTES OF PLANT GROWTH REGULATORS

Attributes		Plant Growth Regulators							
Chemical		Ancymidol	Chlormequat chloride	Daminozide	Daminozide + chlormequat chloride	Ethephon	Flurprimidol	Paclobutralzol	Uniconazole
Trade name(s)		Abide®, A-Rest®	Chlormequat E-Pro®, Citadel®, Cycocel®	B-Nine®, Compress WSG®, Dazide®	—	Florel®	Topflor®	Bonzi®, Downsize®, Paczol®, Florazol®, Piccolo®	Concise®, Sumagic®
Active ingredient		0.0264%	11.8%	85%	—	3.9%	0.38%	0.4%	0.055%
Activity level		++	+	+	++	+	+++	+++	+++
Multiple applications needed		++	+++	+++	++	++	+	+	+
Application type[1]	Foliar spray	yes	yes	yes	yes	yes	yes	yes	yes
	Substrate drench	yes	yes	no	no	no	yes	yes[1]	yes
	Dips	cuttings	cuttings	cuttings	—	cuttings	bulbs, cuttings	bulbs, cuttings	bulbs, cuttings
Chemical absorption	Ease of absorption	+++	+	+	+	++	+++	+++	+++
	Time (hours)	0.5–1.0	4	18–24	18–24	12–16	0.5–1.0	0.5–1.0	0.5–1.0
	Factors that improve foliar absorption	high humidity, limited air movement, cloudy days, early morning or late afternoon applications							
	Translocation within the plant	+++	+++	+++	+++	—	+	+	+
Absorption sites	Leaves	+++	+++	+++	+++	+++	++	++	++
	Stems	+	+	—	+	—	++	++	++
	Roots	++	+	—	—	—	+++	+++	+++
Typical concentrations	Foliar sprays (ppm or mg/L)	15–50	1,000–3,000	1,250–3,000	Daminozide: 750–2,500 + chlormequat chloride 750–1,500	250–1,000	1–50	1–50	0.5–25
	Drench (mg active ingredient per pot)	0.15–0.5	—	300–3,000	—	—	0.01–4.0	0.01–8.0	0.01–4.0
Other factors	Do pine bark substrates affect drenches?	++	—	+	—	—	++	++	++
	Phytotoxicity potential	+	+	+++	+	++	+ (do not apply to stressed plants)	+	+
	Overdose potential	+	+	++	++	++	+++	+++	+++
	Influence of water pH	—	—	—	—	pH 4.0 optimal	—	—	—
Shelf life	In the bottle (years)	<3	<2	<2	—	indefinite	<4	<4	<2
	Mixed solution	within 24 hours	within 24 hours	within 24 hours	within 24 hours	within 4 hours	within 24 hours	within 1 week	within 24 hours

—, not applicable. Degree of activity: (+) least to (+++) greatest.
[1]Check label for legal uses.

Daminozide (commercial names: B-Nine®, Compress WSG®, and Dazide®)

This material is applied only as a foliar spray because it is rapidly broken down when applied to the substrate. It is highly mobile in the plant and will rapidly move from the point of application to all parts of the plant. It is most commonly applied at rates between 1,250 and 5,000 ppm. Daminozide is effective on most crops except lilies. It is highly effective in controlling growth of seedlings in plug flats, and it is most effective in cooler climates.

Chlormequat Chloride (commercial names: Chlormequat E-Pro®, Citadel®, and Cycocel®)

This material is one of the most widely used PGRs in agriculture because it is also used to prevent lodging in grain crops. In greenhouse crops, it is most commonly used on poinsettias, geraniums, osteospermum (Figure 6), and hibiscus. It is usually applied as a 1,000 to 3,000 ppm foliar spray. Foliar chlormequat chloride applications often result in a phytotoxic response (chlorosis), but the symptoms are acceptable because they are usually covered up with new leaf growth. Substrate drenches are also effective at controlling excessive growth, but because rates are similar to what are used with foliar sprays, the practice is usually not a cost-effective option in the United States. In certain crops (i.e., poinsettia and geraniums), a mixture of daminozide and chlormequat chloride (both at reduced rates) may be used. This usually provides for greater height control and reduces the potential for phytotoxicity.

Ancymidol (commercial names: Abide® and A-Rest®)

This chemical is effective at much lower rates than either daminozide or chlormequat chloride. Concentrations applied are usually in the range of 10 to 200 ppm for foliar sprays and 0.15 to 0.5 milligram per 6-inch (15-cm) container for substrate drenches. Ancymidol readily moves through the plant and is usually used on crops where other

Figure 6
Two foliar sprays of Cycocel at 1,500 ppm provided excellent control of osteospermum plant stretch.

chemicals are not effective (most notably in bulb crops) or on very high-value crops (i.e., plugs). Growers often prefer the use of ancymidol on plugs because of the lack of phytotoxicity, and it is a "safer" PGR to apply (because its limited residual allows the plugs to grow out of the growth control effects after being transplanted). Phytotoxicity may occur from applications of high rates of ancymidol (especially under high temperatures) and usually appears as necrotic spots. The primary limitation for ancymidol is that it is a comparatively expensive growth retardant.

Flurprimidol (commercial name: Topflor®)

This chemical is a relatively recent introduction into the U.S. market, although it has been available in Europe since the 1990s. Flurprimidol is chemically closely related to ancymidol, but it has a greater degree of activity. Most commercial spray application rates are between 0.5 and 50 ppm (Figure 7). Flurprimidol is also one of the most cost-effective growth retardants to be used as a drench, with recommended use rates in a similar range as uniconazole on most plants.

Paclobutrazol (commercial names: Bonzi®, Downsize® [labeled for drench applications only], Paczol®, Florazol®, and Piccolo®)

Paclobutrazol (as well as uniconazole) is a member of the family of plant growth retardants known as *triazoles*. These chemicals do not readily move within the plant since they are transported in the xylem and not in the phloem. Therefore, triazoles are absorbed by the leaves, but cannot be transported out of the leaves to other parts of the plant. Because of this fact, it is important that when applied as a foliar spray, triazoles should be applied so that the solution contacts the plant stems. The triazole plant growth retardants are the most persistent (long lasting) of the plant growth retardants, and because these materials are active at very low rates, the potential for error and crop overdose is greater than with other plant growth retardants.

Paclobutrazol is the most widely used growth retardant for greenhouse-grown floriculture crops in the United States. It is commonly applied as a foliar spray and

Figure 7
Topflor foliar sprays of 40 to 50 ppm were effective in controlling salvia "Red Hot Sally" growth when grown in 1203 cell packs. Left to right: untreated control, 40 and 50 ppm.

Figure 8
Sumagic substrate drenches are effective at controlling excessive stretch of "Crystal Blush" calla lilies. Left to right: untreated control, 1, 2, and 4 milligrams of active ingredient per pot.

the trial rates of 5 to 90 ppm are listed for experimental use, but most commercial spray application rates are between 1 and 50 ppm. It is also effective as a substrate drench. It can be applied as a single high-dose drench of 2 to 200 ppm (varies widely among plant species) to provide season-long control of excess growth (rates vary among plant species and cultivars). Additionally, the application of low-dose drenches of 0.1 to 1 ppm can be used to provide temporary control of plant growth that allows greenhouse managers the ability to apply additional drenches as needed.

Uniconazole (commercial names: Concise® and Sumagic®)

Uniconazole is applied as both a foliar spray and a substrate drench (Figure 8). Experimental use rates of 1 to 50 ppm are listed on the label, but most commercial spray application rates are between 0.5 and 25 ppm. Uniconazole can also be used as a drench, at rates 50 percent lower than that recommended for paclobutrazol. This chemical is commonly used on perennials because it is highly effective on a very broad range of plant species.

OTHER GROWTH REGULATORS USED IN GREENHOUSE CROP PRODUCTION

Not all PGRs are used to control plant height. Others are used to cause flower-bud abscission, increase branching, promote flowering, and stimulate shoot elongation.

Abscisic Acid (commercial name: ConTego®)

Abscisic acid (ABA) is one of the newest materials being introduced into greenhouse production. ABA is used for enhancing postharvest performance by extending the shelf life of plants. An application of ABA as a foliar spray at concentrations of 250 to 1,000 ppm induces stomatal closure, thus reducing water loss. Plants simply use less water and dry out more slowly, thus avoiding wilt.

Dikegulac Sodium (commercial name: Augeo®)

Augeo is the product currently registered for greenhouse use; the predecessors to this product were Atrimmec and Atrinal. Augeo temporarily stops shoot elongation, thereby promoting lateral branching. It is thus a pinching agent for greenhouse crops including azaleas, Elatior begonia, bougainvillea, clerodendron, fuchsia, gardenia, grape ivy, geranium, kalanchoe, lantana, lipstick vine, shrimp plant, *Schefflera arboricola*, and verbena. Some phytotoxicity and distorted growth can occur with Augeo, so sufficient time is required to allow new plant growth to cover any damaged leaves.

Ethephon Phosphonic Acid (commercial name: Florel®)

This material is absorbed by the plant tissue, and due to a change in pH once absorbed into the plant cells, it releases ethylene. Ethephon is used to promote flower-bud abortion and vegetative branching in crops. Although it is used in many situations, it is most commonly used where vegetative cuttings are being produced and in hanging basket production. Ethephon is applied as a foliar spray at concentrations of 250 to 500 ppm. Ethephon may also be used to promote flowering in bromeliads.

Benzyladenine (commercial name: Configure®)

Benzyladenine (BA) is used to promote branching and increase flower set. Configure® has specific label recommendations for Christmas cactus (100 to 200 ppm foliar spray) (Figure 9), *Echinacea* (300 to 900 ppm foliar spray), and hostas (500 to 1,000 ppm foliar spray) and a supplemental use label allowing for experimental applications on any annual, perennial, foliage, or tropical plant grown in a greenhouse. Optimal results occur when the plant is actively growing and is physiologically receptive for growth or flower promotion. BA does not readily move within the plant, therefore complete coverage is required.

Gibberellins (commercial names: Florgib® and ProGibb T&O®)

Additional stem elongation may be desirable in some plants such as tree forms of azaleas, poinsettia (Figure 10), and geraniums. For the production of tree forms of these species, the general recommendation is to apply a 50 ppm GA foliar spray after plants are approximately 6 inches (15 cm) tall. Depending on the desired height and

Figure 9
Configure applied as a 100 ppm foliar spray to vegetatively growing Christmas cacti will increase the number of lateral shoots.

Figure 10
Extra stem growth of tree forms of plants can be achieved with the application of gibberellins to encourage cell elongation.

size, an additional one or two GA applications may be used. GAs can also be applied to promote growth and overcome overapplication of GA-inhibiting plant growth retardants. For this use, the general recommendation is to apply 1 to 3 ppm GA as a foliar spray and check for growth stimulation after five days. The application can be repeated if additional shoot elongation is desired.

Benzyladenine + Gibberellin Combinations (commercial names: Fascination® and Fresco®)

These combination products are used on potted lilies as foliar sprays to avoid lower leaf yellowing and leaf drop. A typical recommendation is to apply a 25 to 100 ppm foliar spray. The actual concentration depends on timing (early versus late production applications) and species. Sprays are also beneficial at prolonging flower life of potted lilies.

APPLICATION OF GROWTH REGULATORS

To successfully control the height of greenhouse crops with chemical growth retardants, many factors must be considered.

Environmental Conditions

The environmental conditions can have a significant impact on the efficacy of a PGR. Applying PGRs early in the morning when the evaporation rate is lower will allow for greater chemical uptake. Plants should not be water stressed when PGRs are applied, as this will increase the risk of phytotoxicity. After application, the PGR should be allowed to dry and wetting the leaves should be avoided. Plant foliage should be allowed to dry for four hours after daminozide application before the foliage is rewetted while other PGRs require only one hour.

Under high temperatures, most growth retardants become less effective and higher concentrations or additional applications may be required. Also, under high temperatures, the potential for phytotoxicity is increased. Foliar applications of PGRs are more effective under conditions where drying rate is slower (i.e., low light, high humidity, cool temperatures). This is because the active ingredient is not absorbed after drying, so the longer the foliage remains wet from the spray application, the more active ingredient that is absorbed.

Crop

Different crops and even different cultivars of a crop may respond differently to PGRs. Some crops do not respond to certain PGRs or may respond by different degrees. For each PGR and crop, there is an optimal concentration that should be applied. Also, some crops may be more susceptible to phytotoxicity from certain PGRs than others. For example, poinsettias can be sensitive to chlormequat chloride, and application to poinsettias will often result in phytotoxicity symptoms, but new growth will cover the yellow leaf spots. The growth retardant label will list all crops on which the material may be applied.

Stage of Crop

Crops may be more or less sensitive to growth retardants at different growth stages. Crops should have developed sufficient foliage so that the growth retardant may be applied and so that stunting does not occur. Growth retardants should be applied at the correct stage to prevent undesirable effects on growth. For example, late spray applications of plant growth retardants to poinsettias can result in reduced bract size.

Concentration

For every crop and growth retardant combination, there is an optimal concentration required to achieve the desired results. Concentrations too low will give inadequate height control while concentrations too high will result in stunting (Figure 11) or phytotoxicity (Figure 12). Even when the correct concentration is applied, excessive volumes (see “Volume of Application” section of this chapter) of material can still cause stunting or phytotoxicity. This occurs when an excessive volume is applied as a foliar spray and the growth regulator runs off into the substrate. In this case, the plants receive both a foliar spray application and a substrate drench treatment.

Figure 11
Excessive rates of plant growth regulators will result in stunted growth, as seen here with the center growth of this ornamental cabbage.

Figure 12
Phytotoxicity can occur with higher rates of some plant growth regulators. In most cases, new plant growth will cover up the leaf spots.

Method of Application

Some growth retardants can be applied only as a foliar spray while others may also be applied as a substrate drench. When applying a foliar spray, the volume applied should be sufficient to wet the foliage (and stems in the case of the triazole growth retardants) but without a significant amount of growth retardant draining into the substrate. When applying a growth retardant as a substrate drench, higher volumes are applied but with less active ingredient per plant (Figure 13). Typically substrate drenches are applied in such a way as to provide a specific amount of

Figure 13
Topflor substrate drenches to "Pink Charme" osteospermum as a single application at the start of the vernalization period at 0, 0.5, 1, or 2 ppm.

active ingredient per container (i.e., 0.25 mg per 6-inch [15-cm] container). This requires that not only the correct concentration of solution be prepared but also a specific amount of solution be applied per container. Therefore, substrate drenches allow for a more exact amount of chemical to be applied per plant (increasing uniformity), but they are more labor intensive than foliar sprays. Sometimes a drench application rate recommendation is made using a ppm concentration. In such a case, a given solution is prepared at the indicated ppm and sufficient volume of the solution is applied per container to wet the volume of substrate but without leaching. For example, 4 fluid ounces (118 mL) is typically applied to a 6-inch (15-cm) container.

Two additional methods of plant growth retardant application are liner soaks and bulb soaks. Liner soaks are used to control excessive growth of vigorous vegetative annuals. For liner soaks, a tray of plugs is irrigated 24 hours prior to treatment to even out the moisture level in the plugs. Then the plugs are allowed to dry slightly over the next 24 hours to the point where the plugs would require a normal irrigation. The plugs are placed in a plant growth retardant solution for one to two minutes to allow for uptake of the solution into the root substrate. To allow adequate uptake of the solution, the plugs should be held for two hours prior to transplanting into final containers. The chemicals used most frequently for liner soaks are flurprimidol, paclobutrazol, and uniconazole. Rates vary between northern and southern locations, by species and cultivar.

Bulb soaks involve mixing a known concentration of a plant growth retardant solution and then soaking the bulbs in the solution for 2 to 10 minutes. The bulbs are then allowed to drain for two hours prior to potting. Rates vary by the chemical used (flurprimidol, paclobutrazol, and uniconazole), species, and cultivar. This method works very well for hyacinths, tulips, and potted lilies.

Volume of Application

The general rule of thumb is to spray the foliage evenly with the appropriate concentration of solution just to the point of runoff (some runoff will always occur and is assumed in concentration recommendations). With the triazole growth retardants (i.e., Bonzi and Sumagic), the volume must be sufficient to make stem contact. When applied on a large scale, it is assumed that a volume of 2 quarts of the solution will be applied per 100 square feet of bench space (0.2 L/m^2). In some cases where a dense canopy occurs, 3 quarts of solution per 100 square feet (0.3 L/m^2) may be required. In cases where high volumes are required to achieve stem contact and uniform coverage, the volume applied may be increased and the concentration decreased.

Coverage and Uniformity

Uniform coverage is essential in order to have uniform growth and crop height (Figure 14). Also, where the triazole growth retardants are concerned, stem contact is required for the growth retardants to be effective.

Modifications with Bark-Based Substrates

The substrate environment impacts the efficacy of substrate growth retardant applications. Composted barks absorb and deactivate growth retardants. Therefore, substrate drench concentrations of growth retardants may need to be increased by approximately 25 percent when applied to a substrate containing significant amounts of composted bark.

Figure 14
Complete spray coverage is required with most of the plant growth regulators in order to have even results.

OTHER BENEFITS WITH THE APPLICATION OF PLANT GROWTH REGULATORS

Because of how some plant growth retardants inhibit the production of GA, there are a few other beneficial biochemical processes magnified in the plant. The application of plant growth retardants increase the concentration of chlorophyll in the plant, which results in darker green foliage. Darker green plants have greater consumer appeal.

Along with the more compact growth that occurs with the application of plant growth retardants, there is also a decrease in water use. Thus, in areas where water conservation is a concern, plant growth retardants can be considered a best management practice.

Originally, many of the plant growth retarding chemicals were discovered in fungicide efficacy trials. Therefore, it is not surprising that a few of them (flurprimidol and paclobutrazol) have demonstrated fungicidal activity (Figure 15). This disease protection is an added benefit of using certain plant growth retardants.

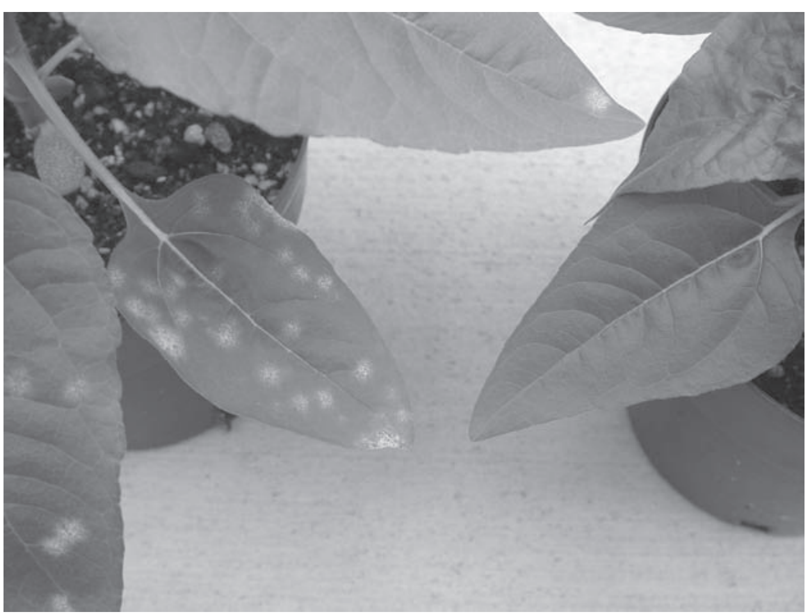

Figure 15
Some plant growth regulators can also provide a limited degree of disease suppression. Here flurprimidol-treated pot sunflowers (right) have not developed powdery mildew like the untreated control (left).

MIXING PLANT GROWTH REGULATORS

When mixing PGRs, great care needs to be given to accurately measure and apply the chemical. Drench applications vary by pot size and desired dose, so refer to the product label for exact mixing instructions. As always, the label contains the legal mixing information.

Correct Dosage

In order to achieve the desired effect on plant growth, a known dose needs to be applied to each plant. The dose to apply to a crop is based on two factors: (1) the solution concentration and (2) volume of solution applied per area.

Foliar sprays require an even application to obtain consistent results. To accomplish this, a dose is based on measuring out a known amount of chemical and adding it to a known volume of water to achieve the desired concentration. Next, the foliar spray needs to be applied to a known area. Most foliar sprays are applied at the rate of 2 quarts per 100 square feet of bench space (0.2 L/m^2). By applying this known concentration over a known area provides a known dose per plant.

Drench applications are based on measuring out a known amount of chemical and adding it to a known volume of water. This provides a solution with a known concentration. Next the solution must be applied at a specific volume of drench solution to each plant or pot. By applying this known concentration with a known amount per pot provides the desired dose per plant. The volume of drench applied increases with the pot size (specifics are listed on each product label). For instance, 2 ounces of drench solution should be applied to a 4-inch pot, 3 ounces to a 5-inch pot, 4 ounces to a 6-inch pot, and 10 ounces to an 8-inch pot.

How well do the PGRs work? The only way to confirm the efficacy of a PGR is to leave a few representative plants untreated. These “check plants” offer a valuable insight into ways to adjust future PGR applications (Figure 16).

Figure 16
Leaving an untreated check plant is an excellent method of gauging the effectiveness of your plant growth regulator application program.

Keys to Successfully Applying Plant Growth Regulators

1. Scout the crop weekly to evaluate the need for growth control using either a PGR or cultural techniques.
2. When a PGR needs to be applied, determine the desired application method (foliar spray, substrate drench, or preplant liner dip).
3. Select an effective PGR that is registered for your location, appropriate for the plant, and application method.
4. Calculate the mixing rate for the given spray area (foliar sprays) or number of pots to be treated (drenches). Adjust the rates to your location, keeping in mind higher rates are typically required in more tropical locations and lower rates should be used in cooler environments.
5. Ensure proper coverage occurs and the proper volume of PGR is applied for the given spray area [2 quarts per 100 ft^2 of bench space (0.2 L/m^2)] or pot size (2 oz of drench solution should be applied to a 4-in. pot, 3 oz to a 5-in. pot, 4 oz to a 6-in. pot, and 10 oz to an 8-in. pot).
6. Keep in mind PGRs are more effective in managing growth early in the production cycle than as a salvage treatment when excessive stretch has occurred.
7. Continue weekly scouting of the crop to evaluate the need for reapplying a PGR.
8. Keep accurate records to evaluate the effectiveness of the PGR application and check plants to confirm whether the desired effects were achieved.

SUMMARY

1. Plant growth can be influenced by both chemical and nonchemical methods (water stress, nutritional stress, light, root restriction, pinching, thigmotropic, and temperature DIF and DROP).
2. PGRs are commonly used in greenhouse production to control excess growth and produce a plant that is proportional to the pot size. Most of these PGRs inhibit GA synthesis that causes cellular elongation, thus resulting in shorter plants.
3. Greenhouse growers have the ability to modify the architecture of plants by using PGRs. PGRs can be used to cause flower-bud abscission, increase branching, promote flowering, and stimulate shoot elongation.
4. There are a number of factors that must be considered in order to successfully modify plant growth with PGRs: crop type and cultivar, stage of development, concentration applied, method of application, volume applied, uniform coverage, and substrate type.
5. The application of PGRs is also an excellent best management practice because they make the plants darker green, decrease water use by the plant, and in some cases provide some fungicidal protection.
6. Additional information about PGRs can be found at the following Web sites: http://www.ext.vt.edu/pubs/greenhouse/430-102/430-102.html; http://www.ces.ncsu.edu/depts/hort/floriculture/crop/crop_PGR.htm.

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Insect and Mite Management in Greenhouses

Raymond A. Cloyd
Kansas State University

There are a variety of insect and mite pests that feed on a wide range of crops grown in greenhouses. Aside from the direct damage done to the crop through feeding, the presence of insect or mite pests on plants sold at retail outlets may be disconcerting to consumers. In fact, most greenhouse-grown crops are sold primarily for their aesthetic value. It is important to understand the life cycle (egg to adult) of insect and mite pests in order to manage them effectively. However, before any pest management strategy can be implemented, it is imperative to identify the insect or mite pest. The reason for this is that certain pesticides (insecticides and miticides) and biological control agents (or natural enemies) may provide control of only specific insect and/or mite pests. This chapter will address a variety of topics including the major insect and mite pests of greenhouses, insect and mite pest–feeding behaviors, pest management, pesticides, pesticide resistance, pesticide storage and shelf life, pesticide safety, and pesticide application methods.

INSECT AND MITE PESTS OF GREENHOUSES

The major insect and mite pests of greenhouses are aphids, caterpillars, fungus gnats, leafminers, mealybugs, mites, scales, shore flies, thrips, and whiteflies. Additional pests that may be encountered in greenhouses include snails and slugs.

Aphids

Aphids attack a diversity of greenhouse-grown crops including herbaceous annuals and perennials, and woody plants. However, certain plant species and/or cultivars tend to be more susceptible to aphids than others. Aphids vary in color from yellow, green, black, orange, brown, and pink; however, this depends on the plant type fed upon, so color should never be used to identify

Figure 1
Green peach aphid, Myzus persicae.

aphids. The two most common species encountered in greenhouses are the green peach aphid, *Myzus persicae* (Figure 1), and melon/cotton aphid, *Aphis gossypii*. The green peach aphid has long cornicles (tube-like protrusions extending from the end of the abdomen) with black tips, whereas the melon/cotton aphid has shorter cornicles. Green peach aphid also has a distinct indentation at the base of the antennae. Aphids, in general, are ⅛ inch (3.0 mm) or less in length. They feed by inserting their piercing–sucking mouthparts through leaf tissues into the phloem (food-conducting tissues) and withdrawing plant fluids. Aphids feed in large colonies on terminal buds and on the underside of leaves causing plant stunting, leaf yellowing, and distorted plant growth.

During the feeding process, aphids excrete a clear sticky, sugary liquid called honeydew. Honeydew is an excellent growing medium for certain species of black sooty mold fungi, which covers leaves and inhibits the plants' ability to manufacture food via photosynthesis. The presence of black sooty mold fungi will also impact plant salability. In addition, ants feed on honeydew and will "farm" or transport aphids among different greenhouse-grown crops. Furthermore, ants protect aphids from their natural enemies such as parasitoids and predators.

Most aphid species, particularly in greenhouses, give birth to live offspring or nymphs, which are predominantly female. In fact, aphids do not have to mate to reproduce (this is referred to as parthenogenesis). These new female nymphs are then able to produce successive generations of female nymphs within 7 to 10 days. Aphids reproduce for a period of 20 to 30 days. One aphid female can give birth to 60 to 100 live nymphs. When plant nutritional quality diminishes or the aphid colony gets too crowded, then winged adult females will develop within the population. This allows aphids to readily disperse so they can locate new food sources. In greenhouses, aphids develop and reproduce throughout the year. Outdoors, however, there will be both males and females, which mate, and then females lay eggs that will overwinter.

Caterpillars

Caterpillars or "worms" are the immature or larval stage of moths and butterflies (Figure 2). There are a wide range of caterpillar species that attack greenhouse-grown crops including beet armyworm (*Spodoptera exigua*), cabbage looper (*Trichoplusia ni*), corn earworm (*Helicoverpa zea*), cutworms, diamondback moth (*Plutella xylostella*),

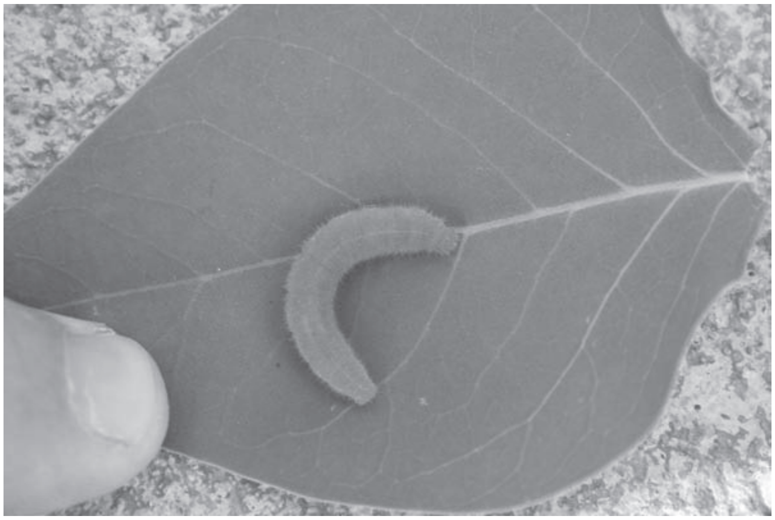


Figure 2
Imported cabbage worm, Artogeia rapae.

imported cabbage worm (*Artogeia rapae*), tobacco budworm (*Helicoverpa virescens*), and the European corn borer (*Ostrinia nubilalis*). Caterpillars are primarily a problem during the summer months when adults (moths) enter greenhouses from outdoors, particularly greenhouses with lighting emanating at night, since the adult moths are attracted to lights. Once inside the greenhouse, females may lay eggs on plant leaves. The adults feed only on pollen and nectar. Eggs hatch into caterpillars that feed on plant tissues including leaves, stems, and flowers. Caterpillars, when mature, may range in size from 0.5 to 2.0 inches (1.2 to 5.0 cm) in length. European corn borer caterpillars may actually tunnel into the stems of many greenhouse- and outdoor-grown plants, particularly chrysanthemum.

Fungus Gnats

Fungus gnat (*Bradysia* spp.) adults are black in color, approximately ⅛ inch (3.0 mm) in length, with long legs and antennae (Figure 3). There is a distinct "Y-shaped" vein at the tip of each forewing. They reside primarily near the surface of moist growing media, and fly short distances only when disturbed. The larvae are white to translucent in color, legless, and approximately ¼ inch (6.0 mm) long when mature. They have a black head capsule. Larvae cause damage by directly feeding on plant roots, which reduces the plants' ability to obtain water and nutrients. Furthermore, larvae may tunnel into plant stems and/or crowns creating wounds, which provide entry sites for soil-borne plant pathogens. Plants attacked by fungus gnat larvae are typically stunted and fail to respond to increased watering and/or fertilization. Fungus gnat larvae are known to vector (transmit) particular soil-borne plant pathogens such as *Pythium*, *Fusarium*, *Verticillium*, and *Thielaviopsis*.

Adult fungus gnat females lay clusters of 20 to 30 white eggs on the surface of moist growing medium. Fungus gnat adults tend to prefer growing media that contain abundant organic matter. Adult females may lay up to 200 eggs during their 10-day lifespan. Eggs hatch within six days into larvae. The larvae feed on plant roots for 12 to 14 days and then transition into a pupae stage. After five to six days, adult fungus gnats emerge from the pupae stage. The life cycle from egg to adult takes approximately 21 to 28 days to complete; however, this is contingent on temperature. If populations are abundant, then it is likely that overlapping generations are present.

Figure 3
*Adult fungus gnat (*Bradysia *spp.).*
(Image Courtesy of Theresa Meers, Parkland College.)

Leafminers

A number of different leafminer species may be encountered in greenhouses including the American serpentine leafminer (*Liriomyza trifolii*), serpentine leafminer (*Liriomyza brassicae*), pea leafminer (*Liriomyza huidobrensis*), and chrysanthemum leafminer (*Chromatomyia syngenesiae*). Leafminer larvae tunnel within leaves creating serpentine or blotched mines that may affect the aesthetic quality of greenhouse-grown crops. Heavy leafminer larval infestations may cause economic losses.

Adult leafminer females are approximately ¼ inch (6.0 mm) long, and are black in color with a yellow head (Figure 4). They also possess distinct yellow markings on the body, which helps to distinguish them from a shore fly adult (described later). Females puncture the leaf surface with their ovipositor and insert an egg. The small punctures in the leaf created by the ovipositor eventually develop into white spots.

Figure 4
*American serpentine leafminer (*Liromyza trifolii*) adult.*

However, females will not lay eggs in every puncture although they feed on the plant sap that exudes from each puncture. Each female may lay up to 100 eggs during her two- to three-week lifespan. Eggs hatch in five to six days into larvae that are bright yellow to brown in color, and ⅛ inch (3.0 mm) long when mature. The larvae tunnel below the epidermal layer of the leaf for up to two weeks, after which time they chew a hole in the leaf and fall to the ground to undergo a pupae stage. Leafminers require complete darkness in order to pupate. This is why the larvae, once on the surface of the soil (underneath benches) or growing medium, will bore several millimeters to escape any light. After approximately two weeks, an adult emerges from the pupa, flies to a new leaf, and after mating, females lay eggs into the leaf tissues. The life cycle from egg to adult takes about five weeks to complete; however, this depends on temperature. It is possible to encounter multiple generations throughout the growing season.

Mealybugs

Mealybugs are oval-shaped, segmented insects that appear white when fully mature because of a wax-like coating that covers their bodies (Figure 5). The body may also have waxy filaments around the periphery that extend out, as well as some longer filaments up to ½ inch (13.0 mm) long protruding from the back resembling a tail. Mealybugs range in size from ⅕ to ⅓ inches (5.0 to 8.0 mm) long. The two species commonly encountered in greenhouses are the citrus mealybug, *Planococcus citri*, and the longtailed mealybug, *Pseudococcus longispinus*. Citrus mealybug females can lay up to 600 yellow-colored eggs during their lifespan, which are deposited in a white cottony sac. Eggs hatch into crawlers (nymphs) within 5 to 10 days. However, some unhatched eggs or young crawlers may reside inside the cottony sac if temperature and relative humidity are not favorable. The crawlers are very active and move freely on plants, eventually settling down to feed. Crawlers feed for six to eight weeks, at which time they reach maturity or become adults. The males of most mealybug species develop into small-winged adults with no functional mouthparts. Their primary function is to fertilize females. In general, the life cycle from egg to adult takes 30 to 60 days; however, this is dependent on temperature. Longtailed mealybug females give birth to live offspring or nymphs; females do not lay eggs. Mealybugs feed on a diversity of greenhouse-grown crops including coleus, English ivy (*Hedera helix*), fuchsia, gardenia, hibiscus, pothos (*Epipremnum aureum*), stephanotis, and orchids.

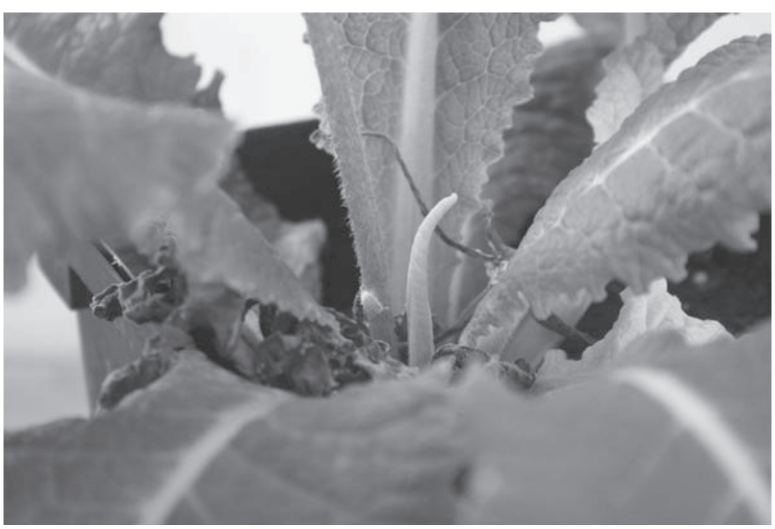


Figure 5
Citrus mealybug, Planococcus citri.

Mealybugs feed by using their piercing–sucking mouthparts to withdraw plant fluids. During the feeding process, mealybugs, depending on the species, may inject a toxic substance into the plant, resulting in leaf chlorosis and distortion of growth. Mealybugs, like aphids, also excrete honeydew, which is an excellent growing medium for certain black sooty mold fungi. The presence of black sooty mold fungi inhibits the plants' ability to manufacture food via photosynthesis. In addition, ants are attracted to and feed on honeydew produced by mealybugs. As a result, ants will protect mealybugs from natural enemies including parasitoids and predators.

Mites

Mites are not insects since they have eight legs (as adults) and two body regions (cephalothorax and abdomen) as opposed to three (head, thorax, and abdomen) for insects. There are a number of mite species that attack greenhouse-grown crops including the two-spotted spider mite, broad mite, and cyclamen mite. Two-spotted spider mite (*Tetranychus urticae*) is the most destructive mite pest feeding on a wide range of greenhouse-grown crops (Figure 6). Adults are oval, and may be green, yellow, or red in color with two dark spots on both sides of the abdomen. Two-spotted spider mites are approximately 1⁄50 inch (0.5 mm) in length. They typically feed in leaf cells, damaging the palisade and spongy mesophyll, and chloroplasts, reducing chlorophyll and moisture content. This also impacts the plants' ability to photosynthesize. Both the adults and the nymphs feed on the undersides of leaves resulting in chlorotic stippling (leaf bleaching), which appears as though very fine tan-to-yellow sand was sprinkled on the leaves. However, not all plant types will exhibit these types of symptoms. When populations are abundant, two-spotted spider mites will produce strands of silk and create webs on the underside of leaves and even on flowers. Leaves and flowers eventually turn brown or desiccate. The life cycle, from egg to adult, may be completed in 10 days at 80°F (27°C) or 20 days at 70°F (21°C). Low relative humidity (less than 50 percent) favors two-spotted spider mite development. Females can lay up to 100 eggs during their three- to four-week lifespan. Eggs hatch in three to five days into six-legged larvae, which feed for a short period of time before transitioning into two nymphal stages (deutonymph and protonymph) that have eight legs. Eventually, the

Figure 6
Adult two-spotted spider mite, Tetranychus urticae.

Figure 7
Broad mite, Polyphagotarsonemus latus.
(Image courtesy of Karen K. Rane, University of Maryland.)

protonymph stage develops into an adult. Adult females do not have to mate to reproduce and can initiate egg laying in one to three days.

Broad mite (*Polyphagotarsonemus latus*) is approximately 1⁄100 inch (0.25 mm) in length when fully mature (Figure 7). It is not visible with the naked eye. Broad mite eggs have conspicuous white protrusions residing on the surface. Broad mite development and reproduction is favored by temperatures between 60° and 80°F (15° and 26°C) and a relative humidity of 80 to 90 percent. The life cycle (egg to adult) may be completed in approximately one week. Broad mites feed on a wide range of greenhouse-grown crops primarily feeding on the lower surface of young leaves, which prevents leaf expansion and causes a downward "puckering" along leaf edges. Leaves heavily infested with broad mites may appear distinctly purple in color. Terminal growth and flower buds may be killed if broad mite populations are abundant. Furthermore, flowers and/or buds may be distorted and thus fail to open. Broad mite feeding damage closely resembles herbicide injury, nutrient deficiencies, and a number of physiological disorders. Broad mites may be distributed among a crop by attaching to the legs of whitefly adults.

Cyclamen mite (*Phytonemus pallidus*) is about 1⁄100 inch (0.25 mm) long when fully mature. These mites are not visible with the naked eye although they are semitransparent with a brownish tinge (Figure 8). Cyclamen mite may be distinguished from broad mite in that cyclamen mite eggs are bare with no conspicuous protrusions. Furthermore, cyclamen mite larvae and adults are larger and less active on plants than broad mite larvae and adults. However, similar to broad mite, development and reproduction is favored by temperatures between 60° and 80°F (15° and 26°C) and a relative humidity of 80 to 90 percent. In general, the life cycle from egg to adult takes two weeks to complete. Adult females live for three to four weeks and can lay up to 80 eggs.

Cyclamen mite feeds on a wide range of greenhouse-grown crops including African violet, begonia, cyclamen, gerbera (transvaal daisy), and English ivy (*Hedera helix*). The mites reside in and feed within the meristematic tissues of terminal buds and/or young expanding leaves. Cyclamen mite has piercing–sucking mouthparts,

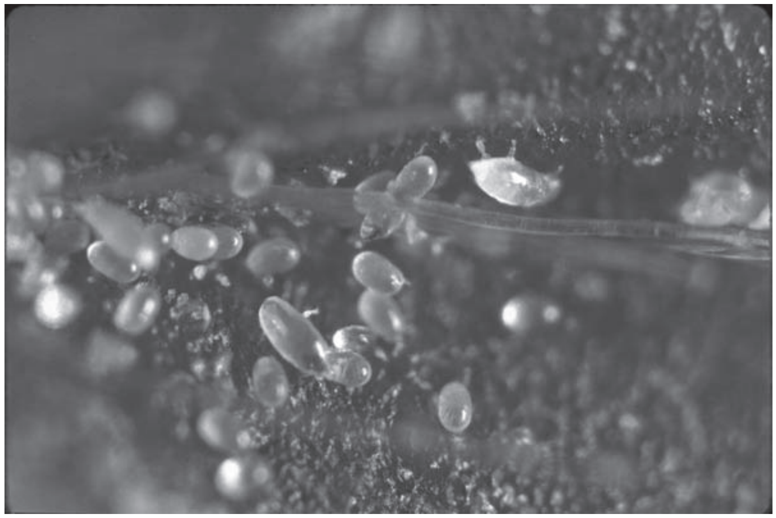


Figure 8
Cyclamen mite, Phytonemus pallidus.
(Image courtesy of Jack K. Clark, University of California.)

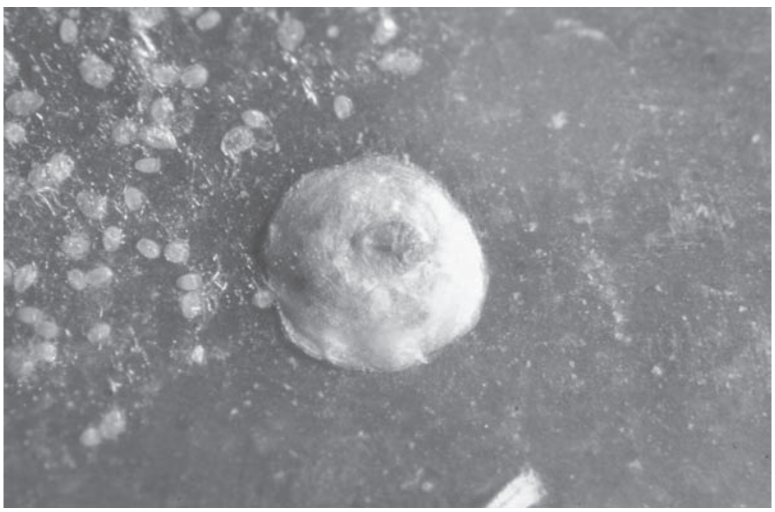
which are used to inject toxins and withdraw plant fluids causing bud distortion, inward curling of leaves or leaflets, and hardened and distorted leaves. Leaves may also appear purplish and thickened, which may be mistaken for boron deficiency. Additionally, flowers fed upon by cyclamen mite may be distorted or fail to open.

Scales

There are a variety of hard or armored (Family: Diasididae), and soft or bark (Family: Coccidae) scales that feed on greenhouse-grown crops (Figure 9). Scales are very similar to mealybugs in terms of life cycle and feeding habits. Mature female scales vary in size from ⅛ to ¼ inch (3.0 to 6.0 mm) in length, and are wingless and typically legless. There are only two life stages that are mobile: the first instar crawler (nymph) and adult male. The first instar nymphs emerge from eggs and migrate on the plant surface searching for a suitable place to feed. The later instar nymphs and adult females are immobile. Females may appear saclike and are usually wingless and legless. Males of most armored and soft scale species eventually develop into a winged individual with legs and one pair of wings; however, they do not feed since they lack mouthparts. Their only function is to fertilize the females. Some scale species give birth to live offspring (young), whereas females of other species lay eggs. In certain scale species, males are absent with virgin females either giving birth to live offspring or actually laying eggs. Scales possess piercing–sucking mouthparts, which are used to withdraw plant fluids. In addition, they may inject a toxic salvia during the feeding process. There may be three to seven generations per year; however, this depends on the scale species.

The integument of mature hard scales is not actually attached to the body, but is composed of waxy secretions and cast-off skins from the molting process. This covering, also called a test, varies in shape and color depending on the scale species. Hard or armored scales do not secrete honeydew. The nymph or crawler stages of nearly all scales have legs, which allow them to migrate on plants in search of a suitable feeding location. The nymphs then use their piercing–sucking mouthparts to withdraw plant fluids. Eventually, as the nymphs reach maturity, they begin to form an outer covering and lose mobility. Eggs are laid underneath the body of the female. Hard scales appear circular or elliptical on plant parts (leaves and stems), and may vary in color depending on the species.

(a)



(b)

Figure 9
(a) Soft and (b) hard scale.

Soft scales are covered by wax and the living scale is easy to distinguish. Furthermore, soft scales are flattened, oval or globular shaped. Unlike hard scales, soft scales produce copious amounts of honeydew, which serves as a growing medium for certain species of black sooty mold fungi. The eggs are produced in cottony sacs that protrude from the end of the female body. Females are capable of laying eggs continuously over a two- to three-month period. Certain species of soft scales actually retain their legs and antennae as adults.

Shore Flies

Shore fly adults are approximately ⅛ inch (3.0 mm) in length and black in color (Figure 10). They are oftentimes misidentified or mistaken for fungus gnats; however, shore fly adults have stout bodies, short antennae and legs. In addition, shore fly adults have darkened wings with around five distinct whitish spots, which fungus gnat adults do not have. Females lay eggs on algae, which hatch into legless larvae that possess breathing tubes with two spiracles (holes) located on the end of the abdomen. Larvae pupate in algae located on growing media or on benches. The life cycle (egg to adult) may be completed in 22 to 24 days depending on temperature.

Figure 10
*Adult shore fly (*Scatella *spp.).*

The adults and larvae primarily feed on algae or decaying organic matter located on the surface of growing media. Shore fly adults may be observed resting on plant leaves. They are highly attracted to certain herbs such as basil. Both shore fly adults and larvae are capable of disseminating certain soil-borne plant pathogens such as *Pythium* and *Fusarium*. Furthermore, adults may deposit fecal matter on plant leaves, and if populations are abundant, this may impact plant salability.

Snails and Slugs

Snails and slugs are not arthropods but are considered mollusks (a group of organisms including clams and oysters). Snails possess a hardened shell covering (Figure 11), which serves to protect them from natural enemies and extreme environmental conditions associated with temperature and sunlight. In contrast, slugs lack any hard

Figure 11
Snail with hardened shell covering.

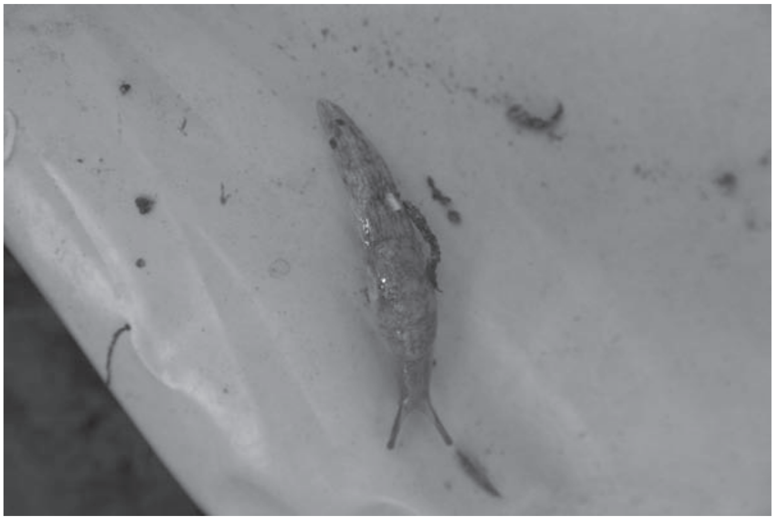


Figure 12
Slug.

outer covering (Figure 12). Both feed on a wide range of greenhouse-grown crops. Snails and slugs range in size from ¾ to 2.0 inches (1.9 to 5.0 cm) in length and vary in color from pale yellow to purple depending on the particular species. Snails and slugs lay clusters of 20 to 100 eggs in the cracks and crevices of moist growing media or underneath plant containers. Eggs hatch within 10 days or less at temperatures above 50°F (10°C). Snails and slugs reach maturity within three months to a year. Slugs have both female and male organs, and can actually alternate sexes during different periods of adulthood.

Snails and slugs have chewing mouthparts that allow them to consume seedlings and leaves. Furthermore, they create holes in stems and leaves. Both slugs and snails feed primarily at night, hiding beneath pots, benches, or debris during the day. Dark, moist hiding places are preferred. Snails and slugs exude a silvery mucus-like liquid as they crawl around on the surface of growing media. When this mucus-like liquid dries, it is shiny, making it easy to assess the presence of either snails or slugs. Snails and slugs may crawl into the greenhouse from vegetation or debris located outside the greenhouse. Thus, it is important to keep the area surrounding greenhouses clear of any weeds or plant material debris. Additionally, snails and slugs may be easily introduced into greenhouses on pots, on flats, on plants, and even in growing medium.

Thrips

Thrips are small insects, approximately 1⁄16 inches (2.0 mm) long, slender, with two pairs of fringed (hairy) wings (Figure 13). Both nymphs and adults may vary in color from brown to yellow to black. Adult females insert eggs into the holes of leaves created with their saw-like ovipositor that extends beyond the abdomen. Eggs hatch into nymphs that begin feeding on leaf tissue. The first and second instar nymphs primarily feed on plant leaves. Eventually, second instar nymphs stop feeding and crawl down the plant stem, entering the growing medium to pupate. The pupa is the transition stage between the nymph and adult, taking approximately one to two days to complete. The pupae stage does not feed. Thrips may also pupate in the open flowers of certain plants such as chrysanthemum and transvaal daisy. Adults emerge from the pupae stage and initiate feeding on both leaves and flowers. Adult females tend to feed in or on opened flowers. The life cycle (egg to adult), in general, may be completed in 18 to 21 days; however, this is dependent on temperature. The higher the

Figure 13
Adult western flower thrips, Frankliniella occidentalis.

greenhouse temperatures, the shorter the time required to complete the life cycle. For example, the life cycle may be completed in 7 to 10 days at 85°F (29°C).

Thrips have distinct piercing–sucking mouthparts that are used to initially scrape the surface of leaves or flower petals. They then feed on the plant sap that exudes from these wounds. Thrips feeding causes leaves and flower petals to appear white or silvery. Thrips damage is oftentimes referred to as silvering. Later, these damaged areas turn brown (necrotic) as the plant cells desiccate. Additionally, thrips feeding may cause leaf tissue to appear sunken. They can also cause distortion of new leaves and flowers, which may resemble broad or cyclamen mite injury. During feeding, both nymphs and adults deposit black fecal matter on leaves, primarily the undersides, and flower petals. Because thrips are so small and tend to reside (and feed) in unopened terminal and flower buds, they may not be detected early enough to prevent considerable damage to the crop.

Thrips populations located outdoors may build up to abundant levels on weeds, and then enter greenhouses as weeds desiccate, through openings such as doors, vents, and louvers. They may be distributed throughout a greenhouse via air currents from horizontal airflow (HAF) fans. Thrips feed on a wide range of greenhouse-grown crops, commonly feeding in terminal buds, in unopened flower buds, in opened flowers, on flower petals, and in the axils of leaves. Adults are typically visible to the naked eye but are usually hidden in unopened buds or flowers. Thrips can be detected by tapping leaves, buds, or flowers over a white sheet (8.5 × 11.0 in. or 21.5 × 27.9 cm) of paper. Thrips that drop onto the paper can be easily observed moving around. Adults may vary in color from yellow, tan, brown, to black, depending on the particular species.

The western flower thrips (*Frankliniella occidentalis*) is the most destructive thrips species of greenhouse-grown crops, and is widely distributed throughout the United States and Europe. Western flower thrips directly damage plants by feeding on both the leaves and the flowers. Furthermore, they may harm greenhouse-grown crops indirectly by transmitting the tospoviruses: impatiens necrotic spot virus (INSV) and tomato spotted wilt virus (TSWV). Plants infected with these viruses must be immediately removed from the greenhouse and placed in sealed plastic bags. There is no cure for a virus infection. The primary means of avoiding problems with viruses is control of the vector, the western flower thrips. However, this is exceedingly difficult due to the wide range of alternate hosts fed upon by western flower thrips, both inside and outside a greenhouse. Furthermore, continual reliance on insecticides to control western flower thrips and frequent applications will eventually lead to populations developing resistance.

Whiteflies

The primary whitefly species that may be encountered in greenhouses are the greenhouse whitefly (*Trialeurodes vaporariorum*) and the sweet potato whitefly B-biotype (*Bemisia tabaci*). Both species feed on a wide range of herbaceous annual and perennial, vegetable, tropical, and woody plants grown in greenhouses. Additionally, whiteflies may transmit viruses including several geminiviruses. Whiteflies, in general, are approximately 1/16 inch (1.5 mm) long with four wings covered with a white, waxy powder (Figure 14). Whitefly adults disperse short distances when plant foliage is disturbed. All the life stages (eggs, nymphs, pupae, and adults) are located on the undersides of young and mature leaves. Greenhouse-grown crops susceptible to whitefly infestations include ageratum, chrysanthemum, fuchsia, hibiscus, lantana, petunia, poinsettia, salvia, tomato, transvaal daisy, and verbena. The life cycles of the greenhouse whitefly and the sweet potato whitefly B-biotype are similar. Adult females may lay up to 20 eggs per day on plant leaves often in a crescent-shaped pattern. Females can lay up to 250 eggs during their 30- to 45-day lifespan. Each egg is attached upright on the leaf surface by means of a thin stalk. Greenhouse whitefly eggs are pale green to purple in color, whereas sweet potato whitefly B-biotype eggs are white to beige with a slightly darkened tip. Eggs hatch in 5 to 10 days, and the newly emerged nymphs or crawlers seek feeding sites on plants. The nymphs insert their piercing–sucking mouthparts into leaf tissues and withdraw plant fluids. Nymphs are flat, scale-like, and transparent to yellow-green in color. They remain stationary for approximately two to three weeks and undergo three molts before transitioning into a pupae (fourth instar nymph) stage. After about one week, adults emerge from the pupae. Females initiate egg laying within two to seven days. The life cycle (egg to adult) may be completed in three to four weeks; however, this is dependent on temperature. Greenhouse whitefly adults are 1/16 inch (1.5 mm) long, whereas sweet potato whitefly B-biotype adults are 1/28 inch (0.9 mm) long. Greenhouse whitefly adults hold their wings flat over the body or abdomen, parallel to the leaf surface. Sweet potato whitefly B-biotype adults hold their wings at a 45° angle (A-frame) or roof-like over the body (or abdomen).

Figure 14
Adult sweet potato whitefly B-biotype, Bemisia tabaci.

Both nymphs and adults feed on plant fluids using their piercing–sucking mouthparts causing wilting, leaf yellowing, leaf distortion, and/or plant stunting. In addition, the nymphs excrete a clear, sticky liquid called honeydew that serves as a growing medium for certain black sooty mold fungi. Whiteflies may be present in greenhouses throughout the year especially if weeds are present underneath benches since certain weed types such as common sow thistle are excellent reservoirs for whiteflies. During the summer, whiteflies may migrate into greenhouses through doors, vents, and louvers from susceptible plants and/or weeds located outdoors. In winter, whiteflies may spread or disperse from one greenhouse range to another on infested plant material or on workers (employees) clothes. Yellow-colored clothing worn by employees may be attractive to whiteflies.

FEEDING BEHAVIORS OF INSECT AND MITE PESTS

It is important to understand the feeding behaviors of insect and mite pests of greenhouses since this will help in determining which pesticide(s) to apply and where to target applications in order to obtain maximum control. Most insect and mite pests that feed on greenhouse-grown crops have either piercing–sucking or chewing mouthparts. Insect pests with piercing–sucking mouthparts include aphids, whiteflies, mealybugs, and soft scales. These insects, in general, insert their mouthparts into the vascular tissues of plants, primarily the food-conducting tissues (phloem), and withdraw plant fluids. Many piercing–sucking insects that feed in the phloem sieve tubes produce large quantities of honeydew, which is a clear, sticky liquid. Insect pests with piercing–sucking mouthparts require amino acids for development and reproduction. In order to obtain the necessary concentrations of amino acids, insect pests with piercing–sucking mouthparts ingest large quantities of plant sap, which contains an assortment of other materials as well as amino acids. The excess is excreted as honeydew. Insect pests that feed within the phloem tissues tend to exhibit a high degree of plant (host) specificity because certain plant-specific chemical compounds serve as important host selection cues. This is why, for example, that many aphid species prefer certain chrysanthemum cultivars than others.

Since insect pests with piercing–sucking mouthparts feed within the food-conducting tissues, they may be controlled by systemic insecticides. Systemic insecticides are typically applied to leaves, stems, and the growing medium. When applied to the growing medium, the active ingredient is taken up by the roots, translocated throughout the plant via the water-conducting tissues (xylem), and then migrates passively into the phloem. As an insect feeds, it withdraws a lethal dose of the insecticide and is killed. For example, the piercing–sucking mouthparts or proboscis of an aphid is inserted into plant tissue, reaching the conductive cells or phloem sieve tubes through which water and food is transported. The aphid takes up the active ingredient of the insecticide as it withdraws plant fluids.

Thrips also have piercing–sucking mouthparts; however, they tend to feed on the cell walls of leaf tissue using a single stylet in the mouth and then insert a set of paired stylets, which function to withdraw plant fluids. As such, thrips feed on many food types within plants. Since thrips do not feed exclusively in the phloem, systemic insecticides, when applied as a drench or granule, do not provide adequate control. Leafminer larvae feed in the mesophyll layer of cells, between the leaf surfaces. This protects them from applications of contact insecticides; however, products with translaminar activity (described later) are effective against the larvae because the material is capable of entering the leaf and killing the larvae. Spider mites, including the two-spotted spider mite, broad mite, and cyclamen mite, do not feed in the vascular tissues. The two-spotted spider mite, while feeding on leaf undersides, uses a stylet-like apparatus that damages the spongy mesophyll, palisade parenchyma, and chloroplasts, reducing the chlorophyll content in the leaf thus inhibiting the plants' ability to manufacture food via photosynthesis. Chewing insect pests are typically non-selective feeders, ingesting macerated whole leaf or root tissue. Some chewing insect pests, however, are more selective in the food type consumed. Chewing insect pests such as caterpillars prefer food with high water content and will select plant leaves with high concentrations of moisture.

In addition to feeding behavior, knowing the feeding location of insect and mite pests will maximize the effectiveness of pesticide applications or releases of natural enemies. For example, both broad and cyclamen mite feed in the meristematic region of small scales of buds, and as such are well protected from spray applications unless a surfactant (described later) is added to the spray solution to ensure penetration into the bud. Most life stages (egg, larvae, nymph, pupae, and adult) of whiteflies, mealybugs, scales, and spider mites are located on leaf undersides, so thorough coverage of all plant parts is imperative in order to obtain effective control of these insect and mite pests. Finally, thrips adults prefer to feed in flowers, whereas the nymphs tend to reside and feed on plant leaves.

Pest Management

Pest management is a holistic program that involves integrating cultural, physical, pesticide, and biological control strategies in order to deal with the diversity of insect and mite pest populations that may be encountered in greenhouses. The principal goals are to obtain an acceptable level of insect and mite pest control or regulation while reducing the use of pesticides, which will minimize the impact of the overall pest management program on the environment and avoid resistance. Furthermore, the intent of any pest management program is not the elimination of pesticides, but proper stewardship by applying pesticides only when all other pest management options have been exhausted. Pest management, in addition to insect and mite pests, may be directed toward dealing with vertebrate (animal), diseases, and weeds. The primary steps involved in this process include the following:

1. Eliminate weeds from within and around the greenhouse to minimize potential problems with insect and/or mite pests.
2. Clean and disinfest equipment, supplies, and benches prior to introducing a crop into the greenhouse.
3. Inspect all newly acquired incoming plant material prior to introducing into any greenhouse. In addition, remove "pet plants" from greenhouses as these plants may harbor insect and mite pests that may have developed resistance from previous exposure to pesticides.
4. Exclude insects from entering greenhouses by placing insect screening on greenhouse openings including vents, sidewalls, and louvers.
5. Scout or monitor the crop regularly in order to identify specific insect and mite pests, and quantify their abundance in greenhouses. Maintain accurate records pertaining to information associated with insect and mite pest location in the greenhouse, plant type, and time of year. Furthermore, scouting will enhance the prospects of detecting localized infestations thus avoiding insect or mite pest outbreaks.
6. Apply pesticides (insecticides and miticides) only when necessary and accordingly so as to maximize their effectiveness against the target insect or mite pest

population. This includes applying the proper pesticide, proper timing of applications based on the presence of susceptible life stages (eggs, nymphs, larvae, and adults), and thorough coverage of all plant parts.

Weed Control

Many broad-leaf and grassy weeds located outside greenhouses may harbor an array of insect and mite pests. Small insects such as thrips may enter greenhouses through openings or through the cellulose distribution pads of cooling systems via air currents. Furthermore, the presence of weeds inside and outside a greenhouse is unsightly, which may discourage customers and provide unsuitable working conditions for employees. In addition, weeds can reduce crop profitability. Weeds should be eliminated from within and the area surrounding the greenhouse because weeds provide hiding places and are a food source for many insect and mite pests. It is important to maintain a weed-free area around greenhouses by manually pulling weeds, using a weed-fabric barrier, or mowing areas regularly. Mowing reduces the types (thrips, leafminers, and whiteflies) and numbers of insect pests that may enter greenhouses. Moreover, mowing prevents weeds from flowering, which reduces the prospect of seeds entering greenhouses and germinating. Inside greenhouses, installing concrete flooring will significantly reduce having to deal with weeds during the production season.

Exercise care when selecting a herbicide (weed-killer) for use in or around a greenhouse since some herbicides are volatile (convert to a gas) and may indirectly damage a crop in the greenhouse. Herbicides labeled for use inside the greenhouse must be handled and applied carefully since the closed environment of the greenhouse may allow herbicides that are volatile to concentrate. Additionally, the high temperatures (greater than 75°F) that commonly occur in the greenhouse may increase volatility thus enhancing the likelihood of crop damage. Herbicides labeled for use in greenhouses are all post-emergent (kill weeds after germination); there are no pre-emergent herbicides registered for use in greenhouses. If a herbicide is inadvertently applied to the soil underneath benches, it may be deactivated by applying activated charcoal. However, this is a very complicated procedure. A general recommendation involves applying 300 pounds of activated charcoal per acre (340 kg/ha). Actually, the amount of charcoal needed depends on the herbicide and the amount used. In most cases, 200 pounds of activated charcoal may be required for each pound of herbicide active ingredient applied. Activated charcoal can be applied as a slurry to a small area using a watering can. For large areas, the activated charcoal may be mixed with water and applied using a high-volume (HV) sprayer. The nozzle must be removed from the end of the spray tube in order to prevent the nozzle from plugging up. Furthermore, the spray solution should be agitated to prevent the activated charcoal from settling in the spray tank. After application, the charcoal should be incorporated into the top 2.0 inches (5.0 cm) of soil using a cultivator. Eventually, 1.0 inch (2.5 cm) of water is applied in order to distribute the charcoal throughout the soil.

Sanitation

The primary means of preventing or minimizing problems associated with insect and mite pests is through sanitation. Additionally, the appropriate time to initiate preventive measures is before the crop is introduced into the greenhouse or prior to planting. For example, growing media may require pasteurization to eliminate any insects or soil-borne plant pathogens. Planting benches, watering systems, plant-support systems, tools, and used plant containers should be sterilized. Residual plants and any plant debris (leaves and flowers) should be discarded promptly from the greenhouse prior to introducing the next crop since these serve as harborage for insect and/or mite pests. All plant material and growing medium debris should be placed into containers with tight-sealing lids, or removed from the greenhouse at the end of each work day.

Algae must be eliminated from benches and floors in order to avoid dealing with certain insect pests such as fungus gnats and shore flies. This may be accomplished by using products that contain bromine, chlorine, hydrogen peroxide, hydrogen dioxide, and/or quaternary ammonium chloride salts as the active ingredient. Algae may be a safety hazard to employees because it is slick, particular when moist. Pressure-washing (water applied at high pressure) growing media from benches and walkways will avoid having to deal with insect and mite pests, and/or diseases. Clogged floor drains should be cleared immediately to eliminate standing water, which provides a suitable habitat for development and reproduction of algae thus leading to increased populations of both fungus gnats and shore flies.

Introduction of Plant Material into Greenhouses

Insect and mite pests may be introduced into the greenhouse via infested plants. Purchased seedlings and cuttings should be visually inspected carefully for insect and mite pests. If any are noticed, then these plants should be isolated and treated with designated pesticides or rejected. Established plants introduced into the greenhouse by customers are a common source of insect and mite pests. It is important to prevent entry of any infested plants into greenhouse production facilities.

Insect Screening/Exclusion

The installation of insect or micro-screening over greenhouse openings reduces or minimizes the entry of flying insects into greenhouses. Screens covering intake vents, doors, louvers, and retractable sidewalls will exclude or prevent the entry of insect pests such as adult thrips, whiteflies, leafminers, winged aphids, and fungus gnats. However, the mesh (hole) size of the screening material will dictate which insects will actually be excluded. For example, aphids and whiteflies, in general, are much easier to screen out than thrips due to their larger size. The smaller the target insect pest, the finer the mesh size of the screening material must be. The use of insect screening may reduce the frequency of pesticide applications and thus "selection pressure," which will lower the potential for resistance developing in insect pest populations. Furthermore, insect screening may reduce the incidence of viral diseases such as INSV and TSWV, which are vectored by the western flower thrips since the screening material, depending on the mesh size, may prevent this insect pest from entering greenhouses.

Some screening material may exclude insects that are smaller than the actual screen mesh size due to the configuration, uniformity, or pattern of the screening material. The shape of the insect may also determine the effectiveness of the screening material. For example, although adult thrips are slender and smaller than adult whiteflies, some insect screening material may actually exclude thrips more so than whiteflies. This may be due to the whitefly wings, which allow them to slip through the holes in the screening material more easily than the fringed (hairy) wings of thrips.

Studies have been conducted to determine the effectiveness of screening materials in excluding thrips and whiteflies. These are the smallest insects generally excluded with screens. Overall, the insect screening materials evaluated varied extensively in their ability to exclude both insect pests, which was correlated with mesh size. As expected, low-air-resistance (large-hole) screening material was the least effective in excluding thrips and whiteflies. However, the most effective screening materials were those with both moderate and high air resistance. This suggests that not all screening materials are equal or the same in regard to the insect pests excluded.

When exhaust fans are operating, negative pressure or a vacuum develops in the greenhouse due to the problems associated with replacing air flowing through the cooling pads. When any type of screening material is placed over cellulose cooling pads, this further increases air resistance, which is referred to as static pressure. An increase in static pressure, created by the insect screening, makes it difficult for the fans to move air efficiently. There is a relationship between the air speed that encounters the insect screening and amount of resistance created. As such, the pressure decline is greater in the greenhouse compared to the outside pressure. As the pressure continues to decrease, the quantity of air removed from the greenhouse also decreases. When resistance is increased, the performance, based on cfm (cubic feet per minute), of the fan declines. This reduces the effectiveness of the cooling system and results in an increase in the greenhouse temperature. To alleviate this problem, wood or metal frames (lean-to, box, or gable-end) must be built and retrofitted with screening material, which are then attached to or placed over greenhouse openings (Figure 15). The ratio of screened area to greenhouse opening may be as high as 5:1 depending on the screening material and mesh size.

Recommended pressure declines in screened greenhouses should not exceed 0.1 inch (2.5 mm) of water pressure. The pressure decline in unscreened greenhouses will rarely exceed 0.03 inches (0.76 mm). However, if the screening material causes a decline in pressure equal to or less than 0.1 inch, then directly place the screening material over a greenhouse opening such as a vent or sidewall. In this case, the screening material is equal in area to the vent or sidewall. However, if the screening material causes enough resistance that the total pressure decline in the greenhouse is greater than 0.1 inch, it will be necessary to use additional screening material to cover the vent and/or sidewall. Contact the National Greenhouse Manufacturers Association (www.ngma.com) for additional information associated with how to calculate the required ratio of screening material needed to cover greenhouse openings.

In addition to excluding certain insects, weed seeds, dust, soil, pollen, and plant material debris will adhere to insect screening. As such, screens must be monitored and cleaned regularly in order to prevent resistance, which will reduce airflow and cooling system capacity. Insect screening material should be easily accessible in order to be rinsed down periodically from the inside (or behind) with a spray nozzle attached to a hose. Although washing the screening material is beneficial, be careful since some screening materials contain holes that are so fine that water may fill the holes by capillary action, which can temporarily halt all airflow. While insect screening restricts insects from entering the greenhouse, the screening material also retains insects already present inside the greenhouse. Moreover, to prevent insect entry into greenhouses, workers should be trained to close doors at all times. Additionally, air leaks around doors, side vents, and louvers must be sealed.

There are other techniques available, in addition to insect screening that may be useful in excluding specific insect, mite, and other pests from feeding on greenhouse-grown crops. For example, wrapping a band of copper foil around bench posts (legs) will inhibit slugs and snails from reaching plant material. Both slugs and snails may gain access to plant material by crawling onto the bench or by being introduced on unsanitized pots, flats, or similar objects. Ants may present a problem when biological control programs are being implemented. Ants protect insect pests such as aphids, whiteflies, mealybugs, and soft scales that exude a clear sticky, sugar-based liquid called honeydew from natural enemies including parasitoids and predators. An adhesive substance is available that can be applied as a band around each bench post (leg). This will entrap ants at the point where they attempt to cross the barrier.

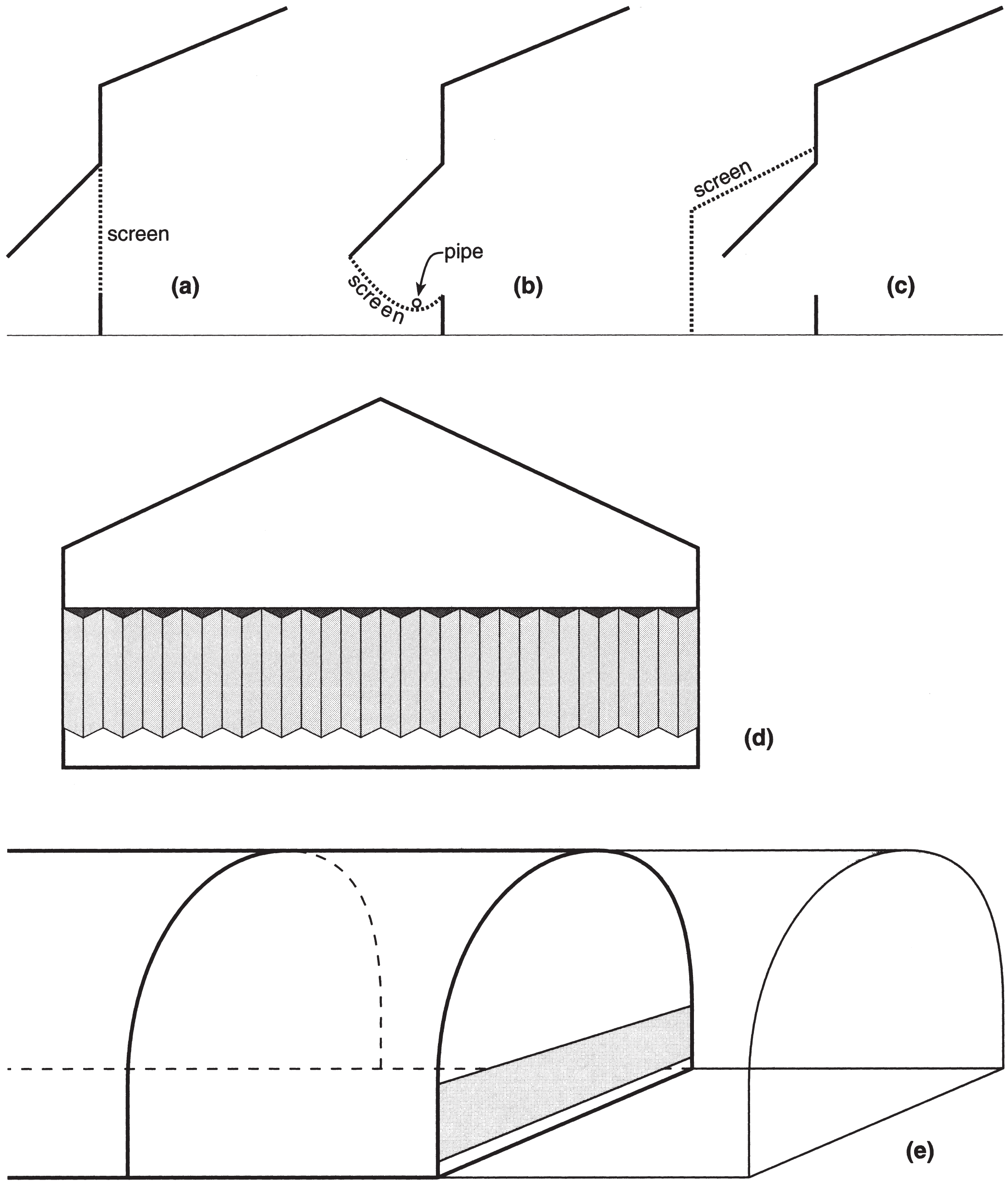


Figure 15
Some possible arrangements for installation of insect screens over ventilators in greenhouses. In the first situation (a and b), the screen has a low air resistance and needs to cover only the same area as the ventilator; in the remaining situations, the screen area needs to exceed the ventilator area and is accomplished by (c) installing a lean-to screen house over the ventilator, (d) installing a pleated screen enclosure over the ventilator, and (e) adding one extra screen-clad section to the length of the greenhouse.

Scouting

During the growing season, the winged forms of certain insect pests such as aphids, whiteflies, thrips, and leafminers may eventually enter the greenhouse. However, if they can be detected early enough, then pest management strategies such as the use of pesticides or biological control agents can be implemented before insect pest populations cause plant damage. In general, insect pests tend to establish populations in localized areas of a greenhouse. This may be a response to warmer temperatures or air currents, which may distribute insect pests to certain portions of the greenhouse. In addition, particular areas may be difficult to reach with pesticide spray applications.

Be sure to identify localized infestations and check frequently so as to avoid outbreaks from occurring. Insect and mite pests often exhibit preferences for certain plants and even varieties or cultivars of plants. As such, these varieties should be monitored routinely. Most insect and mite pests, in general, are located on the undersides of leaves so when scouting be sure to inspect leaf undersides. Pots containing plants should be picked up, turned on their sides, and rotated so it is easier to visually observe leaf undersides. However, other pests, such as slugs and snails, may hide underneath pots, pieces of bark, or leaves on the surface of the growing medium during the day and come out at night to feed. It is important to be aware of these habits and check for the presence of slugs and/or snails or their signs, such as slime trails.

The entire greenhouse should be scouted at least once per week. It is generally recommended to scout at least three randomly selected plants on each bench. If insect and/or mite pests are detected, these plants should be marked or flagged for future observation to determine the development rate and extent of pest population growth. Unless a specific plant has been flagged, different plants should be inspected each time since insect and mite pest populations will be distributed either randomly or clumped. For insect pests, yellow or blue sticky cards (Figure 16) should be

(a)

(b)

Figure 16

(a) Yellow sticky cards deployed throughout a greenhouse of bedding plants. (b) An individual yellow sticky card with numerous trapped insects.

installed vertically, just above the crop canopy, on bamboo stakes attached with a clothespin so they can be adjusted as the crop increases in height. Blue sticky cards are particularly effective in capturing western flower thrips and shore fly adults. For most greenhouses, in general, one sticky card per 1,000 square feet (93 m^2) is recommended. However, there is no justification for this recommendation since the number of sticky cards to use varies depending on the crops grown, whether greenhouse openings are screened or not, and the insect pest(s) complex present. For example, it may be necessary to use more sticky cards in greenhouses containing plants such as impatiens and begonias that are highly susceptible to the tospoviruses, INSV and TSWV, in order to detect low numbers of the western flower thrips.

It is important that both plants and sticky cards be inspected simultaneously. A 10× hand lens will aid in identifying certain insect pests. The type and number of insect pests should be determined and recorded. Sticky cards should be replaced weekly so that it will be easier to assess the most current insect pests captured on the sticky cards. Use one side of the sticky card one week and then the other side the following week (overlay the unused side with the sticky cover), which will double the usefulness of a sticky card. It is critical to inspect both plants and sticky cards because the flying stages of certain insect pests including aphids, fungus gnats, leafminers, thrips, and whiteflies, which are typically captured on sticky cards, may fly away when plants are disturbed and are then caught on sticky cards. In addition, eggs and the immature stages (larvae or nymphs) of most insect and other pests such as spider mites, mealybugs, and scales will not be captured on sticky cards. As such, visual inspection of the crop will be required. Always record the types of insect and mite pests present, their numbers, and life stages (eggs, larvae, pupae, and adults) detected for the following reasons:

1. ***Biological control:*** Information obtained from scouting is essential to the success of a biological control program, especially if biological control agents or natural enemies are to be released. For example, most parasitoids attack only one or two different species of an insect pest, and some attack only one life stage (egg, larvae, or adult) of a specific insect pest.
2. ***Pesticide selection and timing of applications:*** Many pesticide types such as insect growth regulators kill only a specific life stage of insect or mite pest species so scouting will help determine which life stage of an insect and/or mite pest is present. Not all life stages of insect and mite pests are susceptible to pesticides. The life stages primary susceptible include immatures (nymphs or crawlers) and adults. For example, whiteflies are susceptible to pesticide sprays in the crawler stage (first instar to third instar). However, when they reach the fourth instar stage or pupae, they possess a hardened covering, which protects them from wet sprays. Most systemic insecticides are primarily active on the immature stages of insect pests such as aphids, whiteflies, and mealybugs.
3. ***Localized "hot spots":*** Scouting makes it possible to detect designated areas in the greenhouse that require immediate treatment with a pesticide or if nothing should be done based on the abundance of insect and mite pests. This alleviates applying pesticides to the entire greenhouse, which then reduces the potential for resistance developing in insect and/or mite pest populations.

BIOLOGICAL CONTROL

Biological control involves the use of biological control agents or natural enemies of insect and mite pests including parasitoids, predators, pathogens, and entomopathogenic nematodes (insect-killing nematodes). Parasitoids are insects that attack a single prey (or host) and complete development either in (endoparasitoid) or on (ectoparasitoid) a particular prey. Most parasitoids attack only certain insect pests and one specific life stage (egg, larva, or adult). Examples include the aphid parasitoids: *Aphidius ervi* and *Aphidius colemani*. Predators are beneficial insects or mites that, in general, attack a wide range of prey. Examples include ladybird beetles, green lacewings, predatory mites, and predatory bugs. Pathogens are microorganisms including fungi or bacteria that either infest insect pests directly or are consumed by insect pests during feeding. Fungi and bacteria disrupt or consume the internal contents of insect pests, resulting in death. Entomopathogenic or beneficial nematodes are microscopic roundworms that enter insect pests through natural openings such as the anus, mouthparts, and breathing pores (spiracles). The nematode emits a bacterium that consumes the internal contents, eventually killing the insect pest.

Biological control is a pest management approach designed to regulate insect and mite pest populations below levels that either prevent or circumvent plant damage. Biological control avoids the problems associated with continual use of pesticides including resistance, environmental contamination, costs related to purchasing pesticides, and worker exposure to toxic residues. Biological control will be successful only if natural enemies are released when insect or mite pest populations are low. If pest populations are high, it will be necessary to apply a pesticide and then wait a specific period of time, depending on the pesticide, before releasing any natural enemies. The quantity of natural enemies to apply will vary depending on the abundance of insect and/or mite pests present. In order to implement a successful biological control program, it is essential to establish a scouting program (described earlier). Furthermore, insect or mite pests must be properly identified in order to select the appropriate biological control agent or natural enemy. Additionally, an estimation of the insect and/or mite pest population must be known in order to determine the extent of the insect and/or mite pest population in the greenhouse, the quantity of natural enemies that need to be purchased and released, and whether natural enemies should be released initially, or a pesticide must be applied to lower the insect and/or mite pest population before releasing any natural enemies.

It is important to understand that biological control may not work in every instance or under every greenhouse condition. Pesticides known to be directly and indirectly harmful to natural enemies should not be used in greenhouses where biological control is being implemented. Not only will wet sprays directly kill natural enemies but dried residues may be indirectly toxic to natural enemies. In general, the harmful effects of pesticides on natural enemies may be due to direct contact, host elimination, residual activity, and/or sublethal effects:

- ***Direct contact:*** Directed sprays of pesticides may kill natural enemies, or in the case of parasitoids, they are killed while developing inside the insect pest (host).
- ***Host elimination:*** Pesticides may kill hosts, which may result in natural enemies dying or leaving because they are unable to locate additional hosts.
- ***Residual activity:*** Although spray applications of pesticides may not directly kill natural enemies, any residues may have repellent activity thus affecting the ability of parasitoids or predators to locate a food source.
- ***Sublethal effects:*** Pesticides may not directly kill a natural enemy, but may affect reproduction such as sterilizing females, reducing the females' ability to lay eggs, or impacting the sex ratio (number of females to males). In addition, the foraging behavior may be modified thus influencing the ability of a parasitoid or predator to locate a host. Also, those parasitoids that host-feed such as the greenhouse whitefly parasitoid, *Encarsia formosa*, may inadvertently consume residues on hosts after a spray application. Any residues on potential hosts may make them unacceptable to a parasitoid or predator.

Furthermore, any differences in natural enemy susceptibility to pesticides may be associated with a number of factors including (1) whether the natural enemy is a parasitoid or predator, (2) natural enemy species, (3) life stage (egg, larva, pupa, and adult) sensitivity, (4) host development stage, (5) application rate, (6) timing of application, and (7) type or mode of action of pesticide used.

Biological control agents must be purchased and ordered before insect and/or mite pests' populations reach damaging levels. It is recommended to purchase natural enemies at least three weeks in advance to ensure that the natural enemies needed are available. Upon arrival, they should be immediately released in the greenhouse. Be sure to remove any yellow sticky cards prior to releasing parasitoids and certain predators since many natural enemies are attracted to and will be captured on the yellow sticky cards. A wide assortment of natural enemies is commercially available for use in greenhouses, and several insectaries actually produce biological control agents throughout the United States and Europe. Biological control distributors are a good source of information pertaining to natural enemy availability and the insect and/or mite pests they are most effective against. The following are descriptions of the commercially available natural enemies for the major insect and mite pests of greenhouse-grown crops.

Aphid Biological Control Agents

The commercially available biological control agents or natural enemies for aphids include the predators *Hippodamia convergens* (ladybird beetle), *Chrysoperla rufilabris* (green lacewing) (Figure 17), and *Aphidoletes aphidimyza* (predatory midge); and the parasitoids, *Aphidius colemani*, *Aphidius ervi*, *Aphidius matricariae*, and *Aphelinus abdominalis*. When using parasitoids, it is important to identify aphids to species since each parasitoid will attack only certain aphid species. It is also essential to release parasitoids preventatively on greenhouse-grown crops that are susceptible to aphids so that the parasitoids are present when aphids are first detected. Additionally, greenhouse temperatures should be between 65° and 77°F (18° and 25°C) with a relative humidity between 70 and 85 percent. Mixtures of certain aphid parasitoid species may be purchased from several biological control suppliers, which is useful when more than one aphid species is feeding on the crop. If aphid populations are abundant or the numbers on plants are excessive, then it will be mandatory to apply a pesticide with minimal

Figure 17
A ladybird beetle larva predator (Hippodamia convergens).

residues, so as to reduce aphid numbers prior to releasing any parasitoids or predators. Furthermore, ants must be controlled prior to implementing a biological control program since ants will protect aphids from parasitoids and predators. Boric acid baits may be useful in controlling ants.

Caterpillar Biological Control Agents

The commercially available natural enemies for regulating caterpillars in greenhouses are parasitoids in the genus *Trichogramma*, which attack only the egg stage; they do not parasitize caterpillars. As such, they must be released before eggs hatch.

Fungus Gnat Biological Control Agents

The biological control agents or natural enemies commercially available for dealing with fungus gnats include the soil-dwelling predatory mite, *Hypoaspis miles* (or *Stratiolaelaps scimitus*); entomopathogenic nematode, *Steinernema feltiae*; and the predatory beetle, *Atheta coriaria*. All three of these natural enemies attack the larval stage of fungus gnats, and are effective when applied before fungus gnat larval populations reach damaging levels. Furthermore, the growing medium should be thoroughly moistened prior to applying any of these natural enemies. It should be noted that the biological control agents may not be compatible when used together as there may be intraguild predation. For example, larvae of *Atheta coriaria* may be fed upon by the *Hypoaspis miles*. Consult biological control suppliers or distributors regarding information pertaining to release rates.

Leafminer Biological Control Agents

The two commercially available natural enemies of leafminers are the parasitoids, *Diglyphus isaea* and *Dacnusa sibirica*. Adult *Diglyphus isaea* are deep black in color, $\frac{1}{25}$ inch (1.0 mm) long, with short antennae. Adult females attack the second instar of leafminer larvae. This parasitoid larva directly kills leafminer larvae in their tunnels and then lays an egg beside the dead larva. Eggs hatch and the larvae feed on the internal contents of the dead leafminer. *Dacnusa sibirica* adults are slightly larger ($\frac{1}{11}$ in. or 2.5 mm in length) than *Diglyphus isaea* with long antennae. This parasitoid lays an egg inside leafminer larva. The egg hatches into a larva that undergoes development inside the leafminer larva. Eventually, the parasitoid larva transitions into a pupa, and then emerges as an adult from the dead leafminer. Both parasitoids are most effective in regulating leafminer populations on long-term crops such as stock plants and cut flowers. It is important to initiate releases of the parasitoids before leafminer populations' build up to damaging levels. However, prior to releasing either parasitoid species, be sure to remove all yellow sticky cards throughout the greenhouse in order to avoid capturing any parasitoids.

Mealybug Biological Control Agents

The commercially available biological control agents for mealybugs (primarily the citrus mealybug, *Planococcus citri*) include the predatory ladybird beetle commonly referred to as the mealybug destroyer, *Cryptolaemus montrouzieri*; and the parasitoid, *Leptomastix dactylopii*. *Cryptolaemus montrouzieri* feeds on a variety of mealybug species. However, it is primarily used against the citrus mealybug. Both the adult and the larvae are predators. The adults will also feed on aphids and scales if citrus mealybug populations are not abundant. Adult females lay eggs among the egg mass of citrus mealybug females. After eggs hatch, larva feed on mealybug eggs or emerging crawlers. In general, the mealybug destroyer is most effective when citrus mealybug populations are substantially higher than what may be acceptable to a consumer. Conditions that favor development and reproduction are temperatures between 72° and 77°F (22° and 25°C) and a relative humidity of 70 to 80 percent. The parasitoid *Leptomastix dactylopii* attacks only the citrus mealybug, with the females depositing eggs into either third instar nymphs or early fourth instar adults. The immature emerges from the egg and consumes the internal contents of the citrus mealybug during development. The parasitoid prefers temperatures around 78°F (26°C) and a relative humidity of 60 to 80 percent. Females may live up to 27 days. *Leptomastix dactylopii* is very mobile, and is extremely efficient in locating low densities of mealybugs. Similar to using aphid natural enemies, ants must be controlled since they will protect citrus mealybugs from the larval stage of the mealybug destroyer and *Leptomastix dactylopii* adults.

Scale Biological Control Agents

There are several parasitoids and predators commercially available that may be used to regulate populations of both hard and soft scales. However, the parasitoids attack only certain scale species. For example, *Metaphycus helvolus* attacks only black scale (*Saissetia oleae*); *Metaphycus flavus* attacks the brown soft scale (*Coccus hesperidum*) and hemispherical scale (*Saissetia coffeae*); and *Aphytis melinus* attacks only San Jose scale (*Quadraspidiotus perniciosus*). The commercially available predators include *Chilocorus nigritus*, *Chrysoperla* spp. (green lacewing), and *Rhyzobius* (*Lindorus*) *lophanthae*. Releases of either parasitoids or predators must be conducted before scale populations build up to damaging levels. As such, repeat applications will typically be required.

Two-Spotted Spider Mite Biological Control Agents

There are a number of commercially available natural enemies that may be used to regulate two-spotted spider mite populations including certain predatory mite species: *Phytoseiulus persimilis*, *Neoseiulus californicus*, *Amblyseius* (*Neoseiulus*) *fallacis*, and *Galendromus occidentalis*. Each predatory mite species requires a different temperature and relative humidity, which influences their ability to provide control of two-spotted spider mites. For example, *Phytoseiulus persimilis* is most effective at temperatures between 60° and 77°F (15° and 25°C) and a relative humidity of 60 to 80 percent. This predatory mite is less effective in regulating two-spotted spider mite populations at temperatures greater than 85°F (29°C) and a relative humidity less than 50 percent. In contrast, *Neoseiulus californicus* tolerates temperatures greater than 85°F (29°C) and a relative humidity between 30 and 40 percent. Additionally, the predatory mites vary in the types of prey consumed. *Phytoseiulus persimilis*, for example, feeds only on two-spotted spider mite as a food source, whereas the other predatory mites will either feed on alternative prey or on flower pollen in the absence of two-spotted spider mite. Predatory mites must be released when two-spotted spider mite populations are low. Consult biological control suppliers or distributors regarding release rates. Releases of predatory mites may need to be performed routinely (at two- to four-week intervals) in order to maintain two-spotted spider mite populations below damaging levels. Furthermore, it may be necessary to introduce two different predatory mites simultaneously in order to obtain long-term control or regulation of two-spotted spider mite populations on a variety of different crops. Another commercially available natural enemy of two-spotted spider mite is the predatory midge, *Feltiella acarisuga*. The larvae are the only predaceous stage feeding on all life stages (eggs, larvae, nymphs, and adults) of the two-spotted spider mite. Although the adults do not feed, they can fly, which allows them to locate two-spotted spider mite populations more efficiently than the predatory mites. Adults may live up to three days, and are primarily active at night, tending to rest on leaf undersides during the day. The optimum conditions for development and reproduction are temperatures between 68° and 80°F (20° and 26°C), and a relative humidity around 80 percent.

Thrips Biological Control Agents

The commercially available biological control agents or natural enemies of thrips include predatory mites (*Neoseiulus cucumeris*, *Amblyseius swirskii*, and *Hypoaspis miles* or *Stratiolaelaps scimitus*) and predatory bugs (*Orius* spp.). These natural enemies are primarily used to regulate populations of the western flower thrips. It is imperative that releases be implemented before western flower thrips populations are abundant because the predatory mites primarily feed on the first instar nymph (in the case of *Neoseiulus cucumeris* and *Amblyseius swirskii*) or on the pupae stage (in the case of *Hypoaspis miles*). The predatory bug, *Orius* spp., commonly referred to as the minute pirate bug, consumes the nymph and adult stages of western flower thrips. Both the nymphs and the adults are predaceous. In addition, adults may reside in open flowers where adult thrips tend to be located. In the absence of thrips, minute pirate bugs will feed on pollen and nectar, and even predatory mites.

Whitefly Biological Control Agents

There are three parasitoid species commercially available for regulating whitefly populations: *Encarsia formosa*, *Eretmocerus eremicus*, and *Eretmocerus mundus*. Each of these parasitoids may attack a different whitefly species. For example, *Encarsia formosa* attacks only the greenhouse whitefly, *Trialeurodes vaporariorum*. Adult females lay individual eggs into nymphs that hatch into an immature, which consumes the internal contents of the whitefly nymph, and then emerges as an adult from the parasitized pupae. In most cases, the majority of the adults in the population will be female. Adult females will also host-feed on the early instar nymphs. Host-feeding allows *Encarsia formosa* females to obtain essential nutrients that increase egg maturation and longevity. Moreover, host-feeding may contribute more than egg-laying in reducing greenhouse whitefly populations. *Encarsia formosa* performs best at temperatures between 70° and 80°F (21° and 26°C) and a relative humidity of 50 to 70 percent. At 81°F (27°C), *Encarsia formosa* females produce twice as many eggs as greenhouse whitefly females; however, when greenhouse temperatures are less than 70°F (21°C), then greenhouse whitefly females produce 10 times as many eggs as *Encarsia formosa* females. Additionally, *Encarsia formosa* does not reproduce well under low light intensities. In fact, *Encarsia formosa* tends to disperse and attack more whiteflies under "high" light intensity (greater than 8,000 lux) than "low" light intensity (less than 500 lux). Furthermore, *Encarsia formosa* parasitizes more whiteflies when exposed to long-day lengths (16:8 h) than short-day lengths (8:16 h). Overall, *Encarsia formosa* does not forage in darkness, and short-day lengths and low light intensity reduce efficacy. Also, plants with trichomes or leaf hairs may inhibit the effectiveness of *Encarsia formosa*. Both *Eretmocerus eremicus* and *Eretmocerus mundus* are effective in regulating populations of the sweet potato whitefly B-biotype (*Bemisia tabaci*). Additionally, these parasitoids are tolerant of warmer temperatures. Similar to *Encarsia formosa*, both parasitoids will host-feed, which may sustain whitefly populations at low levels. Optimum conditions for development and reproduction are temperatures between 77° and 84°F (25° and 29°C) and a relative humidity around 60 percent. Be sure to remove any yellow sticky cards before releasing whitefly parasitoids since they are attracted to and will be captured on yellow sticky cards.

PESTICIDES

Always read the pesticide label prior to application since there may be changes from one year to the next. The pesticide label is the law and contains all the essential information required to properly use the pesticide including application rate or rates, crops that the pesticide can be applied to, required personal protective equipment (PPE) (described later in the chapter), and restricted entry interval (REI) (described later in the chapter). In addition, the toxicity rating (danger, warning, or caution), symptoms of poisoning, and antidote are typically located on the front panel or pages of the pesticide label. Failure to comply with label recommendations may lead to reduced effectiveness, crop injury or phytotoxicity, and/or hazard to employees (workers).

There are a number of pesticides (insecticides and miticides) that kill a wide range of insect and mite pests; however, many, in general, kill a narrow range of insect and/or mite pests. Some pesticides are very specific in regard to the insect pests that may be controlled. There are different strains or subspecies of the soil-bacterium *Bacillus thuringiensis*, which is commercially available under several trade names that are active on certain insect groups. For example, *Bacillus thuringiensis* spp. *kurstaki* kills only the larval stage of caterpillars, whereas *Bacillus thuringiensis* spp. *israelensis* is solely active on fungus gnat larvae. Insects must ingest the bacterial spores in order to be negatively affected. Once inside the insect, the spores are converted into an endotoxin that binds to the gut (stomach) wall, creating pores that allow the stomach contents to enter the blood stream (hemolymph). Insects stop feeding within 24 to 48 hours and die after three to four days.

Most miticides vary in effectiveness depending on the life stage (eggs, larvae, nymphs, and/or adults) present during application. For example, some miticides are primarily active on the egg, larvae, and nymphs, whereas others are more active against the adult stage. Since, in most cases, all life stages will be present simultaneously, several miticide applications will be required. When temperatures are greater than 80°F (26°C), repeat applications may be required every three to four days. However, continual reliance on miticides to control two-spotted spider mite may result in populations developing resistance. As such, it is essential to rotate miticides with different modes of action (described later).

There are a number of insecticides that may be used to deal with caterpillars in greenhouses. The most widely used are those classified as pyrethroids and stomach poisons. One of the oldest active ingredients used against caterpillars is *Bacillus thuringiensis* spp. *kurstaki* or Berliner. This is a soil-borne bacterium that must be consumed by the caterpillars in order to be effective. Thorough coverage of all plant parts is essential, and repeat applications are typically required as the material is sensitive to ultraviolet (UV) light degradation. Also, it is important to protect the new growth from caterpillar feeding. However, once caterpillars such as the European corn borer enter plant stems or buds, control is extremely difficult. In this case, infested plants should be disposed of and removed from the greenhouse immediately.

The nymph and adult life stages of most insect pests are susceptible to insecticide applications, including both sprays and drenches, whereas the egg and pupa stages are more tolerant of insecticide applications. HV applications and the use of aerosols are effective in killing adults; however, frequent applications (three times per week) may be required if overlapping generations are present simultaneously, especially during the summer months. This is important since it is desirable to kill as many nymphs that emerged from eggs and adults that emerged from pupae. Furthermore, it is essential to rotate insecticides and miticides with different modes of action between each generation in order to minimize the prospect of insect and mite pest populations developing resistance to the pesticides being applied.

Most pesticides commercially available for use in greenhouses do not kill eggs or pupae so the susceptible life stages (nymphs and adults) must be present in order to obtain sufficient control when using pesticides. This can only be achieved by scouting the crop regularly (described earlier). Since most insect and mite pests such as aphids, thrips, and the two-spotted spider mite have high reproductive capacity with new generations, depending on the time of year, occurring every 7 to 10 days, more frequent pesticide applications will be warranted. The number of pesticide applications required to control or manage an insect and/or mite pest population will vary depending on spray coverage, frequency of application, timing of applications based on the insect and/or mite pest life cycle and life stages (egg, larva, nymph, and adult) of insect and/or mite pests present. Furthermore, each pesticide application results in selection pressure that increases the potential for resistance (described in detail later in the chapter). In order to maximize the performance of a pesticide application, it is essential to obtain thorough coverage of all plant parts (leaves, stems, buds, flowers, and roots) where insect and mite pests are located. Any insect and/or mite pests that escape treatment will continue to reproduce subsequently leading to more generations and individuals that can spread among a crop.

Timing of pesticide applications is important to avoid insect and/or mite pest outbreaks, thus minimizing the potential for resistance developing within insect and/or mite pest populations. The length of time or interval between pesticide applications depends on the residual activity of a given pesticide and the life cycle of the designated insect and/or mite pest(s). The interval between pesticide applications will also vary depending on the season (fall and winter vs. spring and summer). Moreover, since most pesticides are active only on the immature (young or nymphs) and adult life stages, frequent applications will most likely be required in order to sustain insect and/or mite pest populations below damaging levels. Applying pesticides every five to seven days may be needed in order to kill most of the susceptible life stages thus avoiding insect or mite pest outbreaks. During the summer months when temperatures exceed 85°F (29°C), applications every three to five days may be necessary particularly when dealing with whiteflies, aphids, western flower thrips, and two-spotted spider mite. If contact pesticides with short residual activity are used, then more frequent applications will be required, whereas translaminar and systemic pesticides may require fewer applications.

The waxy protective coating on mature mealybugs makes it difficult to control them with insecticides, especially contact insecticides. Surfactants (described later) may be needed to allow the insecticide to adhere and penetrate the wax coating. However, better control of mealybugs will be achieved if insecticides are applied when the population consists primarily of crawlers because this stage does not have a waxy-coating. As such, they are more susceptible to many different types of insecticides.

Pesticide recommendations may be obtained from company representatives, university-based extension agents, and extension-related bulletins. See the ***North Carolina Pesticide Manual*** for a complete list of recommendations for greenhouse crops (NCSU College of Agriculture and Life Sciences, 2010). However, it is important that the specific insect and/or mite pest be listed on the label. Some pesticides are designated as restricted-use due to their toxicity to humans or issues associated with negative effects to the environment. As such, they can be sold to and applied only by state-certified applicators who have completed courses in pesticide handling and safety (consult your state-wide extension service for more details).

Pesticides registered for use in greenhouses are available in various formulations, which contain both the active and the inert ingredients. The main formulations are liquid, solid, dry, and ready to use (RTU). Liquid (L) formulations include emulsifiable concentrate (EC), flowable (F), water-soluble concentrate or solution (SC or S), and ultralow-volume concentrate (ULV). Solid or dry formulations include wettable powder (WP or W), water-soluble powder (WSP), soluble powder (SP), water-dispersible granule (WDG), dry flowable (DF), dust (D), pellet (P), and granule (G). RTU formulations require no premixing or loading and include aerosol or total release, and fumigant or smoke. Several other formulations include microencapsulation (ME) and water-soluble packet.

Surfactants

The leaves and stems of many plants grown in greenhouses have a waxy covering or cuticle that tends to prevent water from adhering to the surface. As such, spray droplets may either “bead up” or roll off leaf or stem surfaces. This results in poor coverage of plant parts and inadequate control of insect and/or mite pests. The problem may be avoided by adding a surfactant to the spray solution. Surfactants are also referred to as spreaders or spreader-stickers. The surfactant reduces the surface tension of water thus allowing the spray droplets to spread out over the surface of leaves and stems. There are a number of surfactants commercially available for use in greenhouses. However, it should be noted that some pesticides particularly those formulated as EC may already contain a surfactant as a component of the inert ingredients. Furthermore, it is important to use the recommended label rate of a given surfactant because more surfactant than the label specifies may harm plants or result in phytotoxicity.

Pesticide Label Restrictions Associated with Phytotoxicity and Resistance Management

When reading pesticide labels, it is always important to determine whether there are any restrictions associated with use. Companies and manufacturers invest a considerable amount of money to develop a label and the label is the law; however, due to the diversity of horticultural crops including species and cultivars, it is difficult for companies to test pesticides on every plant type in order to determine tolerance (Figure 18). This is especially the case with the continual introduction of new plant varieties and cultivars. As such, there is typically a section on a pesticide label that defines particular label restrictions, which may include the plant types to which a pesticide should not be applied. Additionally, in order to properly use a given pesticide and avoid the potential for resistance developing in insect and/or mite pest populations, there is commonly a section related to resistance management (described later in the chapter). A good example statement is the following: “Do not apply this product more than two (2) times consecutively or a total of three (3) times during a growing cycle (start to finish for one ornamental crop). Do not apply this product to consecutive crops in a greenhouse structure.” Furthermore, it is important to rotate modes of action, not chemical classes. Table 1 presents the modes of action of insecticides and miticides commercially available for use in greenhouses.

Figure 18
Spray phytotoxicity on petunia.

Table 1

Mode of Action of Pesticides (insecticides and miticides) Registered for Use in Greenhouses with the Common Name or Active Ingredient Presented. The Number and/or Number and Letter Combinations in Parentheses Behind Each Active Ingredient Are the Insecticide Resistance Action Committee (IRAC) Mode of Action Designations

Acetylcholine Esterase Inhibitors

Inhibit the enzyme acetylcholinesterase (AChE) from clearing and degrading the neurotransmitter acetylcholine (ACh). This prevents termination of nerve impulse transmission and results in an accumulation of ACh leading to hyperactivity, respiratory failure, exhaustion of metabolic energy, and death.

Pesticides: Acephate (1B), Chlorpyrifos (1B), and Methiocarb (1A)

Sodium Channel Blockers

Interfere with nerve cell membranes in the peripheral and central nervous system by binding to the sodium channel sites, which delays or prevents closure of sodium channels. This prolongs sodium inactivation stimulating the nerve cells to produce repetitive discharges, eventually leading to paralysis and death.

Pesticides: Bifenthrin, Cyfluthrin, Fenpropathrin, Fluvalinate, and Lambda-cyhalothrin (3)

Nicotinic Acetylcholine Receptor Disruptors

Act on the central nervous system by binding to the postsynaptic enzyme receptors causing irreversible blockage, which leads to disruption of nerve transmission and uncontrolled firing of nerves. This results in rapid pulses from a steady influx of sodium, leading to hyperexcitation, paralysis, and death.

Pesticides: Acetamiprid, Dinotefuran, Imidacloprid, and Thiamethoxam (4A)

Nicotinic Acetylcholine Receptor Agonist and GABA Chloride Channel Activator

Disrupt binding of ACh at nicotinic ACh receptors located at the postsynaptic cell junctures, and negatively affect the gamma-amino butyric acid (GABA)-gated ion channels.

Pesticide: Spinosad (5)

GABA Chloride Channel Activator

Open chloride ion channels and bind to GABA receptor sites thus increasing membrane permeability to chloride ions leading to inhibition of nerve transmission, paralysis, and death.

Pesticide: Abamectin (6)

Juvenile Hormone Mimics

Arrest development, causing insects to remain in the young or immature stage primarily by inhibiting metamorphosis (change in form). Toxicity is most apparent when insects are reaching the onset of metamorphosis. As a result, insects fail to reach adulthood and are thus unable to complete their life cycle.

Pesticides: Fenoxycarb (7B), Kinoprene (7A), and Pyriproxyfen (7C)

Chitin Synthesis Inhibitors

Inhibit formation of chitin, an essential component of an insect's exoskeleton, affecting the firmness and elasticity of the cuticle. As a result, insects (and mites in the case of etoxazole) die while attempting to molt from one stage to the next.

Pesticides: Buprofezin (16), Cyromazine (17), Diflubenzuron (15), Etoxazole (10B), and Novaluron (15)

Ecdysone Antagonist

Inhibit the release of hormones responsible for molting (eclosion hormone and bursicon), thereby blocking molting hormone activity. Furthermore, disrupt the molting process by inhibiting biosynthesis or metabolism of the molting hormone—ecdysone.

Pesticide: Azadirachtin (18B)[1]

Growth and Embryogenesis Inhibitors

Disrupt the formation of the embryo during development or inhibit larval maturation. However, the specific mode of action and target site activity are still not well understood.

Pesticides: Clofentezine and Hexythiazox (10A)

Selective Feeding Blockers

Inhibit feeding behavior of insects by interfering with neural regulation of fluid intake in the mouthparts resulting in starvation.

Pesticides: Flonicamid (9C) and Pymetrozine (9B)

Table 1 (continued)

Disruptors of Insect Midgut Membranes
Toxins bind to specific receptor sites on the midgut epithelial cells resulting in degradation of the gut lining and eventual starvation of the insect. Crystals release protein toxins (endotoxins) that bind to the midgut membrane receptor sites creating pores or channels. This paralyzes the digestive system and ruptures the midgut cell walls allowing ions to flow through the pores disrupting potassium and pH balances. Fluids from the alkaline intestine (pH = 9.0 to 10.5) pass into the blood (hemolymph) and cause the pH to rise from 6.8 to greater than 8.0. This increase in alkalinity of the blood leads to paralysis in insects and eventually death.

Pesticides: *Bacillus thuringiensis* spp. *israelensis* (11A1) and *Bacillus thuringiensis* spp. *kurstaki* (11B2)

Oxidative Phosphorylation Uncoupler
Uncouple oxidative phosphorylation, which is a major energy-producing step in cells, by disrupting the proton (H^+) gradient across membranes in the mitochondria and subsequently impairs the ability of the mitochondria to produce adenosine triphosphate (ATP).

Pesticide: Chlorfenapyr (13)

Oxidative Phosphorylation Inhibitor
Inhibit mitochondrial synthase of ATP resulting in a decrease in oxidative phosphorylation at the site of dinitrophenol uncoupling.

Pesticide: Fenbutatin-oxide (12B)

Mitochondria Electron Transport Inhibitors
Inhibit NADH dehydrogenase (complex I) associated with electron transport or act on the NADH-CoQ reductase site, or bind to the Qo center or cytochrome bc_1 (complex III) in the mitochondria reducing energy production by preventing the synthesis of ATP.

Pesticides: Acequinocyl (20B), Fenpyroximate (21), and Pyridaben (21)

Desiccation or Membrane Disruptors
Damage the waxy layer of the exoskeleton (cuticle) of soft-bodied insects and mites by altering chitin so that it cannot hold fluids resulting in desiccation (drying up); reduce surface tension of water, which allows water to penetrate insect spiracles, decreasing oxygen availability thus killing insects via drowning; or smother insects by covering the breathing pores (spiracles).

Pesticides: Clarified hydrophobic extract of neem oil, Paraffinic oil, Petroleum oil, and Potassium salts of fatty acids

GABA-Gated Antagonist
Blocks or closes GABA-activated chloride channels in the peripheral nervous system and may also inhibit the mitochondria electron transport chain leading to a decrease in the production of ATP.

Pesticide: Bifenazate (25)

Lipid Biosynthesis Inhibitor
Blocks the production of lipids, which are a group of compounds made up of carbon and hydrogen including fatty acids, oils, and waxes. Disrupt cell membrane structures and reduce sources of energy.

Pesticide: Spiromesifen and spirotetramat (23)

Unclassified Modes of Action
Beauveria bassiana (Entomopathogenic fungus)

Pyridalyl

[1] In addition to an insect growth regulator, azadirachtin may act as feeding deterrent/inhibitor, oviposition inhibitor, repellent, egg-laying deterrent, and sterilant.

Pesticide Resistance

The primary means of dealing with insect and/or mite pests in greenhouses is applying pesticides (insecticides and miticides). However, continual reliance on pesticides may lead to insect and/or mite pest populations developing resistance. Resistance is the genetic ability of some individuals in an insect or mite pest population to survive an application or applications of specific pesticides. The bottom line is that the pesticide or pesticides, at the recommended label rates or doses, no longer kill a sufficient number of individuals in an insect and/or mite pest population. Approximately 526 species of insects have developed resistance to insecticides over the last 50 years. Insect and mite pests possess the inherent ability to adapt or evolve to various environmental and human disturbance factors such as pesticide applications. For example, due to the continual reliance on insecticides, populations of western flower thrips and leafminers (depending on demographics) have developed resistance to a number of commercially available insecticides in different chemical classes.

Resistance is an international problem with expanding global trade of plant material, which not only can spread insect and/or mite pests, but may also spread resistance genes associated with insect and/or mite pest populations. Resistance occurs at the population level and is an inherited trait. Those insect or mite pests that survive can transfer traits (genetically) to their offspring (young) or next generation thus enriching the gene pool with resistant genes. The amount of selection pressure or frequency of applying pesticides is the primary factor that may influence the ability of an insect and/or mite pest population to develop resistance. In addition, the life stages (egg, larva or nymph, and adult) may vary in susceptibility based on the presence of particular resistance mechanisms (described later).

It is essential to understand that the genes or genotypes for resistance may already be present in an insect and/or mite pest population before any pesticide is applied although this typically occurs at a very low frequency within a pest population. Moreover, an individual insect or mite pest does not become resistant to a pesticide, but due to frequent applications of a pesticide over multiple generations of an insect and/or mite pest population, susceptible individuals are removed from the pest population leaving only resistant individuals to dominate the population. This results in an insect and/or mite pest population that is no longer susceptible to a given pesticide. Each time an insect and/or mite pest population is exposed to a pesticide application, this results in selection pressure for resistance thus increasing the frequency or proportion of resistant genes occurring in an insect and/or mite pest population.

Insect or mite pest populations may contain different or more than one resistance mechanism. The mechanisms of resistance are (1) metabolic, (2) physiological, (3) physical, (4) behavioral, and (5) natural. ***Metabolic resistance*** is the breakdown of the active ingredient by the insect or mite pest. After a pesticide enters the body, enzymes surround and detoxify or convert the active ingredient into a nontoxic form. Once inside an insect, insecticides may be metabolized and thereby inactivated. Enzymes associated with detoxification convert insecticides, which are hydrophobic or "water-hating," to more hydrophobic and biologically less active compounds that are eliminated via excretion. The three primary enzymes involved are esterases, glutathione *S*-transferases, and cytochrome P450 monooxygenases. ***Physiological resistance*** occurs when an insect or mite pest modifies the target site of the pesticide, which then decreases sensitivity to the active ingredient at the physical point of attachment because the target site has been altered. Examples of this mechanism of resistance occur in the organophosphate, carbamate, and pyrethroid chemical classes. Insects may possess different means to decrease susceptibility to organophosphate and carbamate insecticides including reduced sensitivity of acetylcholinesterase (AChE), which is the enzyme in the central nervous system that is inhibited by insecticides in the organophosphate and carbamate chemical classes, increased activity or overproduction of AChE. Furthermore, insects may have what is known as knockdown resistance (kdr) that reduces the sensitivity of the nervous system to pyrethroid-based insecticides by modifying the sodium channels, which is the target site for most pyrethroid-based insecticides. ***Physical resistance*** is a change or modification in the cuticle (skin) of an insect or mite pest that reduces or delays penetration of the pesticide. Delayed penetration through the cuticle or integument may reduce the effect of the insecticide at the target site, and may also decrease the possibility that the insects' detoxification system will be overloaded. Additionally, this reduces the insecticide concentration that actually reaches the target site and allows more time for detoxification of the incoming concentration. ***Behavioral resistance*** occurs when insect and/or mite pests avoid contact with a pesticide by hiding in plant locations such as the terminal growing points that are difficult for the pesticide to penetrate. Any altered behaviors may allow insect or mite pests to avoid contact and thus reduce exposure to pesticides. ***Natural resistance*** is a general type of resistance in which the insect and/or mite pest, or life stage, is not susceptible to a pesticide. Most insecticides and/or miticides, for example, are not active on the egg and pupa stages.

There are two distinct terms associated with resistance: cross and multiple resistance. ***Cross resistance*** occurs when an insect or mite pest population is resistant to pesticides with similar modes of action due to analogous resistance mechanisms. ***Multiple resistance*** refers to an insect and/or mite pest population that is resistant to pesticides with different modes of action. This is a consequence of insect and/or mite pests in a population having more than one defense mechanism against a particular class or mode of action. As a result, the active ingredient of a pesticide is besieged by several different enzymes.

A number of factors may influence the rate of resistance in an insect or mite pest population including (1) length of exposure to a single pesticide; (2) level of mortality (high vs. low); (3) relatedness of a pesticide to another one; (4) generation time (long vs. short); (5) female fecundity or reproductive capacity, which is associated with the number of offspring (young) produced per generation; (6) mobility of individuals in an insect and/or mite pest population; and (7) season (fall/winter vs. spring/summer), which is related to differences in selection pressure or the number of pesticide applications that an insect or mite pest population is exposed to. This is based primarily on abundance in a greenhouse at a particular time of year. There are a variety of operational factors (conducted by greenhouse producers) and biological characteristics of insect and mite pests that may be responsible for enhancing the development of resistance. These are the following:

1. Operational Factors
   a. Frequency of pesticide applications (selection pressure).
   b. Constantly using the highest recommended label rate.
   c. Using the same mode of action for an extended period of time or exposing several generations to the same mode of action.
2. Biological Factors
   a. Rapid development time or short generation time of insect and mite pest population.
   b. High reproductive rate of females or large numbers of offspring (young) produced per generation.
   c. Individuals in the insect or mite pest population are highly mobile.
   d. Insect and mite pests feed on a wide range of plant types.

Resistance Management

Resistance management involves judicious selection and accurate application of pesticides, and integrating them with other control strategies consistent with basic pest management philosophy. This is the primary and most effective means of avoiding resistance. Because resistance is genetically based, it is the frequency of resistance in an insect or mite pest population that a greenhouse producer attempts to minimize in a resistance management program. The following are guidelines to forestall insect and mite pest populations developing resistance to pesticides:

1. Scout greenhouse-grown crops regularly to appropriately time pesticide applications at the most susceptible life stage (larva, nymph, and adult) of an insect and mite pest.
2. Implement proper cultural (irrigation and fertility) and sanitation (weed and plant debris removal) practices.
3. If feasible, screen all greenhouse openings such as sidewalls, louvers, and vents.
4. Implement the use of biological control agents or natural enemies (parasitoids, predators, pathogens, and/or entomopathogenic nematodes).
5. Rotate as many pesticides with different modes of action (refer to Table 1) as possible. One specific mode of action should be used within a generation of an insect or mite pest population. For example, when dealing with western flower thrips during mid-spring and summer, an insecticide with one mode of action should be used for 10 days to 2 weeks before switching to an insecticide with a different mode of action. This avoids the development of resistance to the first insecticide while retaining the effectiveness of the second insecticide.
6. Use pesticides with broad modes of activity including insect growth regulators, insecticidal soap, horticultural oil, selective feeding blockers (inhibitors), beneficial bacteria and fungi, and related microorganisms.
7. If appropriate, use synergists when applying pesticides as synergists inhibit enzymes associated with detoxification. However, be sure to consult either the pesticide label or the manufacturer to assess if it is recommended to include a synergist in the spray solution.

A number of pesticides contain information mandating particular application procedures so as to minimize the risk of pesticide resistance. For example, one insecticide commonly used to control western flower thrips is restricted to six applications within a production area during a 12-month period regardless of the insect and/or mite pest or crop that is being treated. One widely used miticide can only be applied twice to a given crop in one year and must be rotated with another miticide with a different mode of action.

Pesticide Mixtures

Greenhouse producers may mix together two or more different pesticides due to convenience because it is less time consuming, costly, and labor intensive to tank mix two or more pesticides and then perform one spray application as opposed to making two or more separate applications. Furthermore, a pesticide mixture may result in enhanced effectiveness in controlling certain insect and/or mite pests, resulting in greater mortality than if either pesticide was applied separately. In addition, pesticide mixtures may be more effective on certain development stages of insect and mite pests. The condition of enhanced efficacy, when two or more pesticides are mixed together, is called synergism or potentiation.

Just as synergism enhances the efficacy of two or more pesticides, the opposite, which is termed antagonism, may also occur. Antagonism is when tank mixing two or more pesticides reduces the effectiveness of the pesticide mixture compared to if the pesticides were applied separately. The pesticide mixture is less effective based on percent mortality of the insect and/or mite pest population, then if the pesticides had been applied individually.

Moreover, pesticides should not be mixed together until it has been determined that they are compatible in a spray solution. This can be ascertained by conducting a jar test, which involves mixing a small sample of the spray solution and placing into

Figure 19
A jar test for determining compatibility of mixed pesticides. The pesticides are mixed together in water in a jar and allowed to sit for 15 minutes. Appearance of separation of layers or precipitation, such as flakes or crystals, indicates incompatibility.

an empty jar or 1-pint container, and allowing the solution to remain ideal for approximately 15 minutes (Figure 19). If the pesticides are not compatible, there will be a noticeable layering or separation, or precipitates such as flakes or crystals may form. Incompatibility may be due to the chemical or physical properties of the pesticide(s), water temperature, impurities in the water, or the types of formulations mixed together. However, if the pesticides are compatible, then the solution will appear homogeneous or possibly resemble milk. Oftentimes, two pesticides that can be used individually on a given crop without incident may be harmful or phytotoxic when mixed together. As a general rule, certain pesticide formulations, such as WP and EC, should not be mixed together. Additionally, most pesticides should not be mixed with alkaline solutions (pH greater than 7.0).

Plant Injury or Phytotoxicity

Plant injury or phytotoxicity may occur to crops grown in greenhouses after a pesticide application. Temperature and relative humidity at the time of a pesticide application may significantly impact the potential for phytotoxicity. As such, it is essential to utilize pesticides properly and avoid using those pesticides that may be harmful to plants. Phytotoxicity may be influenced by a number of factors including plant sensitivity, use of excessive pesticide application rates (above those recommended by the label), frequency of pesticide applications, improper pesticide dilutions, inappropriate pesticide mixtures, stage of plant growth during pesticide application, and environmental conditions (temperature, light, and relative humidity) outside and within the greenhouse. The extent of plant injury from pesticides may vary depending on the pesticide formulation (EC vs. WP), weather conditions (sunny vs. cloudy days), ambient air temperature (low vs. high), and leaf temperature. Furthermore, plants stressed due to a lack of moisture or nutrients tend to be more susceptible to injury from pesticide applications. It is important to understand that the active ingredient in a pesticide may not be responsible for causing plant injury. The inert ingredients including solvents or carriers in the formulation or impurities (salts) in the water that is used to mix the pesticide may actually cause phytotoxicity.

Symptoms of phytotoxicity include leaf yellowing, leaf drop, stunting, abnormal plant growth, necrotic spotting on plant parts, and delayed growth. Pesticides may inhibit plant growth either acutely (short-term) or chronically (long-term) by negatively affecting plant height or stem elongation. It is recommended to test a designated number of plants (e.g., 10) to determine the effects of a given pesticide, which is less expensive than discovering later when the entire crop is not saleable. In general, check plants 7 to 10 days following the application of a pesticide to assess any injury. Be sure to record any problems for future reference. Pesticides, in most cases, will not cause phytotoxicity when used according to label directions; however, if the label rate is increased by two, three, or four times, then plant injury is likely to occur. Although there are advantages to tank mixing pesticides together (as described previously), there may be risks associated with phytotoxicity. For example, if two or more pesticides are not compatible in a spray solution, and the mixture is applied, this could lead to significant crop injury. It is recommended to refer to the pesticide label for information associated with the compatibility of pesticide mixtures. Again, it is important to test all pesticide mixtures on a designated number of plants (e.g., 10) before treating the entire crop.

Be sure to clean all spray equipment thoroughly between applications so as to avoid phytotoxicity. Also, never use one sprayer for herbicides, insecticides, and miticides. Always have a separate sprayer for herbicides, and one for insecticides and miticides. In addition, all pesticide mixtures should be agitated frequently during application to prevent settling in the spray tank, which could increase the likelihood of phytotoxicity. Pesticide manufacturer labels commonly list the plants, which a particular product is safe to use on. However, it is difficult to evaluate all pesticides registered for use in greenhouses to determine safety on the diversity of plant cultivars grown. Furthermore, many pesticide labels state that the product should not be applied to plants that are in flower or bract (e.g., poinsettia) since these plant parts tend to be more sensitive to pesticide residues than green leaves.

Insecticidal soaps and/or horticultural oils that are applied at frequent intervals (three times per week) may damage certain plant types. Horticultural oils may harm the new growth and foliage of particular sensitive plant types or species. Furthermore, applications of horticultural oils may cause injury to greenhouse-grown crops under the following conditions: (1) relative humidity greater than 70 percent, (2) overcast or cloudy days, (3) insufficient airflow within the greenhouse, (4) excessive temperatures (85°F or 29°C) and/or "high" light intensity for extended periods of time, and (5) frequent applications (three to four per week).

Phytotoxicity can reduce the marketability and sale of a crop, resulting in economic losses. The primary means of avoiding phytotoxicity include the following: (1) read the pesticide label prior to application to assess whether the pesticide is registered for use on specific plant species, (2) use the recommended label rate of a pesticide and apply at the appropriate intervals, (3) always read the pesticide label thoroughly to determine the designated application intervals, (4) test all pesticide mixtures on a select number of plants (e.g., 10) before applying to an entire crop, (5) always test all new pesticides on a designated number of plants (e.g., 10) before making an application to the entire crop, (6) make sure all application equipment is well maintained and properly calibrated, (7) agitate spray solutions frequently during an application, (8) avoid applying pesticides when temperatures are greater than 85°F (29°C) and when plants are exposed to intense direct sunlight, and (9) do not apply pesticides to moisture- or nutrient-stressed plants.

Pesticide Storage and Shelf Life

Pesticides must be stored in an insulated, well-ventilated, sufficiently lit, dry-locked storage compartment or room that is inaccessible to children and other unauthorized

Figure 20
A labeled, ventilated pesticide storage cabinet located in a dry, temperature controlled room with impermeable floor capable of containing liquid spills.

personnel (Figure 20). Pesticides should be kept cool, dry, and located out of direct sunlight. It is important that all storage rooms or compartments have an impermeable floor with dikes so as to contain any spills. Fans should be installed to withdraw air away from the area where pesticides are stored. Additionally, heat must be available with temperatures controlled with a thermostat.

Be sure to maintain accurate records of all stored pesticides. These records should at least include the date of purchase and date each pesticide was placed in storage. In addition, know where the batch number is on the label in case there are any inquiries. Warning signs must be posted near all primary entrances so that all personnel are aware that the compartment or room contains pesticides. All warning signs should state "Pesticide Storage, Authorized Personnel Only, In Case of Emergency Call. . . ." A floor plan of the building, which shows the location of the pesticide room or compartment as well as a list of the pesticides (and other chemicals) stored, should be provided to the local fire department. Also, a listing of all pesticides (and other hazardous chemicals) and the Material Safety Data Sheets (MSDS) should be placed in a three-ring binder that is centrally located in a separate building. The MSDS are provided by the manufacturer or supplier, and they include all pertinent information regarding toxicity of each pesticide stored. Pesticides should never be stored in working or living areas.

Most pesticide containers do not have the manufacturing date on the label. As such, it is important to record the date of purchase on the label because certain pesticide formulations lose effectiveness and may be harmful to plants if either stored for extended periods of time (10 years or more) or not stored properly. To extend the shelf life of pesticides, they should be exposed to temperatures between 55° and 65°F (12° and 18°C) with a relative humidity between 40 and 50 percent. Temperature extremes (both cold and hot), continuous exposure to UV light, and excessive relative humidity (greater than 70 percent) may cause pesticides to degrade. In fact, most pesticides tend to break down when exposed to extreme heat (temperatures greater than 100°F or 37°C) or cold (temperatures less than 32°F or 0°C) over extended periods of time (two weeks). Pesticides formulated as liquids will expand when either heated or frozen causing containers to rupture. Low temperatures (less than 32°F or 0°C) will cause some materials to settle out or crystallize out of solution. Proper ventilation and temperature controls will avoid exposing pesticides in storage areas or compartments to any temperature extremes. A relative humidity greater than 70 percent may alter the properties (or composition) of some pesticides, particularly those stored in unsealed containers. For example, pesticides formulated as solids including D, WP, and WDG may solidify or cake when exposed to high relative humidity. Finally, keep pesticide containers on shelves or pallets to minimize exposure to excess moisture.

Routinely check the storage area or compartment to make sure all pesticide containers are in adequate shape, and there are no leaks or spills. For example, solvents and petroleum-based compounds may deteriorate certain types of pesticide containers after a given time period. Avoid storing any herbicides (weed-killers) along with insecticides and miticides so as to prevent cross-contamination among the containers. Also, be sure that all pesticide containers are sealed tightly. A number of pesticide formulations may not store well over extended periods of time. For example, L formulations that are not used after approximately three years may settle out or separate into layers (both the active ingredient and the carrier), and/or form precipitates that accumulate in the bottom of the containers. This then makes it difficult to get the active ingredient and/or carrier into a suspension so that the pesticide is useable. As such, it is recommended to agitate or shake pesticides formulated as liquids (or solutions) before use so as to homogenize the mixture. Moreover, extended storage (greater than 10 years), particularly after exposure to temperature extremes, may result in chemical changes, which can lead to a reduction in effectiveness and/or increased potential harm to plants or phytotoxicity. Pesticides, in general, should not be stored any longer than five years; however, this is dependent on the formulation, concentration of active and inert ingredients, and storage conditions. Pesticide products containing microorganisms such as bacteria, fungi, and entomopathogenic nematodes may have a shorter shelf life than most conventional pesticides.

Pesticide Safety

Pesticides are routinely applied in greenhouses in order to deal with the array of insect and mite pests feeding on greenhouse-grown crops. However, certain rules and regulations must be adhered to regarding PPE (described in detail later in the chapter), the crop to be sprayed, and the environment. Greenhouse producers should contact the county or state government agency associated with pesticide enforcement to obtain a copy of the rules and regulations pertaining to applying pesticides in greenhouses.

Never eat, drink, or smoke while preparing or applying pesticides. These activities increase potential exposure to pesticides and thus entry into the body. Keep all foods and beverages away from pesticide storage facilities. In addition, do not eat any food or drink any liquid beverages in a greenhouse where plants have been treated with a pesticide. Employers are responsible for designating specific areas for lunch and coffee breaks that are located far from pesticide storage buildings or compartments thus avoiding any inadvertent contamination.

Worker Protection Standards

In 1992, the EPA established the Worker Protection Standards (WPS) to protect agricultural workers and pesticide handlers by limiting their exposure to pesticides, educate workers and handlers about the hazards associated with pesticide use, and provide precautions to eliminate exposure. A *worker* is anyone who (1) is employed (including self-employed) for any type of compensation and (2) is performing tasks related to the production of agricultural plants on farms, nurseries, and greenhouses such as harvesting, weeding, or watering in a pesticide treated area within 30 days following the application of a pesticide. A *pesticide handler* is someone who (1) is employed (including self-employed) for any type of compensation by an agricultural or a commercial pesticide-handling establishment that uses pesticides to protect agricultural plants on a farm, nursery, or greenhouse and (2) performs any of the following tasks:

- **a.** Mixes, loads, transfers, or applies pesticides.
- **b.** Handles opened pesticide containers.
- **c.** Acts as a signal person or "flagger."
- **d.** Cleans, handles, adjusts, or repairs parts of any mixing, loading, or application equipment that contains pesticide residues.
- **e.** Assists with the application of pesticides including incorporation into the growing medium.
- **f.** Enters a greenhouse or other enclosed area to (1) operate ventilation equipment, (2) adjust or remove coverings, such as tarps, used in fumigation, or (3) check air concentration levels.
- **g.** Enters a treated area outdoors after any soil fumigant application to adjust or remove soil or growing medium coverings such as tarps.
- **h.** Disposes of pesticides or pesticide containers.

While each state must abide by the WPS rules, most states have the opportunity to apply more stringent rules and regulations. The major responsibilities of employers under the current WPS include the following: posting information, pesticide safety training, decontamination supplies, emergency assistance, and application restrictions. This list is not complete; thus, greenhouse producers should refer to their state's lead agency responsible for pesticide regulation, or to the WPS.

Information on WPS is available from the U.S. Government Printing Office (GPO). Employers can obtain the EPA manual, ***The Worker Protection Standard for Agricultural Pesticides—How to Comply: What Employees Need to Know***, by contacting the GPO (Washington, DC 20402). The publication number of the manual is 055-000-00442-1. Greenhouse producers should consult the state Department of Agriculture regarding any interpretations or inquiries associated with WPS.

Posting Information Each employer must post and regularly update, at every central location, pesticide safety application information such as the EPA–WPS safety poster that must be easily accessible so that employees can protect themselves from pesticides. Furthermore, employers must inform their employees where this central location is and notify them if there are any changes in the posted emergency facility. The following information must be included:

1. Contact information including name, address, and telephone number of the nearest emergency medical facility.
2. Information pertaining to each pesticide application (prior to each application and 30 days after the REI) such as:
   - **a.** Product name, Environmental Protection Agency (EPA) registration number, and active ingredient(s).
   - **b.** Location and description (crop type) of the treated area.
   - **c.** Time and date of application and the REI. The REI is the designated period of time indicated on the pesticide label in which workers or personnel are not allowed to enter a treated area.

Pesticide Safety Training Every employer is responsible for having each pesticide worker and handler trained by a certified applicator or a WPS designated trainer. Certified applicators should have available written and/or audiovisual EPA–WPS materials for training workers and handlers. Each worker and handler must be provided with pesticide safety information and fully trained within the first five days of employment and at least once every five years.

Decontamination Supplies Employers must provide workers and handlers with the following: (1) sufficient volume of fresh rinse water for routine hand washing and emergency eye flushing (at least 16 fl oz or 0.5 L per worker); (2) sufficient quantities of soap and single-use paper towels; (3) a sturdy shower; (4) change of clothes for all employees after they have worked in a treated area; and (5) for the handler, all of the above plus clean coveralls. Decontamination supplies must be accessible and within ¼ mile from where employees are working, but not in the treated area.

Emergency Assistance When a worker or handler has been inadvertently poisoned or injured during the course of applying a pesticide, the employer is responsible for the following procedures:

1. Provide transportation to the nearest medical facility.
2. Provide the following information to any medical personnel:
   a. Product name, EPA registration number, and active ingredient(s).
   b. First aid and medical information provided on the pesticide label.
   c. Description of how the pesticide was applied.
   d. Information associated with the victim's level or duration of exposure.

Application Restrictions The following procedures must be strictly adhered to during any pesticide application:

1. Only appropriately trained and equipped handlers may enter a greenhouse prior to ventilation criteria being performed.
2. Handlers are not allowed to apply a pesticide so that it contacts, directly or via drift, anyone other than a trained and/or equipped handler.
3. There must be voice or visual contact, at least every two hours, with personnel handling restricted-use pesticides (skull and crossbones on the label).
4. Trained handlers must wear appropriate PPE (described later in the chapter) as stated on the pesticide label. Furthermore, handlers must maintain constant voice or visual contact with any applicator or handler in a greenhouse performing fumigant-related tasks.

Restricted-Entry Intervals All pesticide labels must provide an REI ranging from 0 to 48 hours. The REI is located under the heading, "Agricultural Use Requirements," of the pesticide label. This is a period of time following application of a pesticide in which only suitably trained and equipped handlers are allowed to enter a greenhouse or treated area. However, there is one exception to this rule, which allows employees or workers to enter the greenhouse during the REI period to perform emergency tasks or irrigate plants. In most cases, early entry into greenhouses is not allowed until four hours after a pesticide application and after any inhalation exposure level (as listed on the pesticide label) has been reached or exceeded, or WPS ventilation criteria are in compliance. Each worker is restricted to eight hours of early-entry exposure within a 24-hour period. All workers must receive proper training prior to entering a greenhouse or treated area. Furthermore, all workers must be wearing the required PPE as specified on the pesticide label before early entry.

Notice of Application Some pesticide labels require employers to notify workers orally and by posting warning signs on greenhouse openings (doors) or near treated areas after an application (Figure 21). When orally notifying workers, it is important that the employer provide an accurate description and the location of the greenhouse and/or treated area, the REI, and specific instructions to not enter the greenhouse or treated area until after the REI expires. Warning signs

Figure 21
A pesticide warning sign posted on a greenhouse during and after application of pesticides.

must be posted so they are visible from all points of entry (doors) at a distance of at least 30 feet. Furthermore, warning signs must be posted 24 hours before the scheduled pesticide application and should be removed within three days after the REI.

Application Equipment Safety Equipment used to mix and/or apply pesticides must be inspected prior to application. Repair or replace specific equipment parts as needed. Old spray hoses, in particular, should be replaced routinely before they break and expose the applicator to any pesticide sprays. Employers must train all workers and employees on the appropriate procedures associated with cleaning or repairing pesticide application equipment and how to safely operate all equipment.

Personal Protective Equipment All pesticides must state the PPE to be worn when applying any pesticide. This information is located under the heading, "Agricultural Use Requirements," of the pesticide label. PPE refers to all apparel and additional items that must be worn including coveralls, chemical-resistant suits, gloves, footwear (rubber boots), aprons, headgear, protective eyewear (goggles), and respirators to protect the body from contact with pesticides or pesticide residues (Figure 22). Employers must abide by the following guidelines associated with PPE for all workers or employees:

1. All required PPE, as designated on the pesticide label, must be cleaned daily. Each handler is legally responsible for wearing the required PPE when mixing and applying pesticides.
2. Handlers must wear the appropriate PPE when working with pesticides, which is also in accordance with the manufacturer's label instructions. Handlers wearing a respirator must be sure it fits tightly against the skin. As such, anyone with a beard cannot apply pesticides since the respirator will not fit tightly against the skin to prevent exposure from pesticide odors.

Figure 22
A pesticide applicator wearing appropriate personal protective clothing and equipment as specified on the label for the pesticide being applied.

3. Inspect all PPE prior to applying a pesticide for leaks, holes, tears, or worn places, and repair or discard any damaged equipment.
4. Handlers must be provided with a specific designated location, away from pesticide-storage and pesticide-use areas, to store personal clothing and PPE equipment. Moreover, this location must be such that handlers can wear all required PPE before coming into contact with any pesticide, and also wash PPE following application of a pesticide. Avoid having handlers apply pesticides when temperatures in the greenhouse exceed 85°F (29°C).
5. Do not allow any handler to wear or take home any PPE contaminated with pesticides. Employers must inform individuals who clean or launder PPE that such equipment may be contaminated with pesticide residues and as such provide information on potential exposure and how to safely handle PPE.

Pesticide Containers and Disposal

Always keep pesticides in their original containers. Never store in unmarked or household containers such as soda bottles, which may be inadvertently discovered by a child. If the label is missing and there is uncertainty regarding the contents, contact your local county hazardous waste management office for instructions. Do not reuse old unwashed pesticide containers since any residues may be potentially dangerous. Empty pesticide containers are a potential hazard due to the difficulty of removing all residues from within the containers. All pesticide containers must be triple-rinsed and punctured with holes before being sent to a landfill. However, each county and state has designated rules and regulations associated with disposing of pesticide containers. Contact your state-wide extension office to obtain more information regarding the disposal of pesticide containers.

Pesticide Toxicity (LD_{50} values)

Pesticide toxicity is categorized and quantitatively based on the LD_{50} value, which refers to the lethal dose of a toxicant (in this case, pesticide) that kills 50 percent of a test population of animals (rats, guinea pigs, or rabbits) in a designated time interval.

LD_{50} is expressed as milligrams (mg) of toxicant per kilograms (kg) of body weight. These values are then extrapolated to humans. The lower the LD_{50} value, the more toxic the pesticide, since less material is required to cause harm. LD_{50} values may be associated with both oral (ingestion through mouth) and dermal (absorption through the skin) exposure. In addition, there are two types of poisonings: acute and chronic. Acute refers to an illness or death from a single dose of a pesticide, whereas chronic involves illness or death due to long-term exposure to levels of a pesticide not high enough to kill in a single dose but that increase in toxicity over overtime. Pesticides in Category I have an acute oral LD_{50} (to rats) less than 50 mg/kg and are designated ***Highly Toxic***, and the words ***Danger*** and ***Poison*** along with a drawing of skull and crossbones on the label. Category II pesticides have an acute oral LD_{50} (to rats) between 50 and 500 mg/kg. These pesticides are designated ***Moderately Toxic***, and the word ***Warning*** is stated on the label. Category III pesticides have an acute oral LD_{50} (to rats) greater or equal to 500 mg/kg and are designated ***Toxic***, with the word ***Caution*** stated on the label.

Pesticide Application Methods

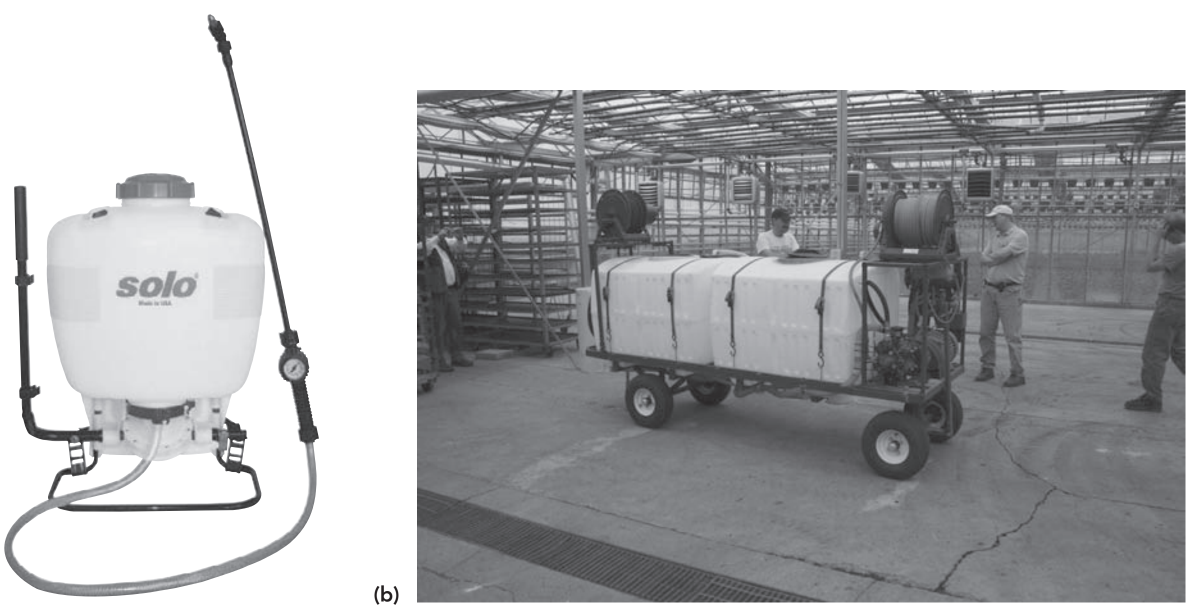
There are a number of application methods used to deliver pesticides in order to kill insect and mite pests. In some cases, more than one method may be needed to provide sufficient control of insect and/or mite pest populations during the crop production cycle. Moreover, application equipment type, weather conditions, plant type and stage of crop growth, age structure of insect and/or mite pest population, and size of area to be treated may influence which application method to use. In general, those pesticides applied as a spray have contact activity meaning that they kill insect and mite pests that directly come into contact with the wet residue. For example, some application methods such as aerosols, fogs, and smokes distribute fine spray droplets into the air so that any insects located on the crop are killed on contact. Although aerosols, fogs, and smokes are easy to use, only a limited number of pesticides are available in these formulations. In most cases, repeat applications are warranted when using pesticides with contact activity. However, some pesticides applied as sprays may kill insect or mite pests even after spray residues dry on the leaf surface. Translaminar insecticides and miticides actually penetrate leaf tissues and form a reservoir of active ingredient inside the leaf. This provides residual activity against insect and mite pests after the residues from the application dry. Systemic insecticides are those that are typically applied to the growing medium, and are formulated as either solids (granules) or liquids. The active ingredient is taken up by the roots and translocated (distributed) throughout the plant tissues (leaves and stems). Systemic insecticides applied to the growing medium may provide up to 10 weeks of residual activity, and possibly even longer depending on the systemic insecticide. The use of systemic insecticides, in some cases, may eliminate the need to apply foliar contact insecticides.

Spray Droplet Size Droplet size may influence the volume of spray solution required for effective coverage of plant parts. For example, if a droplet size of 200 microns is applied instead of 400 microns, then only one-eighth of the volume is required for effective coverage. If a droplet size of 100 microns is applied, this reduces the required spray volume again from one-eighth to one-sixty-fourth of the original volume. Droplet size uniformity is important so that the spray droplets will thoroughly cover all plant parts, particularly the underside of leaves where most insect and mite pest life stages are located. It is always recommended to avoid spraying pesticides during conditions of low relative humidity and high ambient temperatures since this will increase the evaporation rate of spray droplets.

High-Volume Application HV or hydraulic spray applications are commonly performed in greenhouses to deliver pesticides to target insect and/or mite pests feeding on greenhouse-grown crops. This type of application is commonly called wet spraying. The equipment required is typically less expensive than other pesticide delivery systems, and utilizes a spray pump providing moderate to high pressure with relatively high output. Furthermore, most pesticides are formulated for delivery using HV application equipment including SP, WP, and EC. The spray droplets emitted from HV application equipment are relatively large (100 to 500 microns). In addition, most HV application equipment is capable of delivering a spray volume of 50 to 100 gallons per acre (475 to 945 L/ha).

HV application sprayers may range from 1.0 to 4.0 gallon (4.0 to 15.0 L) capacity as hand-pressurized backpack sprayers to motorized (electric or gasoline motor-powered) sprayers with 10.0 to 200 gallon (40.0 to 750 L) capacity that use high pressures and flow rates (Figure 23), which results in the production of finer droplets. These finer spray droplets result in better coverage of plant parts although less solution is used. Larger sprayers are typically mounted on metal frames with wheels to allow for easy movement throughout the greenhouse. A hose attached to the sprayer unit can be moved along walkways so that applications to the crop may be performed on both sides of benches, thus allowing for better coverage of all plant parts. Nozzle sizes are an important consideration since they may vary in terms of the size of the openings, which will impact the droplet size emitted. The optimum pressure to ensure that the proper spray droplet size (small or large) is being emitted ranges from 200 to 1,000 pounds per square inch (psi) (1,380 to 4,140 kilopascal [kPa]) with flow rates between 0.5 and 4.0 gallons per minute (2.0 to 9.0 L/min). The pressure gauge installed on the sprayer unit should be monitored routinely to make sure the appropriate pressure is maintained.

In order to obtain thorough coverage of all plant parts, especially the undersides of leaves, the sprayer handle should be held at a 45° angle or a sprayer with several nozzles oriented at different angles may be used (Figure 24). The sprayer handle should be rotated in a sweeping motion so that all parts of the plant are covered with the spray solution. This will avoid localized outbreaks of insect and/or mite pests occurring on plants or plant parts that were not treated. Always mix enough solution



(a) (b)

Figure 23

A hand-pumped backpack sprayer (a) and a large motorized sprayer (b) typical of the size range of equipment used for high-volume spraying in greenhouses.

Figure 24
High-volume application of pesticide through a spray nozzle rotated at a 45° angle to the plants.

so that there is minimal remaining after completing the application, which avoids having to deal with surplus spray solution. If there is any extra spray solution, it is recommended to apply it to the crop. Furthermore, after use, it is important to thoroughly clean spray equipment by pumping clear water through the entire system at least three times. Also, be sure to apply a lubricant such as WD-40 or silicone to any moving parts and replace spray nozzles routinely.

Low-Volume Application Low-volume (LV) application refers to the amount of solution needed with equipment designed to create small or fine droplets (less than 100 microns in size) thus reducing the required volume necessary to obtain thorough coverage. Smaller spray droplets often cover more leaf surface area, resulting in less runoff, uniform coverage of plant parts, and sometimes less solution is needed in order to spray a greenhouse. Furthermore, smaller spray droplets may reach the interior canopy of plants more effectively than spray droplets greater or equal to 100 microns. This may also decrease pesticide use, worker exposure, and increase efficiency. It is important to understand that "low volume" does not mean a reduction in the amount or volume of pesticide used, but that less solution volume is required. LV application equipment typically uses less water and carrier during the application process. There are two types of LV application: targeted low volume and ultralow volume.

Targeted LV application sprayers use low flow rates and create small droplets that are 40 to 100 microns in diameter. Since the droplet size is larger than the ultralow volume droplets, they are less susceptible to air movement (drift) and they settle faster. However, targeted LV applications typically require more solution compared to ultralow volume since the droplets are larger. Furthermore, this spray technique involves more labor because targeted LV application is similar to hydraulic spraying; however, less water is needed and it is faster than performing applications with hydraulic sprayers. Spray equipment classified as targeted low volume include high-pressure systems, which use hydrostatic pumps and pressures greater than 1,000 psi along with low flow rates. In addition, specialized nozzles are commonly needed. The spray velocities created make it possible to rustle plant leaves and swirl the spray so that the solution can penetrate plant canopies. Examples of targeted LV equipment include cold foggers, directed aerosol generators, rotary disc atomizers, mist blowers, and electrostatic sprayers.

Rotary disc atomizers produce spray droplets that are 50 to 100 microns in size resulting in a lower volume of pesticide solution needed per acre (1.0 gallon or 10 L per hectare). The concentrated pesticide solution is delivered to a spinning disk either by gravity flow or under low pressure. The liquid moves by centrifugal force to the outer perimeter of the disk, where the small droplets spread out into the air. For some applicators, the centrifugal force continues to distribute the droplets onto the main crop. As such, a high proportion of spray droplets will land on the upper leaf surfaces unless the applicator is careful to direct the spray toward all plant parts.

An electrostatic sprayer produces small droplets that acquire a negative electrical charge as they are emitted. Because the droplets have a similar charge, they repel one another, thereby distributing themselves uniformly. Since the spray droplets have a negative electrical charge, they are highly attracted to plant surfaces, which have positive charges (opposite charges attract one another). In this way, the spray droplets may penetrate the inner canopy and reach the undersides of leaves. When using electrostatic sprayers, it is important to note that both air and the pesticide solution enter the nozzle from separate intake tubes. As the pesticide solution leaves the nozzle, it is sheared into 30- to 60-micron-size droplets by the air stream. The air-stream then propels the spray droplets toward plants.

Ultralow volume is the most efficient (based on ease and quickness) application method with equipment producing droplets of homogeneous particle size that are 5 to 25 microns in diameter, which provide even, uniform drift and coverage throughout the greenhouse. Due to the small size of the droplets, they tend to drift on air currents and disperse within a greenhouse, covering all surfaces. This system uses less water and there is no need for the applicator to walk down each aisle. Sprayers classified as ultra low volume include thermal foggers, aerosol generators, and total-release pesticides.

Some LV application sprayers are designed to be carried by the applicator throughout the crop, whereas others are positioned in a centralized location of the greenhouse without the need for an applicator. These stationary units are turned on and off, usually during the night, by a timeclock or computer (Figure 25). The

Figure 25

An ultralow-volume stationary fogger. Air is funneled under pressure through a venture nozzle where the pesticide formulation is siphoned into the air stream that atomizes it. This equipment is placed in a stationary position in the greenhouse. During the night, it is turned on automatically by timeclock or computer. The emitted 5- to 25-micron droplets move in the air stream circulated by the conventional convection tube or HAF air circulation system. After a set time period, often two hours, air is automatically evacuated from the greenhouse to prepare it for workers in the morning.

(Picture courtesy of Dramm Corp., P.O. Box 1960, Manitowoc, WI 54221–1960, Web: www.dramm.com.)

(a) (b)

Figure 26

(a) An aerosol applicator can containing Micro Total Release Insecticide. (b) A button is pressed at the top of the aerosol can to begin release of the aerosol into the greenhouse atmosphere. The can pictured treats 3,000 square feet of greenhouse.

(Pictures courtesy of BASF Professional Turf and Ornamentals.)

pesticide is loaded into a container, and then the unit is plugged into an electrical circuit. A computer is programmed to turn the unit on for a predetermined time interval during the night. Then convection tubes or HAF fans are used to circulate the spray solution throughout the greenhouse for a given period of time. At the end of the time interval, the computer activates exhaust fans so as to purge the greenhouse before entry by employees.

Aerosol Application Aerosols are another form of LV application (Figure 26). A number of pesticides (insecticides and miticides) are available in aerosol canisters. The propellants used in these cylinders are under pressure in liquid form as hydrocarbons such as isobutane and isopropane, and compressed carbon dioxide gas. When released into greenhouses, they expand into a gas and travel at a high velocity, distributing small droplets (15 to 20 microns). The carbon dioxide gas likewise expands when released.

The liquid droplets are small enough to be distributed on air currents, quickly dispersing throughout a greenhouse. After a designated time period, the fine droplets settle on the upper surfaces of plant leaves. Residues typically do not accumulate on leaf undersides unless plants are small. In general, the amount of insecticide to be applied is related to the volume of the greenhouse. Aerosol canisters are strategically positioned in the greenhouse typically on walkways or aisles prior to being released. Temperature may influence the effectiveness of aerosol applications so temperatures should be between 70° and 80°F (21° and 27°C). Greenhouse temperatures less than

60°F (16°C) result in inadequate distribution of the droplets, which may reduce effectiveness in controlling insect and/or mite pests. At temperatures greater than 85°F (29°C), plant injury may occur. The appropriate temperatures should be maintained in the evening hours of summer or in the late afternoon hours of winter. After applying an insecticide formulated as an aerosol, the greenhouse must remain closed for at least two hours. Furthermore, any moisture on plant leaves during an application may lead to plant injury. As such, plant foliage should be dry at the time of application.

Fog Application This LV application method is very similar to the use of aerosol canisters. Pesticides formulated as EC, WP, SP, or F may be applied with this type of equipment. The pesticide is diluted and then heated by a device that forms small droplets (10 to 60 microns), which are then propelled into the greenhouse. A white "fog" forms, which makes it easy to determine if all areas have been treated (Figure 27).

Fog application equipment may involve the use of a gasoline motor or propane burner, which may be carried on the applicators' back or transported through the greenhouse on wheels. Avoid directing the fog onto plants because any heavy deposits may result in injury to certain plant types. Additionally, the oils used may also be harmful to some plant species. Flowers, in general, tend to be more susceptible than foliage. As such, the fog should be directed into the greenhouse aisles. Any leaks in the greenhouse and prevailing wind conditions outside may make it difficult to obtain uniform distribution during the fogging application. Furthermore, any carbon buildup in the application equipment may impair distribution and effectiveness. Be sure to consult the manufacturers' instructions on the appropriate procedure to clean the equipment.

Smoke Application This is another form of LV application, and one of the easiest to perform although only a limited number of pesticides are formulated for this type of application. Small containers of a combustible material impregnated with

Figure 27

A thermal fogger. Gas from combustion of fuel moves down the barrel to the end where this force atomizes the pesticide formulation. Heat from the combustion helps to create a fog by thermally exciting the droplets. Larger units can propel fog hundreds of feet, treating an area of 50,000 square feet in 15 minutes.

(Picture courtesy of Dramm Corp., P.O. Box 1960, Manitowoc, WI 54221–1960, Web: www.dramm.com.)

the pesticide are placed in the center aisle of the greenhouse and ignited, usually with a sparkler. The pesticide is distributed with the smoke throughout the greenhouse. In general, pesticides formulated for smoke applications are less phytotoxic to plant foliage and flowers than aerosols and fogs. In order to determine how many containers to use, the greenhouse volume must be calculated and then this number is divided by the volume one container will treat. Be sure to follow manufacturers' recommendations as to use rates and precautions during application. Treated greenhouses must be ventilated one hour before personnel can reenter greenhouses. The following are precautions when using smoke, as well as aerosol and fog applications:

1. Do not make any applications when greenhouse temperatures are greater than 85°F (29°C) or less than 60°F (16°C).
2. Close all vents and turn off exhaust fans.
3. Avoid using these application methods when windy conditions persist outdoors.
4. Be sure that all plants within the greenhouse are well watered and the leaves are dry.
5. After the pesticide has been applied, follow the label instructions concerning the posting of warning signs on all greenhouse entrances.

Growing Medium Applications Insects that reside or inhabit the growing medium such as the larval stages of fungus gnats and shore flies may be killed directly by applying insecticides. Systemic insecticides may be applied as a drench or granule to the growing medium where the active ingredient is taken up by the roots and distributed throughout the plant, via the transpiration stream, into tissues where insects such as aphids, whiteflies, and mealybugs feed. If these insect pests ingest a lethal concentration of the active ingredient during the feeding process, they will be killed. Applying systemic insecticides to individual containers may be accomplished by using a small spoon or there is equipment that has been modified to meter out specific quantities of the material, which may be used to deliver systemic insecticide to large numbers of containers. Systemic insecticides should be uniformly applied over the surface of the growing medium, and then watered in to ensure uptake by plant roots and thus distribution throughout plant tissues. Furthermore, when applying granular formulations, be sure that plant leaves are dry so any granules will drop on the growing medium surface. After application, the granules should be watered, which will allow the root system to uptake the solubilized active ingredient. Avoid overwatering the growing medium for one week to prevent leaching out the active ingredient. Systemic insecticides should be applied only after plants have developed well-established root systems. Systemic insecticides provide the following benefits: (1) plants are protected throughout most of the growing season without the need for repeat applications; (2) less susceptible to UV light degradation or "wash off" following an application; (3) plants, in general, are less harmful to employees (workers) and customers when compared to plants that have been treated with a contact insecticide; and (4) minimal direct impact on natural enemies.

Systemic insecticides applied as drenches to root substrate are prone to leaching if overwatering occurs. When applied to the root substrate, systemic insecticides taken up by plant roots may provide up to 12 weeks of residual activity; sometimes longer depending on the systemic insecticide. However, the substrate applied active ingredient usually takes longer to be distributed throughout the plant, whereas systemic insecticides applied to the foliage may provide up to four weeks of residual activity but they typically provide quicker kill of target insect pests than drench applications.

Applications to the growing medium (root zone) must be performed when plants are actively growing and have extensive, well-established root systems so as to enhance uptake of the active ingredient. Uptake of the active ingredient is inhibited when plants do not have well-established root systems. Applications performed during warm, sunny days will lead to increased movement and distribution of the active ingredient through the transpiration stream. High relative humidity and low light conditions may lead to reduced uptake of the active ingredient. As such, any delayed uptake and movement of the active ingredient may result in the material taking longer to kill insect pests. Systemic insecticides, in general, are more effective when plants are herbaceous rather than woody, particularly on stem-feeding insects such as aphids, mealybugs, and scales. Systemic insecticides, when applied to the growing medium, need to be used preventatively in order to control phloem-feeding insects (aphids, mealybugs, whiteflies, and soft scales). If applied after insect populations have already established or plants have developed woody tissue, this may delay control, resulting in insect pest populations causing damage before ingesting enough active ingredient to kill them and in the meantime producing additional generations.

SUMMARY

1. Insect and mite pests can be a major problem when growing crops in greenhouses. The major insect and mite pests of greenhouse-grown crops include aphids, caterpillars, fungus gnats, leafminers, mealybugs, scales, shore flies, spider mites, thrips, and whiteflies. In addition, slugs and snails may be a concern in greenhouses. A holistic pest management approach should be implemented that maximizes effectiveness and minimizes reliance on pesticides (insecticides and miticides). This involves weed removal in and around the greenhouse since many types of weeds may harbor insects and diseases (viruses in particular). The greenhouse should be cleaned daily, and growing media should be pasteurized prior to planting. Newly introduced plants should be checked for insect and mite pests, and treated if necessary. Scouting or monitoring using colored sticky cards (yellow or blue) or visually inspecting plants should be performed routinely throughout every greenhouse, and diligent records should be maintained. Finally, pest management strategies including the use of pesticides (insecticides and miticides) and/or biological control agents (natural enemies) should be implemented prior to establishment and outbreaks of insect and mite pests.
2. Biological control involves periodic releases or applications of natural enemies such as parasitoids, predators, and/or entomopathogenic nematodes. The use of natural enemies must be initiated before insect and/or mite pests establish or reach outbreak proportions. Many natural enemies are commercially available from distributors or suppliers.
3. In order to avoid insect and/or mite pest populations developing resistance to commercially available pesticides (insecticides and miticides); it is important to rotate pesticides with different modes of action throughout the growing season. This will alleviate having to deal with insect and/or mite pest populations that may exhibit either cross (resistant to pesticides with the same mode of action) or multiple (resistant to pesticides with different modes of action) resistance.
4. There are a number of ways to apply pesticides in greenhouses including HV, LV, aerosol, fog, smoke, and drench. The method used will depend on several factors including the size of area to be treated and target insect and/or mite pests to be controlled. Pesticides must be used in accordance with the label and all recommendations associated with PPE and WPS must be followed accordingly.
5. Proper selection of pesticides and timing of applications is important in order to maximize effectiveness and avoid the potential of resistance developing in insect or mite pest populations.
6. Human safety is a major concern when applying any pesticide. Safety precautions include the following:
   a. Comply with state and federal regulations regarding safe applications of pesticides. In the United States, this is determined by the WPS. Be sure all required display posters are located in areas accessible by workers (employees).
   b. All pesticides must be stored in a designated, well-posted, environmentally controlled, locked

storage area or compartment that is located away from all eating and break rooms within the greenhouse facility. Eating, drinking, and/or smoking is prohibited in areas where pesticides are either stored or being applied.

c. Labels and the MSDS for all stored pesticides must be placed in a three-ring binder, which is accessible by all workers (employees). The original labels for each pesticide must be located on the designated pesticide containers.

d. Pesticide workers and/or handlers must be fully trained by employers and all personnel handling pesticides must be familiar with the toxicity of each pesticide that is being applied.

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Disease Management

Megan M. Kennelly
Kansas State University

Raymond A. Cloyd
Kansas State University

Diseases of greenhouse-grown crops can be very destructive. Most disease-causing plant pathogens have rapid life cycles, so epidemics can develop quickly. As such, preventing diseases from becoming established is critical. Plant pathogens may be introduced in water, in growing medium, in air currents, and on plant material, so steps must be taken to eliminate these points of entry. In addition, implementing proper cultural practices as well as making the greenhouse environment less favorable to pathogens is essential. Diligent scouting is also important, and if a disease develops, it must be properly identified in order to implement appropriate management strategies. This chapter will discuss (1) the major categories of disease-causing organisms, including examples of common diseases; (2) disease diagnosis and detection; (3) disease management strategies; and (4) disease control materials.

INTRODUCTION TO PLANT DISEASES

For a plant disease to occur, three factors must be present: (1) a virulent pathogen; (2) a susceptible host (the plant); and (3) environmental conditions (temperature, relative humidity, light) that favor disease development. In plant pathology, this concept is referred to as the *disease triangle*. Additionally, time for disease development and infection must be taken into consideration. As such, the following disease management strategies should be undertaken: (1) prevent the introduction of the pathogen; (2) implement appropriate cultural practices and make the environment less conducive to disease development; and (3) if possible, use resistant cultivars and species. All the interacting factors associated with the disease triangle must be considered when developing a comprehensive disease management program.

There are four categories of organisms that include most plant pathogens: fungi, bacteria, viruses, and nematodes. It is important to understand the characteristics of each group in order to manage them effectively.

Fungi

Fungi are multicellular organisms, much larger and structurally more complex than viruses or bacteria. Most of the pathogens described later are true fungi; that is, they are in the kingdom Fungi. However, there are several important plant pathogens (downy mildews, *Phytophthora*, and *Pythium*) that physically resemble fungi but belong to another group of organisms called *oomycetes* (also called water molds). This is an important distinction, because some fungicides labeled for true fungi are not effective on oomycetes, whereas some fungicides labeled for control of oomycetes have no activity on true fungi. For simplification, the word *fungi* will be used to describe both groups.

How Fungi Are Spread Most fungi and oomycetes reproduce and spread by microscopic spores that are dispersed within a greenhouse by means of air movement or water-splash. Fungi and oomycetes require certain temperatures in order to infect a host; however, different species may have slightly variable optimum temperatures. The spores of most fungal species require a wet (moist) plant surface in order to germinate and initiate an infection. Under optimal temperatures with moist or humid conditions, many fungi complete a full life cycle in only a few days, leading to rapid population growth. In their nonreproductive state, fungi and oomycetes proliferate as microscopic threads called *hyphae* or *mycelia*. Some species produce hard masses of mycelia called *sclerotia*, which serve as long-term survival structures.

Management of Fungi. Proper sanitation practices can prevent the introduction and spread of fungi. Manipulating the environment to be less favorable to disease-causing fungi can significantly reduce disease pressure. For example, reduce relative humidity and manage moisture to avoid prolonged periods of leaf wetness. Appropriate plant spacing and the use of raised mesh benches will improve air circulation. Sloped or gravel floors will allow water to drain away, thus lowering relative humidity. In situations where sanitation and environmental manipulation alone are not sufficient, fungicides may be applied. Fungicides will be discussed later in the chapter.

Common Fungal Diseases. Several common fungal and oomycete diseases of greenhouse-grown crops are described next. They are categorized by the type of disease: foliage and flower, root and crown, damping-off, and wilt.

Foliage and Flower Diseases Powdery Mildews. *Powdery mildew* is a general term that describes many plant pathogen species. Powdery mildews are host (plant) specific. For example, the powdery mildew of rose is caused by a different fungus than the one that infects poinsettia. Powdery mildew spores are spread from plant to plant by air currents. Powdery mildew appears as a white or gray powdery growth on the upper or lower surfaces of leaves, flowers, and stems (Figure 1). Some colonies are dense and easy to see while others are more diffuse. Observing a leaf at an angle, instead of straight down, makes it easier to observe the colonies. In addition, a 10x hand lens can aid in diagnosis. On some plant species, powdery mildew causes small, necrotic lesions. In some cases, the powdery mildew–infected tissue becomes twisted or distorted.

Cultural Management Most fungi require a certain period of leaf wetness for infection; however, powdery mildew does not since the spores can germinate on dry leaf surfaces. Powdery mildew is more severe when the relative humidity is greater than 90 percent. Thus, reducing relative humidity by venting and heating will decrease powdery mildew severity. In addition to environmental control, regularly scout plants, including the undersides of leaves, and rogue out infested plants.

(a)

(b)

Figure 1
Powdery mildew fungi grow as whitish colonies on leaves and flowers. (a) Powdery mildew on rose leaves. (b) Powdery mildew on African violet flowers.

Chemical Management Under certain conditions, fungicides are essential for powdery mildew control. There are several systemic and contact materials commercially available.

Downy Mildews. Unlike powdery mildews, downy mildews are oomycetes, not true fungi. Similar to the term powdery mildew, *downy mildew* refers to numerous species of plant pathogens. For example, downy mildew of rose is caused by a different species than the one that infects coleus. Most downy mildews of greenhouse-grown crops are in the genus *Peronospora*. Downy mildews cause a variety of symptoms depending on the host (plant). On some host or plant species, downy mildew causes yellow lesions on the upper leaf surface that may be restricted by leaf veins, resulting in a blocky, angular appearance. Downy mildew can become systemic, especially in young plant

Figure 2
Downy mildew sporulation is visible as fuzzy brown or purple growth on the undersides of leaves.

tissue, causing distorted growth. Under conditions of high relative humidity, downy mildews produce spores on stalks, which emerge through the host's stomates. Fungal sporulation appears as white, gray, or purple downy growth (Figure 2).

Cultural Management Downy mildews require high relative humidity (greater than 80 percent) for sporulation, and the spores require a wet or moist leaf surface on which to germinate. Thus, it is important to avoid high relative humidity and to minimize leaf wetness. Ventilate and heat to reduce relative humidity. Furthermore, avoid overhead irrigation and water-splash.

Chemical Management Fungicides are available for downy mildew management. Remember that downy mildews are oomycetes, and some materials for downy mildews are not effective against powdery mildews, and vice versa.

Botrytis Blight (gray mold). The fungus *Botrytis cinerea* causes gray mold on a wide range of greenhouse-grown crops. Under humid conditions, the pathogen sporulates profusely making it easy to recognize due to the fuzzy gray appearance (Figure 3). Spores are produced on the tips of the "fuzz" and spread from plant to plant through air currents or water-splash. The disease is commonly present during periods of cold, cloudy weather when air movement is reduced and relative humidity in the greenhouse is greater than 85 percent. *Botrytis* attacks different parts of the plant including stems, leaves, and petals. The fungus is considered to be an "opportunistic" pathogen, since it tends to affect weak, wounded, succulent, or senescing tissues. *Botrytis* rarely infects healthy, unwounded plant tissues. For example, stem infection occurs most commonly on wounded cuttings or small seedlings. Senescing leaf and flower parts are also highly susceptible, and the infected leaves and petals can spread *Botrytis* after falling onto lower leaves or onto plants located underneath benches (Figure 3).

Cultural Management *Botrytis* requires high relative humidity (greater than 85 percent) to sporulate and six to eight hours of leaf wetness for the spores to infect host tissues. Therefore, cultural controls that reduce relative humidity and leaf wetness

(a)

(b)

Figure 3
Botrytis cinerea, *cause of gray mold, sporulates profusely under conditions of high relative humidity. (a) Gray mold on senescing tissues. (b) Botrytis spreading from infected tissue that has fallen onto a geranium leaf.*

will decrease disease pressure. It is important to ventilate, heat, and use horizontal airflow (HAF) fans to reduce relative humidity. Moreover, space plants appropriately, and use raised mesh benches to improve air circulation. Consider using drip rather than overhead irrigation to minimize leaf wetness. In addition, implement proper sanitation practices and routinely remove senescing plants and tissues such as old flowers that can harbor the fungus. Immediately place all plant debris into a sealed plastic bag to avoid spreading spores. Also, do not store old plant debris in unsealed trash containers in the greenhouse, because this may serve as a source of spores for new infections.

Chemical Management Fungicides may be required under certain greenhouse conditions, and numerous products are available. Some populations of *Botrytis* have developed resistance to a number of fungicides, so follow all label instructions regarding resistance management.

Root and Crown Diseases *Rhizoctonia* and *Thielaviopsis* are true fungi, while *Phytophthora* and *Pythium* are oomycetes. These root-rot pathogens are spread by means of infested growing medium, pots, water, or plant debris. Some root diseases are favored by wet or moist growing medium. Therefore, for root-rot pathogens, it is critical to implement proper sanitation practices and water management.

Pythium Root Rot. *Pythium* is an oomycete that causes a dark brown to black rot, which often results in softening of roots. The plants may also appear chlorotic, and the root cortex (outermost tissue) will slough off easily leaving a “rat-tail” appearance (Figure 4). The disease may occasionally attack the lower stem tissues.

Cultural Management *Pythium* is favored by cool, wet, poorly drained growing medium. Avoid overwatering, and use a growing medium that drains well. Utilize drip irrigation, and carefully monitor water output. In addition, do not reuse old growing medium. If reusing pots, be sure to clean and disinfest them beforehand. Avoid irrigating with pond or river water that may contain *Pythium* spores. Furthermore, monitor and manage greenhouse environmental conditions and growing medium temperatures. *Pythium* development is favored by excessive soluble-salt contents in the growing medium, so avoid overfertilizing plants and regularly check the pH and electrical conductivity (EC) of the growing medium.

Chemical Management There are products commercially available for control of *Pythium*; however, some *Pythium* strains have developed resistance to certain fungicides. As such, always follow all label instructions regarding resistance management.

Phytophthora Root Rot. *Phytophthora* is an oomycete that causes root, stem, and crown rots. Leaves may appear yellow or wilted, and entire plants may be stunted.

Figure 4
Plants infected with Pythium *root rot are often chlorotic, and the outermost root tissue sloughs off easily leaving a slender “rat-tail” appearance.*

Infected roots turn black, and the cortex may slough off as described for *Pythium* root rot.

Cultural Management Similar to *Pythium*, *Phytophthora* occurs commonly in wet, poorly drained growing media. Follow the same recommendations for *Pythium*.

Chemical Management There are products commercially available for control of *Phytophthora*; however, a number of *Phytophthora* strains have developed resistance to certain fungicides. Refer to current recommendations and follow all label instructions regarding resistance management.

Rhizoctonia Root and Crown Rot. The fungus *Rhizoctonia solani* has a wide host range causing brown or tan lesions that appear drier than those caused by *Pythium* or *Phytophthora*. *Rhizoctonia solani* is favored by warm temperatures (greater than 75°F or 25°C), high relative humidity (greater than 80 percent), and an intermediate range of moisture: neither too wet nor too dry. Cankers formed by *Rhizoctonia* usually appear at the surface of the growing medium and progress upward, causing stems to become constricted. Stem cuttings are particularly susceptible, and roots may also be affected. On some plants, *Rhizoctonia* can develop on aboveground plant parts, growing as cobweb-like mycelium on stems or leaves.

Cultural Management *Rhizoctonia* can be introduced in contaminated growing media, pots, and plant debris. Practice good sanitation during all phases of production, and keep potting and growing areas free of growing media and plant debris. Additionally, remove and discard infected plants, and avoid splashing water from pot to pot.

Chemical Management There are a number of commercially available fungicides labeled for control of *Rhizoctonia* that are applied as foliar sprays or drenches to the growing medium.

Thielaviopsis Root Rot (black root rot). The fungus *Thielaviopsis basicola* infects a wide range of greenhouse-grown crops. *Thielaviopsis* causes a drier-appearing lesion than *Rhizoctonia*, and lesions often turn black due to the presence of abundant black fungal spores. However, in the absence of spores, the lesions are brown and may be mistaken for *Rhizoctonia*. Infected plants appear chlorotic, wilted, or stunted. High growing medium pH (greater than 6.8) and poor drainage promote *Thielaviopsis* root rot.

Cultural Management Disease pressure is significantly lower at growing medium pH levels greater than 5.5, so consider growing plants at a pH of 4.5 to 5.0 if appropriate for the plant species. *Thielaviopsis* can be spread by fungus gnats and shore flies. Additionally, *Thielaviopsis* may be introduced by means of growing media, so be sure to sterilize growing media, use sterile pots, and implement appropriate sanitation practices.

Chemical Management There are a number of commercially available fungicides labeled for control of *Thielaviopsis* that are usually applied as foliar sprays or drenches to the growing medium.

Damping-Off Diseases *Damping-off* is a broad term used to describe several diseases of seedlings. *Pre-emergence damping-off* refers to seed decay before germination or rot of seedlings before they emerge from the growing medium. This type of damping-off is commonly caused by *Pythium* and *Phytophthora. Post-emergence damping-off* refers to stem or crown rots that occur soon after emergence. This type of damping-off is commonly caused by *Rhizoctonia* but may also be caused by *Botrytis* and *Fusarium*.

Cultural Management Many damping-off pathogens are spread by means of infested growing media or plant debris. As such, be sure to thoroughly clean and disinfest all pots and potting benches. Furthermore, avoid leaving hose ends on the ground where they might become contaminated by damping-off pathogens.

Chemical Management Fungicide-treated seed is available for some crops in order to inhibit damping-off pathogens. Fungicide applications should be avoided if possible, since germinating seeds and seedlings are susceptible to phytotoxic reactions. Growing media incorporated with beneficial microbes and other biological control agents are available, which may reduce disease pressure.

Wilt Diseases Wilt-causing fungi usually infect through the roots and then invade the vascular tissues, disrupting water flow and nutrient uptake by the plant. The two primary wilt diseases of greenhouse-grown crops are *Verticillium* and *Fusarium*.

Verticillium Wilt. *Verticillium* is a fungus that infects a wide variety of ornamental plants. Symptoms vary depending on the host but may include yellowing of leaves or leaf margins, leaf necrosis, and wilting of leaves or entire plants. Dark streaking is sometimes visible in the vascular tissue when stems are cut. The pathogen can be spread in cuttings. It is important to note that some infected plants may remain symptomless.

Cultural Management Use *Verticillium*-free propagation material from indexing programs (see “Virus” section in this chapter). However, be sure to practice good sanitation to avoid the spread of infested growing media, and always use soilless growing media.

Fusarium Wilt. *Fusarium* infects a number of greenhouse-grown crops including cyclamen, lisanthus, and chrysanthemum. Symptoms include leaf yellowing, necrosis, and wilting. In fact, entire plants may wilt. Dark or brown streaking is sometimes visible in the vascular tissue when stems are cut. *Fusarium* can also cause damping-off of seedlings.

Cultural Management Practice good sanitation to avoid the spread of infested growing media, and always use soilless growing media. This disease may be spread by fungus gnats and shore flies.

Chemical Management Preventative fungicides are commercially available and labeled for *Fusarium*.

Bacteria

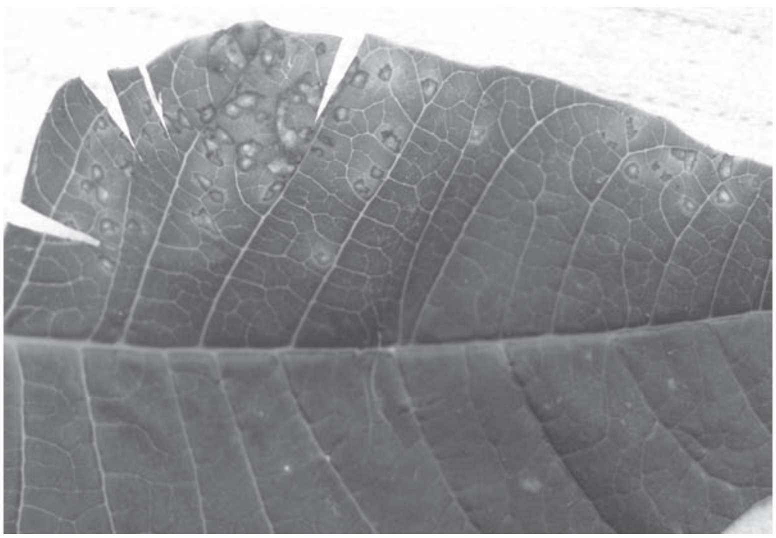
Bacteria are single-celled organisms with a cell wall. They are approximately 0.001 to 0.002 millimeters in size, and can be observed using microscopes with 400x magnification. Bacteria divide by “fission,” meaning one cell divides and becomes two daughter cells. Bacteria can undergo fission and multiply very quickly. For example, some bacterial species can multiply from one cell to millions of cells in 24 hours. Bacteria, in general, cause a wide range of symptoms including leaf spots, wilts, galls, and cankers.

Spread of Bacteria Bacteria are favored by wet or moist surfaces and can be spread by means of splashing water, infested growing medium or plant debris, and in some cases, infested seed. Some bacteria are spread by insect vectors.

Management of Bacterial Diseases Start with clean plant material and implement proper sanitation practices such as disinfesting tools and benches. Avoid excessive moisture and high relative humidity. Consider utilizing drip irrigation to reduce water-splash. Always be sure to discard infected plants. There are a few commercially available bactericides, but these are not very effective, particularly when an outbreak has begun. As such, management of bacteria is achieved primarily through prevention, sanitation, environmental control, and removal of infected plants.

Examples of Common Bacterial Diseases Some common bacterial diseases of greenhouse-grown crops are described next. The scientific names of bacteria are being revised as researchers discover new information about their taxonomy. For nearly all bacterial diseases, the management recommendations described earlier are relevant. Additional management strategies are presented here for several specific diseases.

Bacterial Leaf Spots (general). There are many bacterial species that cause leaf spots on various hosts (plants). The bacterial genera *Pseudomonas* and *Xanthomonas* include several common leaf spot pathogens. Lesions may be circular, angular, or sometimes wedge shaped (Figure 5). Moreover, lesions sometimes have a yellow halo or appear water soaked. Leaf spot–causing bacteria are spread by splashing water, so water and relative humidity management are critical.



(a)

(b)

Figure 5
Bacterial leaf spots can be round, wedge-shaped, or angular as shown here in symptoms of Xanthomonas *leaf spots of poinsettia (a) and ivy (b). These leaf spots also have a chlorotic (yellow) halo that occurs with some bacterial diseases.*

(Poinsettia photo by Megan Kennelly, Kansas State University. Ivy photo courtesy Janna Beckerman, Purdue University)

Bacterial Wilt of Carnation. This is a vascular wilt caused by *Burkholderia caryophylii* (also called *Pseudomonas caryophylli*). The pathogen infects the vessels, causing yellowing and wilting of foliage, stem cracking, stem cankers, and sometimes root rot. Dark streaking may be visible in the vascular tissue. This disease can be spread by taking cuttings from infected plant material. As always, use disease-free plant material.

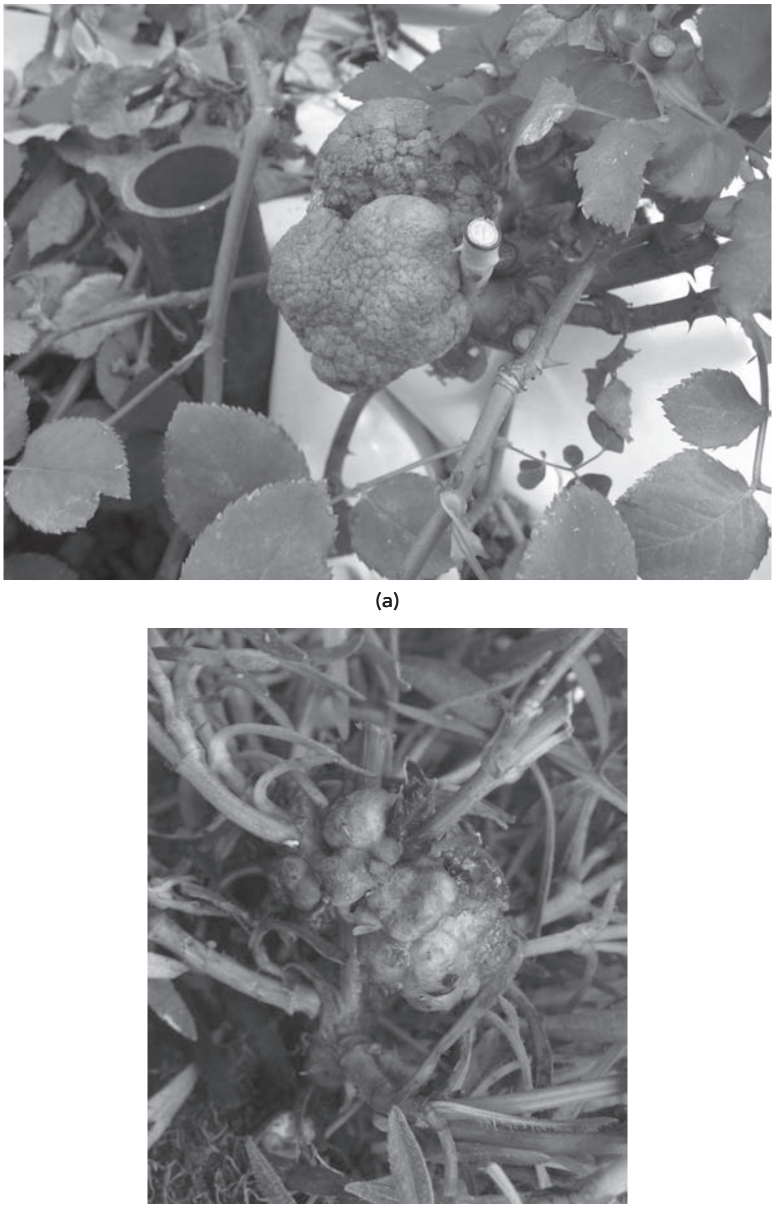
Bacterial Soft Rot. Soft rot is a wet, foul-smelling rot of cuttings, corms, and bulbs. Oftentimes the entire plant collapses. Soft rot is caused by several species in the genus *Dickeya* (formerly *Erwinia*), which may infect a wide range of greenhouse-grown crops. The pathogen enters the host (plant) through wounds and can be spread on infested tools, by using infected plants for propagation, as well as the movement of infested plant debris or water-splash. It is important to use disease-free propagation material and sterilize cutting tools. If possible, use bottom heat to encourage root growth during cutting production.

Bacterial Fasciation. This disease is caused by *Rhodococcus fascians* and the symptoms include stunting or a broom-like proliferation of shoots. The disease commonly occurs in carnation, chrysanthemum, geranium, and petunia, but the bacteria may also infect many other plant species. Be sure to discard infected plants, and examine new stock in order to avoid introducing this disease into the production facility.

Crown Gall. Crown gall is caused by *Agrobacterium tumefaciens* and is common on rose, chrysanthemum, and geranium; however, many other species are susceptible. The disease usually causes swelling and galling of host tissue at the crown, but galls are occasionally found on roots or branches. Young galls are cream colored and smooth, whereas older galls appear rough and woody in texture (Figure 6). Infected plants should be discarded immediately. Bacteria are easily spread on tools, so be sure to disinfest tools regularly. The pathogen survives in soil or growing medium, so growing media that contain soil should be sterilized.

Bacterial Wilt (southern wilt). This disease is caused by *Ralstonia solanacearum* and results in yellowing and wilting of plant leaves. This pathogen has a wide host range, but in recent years it has been particularly problematic on geranium. There are different subgroups of *Ralstonia solanacearum* called "races," and some races are serious pathogens of several food crops such as potato. A group called race 3, biovar 2 is a quarantined pathogen that affects geraniums and potatoes. When race 3, biovar 2 is detected, federal quarantine officials (from the U.S. Department of Agriculture) may order destruction of all crops within the greenhouse. Therefore, proper diagnosis is critical for this disease. As always, start with disease-free indexed plants, and separate different shipments of cuttings in order to easily track the source. Furthermore, avoid hanging geraniums above other greenhouse-grown crops.

Bacterial Blight of Geranium. This disease is caused by *Xanthomonas pelargonii*. Leaves on infected plants develop small spots (1.6 to 3.2 mm) or wedge-shaped yellow areas. The disease can become systemic, causing plants to wilt during hot, humid weather. Disease-free plant material is available from indexing programs. As with most bacteria, avoid water-splash and practice good sanitation to prevent spread of the bacteria. Also, avoid hanging geraniums above benches with other geraniums. Immediately remove and discard symptomatic plants. Be sure to exercise extreme care when handling stock plants. Grow geranium cuttings and seed-grown or rooted cuttings in separate greenhouses. Disinfect cutting tools and disinfest the production area between crops. During the wilt phase, this disease is sometimes confused with the *Ralstonia* disease described earlier, but *Ralstonia* does not cause leaf spots. Finally, due to the quarantine implications for *Ralstonia*, it is important to obtain an accurate diagnosis.



(a)

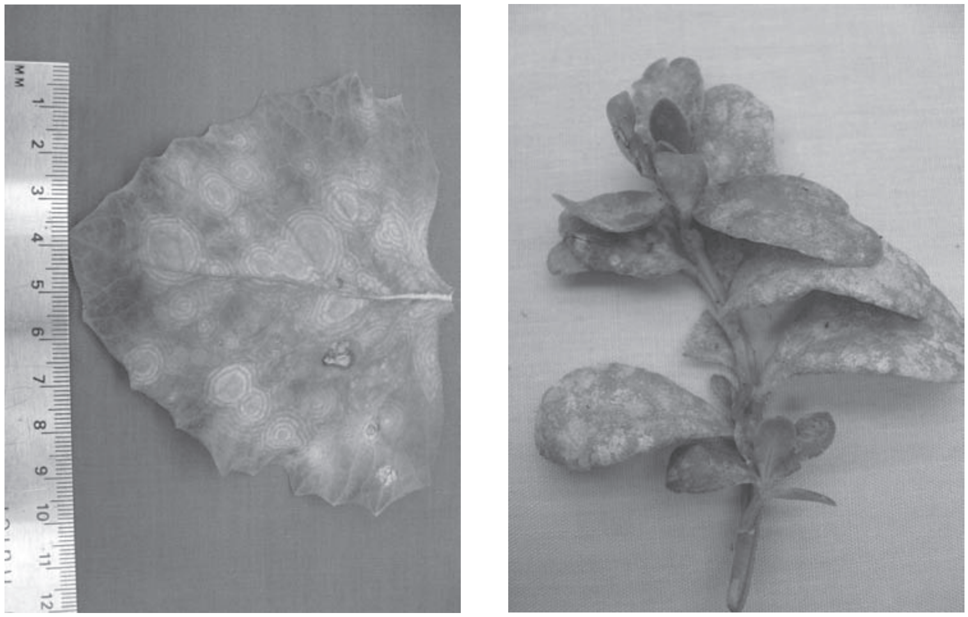
(b)

Figure 6
Crown gall, caused by Agrobacterium tumefaciens, *causes swollen growths on many plant species, including rose (a) and coreopsis (b).*

Viruses

Viruses are minute particles composed of DNA or RNA surrounded by a protein coat. They range in size from 0.00003 to 0.002 millimeters, and they can be seen only with the aid of an electron microscope. Viruses utilize the host plant's cellular machinery to multiply and survive, and therefore they require a living host (plant). Once a plant is infected with a virus, it is systemically infected for life, even if the symptoms become masked or the infected plants appear to grow out of it. Viruses spread from cell to cell within the plant. Plants have no immune system to eradicate viruses, and infected plants can be a source of disease for later crops.

Symptoms Caused by Viruses In general, viruses alter the normal growth of the host (plant) causing unusual colors, textures, and sizes. Symptom expression varies



(a) (b)

Figure 7
Viruses often cause unusual patterns such as ringspots and mosaic patterns. (a) Ringspot symptoms of tomato spotted wilt virus on emelia. (b) Mosaic symptoms of papaya mosaic virus on purslane.

based on the species and/or cultivar, which can complicate diagnosis. Leaves may develop abnormally colored spots, streaks, blotches, mottling, or mosaic or ring patterns (Figure 7). Leaves may also become distorted, with puckering, thickening, or rolled margins (Figure 8). Similar to leaves, petals may develop abnormal coloration such as streaking. Petals may also appear faded or green, or even develop into leafy tissue. Some viruses can cause necrosis, or death of host tissue. Entire plants may be stunted or deformed; however, some infected plants may exhibit no apparent symptoms, thus acting as “symptomless carriers” or “sleepers.”

Spread of Viruses Viruses cannot move from plant to plant by themselves. As such, many viruses are spread by insects. Insects that transmit plant viruses to

Figure 8
Puckering and distortion caused by hosta virus X.

greenhouse-grown crops include aphids, thrips, and whiteflies. The general term for insects that spread pathogens is *vector*, and an important component of managing viral diseases is by controlling the vector. For example, in order to prevent impatiens necrotic spot virus (INSV), it is essential to control the vector, the western flower thrips (*Frankliniella occidentalis*). Other viruses, such as hosta virus X (HVX) and tobacco mosaic virus (TMV), are spread mechanically, such as by transfer of infected sap on pruning tools. Some viruses are spread by cuttings and other propagation methods such as grafting. Furthermore, several viruses, such as tomato ringspot virus and tobacco ringspot virus (which affect geraniums and other ornamentals), are seedborne.

Management of Viruses There is no cure for viruses, so any infected plant should be discarded immediately. To prevent the introduction of viruses into the greenhouse, start with virus-free plant material. The use of pathogen-free propagation materials from virus indexing programs (described later) is extremely important in any disease control program, particularly for viruses due to their long-term, systemic nature and lack of postinfection controls. Indexing is used to eliminate viruses from the propagative material of many plant species. It is important to note that virus-indexed plants are not resistant to viruses; they can still become infected at later stages.

Several techniques are used in virus indexing programs, including serological (antibody-based) assays, DNA/RNA detection assays, and/or by inoculating indicator plants that develop diagnostic symptoms. Each test is designed for a specific virus. Diseases of several greenhouse-grown crops for which indexing programs for viruses and other pathogens have been developed are listed in Table 1.

Table 1
Examples of Greenhouse-Grown Crop Diseases for Which Indexing Programs Have Been Developed[1]

Crop	Type of Organism	Disease
Chrysanthemum	Fungus	Verticillium wilt
	Virus	Chrysanthemum stunt
		Chrysanthemum mosaic
		Chrysanthemum aspermy
		Chrysanthemum chlorotic mottle
Carnation	Fungus	Phialophora wilt
		Fusarium wilt
	Bacterium	Bacterial wilt (*Ralstonia*)
	Virus	Carnation mottle
		Carnation ringspot
		Carnation mosaic
		Carnation streak
		Tomato spotted wilt
		Carnation etch-ring
		Necrotic fleck
Geranium	Fungus	Verticillium wilt
	Bacteria	Bacterial blight (*Xanthomonas*)
		Bacterial wilt (*Ralstonia*)
	Virus	Tomato ringspot
		Tobacco ringspot
		Pelargonium flower break

[1]Bennett et al. (2008).

Examples of Common Greenhouse Viruses New plant viruses are discovered every year so it is important to stay informed through extension and trade publications, and workshops, in order to be aware of new viral diseases. Viruses are generally named based on the symptoms expressed in the plant species in which they were first discovered. Many viruses may infect multiple species. The following are examples of some common greenhouse viruses.

Impatiens Necrotic Spot Virus. INSV is one of the most damaging viruses in the greenhouse industry. It is classified as a tospovirus. INSV has an extremely broad host range, including many weeds. This virus is vectored by the western flower thrips, an insect pest that is widespread and difficult to control. Symptoms vary with the host (plant), but may include ringspots or necrotic lesions.

Tomato Spotted Wilt Virus. TSWV is another tospovirus that has a wide host range and is vectored by a number of thrips species. Symptoms vary with the host, but may include lesions or mottling of foliage.

Hosta Virus X. HVX is a disease of hosta causing a variety of symptoms including mottled colors, dark green streaking along veins, and leaf distortion (Figure 8). This virus is spread by means of contaminated tools and through propagation of infected source plants. It is important to note that some hosta cultivars do not display symptoms when infected.

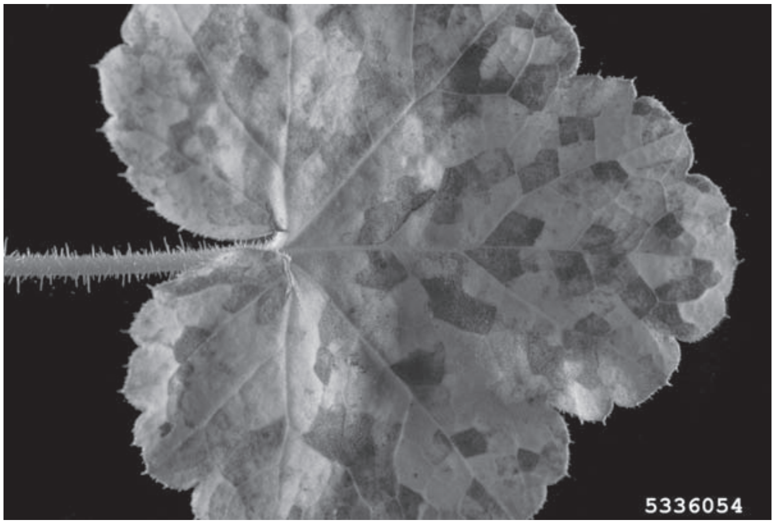
Tobacco Mosaic Virus. TMV infects plants in the potato family (Solanaceae). Depending on the host (plant), TMV causes mosaic patterns, mottling, yellowing, stunting, leaf curl, and necrosis. This virus is spread by contaminated tools and hands. TMV is very stable, and workers who contact the virus by means of infected tobacco in cigarettes can then spread the virus to plants by handling them. TMV can also be spread by seed.

Nematodes

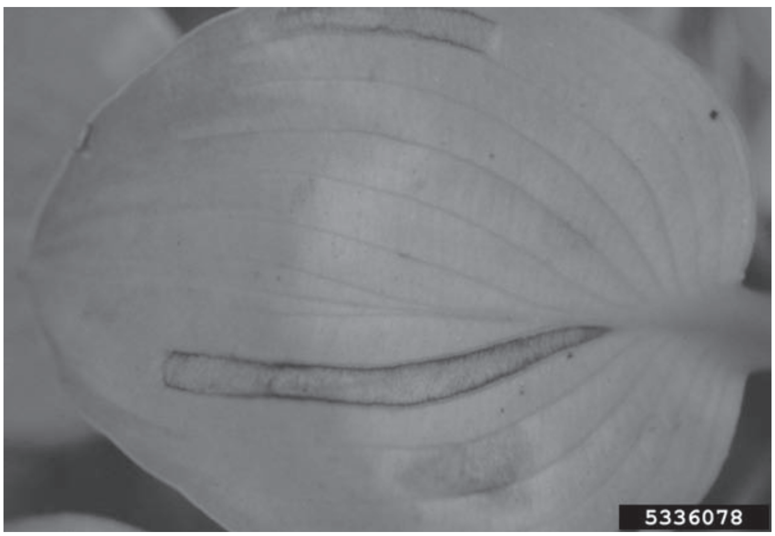
Nematodes are microscopic roundworms, 0.5 to 5.0 millimeters long, which usually live in soil. A typical nematode life cycle includes an egg, several juvenile stages, and an adult stage. Many nematode species are beneficial organisms that help cycle nutrients in field soils. However, plant-parasitic nematode species can be damaging by infecting either roots or leaves. They have a needle-like mouthpart called a *stylet* that is used to feed on plant tissue. Plant-parasitic nematodes are present in nearly all field soils, and they are spread through the movement of soil on shoes, via pots or equipment, or in contaminated plant material. Nematodes are rarely a problem in a soilless growing medium, and they should not be a problem in a soil-based growing medium that has been steam sterilized. There are no nematicides registered for use in greenhouses.

Foliar Nematodes There are several species of foliar nematode in the genus *Aphelenchoides*. Nematodes enter hosts (plants) through wounds or natural openings and may be spread by tools, by water-splash, and through propagation. Foliar nematodes cause leaf lesions that are restricted by the major leaf veins (Figure 9). Thus, the shape of the lesion varies with the vein pattern. For example, lesions on chrysanthemum are often V-shaped, whereas on hosta the lesions appear as elongated rectangles.

Management of Foliar Nematodes. Plants infested with foliar nematode should be discarded immediately. Do not use infected plants for propagation. Remove and discard all plant debris, and carefully inspect stock to avoid introducing foliar nematodes into greenhouses. It is recommended to use drip irrigation instead of overhead irrigation to avoid splashing water from plant to plant.



(a)



(b)

Figure 9

*Symptoms of foliar nematode on coralbells (*Huechera sanguinea*) (a) and hosta (b). Lesions are blocky in appearance, limited by major leaf veins.*

(Photos courtesy Jonathan D. Eisenback, Virginia Polytechnic Institute and State University, Bugwood.org.)

DISEASE DETECTION AND DIAGNOSIS

Some plant diseases can be readily diagnosed based on their symptoms, but many are difficult to identify. In addition, it is easy to confuse certain disease symptoms with problems caused by abiotic problems such as nutrient imbalances, over- or underwatering, or inappropriate growing medium pH. It is important to stay informed of newly emerging diseases, and develop a library of printed and electronic resources for reference when symptoms occur. Learn which diseases are likely to occur on specific greenhouse-grown crops. When the disease is difficult to identify based on visual symptoms, consider contacting a state or regional plant disease diagnostic laboratory. An appropriate sample with detailed background information is critical in order to obtain a timely and accurate diagnosis. If possible, send an entire plant, including roots. Some laboratories offer soil-testing packages to determine if the problem is associated with nutrition. Be sure to send the sample in a sturdy container with packing material, and ship the sample early in the week or through an overnight service so that the sample does not remain in transit over a weekend. In addition to the physical sample, it is important to provide information regarding the spatial pattern, timing of symptom appearance, cultivars affected, fertility program, and recent pesticide applications. Digital or printed photographs are useful in providing additional background information.

Several companies sell test kits that can be used on-site to determine if a plant is infected with a certain pathogen. These tests can be conducted in a time frame ranging from a few minutes to about an hour. Many tests involve grinding leaf tissue from a plant displaying symptoms in a mesh bag or tube with chemicals provided by the company. There are test kits for several greenhouse fungi, bacteria, viruses, and nematodes.

DISEASE MANAGEMENT

Disease management in greenhouses requires integrating a variety of strategies during all phases of production. The following are the cultural practices that must be implemented in order to reduce disease problems in the greenhouse.

Start with Clean Plant Material

Select plant sources carefully to avoid introducing infested plant materials, and use indexed material if possible. Despite this, an occasional pathogen may be present on purchased plant material. Therefore, hold incoming plants in an isolated area and inspect them promptly for disease symptoms. Use colored (yellow or blue) sticky cards to check for the presence of insect vectors. Inspect the new plants again after several days. If a disease (or any other pest) is present, either discard or immediately treat (may be possible with some diseases) the plants. However, virus-infected plants must be discarded. If a disease is present that has not been observed previously, consider contacting a state or regional diagnostic laboratory or representative from the department of agriculture. Notifying state authorities may help prevent the introduction of an exotic disease.

Maintain Clean Stock Plants

Maintain a diligent disease prevention program for stock plants. Carefully inspect stock plants regularly, and avoid taking cuttings from any infected plants. Be sure to discard any plants displaying disease symptoms. Always sterilize tools periodically by dipping them in alcohol (rubbing alcohol). Transport cuttings in clean containers and sterilize all work surfaces. Furthermore, it is important to wash hands after handling plant material, or use clean disposable gloves.

Use Resistant Species and Cultivars

If possible, utilize plant material that is resistant to diseases. For example, vegetable cultivars are available with resistance to certain viruses, and some hosta cultivars are reported to be less susceptible to HVX. There are some hydrangea cultivars with reduced susceptibility to powdery mildew. Be sure to stay informed of any new developments in disease resistance breeding.

Sterilize Pots and Tools

Clean and sterilize all pots, tools, flats, and wire or plastic supports. A 10 percent bleach solution is one option; however, there are other commercially available disinfestant products. A new batch of bleach solution should be prepared after several hours since the active constituents lose activity, and any growing medium will bind to bleach. Always be sure to follow all safety guidelines on the label.

Use Clean Growing Media

Do not reuse growing media from a previous crop or growing media that may have come into contact with contaminated water, field soil, or plant debris. Try to always use fresh soilless growing media. If a soil-based growing medium is used, it should be steam sterilized to kill any pathogenic organisms. Containers of growing media should be covered to prevent the introduction of dust or plant debris. In addition, water should not be allowed to drip into growing media storage containers. Avoid spreading soil or spilled growing media from the greenhouse floor onto benches by means of contaminated brooms or hoses.

Sterilize Potting Benches

Keep potting benches clean and avoid accumulating pots, tools, growing media, and plant debris. Use a broom to remove debris from benches, but do not use a broom that is primarily used to clean floors.

Clean Up and Discard All Plant Debris

Discarded plant material should never be stored in production areas. Poorly rooted cuttings, pinched tops of plants, and diseased tissues should be promptly placed into secured plastic bags or sealed garbage containers. In addition, remove old, declining plants and do not retain plants from one cropping cycle to the next. Discarded plant debris and growing medium should never remain in the greenhouse. All plant and growing medium debris should be placed in a compost pile or refuse site far enough away from the greenhouse so that any pathogen-infested debris or vectors will not be distributed back to the greenhouse.

Manage Relative Humidity and Leaf Wetness

Many pathogens require leaf wetness and/or high relative humidity to reproduce and cause an infection. Warm air holds more moisture than cold air, so heating and venting will reduce relative humidity. HAF fans will also reduce relative humidity and leaf wetness. In addition, irrigate during the day to promote rapid drying of plant leaves. If possible, incorporate gravel or sloped concrete floors to reduce the accumulation of standing water. Furthermore, grow plants on raised mesh benches, and provide adequate spacing between plants. Finally, utilize irrigation methods such as subirrigation that do not wet plant leaves.

Manage Growing Medium Moisture

A number of root-rot and damping-off diseases are promoted by high moisture levels in the growing medium. As such, a well-drained growing medium should always be used. In addition, watering too frequently encourages development of many root-rot pathogens. Drip or subirrigation minimizes the splashing of growing medium from pot to pot and eliminates the use of a nozzle, which may spread contaminated growing medium.

Remove Weeds

Weeds may harbor insects and diseases.

Scout Crops and Maintain Records

Scouting is essential when implementing a disease management program. Many diseases can spread quickly, and are easier to manage if detected early. It is essential to maintain detailed notes on the timing, location, symptoms, and host species and cultivars affected.

DISEASE CONTROL MATERIALS

The primary approach to disease control should be an integrated program that utilizes the cultural practices described earlier. In some cases, pesticides (fungicides and bactericides) may be necessary. An established scouting program will help determine specific crops and areas within the greenhouse that require treatment with a pesticide.

Pesticide labels change frequently so contact state extension personnel for the most current information associated with pesticide recommendations. Additionally, trade magazines, workshops, and conferences may provide current information on pesticides and their use. Remember, the label is the law so always read the pesticide label prior to making any pesticide applications. Be sure the crop is listed and that the product (fungicide or bactericide) is labeled for greenhouse use. It is important to note that certain pesticides labeled for greenhouse-grown ornamentals may not be labeled for greenhouse-grown herbs and vegetables. Furthermore, certain disease control products can be phytotoxic to different plant species or cultivars. Many pesticide labels include information about phytotoxic interactions, so read the label thoroughly. In addition, products used incorrectly such as applying twice the label rate or applying the pesticide too frequently may result in phytotoxicity. Remember that products labeled for true fungi and oomycetes may be different in terms of the types of diseases controlled.

Fungicides

Similar to insecticides, fungicides are grouped by their mode of action. Contact fungicides, which are also referred to as protectants or preinfection materials, need to be present on the plant surface in advance of a pathogen infection. Contact fungicides remain on the plant surface, and are not taken up systemically. As a result, thorough coverage is important since the material is not systemic and needs to be uniformly distributed on the plant surface to ensure contact with the pathogen. Most contact fungicides either bind to or chemically modify the amino acid cysteine, a reactive amino acid involved in numerous cell functions. Contact fungicides, in general, have broad modes of action, affecting multiple processes within the fungal cells. Thus, it is unlikely that pathogens will develop resistance to contact fungicides. Examples of these types of fungicides are mancozeb, maneb, chlorothalonil, captan, and copper formulations.

Systemic fungicides actually penetrate plant tissues. These are sometimes referred to as curative or postinfection materials; however, most systemic fungicides are effective when applied preventatively. Certain systemic fungicides have more postinfection activity than others. In addition, most systemic fungicides are actually "fungistats" in that they don't kill the fungus but arrest or suppress development and establishment. Each systemic fungicide group has a narrow mode of action, usually targeting one specific step in the pathogen's cellular activities. For example, sterol demethylation inhibitors inhibit sterol biosynthesis, thus interfering with the function of fungal cell membranes. Strobilurin fungicides suppress one step in cellular respiration, depriving the pathogen of energy in the form of adenosine triphosphate (ATP). Benzimidazole fungicides inhibit the assembly of beta-tubulin, interfering with fungal cell division.

The narrow mode of action of systemic insecticides increases the risk that pathogens will develop resistance to these fungicides. For example, pathogens with slightly altered target sites may be less susceptible or completely immune to a specific mode of action. Each application of a systemic fungicide will create "selection pressure" thus increasing the proportion (frequency) of resistant individuals. The proportion of resistant individuals in the population will continue to increase with repeated use of a systemic fungicide or fungicides with the same mode of action.

Resistance is a major concern for certain pathogens such as *Botrytis*, *Pythium*, powdery mildews, and downy mildews. Be sure to follow all label instructions regarding resistance management.

Systemic fungicides may differ in regard to their mobility in plant tissues. Some materials are very mobile and are distributed quickly from one part of a plant to another (usually from lower parts toward upper parts), whereas other fungicides have local systemic or translaminar mobility and are distributed from one side of the leaf surface to the other.

Bactericides

Bactericides are materials that either kill or slow the growth of bacteria. The most common bactericides for use in greenhouse production are copper-based materials such as copper hydroxide or copper salts. These are contact materials, and they work best when used preventatively.

Biological Controls

There are a number of beneficial microorganisms available for plant disease control. Biological control products are usually formulations of living fungi or bacteria that have activity against certain plant pathogens. They may be directly antagonistic to the pathogen, or they may outcompete the pathogens for space or nutrients, thus preventing the pathogen population from establishing and growing. Additionally, some biological control agents are reported to stimulate plant defenses. Biological control products are applied as foliar sprays, growing medium drenches, or premixed into growing media. These products contain living organisms, so it is essential to read label instructions to ensure that production practices do not compromise their viability.

SUMMARY

1. The major groups of organisms that cause plant diseases are fungi, bacteria, viruses, and nematodes. Each group has unique characteristics, and it is important to diagnose diseases accurately in order to manage them properly.

2. The foundation of a greenhouse disease management program is prevention. Use disease-free plant material from reputable suppliers. Isolate and inspect incoming plant shipments the day they arrive and again several days later, before introducing the new plant material into the greenhouse. Sterilize all soil-based growing media, reused growing media, used containers, and tools. Prevent weed establishment in the greenhouse and around the exterior. Clean up old plant material and growing medium debris. Maintain proper air circulation, heating, and ventilation. Finally, utilize watering practices that minimize leaf wetness.

3. Fungi and oomycetes constitute a large group of multicellular organisms. Common fungal pathogens of greenhouse-grown crops include powdery mildews, *Botrytis* blight, *Verticillium*, *Fusarium*, *Rhizoctonia*, and *Thielaviopsis*. Common oomycetes include downy mildew, *Pythium*, and *Phytophthora*. Reducing relative humidity, avoiding leaf wetness, and maintaining proper moisture levels in growing media will create an environment that is less conducive to fungal pathogens. Implementing proper sanitation practices such as discarding infected plant material and growing debris, and sterilizing pots will also prevent fungal diseases. Furthermore, always use fresh soilless growing media. Finally, there are contact and systemic fungicides commercially available for control of many fungal diseases.

4. Bacteria are single-celled microorganisms that cause leaf spots, wilts, stem rots, soft rots, shoot proliferation, and galls. Bacterial diseases can be prevented through proper sanitation practices such as discarding infected plants, utilizing pathogen-free growing media, and sterilizing pots and tools. In addition, reducing relative humidity and leaf wetness will decrease disease pressure. Bacterial diseases are difficult to control once established since the pathogens reproduce very quickly and bactericides are only moderately effective.

5. Viruses are the smallest of the major plant pathogen groups. A virus infection is systemic, and although symptoms may initially disappear, the plant is still infected. Virus prevention depends upon procurement of virus-free plants, insect control, and disposal of infected plants. Common virus symptoms include stunting, distortion, and discoloration. Viruses are commonly spread by vectors such as aphids, thrips, and whiteflies, or through vegetative propagation.
6. Nematodes are microscopic roundworms. The most common nematode affecting greenhouse-grown crops is the foliar nematode, which infects leaves, causing yellow or brown lesions and occasionally leaf death. Foliar nematodes can only be controlled by preventing introduction into the greenhouse and discarding infected plants.
7. Always follow pesticide (fungicide and bactericide) label instructions regarding rate or dose, restricted entry intervals (REI), and personal protective equipment (PPE). The pesticide label is the law and must be adhered to strictly.

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Maintaining Postproduction Quality

John M. Dole
North Carolina State University

Postharvest performance of floriculture crops has emerged as one of the most important issues in floriculture. The poor performance of cut flowers is increasingly viewed as resulting in depressing sales relative to that of other floriculture crops and gift items. Potted flowering plants, bedding plants, and foliage plants may be less susceptible to postharvest problems, but still must be handled properly for maximum enjoyment by the consumer. Overapplication of plant growth regulators, for example, can leave plants stunted in the garden and lead consumers to think they have done something wrong. Every incidence of poor product performance reduces future purchases by the end user and anyone else he or she tells about the product.

Proper postharvest care must be accomplished at every stage of the marketing chain. Floriculture crops are marketed through a variety of methods, each of which has unique postharvest challenges. The most direct sales path is from the grower to the final consumer; a large portion of bedding plant and specialty cut-flower sales and a small portion of the potted foliage and flowering plant sales are made by this route (Figure 1). The longest typical marketing chain involves the production of cut flowers and foliages by off-shore producers; the product then moves through importers, wholesalers, and retailers to the final consumer. Imported cut flowers are subjected to the environmental conditions and storage duration at each step in the marketing chain before they are sold to the consumer. However, even growers selling products directly to the consumer have to be concerned about postharvest handling—for example, every grower of hanging baskets has watched with trepidation as large, full plants are crammed into consumers' cars.

Cut flowers and ornamental plants differ from edible agricultural products because the latter are consumed or processed within days of harvest, while the former are expected to maintain an aesthetically pleasing appearance as long as possible. The postproduction period for cut flowers is referred to as *vase life*; for containerized plants, it is called *shelf life*.

Figure 1
Many garden centers grow and sell their own plants.

Postproduction longevity is determined by conditions during a chain of periods, beginning with early plant production (preharvest) and harvest from the greenhouse and extending through holding, shipping, and retailing (postharvest). Thus, the decision-making process leading to maximum postproduction quality begins with the crop production planning step prior to planting.

This chapter will begin with five general issues that impact all floriculture crops and then discuss the development of a crop from preharvest to harvest, storage, and shipping and finally to placement in the retail environment. We will also make comments on specific issues regarding containerized plants; cut flowers, foliage, stems, and fruits; and unrooted cuttings. At the end of the chapter, we will discuss how businesses can easily test the postharvest life of their plant materials.

GENERAL ISSUES

Five issues are of primary importance in the postproduction care and handling of floriculture crops: water, temperature, light, disease, and ethylene. These issues must be considered in every step of the marketing chain and are often influenced by each other. For example, high temperatures increase disease and ethylene damage. In this section we will discuss the physiology involved in these issues and details on how to deal with them will be discussed in subsequent sections.

Water

All plant materials must be turgid and have sufficient water to survive the harvest and postharvest handling processes. Water maintains protoplasm in the cells, allowing enzymes and other cellular processes to continue after harvest. Vase life of cut flowers may be shortened if they are allowed to wilt, lower foliage on potted flowering plants may turn yellow and drop if the root substrate dries out too much, and wilted unrooted cuttings may not form roots in a timely manner after being inserted in the substrate. On the other hand, mild water stress near the end of the production phase on bedding plants may improve postharvest performance, assuming that plants are well watered when harvested.

However, the process by which water is provided to floriculture crops must be considered carefully. If plant materials are packed into sleeves or boxes with water on

Figure 2
Condensation occurring on sleeved poinsettias packed too warm, which can lead to botrytis development.

the petals and foliage, botrytis disease may occur and greatly damage the plants. Condensation must also be avoided as warm plants packed into boxes will continue to release water, which can then condense on plant tissue when the boxes are cooled, promoting botrytis development (Figure 2).

The substrate of container-grown crops should be moist, but the foliage must be dry before packing and shipping. Wet foliage and flowers can be readily infected by *Botrytis*. Often potted plants are irrigated in the morning and packed in the afternoon. Remember, however, that water stress during marketing is considered by many to be the major factor limiting potted-plant sales. Cut materials should be harvested when fully turgid, usually in the morning, because the water content of the flowers is a major factor in postharvest life (see “Harvest Time” section later in this chapter). Wilting of cut materials may reduce vase life.

Temperature

Low temperature plays a valuable role, by reducing the respiration rate of plants. When plants are in the dark or at a low light intensity, net photosynthesis does not occur. Under conditions of low photosynthesis, a high rate of respiration would result in rapid depletion of the carbohydrate stores in the plant. The consequence would be a short postharvest life. Temperatures during shipping should be as low as possible without causing injury (Figure 3). High temperatures after harvest are considered the greatest cause of cut-flower postharvest problems and are likely to be similarly important in other floriculture crops as well.

Light

While typically not as crucial as temperature, the effect of light must be considered. A crop grown under dirty glass or during a period of inclement winter weather, so that light is a limiting factor for photosynthesis, will be low in carbohydrate content.

Figure 3
The temperature of boxes of cut flowers are regularly checked to ensure that they are cold.

Respiration continues after the flowers are harvested, but little photosynthesis occurs because light is limited in the packing house, the florist's shop, and the consumer's home. When carbohydrates are low, respiration is very low, and flower senescence (deterioration) occurs. Optimum light intensity during growth of the crop is very important to postharvest life.

Diseases

The main postharvest disease is botrytis, which can rapidly infect and damage plant materials. Botrytis can occur at any stage of production, from propagation to final production. Botrytis can develop on fallen leaves, petals, and other debris and on senescing plant tissues still attached to the plants. Botrytis is favored by warm temperatures and high humidity and is one of the most common plant diseases in commercial greenhouse production. The gray hyphal growth of the fungus is often visible on infected plant materials, especially when the humidity is high (Figure 4). Control of botrytis during production is paramount to preventing problems during postharvest handling. If control cannot be maintained during production, chemical sprays can be used prior to harvest. However, applying chemicals in water to plant materials can make the problem even worse if the surfaces are not allowed to dry and the chemicals are not close to 100 percent effective. In addition, reentry interval (REI) must be maintained before plant materials can be handed.

Other diseases can occur during postharvest, but they are often uncommon and often simply continuations of disease development during production. One exception is bacterial soft rot (*Erwinia*), which can occasionally present a postharvest problem. However, diseases, insects, and nutritional problems during production can result in dead tissue, such as leaf edges, which then become infection sites for botrytis.

Figure 4
Botrytis development on impatiens flowers due to high humidity.

Ethylene

Numerous floriculture crop species are prone to ethylene damage during the marketing process (Figure 5). Sensitive plants exposed to an ethylene concentration as low as 0.1 ppm for 24 hours or 0.25 ppm for 12 hours can be damaged. Exposure to 10 ppm for a few hours can lead to plant death. The threshold concentration appears to be in the range of 0.01 to 0.1 ppm. Confined atmospheres such as sleeves, boxes, coolers, trucks, and storage rooms allow for ethylene buildup. Flexing of leaves from handling and sleeving and bruising of foliage stimulate excess ethylene release. Even plants under normal circumstances release ethylene. Exhaust from fossil-fuel engines contains ethylene. Gasoline-engine exhaust can contain from approximately 100 to over 200 ppm ethylene, depending on the condition of the engine, while diesel engines produce about 60 ppm. Propane engines likewise produce ethylene.

Figure 5
Delphinium petals that abscissed due to ethylene exposure during storage.

Symptoms can include chlorosis of foliage; abscission of leaves, buds, and flowers; abortion of buds; premature death of flowers; and epinasty of plants. The major problems are premature dropping of petals (shatter) in geranium, flower drop during transportation and marketing of holiday cactus (*Zygocactus*), and bracteole drop from bougainvillea plants brought on by water stress. Tulip bulbs exposed to 0.1 ppm ethylene or greater during storage and shipping may fail to flower. Additionally, if planted in landscapes, these bulbs generally produce more, but smaller, daughter bulbs that do not flower well the second year. Purging ethylene-contaminated air from tulip containers is expensive, since temperature control is critical. Use of an ethylene blocker, such as 1-MCP (1-methylcyclopropene) has been shown to be an economical alternative.

A number of steps can be taken to lower ethylene levels. Old and damaged foliage and flowers should be removed from plants before packing the plants for shipment. This will eliminate a major source of ethylene and will make the plant more marketable. Old plants and leaves should be removed from packing and holding areas and shipping trucks. The effect of ethylene in engine exhaust can be minimized by using carts with electric motors rather than fossil-fuel motors for moving plants, turning off truck engines whenever possible, and providing good ventilation in the packing and holding areas. Many plants are shipped in cartons. Less ethylene will build up around plants if ventilated cartons are used. Whenever possible, the truck compartment should be ventilated.

In addition to removal of ethylene itself and ethylene-generating tissue, steps can be taken to reduce the deleterious effect of any remaining ethylene. Both ethylene production and the sensitivity of plants to ethylene diminish as temperature decreases. At 40°F (4°C), many plants do not show symptoms of ethylene toxicity. Holding and shipping spaces should be set at as low a temperature as is tolerated by the plant types being handled.

Ethylene Control

Four products are available for controlling ethylene in plant material. Two, AVG (aminoethoxyvinylglycine) and AOA (aminooxyacetic acid), block ethylene production within the flower or plant. The other two, STS (silver thiosulfate) and EthylBloc (1-methylcyclopropene), control internally produced as well as external ethylene coming from such sources as engine exhaust and faulty heaters. Since it is external ethylene that causes most of the damage in floral products, the latter two products are primarily used in the floral industry (Figure 6). The former products are mainly used for fruit treatment.

Silver Thiosulfate Silver has a bactericidal activity. However, when silver is applied in the form of a soluble salt (most commonly, silver nitrate), the silver is only slightly absorbed by cut flowers. Most is wasted, and results are limited. In 1978, it was found that silver in the complex form of silver thiosulfate (STS) is readily taken up and translocated in plants and cut flowers (Veen and van de Geijn, 1978). In this form, it is very active in preventing postproduction problems. Silver acts as an antagonist of ethylene (Beyer, 1976), thereby blocking the aging effects of ethylene.

STS treatment works well for a number of cut flowers, including alstroemeria, carnation, echium, larkspur, penstemon, snapdragon, stock, and sweet william. The vase life of gladiolus is not improved by STS; however, it improves the quality of gladiolus flowers. STS used in combination with floral preservatives further increases vase life beyond that of the floral preservative or the STS alone. STS can be purchased in commercial, ready-to-use liquid concentrates, which are then diluted to the desired concentration.

Figure 6
Waxflower treated with water, STS, or 1-MCP, from left to right, prior to storage. Note loss of flowers on water-treated stems.

The concentration of STS to use depends on the length of time stems are left in it. Reid and Staby (1981) developed a graph relating the required concentration for any given desired exposure time. Three effective alternatives from their work include a 10-minute pulse with 4 mmol STS at room temperature, a 1-hour pulse with 2 mmol STS at room temperature, or an overnight (20-hour) treatment with 1 mmol STS in a cool room at 32° to 35°F (0° to 2°C).

STS poses problems for the user. It is important to time application precisely because overapplication often leads to silver toxicity. Disposal of silver in the used solutions is an environmental problem. Many regulatory agencies throughout the world do not allow direct disposal of silver at the concentrations used in floral solutions. A bucket kit is commercially available, into which the used solution is poured for silver reclamation.

1-Methylcyclopropene (EthylBloc) In order for ethylene, a gaseous molecule, to carry out its hormonal functions, it must attach to a receptor molecule in plant tissue. It is these hormonal functions of ethylene that lead to unacceptable deterioration of flowers. Drs. Sylvia Blankenship and Ed Sisler at North Carolina State University discovered an alternative gas, 1-MCP, that similarly attaches to the receptor molecule (Blankenship and Dole, 2003). The union of 1-MCP and the plant receptor molecule is permanent and does not result in ethylene-type reactions. This leaves ethylene with no receptor molecule; thus it remains safely inactive. The product, EthylBloc, supplies 1-MCP. For many crops, EthylBloc is equal in effectiveness to STS for short-term treatments and works on virtually all plants that are sensitive to ethylene.

EthylBloc is purchased as a powder. It releases a gas upon addition of water. The supplier provides a mixing solution to be used in lieu of water. It consists of a common wetting agent that ensures contact of all powder with water. This is particularly important when large quantities of powder are used.

Since EthylBloc is active as a gas, it must be released inside an enclosed chamber. The chamber can take on many forms. In the case of a greenhouse filled with potted plants ready for market, the greenhouse can be the chamber. Cut-flower holding rooms, coolers, and delivery truck bodies can also be used. A chamber can be constructed by covering open dry-pack boxes of cut flowers or cans of cut flowers in solution with a plastic sheet that is taped to the floor.

One application of EthylBloc is sufficient for some single-bloom crops since all ethylene receptor sites are present at the time of application. In other crops, such as snapdragon, gypsophila, and geranium, multiple applications are best because new florets with unprotected receptor sites open after the initial treatment. Application can be repeated whenever beneficial in the market chain, by grower, shipper, wholesaler, or retailer. Wholesalers and floral trucking firms have taken the initiative of applying EthylBloc within their delivery trucks to ensure greater customer satisfaction. Repeated applications do not lead to phytotoxicity. EthylBloc is nontoxic to plant tissue. Rates up to 1,000 times the recommended concentration have been shown to be safe. The preferred temperature range for treatment is 55° to 75°F (13° to 24°C). In this temperature range, 1.5 grams of EthylBloc will treat 100 cubic feet (2.8 m^3) of chamber if exposed for 4 to 8 hours and 200 cubic feet (5.7 m^3) if exposed for 10 hours. When temperature is in the range of 35° to 55°F (2° to 13°C), an exposure time of 10 hours and a rate of 1.5 grams EthylBloc are used to treat 100 cubic feet (2.8 m^3). EthylBloc is nontoxic to humans at the indicated concentrations. It has a REI of four hours. This is the time between application and reentry into the treated area.

PREHARVEST FACTORS

Cultivar

Industry workers and researchers have long noticed that cultivars within the same species can vary greatly in postharvest life. For example, Macnish and colleagues (2010) tested 38 rose cultivars and noted that vase life varied from 4.5 to 18.8 days. Variability among cultivars may be due to xylem anatomy, which can greatly influence hydraulic conductivity (Twumasi et al., 2005; Nijsse et al., 2001), levels of endogenous starch and soluble sugars (Ichimura et al., 2005), stomatal function (Mayak et al., 1974), ethylene sensitivity (Ahmadi et al., 2009), and a great many other potential factors.

Unfortunately, many factors must be taken into account when selecting cultivars to grow, and postharvest life is only one of them. For example, the rose cultivar "Forever Young" is well named as it can have a vase life of two and half weeks, but, unfortunately, is little grown because it has relatively low productivity and is not "the right shade of red."

Light

As mentioned earlier, high light levels during production are important to maintaining high carbohydrate levels within the plant tissue prior to harvest. In addition, the time of day when flowers are harvested can be very important for some crops—for instance, rose. Carbohydrates build up during the day through photosynthesis and reach a peak in late afternoon. During the night, carbohydrates are utilized during respiration. Roses cut at 4:30 P.M. were found by Howland (1945) to last longer than those cut at 8:00 A.M. In addition, researchers at Clemson University (Rapaka et al., 2007a,b) found that lantana and portulaca cuttings need to be harvested in the afternoon, when carbohydrate levels are high, to be able to survive shipping and storage and subsequently root well.

Acclimatization, also known as low-light toning, is the process by which decorative plants intended for long-term indoor use are adapted over time from the high light levels found in greenhouses and shade houses during production to the low light levels found indoors in stores, homes, and offices. Acclimatization lowers the light saturation point and, more importantly for the consumer, reduces the light compensation point, allowing plants to survive better in a low-light environment. The *light compensation point* is the level of light at which energy received during photosynthesis is balanced by energy used for respiration. As the light level increases above the compensation point, more energy is available to allow the plant to grow. Acclimatization also lowers the plant's respiration rate, which in turn reduces the amount of carbohydrates that needs to be produced from light. Some plant species such as poinsettias are not easily acclimatized, whereas other species such as Benjamin fig acclimatize readily. Leaves on a poorly acclimatized plant will often yellow and abscise when switched between high- and low-light environments. If the change from a high- to a low-light environment is not too great, the plant will survive and produce new leaves that are acclimatized to the lower light.

Generally, only foliage plants for indoor use are acclimatized because most potted flowering plants and cut flowers are grown under maximum light levels to maximize carbohydrate accumulation and encourage a long postharvest life. Although plants such as chrysanthemums can be acclimatized, the postharvest life is not extended and may actually be shortened due to decreased carbohydrate accumulations and heavy demand for carbohydrates by the flowers (Nell et al., 1981).

Temperature

Temperature influences photosynthesis and respiration, which in turn influences carbohydrate accumulation. During hot periods of the year, crops sensitive to high temperatures, such as carnation and rose, have shorter vase lives because these flowers contain low carbohydrate levels. When the temperature is raised to an adversely high level to force earlier flowering, the same problem occurs. Generally high night temperatures have the most influence on postharvest life, by raising respiration at a time when there is no photosynthesis. Although every plant species has a different temperature that is considered high, in general, night temperatures consistently above 70°F (21°C) cause problems for many species.

Nutrition

Shortages or toxicities of nutrients that retard photosynthesis will reduce postharvest life. Deficiencies in a number of nutrients, including nitrogen, calcium, magnesium, iron, and manganese, result in a reduction in the chlorophyll content, which in turn reduces photosynthesis. The net result is a low carbohydrate supply. In addition, the foliage on nutrition-deficient plants is often pale green or yellow, mimicking the symptoms that occur when plants have been stored too long. Consequently, nutrient-deficient plants will often appear to be "old" in terms of postharvest life and can be rejected by the customers.

On the other hand, high levels of nitrogen at flowering time can have an adverse effect on keeping quality. Although good nutritional practices should be followed during the entire production time, the final few weeks have the greatest effect on postharvest life. For many potted flowering plants, such as chrysanthemums and poinsettias, fertilization should be reduced or terminated one to three weeks prior to sale. For bedding plants such as petunia, marigold, and ageratum, the fertilizer rate should probably be reduced by one-half at visible bud (Armitage, 1993). Completely eliminating fertilizer applications is not advisable for bedding plants because the small amount of substrate provides little reservoir for the plants. Also, bedding plants often dry out rapidly in the retail areas and are watered frequently, which leads to further nutrient leaching.

For most potted flowering plants, the percentage of nitrogen as ammonium should be reduced to 0 to 40 percent of the total N in the final weeks of production. With some species, 100 percent nitrate N is best. In addition, media EC levels should be low and plants should not be given a shot of fertilizer prior to sale. High soluble-salt concentrations in the medium can cause rapid deterioration if the customer allows the plants to become excessively dry.

Growth Regulators

Application of growth regulators will enhance the postharvest life of many potted and bedding plants, by increasing the chlorophyll concentration, which enhances photosynthesis, and by making plants more compact, which reduces shipping and handling damage. Compact plants also lose less water as compared with taller, untreated plants.

Pests

Diseases and insects reduce the vigor of plants and directly reduce vase life. Diseases also reduce vase life indirectly; injured tissue releases large quantities of ethylene gas, which hastens senescence of cut flowers, and provides entry points for botrytis. The botrytis can then become a major postharvest problem. In addition, the presence of insects and diseases can often lead to rejection by customers or, when the product is being imported into the United States, by the U.S. Department of Agriculture (USDA). In such cases, the product is either dumped or fumigated by the USDA with the producer paying for the treatments.

HARVEST

Developmental Stage

Crops should be harvested at the optimum stage for maximum postharvest life. Unfortunately, the proper developmental stage varies greatly among species. For example, potted poinsettias should not be sold until the center flowers (cyathia) open and bracts are well colored, whereas crocus should be sold wholesale when the flower color is just beginning to be visible. Fortunately, the marketing window is much greater for bedding plants and foliage plants. However, immature or overgrown bedding plants will be difficult for the consumer to use. For cut flowers, the developmental stage is especially important. For example, gerbera flowers should be harvested when fully opened and colored, whereas species such as peonies and Dutch iris are harvested when the buds first show color (Figure 7). For many species, flowers harvested in a tight bud stage can be more easily shipped than those harvested fully open. Buds of some species respond to postharvest solutions and open into acceptable flowers. For cut-flower species that must be harvested when partially or fully open, the individual flowers are often enclosed in a soft, flexible net that protects the petals. The nets are often placed on the flowers in the greenhouse prior to harvest (Figure 8a) or on the flowers after harvest (Figure 8b).

When growing a new species, producers should test a few stems at two or three different stages of flower development. Most species with spike-shaped inflorescences (or other types of flowers with multiple flowers per stem) are harvested when one-third to one-half of the florets are opened. Asteraceae family flowers (daisy types) are often harvested when the outer petals are fully developed and only one or two rings of inner disk florets are showing pollen. The use of carbohydrates in floral preservatives may increase the number of flowers to open on inflorescences and allow the successful opening of flowers harvested as buds (see “Floral Preservatives” section).

(a) (b)

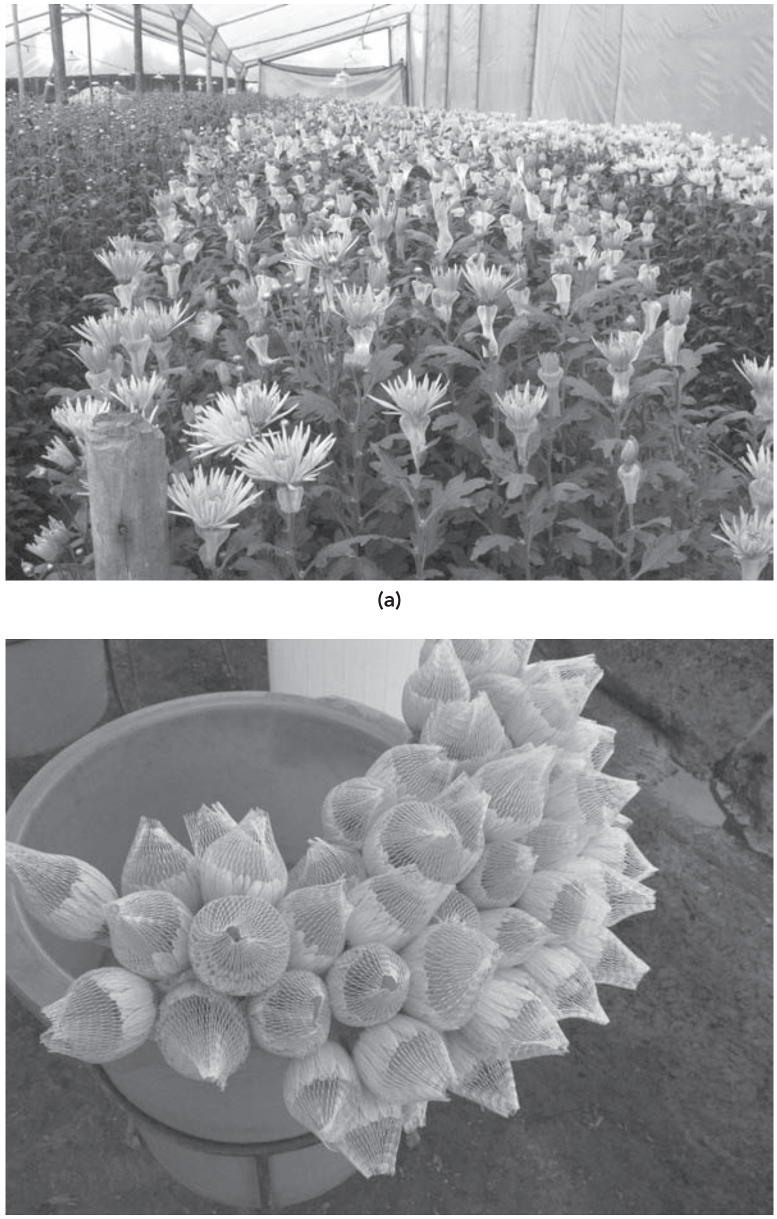
Figure 7
Peony flowers open quickly after harvest and are cut when the buds are firm and first show petal color or first become soft when gently squeezed. (a) Cut stage 2 is a tight bud with color showing and (b) cut stage 3 is a soft bud.

Plants that will be sold immediately to the final consumer can be harvested more mature than plants sold to wholesalers or shipped long distances. Also, some crops can be harvested at a younger stage of development during the summer than the winter because higher light (greater carbohydrate levels in the plant) and warmer temperatures contribute to faster flower development in the marketing chain or in the consumer's home.

Harvest Time

Cut flowers are generally harvested in the morning because that is when the plants have the highest water content and tissue is coolest. Although harvesting later in the day would allow for a higher carbohydrate status, the postharvest life of cut flowers and foliage is thought to be influenced to a greater degree by the water status. There is also less field heat in the plant material, which must be reduced. In addition, morning harvest saves the rest of the day for grading, packaging, and shipping. However, many times cut flowers are harvested all day long when demand is great and harvest time is limited or when the individual flowers open fast, as with roses. Many cut flowers, such as gerbera, should be immediately placed into buckets of water and hydrating solution in the greenhouse or field. Some cut-flower species, such as carnations and alstroemeria, can remain dry after harvesting. Stems are recut and placed in water or floral preservatives after grading, sorting, and bunching.

Ideally, potted and bedding plants should be watered in the morning and foliage allowed to dry to reduce disease development during shipping; they should be packed in the afternoon when the carbohydrate status is the highest. Boxes should be placed in the cooler prior to shipment. Trucks can be loaded either in the evening or early the next morning and should be refrigerated.



(a)

(b)

Figure 8
(a) Protective flexible nets placed on chrysanthemum flowers prior to harvest to prevent petal damage during harvest and postharvest shipping and handling and (b) flexible nets placed on gerbera flowers after harvest to prevent petal damage during postharvest shipping and handling.

STORAGE AND SHIPPING

Potted plants should be watered thoroughly and excess water allowed to drain; foliage and flowers should be allowed to dry before packing and shipping. Diseases such as botrytis can develop rapidly in the moist, closed atmosphere of a shipping container. In addition, long-term shipping (two to five days) can allow naturally occurring ethylene to build up. The warmer the shipping temperature the greater the resulting problems from botrytis and ethylene. Many cut flowers can be shipped dry, but some species need to be shipped with their stem bases in water (Figure 9). Many species with long spike inflorescences, such as gladiolus and snapdragon, need to be shipped upright to prevent the tips from bending upward or treated to prevent bending if shipped in a horizontal position.

Figure 9
Cut flowers packed into boxes dry for shipping by air freight.

Refrigeration after packing and during shipping can significantly increase the postharvest life of crops that are shipped long distances. Refrigeration reduces the transpiration and respiration rates, which, in turn, slows the depletion of carbohydrates and water and the senescence process. Controlled-atmosphere storage and shipping using low oxygen, elevated carbon dioxide, and low temperature also show potential for cut-flower and unrooted cutting handling.

Most, but not all, plant species benefit from cooling. Those species that are intolerant include species sensitive to chilling such as African violet, dieffenbachia, dracaena, ficus, heliconia, spathiphyllum, and strelitzia, which can be damaged at temperatures below 54° to 60°F (12° to 16°C). Most cut flowers respond to hydration and cooling as soon as possible after harvest, which can be done in a number of ways: (1) Sort and pack flowers in a cold room; (2) cool flowers first, then sort, pack, and return to the cooler; or (3) sort and pack flowers and force cooled air through the boxes. With the last method, cool air is forced or removed through end flaps or holes in the boxes when in cold storage. Forced air cooling should also be used after boxes are shipped by air as they warm up and the flowers need to be cooled again. For field-grown cut flowers, flowers should be brought to the cooler frequently during harvest. If no cooler is available, the flowers should be placed in the coldest place possible and shipped or sold immediately. Also, condensation on the flowers during refrigeration, which can lead to botrytis, must be checked for. If condensation is found, boxes should be temporarily opened and tissue allowed to dry before shipping. On the receiving end, all plant materials should be unpacked as soon as possible, because heat can accumulate in the shipping boxes through respiration of the plant materials.

Cold storage is imperative for cut flowers. With most species, the colder the better as long as the cooler is above freezing. The optimum temperature is frequently 33° to 35°F (1° to 2°C). Many coolers are kept too warm for optimum storage, especially when people are constantly entering the cooler during the day. Field cut growers have noted that some cut flowers, such as celosia and zinnia, are sensitive to cold storage temperatures below 40°F (4°C) when placed into cold storage immediately after harvesting on a hot day. In such cases, rehydrate the flowers and precool at a temperature above 40°F (4°C) before placing them in the cooler.

RETAIL ENVIRONMENT

Environmental conditions in the retail area should allow for a low level of net photosynthesis for containerized plants. Under these conditions, plants are able to maintain carbohydrate levels and grow slowly. If the light level is too low, respiration will outpace photosynthesis, resulting in a depletion of carbohydrates. At the very least, consumer longevity will be shortened. With time, these plants can develop chlorotic leaves, exhibit paler flower colors, and drop leaves and buds. On the other hand, if conditions are conducive to rapid growth, bedding plants will outgrow their space in flats and will stretch. Flowering potted plants will mature through much of the postproduction stage that was intended to be enjoyed by the consumer. Foliage plants will lose the level of acclimatization achieved at the end of the production phase and fail to adjust to the consumer environment. A heavily shaded greenhouse constitutes a very desirable retail environment. A 75 percent shade level may be necessary to reduce light to the required level to prevent rapid growth during brighter months. Less shade can be used in the winter. A light level of 500 to 1,000 fc (5.4 to 10.8 klux) is desirable for foliage plants (Blessington and Collins, 1993), and a level of 250 to 700 fc (2.7 to 7.5 klux) serves well for bedding plants (Nelson and Carlson, 1987). Light is less critical for retailing cut flowers, but low light levels can be beneficial at preventing yellowing of the foliage.

Temperature is an important factor in the retail area for containerized plants and critical for cut flowers. If it can be held low, growth will be contained and high light levels will not be a detriment. Consumer comfort must be balanced with plant needs. When plants are displayed in a greenhouse, it should be possible to maintain a low temperature. Hard goods, information, and the cashier can be housed in a retail building at a comfortable temperature. When plants are in the retail building, the lowest acceptable temperature for consumers should be maintained. Foliage plants differ from bedding and flowering potted plants in respect to retail conditions. They perform well in a retail area at temperature, light, and relative-humidity conditions that will exist in the subsequent consumer environment. Walk-in or reach coolers with glass doors can be used to provide the cold temperatures optimum for cut flowers.

Toxic levels of ethylene must be avoided in the retail area. This is a particular problem for bedding plants, which are often displayed outdoors. Since parking lots are usually an integral part of retail settings, auto exhaust is a problem. A few steps can be taken to reduce ethylene exposure. Keep plants as far removed from vehicular traffic paths as possible. Display the more tolerant species closest to these traffic paths. Ensure that there is good natural air movement in the plant area. When other measures fail, 1-methylcyclopropene can be applied.

Fertilizer is usually not applied during the retail phase. It could stimulate growth that is not desired. Care is taken to restrict water so that soft leaf expansion is avoided. Water is applied at the onset of stress. Of course, cut flowers are displayed in containers of water or water plus floral preservatives.

CONTAINERIZED PLANTS

Container Size

With bedding plants, the larger the final container size the better for the retailer and the customer because wilting is delayed. Bedding plant flats, hanging baskets, and pots are often displayed in open, high-light areas, which have the potential to rapidly dry and reduce postharvest life. Large container sizes will reduce the irrigation frequency. Note that the volume of containers with the same diameter can differ. Excessive wilting is especially common with hanging baskets because they are often placed in locations with high air movement. Though small pot sizes for potted plants are popular with consumers and profitable for producers, the rapid drying and wilting limits the distribution and marketing of plants in pots smaller than 4 inches (10 cm) wide.

Overall Production

The environmental and cultural conditions that ensure best production quality also ensure the best postproduction keeping quality. Conditions include temperature, light, nutrition, water, and CO_2.

When a suboptimum level of light is supplied during production, plants accumulate a lower level of carbohydrates. It is important that there is an extra supply of carbohydrates in the plant to provide energy during dark or dimly lighted conditions that occur during shipping, retailing, and placement in the consumer environment. Low-carbohydrate plants in these situations may abort flower buds, develop smaller and paler flowers, or develop chlorotic leaves that later drop off.

Care should be taken during production to ensure the plants are as compact as specified for each crop grown. This may be accomplished through chemical growth regulators or cultural procedures. Compact plants are less susceptible to mechanical damage during handling in the market channel. Also, compact plants tend to transpire less water, which reduces the likelihood of injurious drying during transport and marketing.

Plug trays for growing plug seedlings and flats for bedding plants are available in various depths, all with the same surface area. Deeper cells in these containers favor maintenance of postproduction quality. The deeper cells hold more root substrate; thus, they hold more water. There is less chance of drying while being shipped.

Toning During Late Production

All categories of containerized plants are less subject to quality deterioration in the market and consumer environments if they have been toned at the end of the production period. *Toning* is a process in which a reversible stress is applied to a plant for the purpose of increasing its tolerance of mechanical and environmental adversities. Less-than-adequate levels of fertilizer, water, heat, or light can be used to tone a plant. The stress is applied at the end of the production period, usually during the last two weeks. A longer period of toning is necessary for indoor foliage plants that have long production times. Toned plants withstand mechanical stress, drying, extreme cold, and heat better than untoned plants. They also last longer in the retail and consumer environments.

One of the most effective toning stresses is a shortage of nutrition. Nitrogen appears to have the predominant effect among all of the nutrients. However, the stress is generally applied by cutting back application of all fertilizer because nitrogen runs out sooner than the other nutrients. If the nutritional stress is too great, postproduction quality will be impaired. Foliage may be chlorotic, flowers may be smaller, and shelf life may be reduced. To apply the correct level of stress, it is important to know the nutrient status of the substrate two weeks before market date so that fertilizers can be reduced to the correct level. When substrate analysis indicates that nitrogen is in the mid-to-high end of the optimum range, fertilization can be discontinued for the last two weeks of production. If nitrogen levels are quite high, substrate should be leached by irrigating with plain water twice within a short period of time. If nitrogen is in the low-to-mid end of the optimum range, fertilization can be cut in half for the last two weeks. This may be done by reducing the fertilizer concentration to one-half or by applying the full-strength fertilizer at half the frequency. If the crop is receiving insufficient nitrogen when the last two weeks start, it would be best to continue fertilization up to market date.

Water stress is perhaps the second most popular method for toning containerized plants. As the frequency of water application to a crop increases, the percentage of water in the plant increases, often without any increase in dry-matter content. Plants in this state are said to be *soft*. Soft plants wilt quickly in high light, in drying wind, or in adverse settings such as a sidewalk or a parking lot at a garden center. Toned plants stand up to these hostile situations much better. As in the case of fertilizer toning, the degree of water stress is important. During the last few weeks of production, plants should be allowed to wilt moderately before each watering. They should not be allowed to wilt to the point where root or leaf tips burn. This extra level of water stress is applied to bedding plants after the visible-bud stage.

Low-temperature toning is used for flowering potted plants and bedding plants but generally not for indoor foliage plants. Foliage plants are, for the most part, tropical or subtropical plants that perform best at warm night temperatures of 60° to 70°F (16° to 21°C). For most species, it is best not to lower the temperature below this range. When the temperature is lowered for the last two to three weeks of production, flowering potted plants develop deeper-colored flowers and sometimes larger flowers. These plants typically last longer in the consumer environment. Depending on the plant species, the temperature can be lowered by 5° to 10°F (3° to 6°C). With white-flowered plants, care must be taken not to lower the temperature too much, because some can develop a pink or yellowish tint at lower temperatures. Bedding plants grown at lower temperatures after the visible-bud stage are more resistant to mishandling, in high transpiration situations, and to light frosts.

The best overall toning method for bedding plants is to grow them outdoors for a period of time or use retractable roof greenhouses. Low-cost outdoor container pads are quite economical, considering the cost of building and running a greenhouse. Crops can be grown entirely on the container pad but crop schedules may be hard to maintain if weather is cool. Crops can be produced primarily in the greenhouse and moved outdoors to finish but that adds labor cost. Of course, when the greenhouse is completely full in the spring, having a container pad for overflow can be a welcome relief.

Retractable roof greenhouses are the most convenient way to tone bedding plants. The roof can be kept closed during cool or rainy weather, allowing crop schedules to be maintained. The roofs can be opened during the rest of the time to provide very high light, air movement, and cool temperatures, which harden the plants without having to move the plants outdoors or subject the plants to specific toning stresses, which can require careful attention from the grower. Retractable roof greenhouses are typically more expensive to construct than standard greenhouses but recent designs are more affordable and have become quite popular.

Low-light toning is not practiced for bedding plants. Greenhouse production of bedding plants encompasses the early portion of the life cycle of these plants when high photosynthetic rates are needed to drive growth. After the market stage, these plants will go to gardens where light conditions will be even higher than in the greenhouse. A period of restricted light at the end of the production period could lead to undesirable tall and weak plants, chlorosis of leaves, and poor adaptation to the outside environment upon transplanting. Flowering potted plants are likewise not light toned. If done, this would lead to low carbohydrate levels that would limit shelf life.

Low-light toning is restricted mainly to foliage plants intended for indoor use. Many foliage plants originate in environments brighter than those in which they will be placed in consumer buildings. They will grow most rapidly at these higher light intensities in the production greenhouses or shade houses. However, if they are shifted directly from high- to low-light situations, leaves will become chlorotic and possibly will abscise. It is necessary to lower the light intensity near the end of production. The length of this period depends on the species and size of plant and can extend from six weeks to six months or longer. Water and fertilizer toning are not substitutes for light toning in foliage plants, but can be also applied.

Shipping

Ideally, plants should be lighted during shipping, but that rarely occurs. Lighting is generally not possible inside trucks, because bedding plants are carried on closely spaced shelves and flowering potted plants are often boxed (Figure 10). The adverse effects of low light are chlorosis, leaf drop, pale flower color, and floral abortion. These problems diminish at lower temperatures, which slow plant development. When a truck without cooling is used for shipping, it is advisable to insulate the truck, avoid parking it in the sun for prolonged periods, and travel in the early morning or late afternoon as much as possible. Bedding plants can be shipped successfully in darkness for a period of two days, and foliage plants for seven days, when precautions are taken to lower temperature. Carts loaded with plants are often wrapped in plastic to prevent plants from being damaged or falling off shelves during transport (Figure 11).

Figure 10
Bedding plants on carts with closely spaced shelves for shipping.

Figure 11
Carts can be wrapped in plastic prior to loading on the trucks to prevent damage to plants during shipping.

CUT FLOWERS, FOLIAGES, STEMS, AND FRUITS

As an industry, we have not been highly successful in preserving the potential life of cut flowers. It has been estimated that 20 percent of harvested cut flowers become unmarketable as they move through the market channel (harvesting, packaging, transporting, and selling). A very significant proportion of the remaining flowers are sold in a weakened condition, which leads to consumer dissatisfaction. Fortunately, there are well-known solutions for the bulk of this problem.

Stem Blockage

Cut flowers deteriorate for one or more reasons. Five of the most common reasons for early senescence are the following:

1. Inability of stems to absorb water because of blockage
2. Excessive water loss from the cut flower
3. A short supply of carbohydrates to support respiration
4. Presence of diseases
5. Negative effect of ethylene gas

Inability to absorb water is a very common reason for premature wilting. The water-conducting tubes in the stem (xylem) become plugged (Figure 12). Bacteria, yeast, and/or fungi living in the water or on the foliage and stems proliferate in the containers holding the flowers. These microorganisms and their chemical products plug the stem ends, restricting water absorption. They continue to multiply inside and eventually block the xylem tubes. Strict sanitation is the best way to prevent plugging from microorganisms. Buckets, clippers, and work surfaces should be regularly cleaned and disinfected. In particular, buckets should be cleaned between each use. It is best to use light-colored buckets because it is easier to see if they are

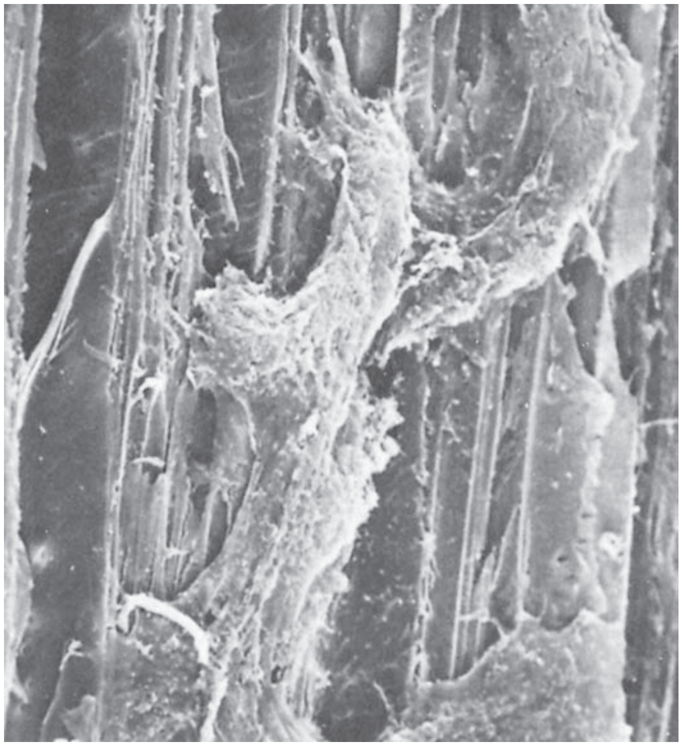


Figure 12
A longitudinal section (1,500× magnification) of a rose stem, showing the interior of water-conducting cells and a slime plug blocking some of the cells. Such slime plugs can be composed of microorganisms, particularly bacteria, and solidified compounds from the flower itself.
(Photo courtesy of H. P. Rasmussen, Department of Horticulture, Michigan State University, E. Lansing, MI 48824.)

clean (Figure 13). The gold standard for sanitation is to ask, Would someone drink out of the buckets after they are cleaned? If not, they are not clean enough.

Chemical blockage also can occur. Chemicals that are present in some stems, upon cutting, change into a gumlike material that blocks the end of the stem. This material is suspected to be composed of oxidized tannins in some plants, and in others, it is unidentified.

A third source of blockage can be air trapped in xylem tubes. When flowers are received at wholesale or retail establishments, it is advisable to cut the ends of the stems off under water. Machines are available with cutters mounted under water in tubs for this purpose (Figure 14). When stems are cut in this fashion, water rather than air enters the end of the stem. After cutting, the stems can be removed immediately from the water. This procedure is particularly effective for rose. Care must be taken to ensure that the water used during cutting is continually clean or the benefits will be lost. Water in which many stems have been cut can be loaded with bacteria feeding on the plant sap and other organic matter and will plug the stems, negating the advantages of recutting the stems under water.

Excessive water loss from flowers can lead to wilting and reduction in quality and vase life. After harvest, flowers should be removed from the field or greenhouse and refrigerated as soon as possible. Leaving the flowers out of water and in warm air or in warm drafts, as from a heater, causes considerable damage. Flowers should be in water or cool temperatures as much as possible from the time they are cut until they reach the final customer.

Figure 13
White buckets cleaned and stacked for drying.

Figure 14
A commercial stem cutter that cuts stem ends while under water.

Low carbohydrates are another reason for flower deterioration. A low carbohydrate supply can occur as a result of improper storage temperature and handling. After harvest, respiration continues to be governed by temperature. Low temperatures reduce respiration and conserve carbohydrates, thereby prolonging quality and vase life. Each of the many stages in the marketing channel must be watched. Flowers should be placed in cold storage as soon after harvesting as possible. They should be refrigerated during surface transport and during holding periods by the wholesaler and retailer. Serious damage occurs when flowers are left on a heated loading dock at the motor- or airfreight terminal or when they are left sitting in a hot warehouse for a day or so.

The harmful effects of disease and pests, as well as the effects of ethylene, have already been pointed out. Fruits, especially apples, give off large quantities of ethylene gas, making it inadvisable to store lunches containing fruits in coolers. It has already been mentioned that ethylene is evolved from plant tissue, particularly injured and old plant tissue. Coolers should be kept clean of plant debris such as cut stems and leaves that might accumulate on the floor. Old unsalable flowers should be discarded.

Elevated levels of ethylene gas have many deleterious effects on cut flowers. Symptoms can include leaf, bud, petal, or flower abscission; bud abortion; leaf yellowing; petal color loss; curling or wilting of petals; and general senescence of flowers.

Water Quality

The quality of the water used during postharvest can affect the vase life of flowers. In many parts of the world, water is high in soluble salts and the pH may be very high as well. Recent testing with roses indicates that the longest vase life resulted when stems were placed in a solution with a pH between 3.1 and 4.0 and an EC of 1.0 and 1.3 dS/m, regardless of cultivar tested. Increasing solution pH decreased vase life, as did very high (greater than 2.0 dS/m) or very low water EC (lower than 0.25 dS/m). The EC effect was noted regardless of the use of floral preservatives. Short durations of two hours or less in high pH solutions can be used but longer-term storage should be in low pH, moderate EC water. Other species appear to be more or less sensitive to water quality. For example, the optimum EC is higher for carnations and chrysanthemums but lower for zinnias.

Floral Preservatives

Considerable research has been conducted over the past decades to find floral preservatives (flower foods) that will combat some of the causes of flower deterioration and reduction of vase life. A variety of home remedies can be found in publications and on the Internet; however, research studies have determined that most are either ineffective or even detrimental. However, a recent study showed that combining commercial sodas with water, 50:50, extended the vase life of cut roses, snapdragons, lilies, and gladiolus flowers as well as commercial floral preservatives. The soft drinks should contain sugar or related sweeteners but not aspartame or similar no-calorie substances.

Floral preservatives perform up to three functions:

1. They provide sugars (carbohydrate).
2. They supply a bactericide to prevent microbial growth that causes blockage of the water-conductive cells in the stem.
3. They acidify the solution. This function suppresses bacterial development and, through some unknown process, prevents wilting of flowers. It is suspected that the acidity helps prevent chemical blockage.

Some floral preservatives also contain plant growth regulators, such as gibberellins, cytokinins, or plant growth retardants, to prevent stem bending, limit postharvest stem elongation, and prevent leaf yellowing. Growth regulators are often included in specialty preservatives targeted toward the species that will benefit the most, such as products for alstroemeria, lilies, tulips, and gerberas.

Other treatments may be used to extend vase life, such as pulsing for 4 to 24 hours with 5 to 20 percent sucrose, placing in 100°F (38°C) water, or treating with anti-ethylene agents as discussed earlier in this chapter. Be wary of recommendations that call for mashing or splitting the stem ends of woody cuts, searing the ends of latex-producing cuts with a flame, or by placing in boiling water or *filling* the cavities of hollow stems with water. There is no evidence that these treatments work and may actually reduce vase life in some cases.

Commercial floral preservatives can be arranged into three main groups:

1. Hydrators promote water uptake and typically contain chemicals to either reduce water pH or act as bactericides. Hydrators usually do not include sugar and, thus, are not used for holding flowers long term. Some flowers may be damaged by keeping cut stems in hydration solution too long. Commercial hydration solutions are available, and the amount of time the stems should be kept in the hydration solution varies from a few seconds to 48 hours. The *quick dip*-type solutions primarily reduce the amount of microorganisms on the stems. The long-duration solutions are used for holding flowers from 4 to 48 hours until final processing or for shipping in water. Chlorine tablets added to water also produce solutions that can be used as hydrators.

2. Processing and holding solutions usually contain sugar, an acidifying agent, and an antimicrobial compound. These solutions are used for the transport and storage of flowers. Products with a greater percentage of sugar are used to open buds and promote flower development.

3. Consumer preservatives and vase solutions are intended for the arrangements and bouquets used by the final consumer. Consumer preservatives normally contain sugar (normally at higher levels than in processing solutions), an acidifying agent, and an antimicrobial compound. The preservatives are available in bulk for retailers to use or in individual packets for the customer to mix into the water when the flowers are brought home.

Floral preservatives are very effective in maintaining quality and extending longevity (Figure 15). On the average, preservatives can double the vase life of cut flowers when compared to water. Snapdragons with a life expectancy of 5 to 6 days last up to 12 days in preservative. The life expectancy of roses can be extended to as long as 14 to 16 days in some cultivars. Carnations with a vase-life expectancy of 5 days, after extensive shipping, have been shown to last 12 days in preservatives.

There are a number of commercial floral preservatives on the market. The efficacy of floral preservatives will vary greatly with the water quality and species. Be sure to test several preservatives to find the ones that are best for your operation. Always follow mixing directions or use the pumps or dosing units, because floral preservatives

Figure 15
The use of floral preservatives can increase vase life; zinnia flowers on left were treated with flower foods and those on right received only water.

can be either ineffective or detrimental if supplied to the flowers in the wrong concentration. Dosing units are similar to fertilizer injectors but dispense liquid floral solutions into the water in accurate concentrations. Flowers will be damaged if the preservative is too concentrated and the biocide will be too dilute to be effective if the floral preservative concentration is too low.

The products follow the *chain of life* of cut flowers—that is, their progression from harvest in the greenhouse or field to their finally being a source of enjoyment in the consumer's vase. The first product is used by the grower at the point of harvest, which is sometimes just clean water, followed by more products used by the shipper and wholesaler; then a product used by the retail florist, and finally a product is provided with the flowers to the consumer for final vase life.

Many growers, wholesalers, and retailers believe that these procedures, particularly the use of floral preservatives, are not necessary. Undoubtedly, they have partial evidence to support their view. However, if they looked at the whole market channel, they would realize they are wrong. It is too late for the retailer to get maximum effectiveness from a preservative if the grower or the wholesaler has failed to use one. Flowers left to wilt in the greenhouse, while others are cut, have already lost a significant portion of their quality and longevity. Precautions taken after this time will have diminished effects and at times may appear to be without effect. Very often, abusive handling is the main culprit in flower deterioration.

UNROOTED CUTTINGS

Cuttings are harvested from stock plants during the morning and early afternoon. The cuttings are usually counted and bagged in the greenhouse or field and then placed in a cooler, where the orders are sorted and boxed. Cuttings of cold-tolerant species, such as geraniums and petunias, should be held at 35° to 50°F (2° to 10°C) and those of chilling-sensitive species, coleus, lantana, and sweet potato, at 50° to 65°F (10° to 18°C) (Faust et al., 2006). Vacuum cooling or forced-air cooling is often performed to remove the greenhouse heat from the packages of cuttings. Frozen gel packs or ice may be included in the packed boxes to maintain cool temperatures during transit. Cuttings of geranium (*Pelargonium* spp.) and other species may be treated with 1-MCP (EthylBloc) by including an EthylBloc sachet in the box. The high humidity in the box during shipping releases the 1-MCP, preventing leaf yellow and/or defoliation of the cuttings.

After packing and cooling, the cuttings are taken to the airport in the afternoon or evening and transported by plane to a port of entry, such as Los Angeles or Miami. In some situations, the boxes are re-iced at the port of entry—that is, the melted ice or gel packs are replaced with frozen ice or gel packs. APHIS, USDA (U.S. Department of Agriculture's Animal and Plant Health Inspection Service) inspects the cuttings; if acceptable, the boxes are transported to the customer via an express mail carrier or a temperature-controlled truck (Figure 16). Express mail shipments are usually delivered to the customer within 48 hours from the time the cutting is harvested. Truck delivery may require an additional day; however, temperature control can be maintained throughout the additional time.

Growers must check the cuttings immediately upon arrival for any noticeable signs of damage, disease, or death. The condition of the cuttings affects their storage longevity as well as their performance in propagation. Ideally, the cuttings should be stuck immediately upon arrival. However, if the cuttings cannot be stuck right away and if they are sufficiently hydrated, they can be stored in a cooler with high relative humidity (80 to 95 percent) for up to 24 hours. The temperature should be 35° to 50°F (2° to 10°C) for cold-tolerant species (which

Figure 16
Unrooted cuttings packaged into plastic bags and packed in a styrofoam-lined box for shipping by air freight.

includes most species), and 50° to 65°F (10° to 18°C) for chilling-sensitive species. Some growers will schedule the cuttings to be placed in the cooler prior to stick, since cooled cuttings maintain turgidity better when stuck. If no cooler is available, the cuttings can be placed on the propagation bench under mist and shade cloth until they can be stuck. The mist should keep the cuttings well hydrated; however, if the cuttings are laid horizontally, the stems will bend, making them more difficult to stick. The cuttings will decline rapidly after arrival if the boxes are placed in a location warmer than 70°F (21°C). Botrytis often limits the storage longevity of unrooted cuttings, even when cuttings are held at optimal temperatures.

COMMERCIAL TESTING

Detailed postharvest information is limited to only a few species; consequently, every grower should routinely sample a few potted plants or cut stems of each species or cultivar to observe and determine the postharvest life (Figure 17). In particular, new species or cultivars should be tested as they appear on the market. Dramatic differences in postharvest life can occur among cultivars. Cultural conditions vary from grower to grower, and the postharvest life of a crop for one operation often differs from that of another. Knowing the weekly postharvest qualities of your cut flowers, potted flowering plants, or potted foliage plants will allow you to adjust your cultural procedures to improve postharvest longevity. Proper cultural procedures in combination with postharvest cultivar screening will ensure that a firm is selling high-quality crops with optimum postharvest life. In-house postharvest testing is also valuable in identifying when problems occur within an operation, handling customer complaints, and providing customers with current postharvest information.

A postharvest testing system does not need to be elaborate and should take only a few minutes to set up and monitor each day. In fact, the simpler the system the more consistent and useful the results are likely to be. Testing can be as easy as growing a few plants of several bedding plant species in a display garden.

Figure 17
Commercial facility for postharvest testing of cut flowers. Note homemade containers from pieces of PVC pipe.

A postharvest test facility for cut flowers, potted flowering plants, or foliage plants can be in the lunchroom or on a countertop in the office. For potted plants, select one to three samples weekly from various crops, label with the date, and record the date the plants are no longer acceptable.

In setting up a testing system for cut flowers or foliage, obtain clean bottles or vases. Use the same preservatives and water as normally used in the operation. The easiest test for a new species is to place half of the flowers in water as a control treatment and the other half in water plus preservative. For current crops, compare a few untreated flowers to a few flowers after treatment, which will allow you to determine if your handling procedures are effective. If plant material is limited, one stem can be placed per bottle or vase, but typically whole bunches should be used to provide a more accurate evaluation.

Place the flowers in an area permanently set aside for the postharvest tests. Check the flowers each day; note which flowers are no longer acceptable and record the number of days from harvest to the end of vase life. The stems can be individually tagged with the harvest date and treatment by using small stickers or paper tags with string.

SUMMARY

1. A crop is at its highest quality at the time of harvest and must be properly handled to minimize the loss in quality.
2. Factors influencing the postharvest life of a crop occur well before the crop is marketed. They include the cultivar grown, light intensity, temperature, nutrition, growth regulators, and pest control.
3. To maintain quality during marketing and in the final consumer's location, containerized plants and cut materials must be handled at the correct temperature, have a high carbohydrate level, and be free from water stress, diseases, and ethylene. Of these, temperature is generally the most critical; crops should be stored and shipped as cold as possible for the species.
4. Every grower should routinely sample a few potted plants or cut stems of each species or cultivar to observe and determine the postharvest life.

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Business Management

Robin G. Brumfield

Management can be summarized as *plan*, *execute*, and *measure*. The first part of the plan begins with formulating the company's *mission* or *vision*. Once the mission statement is developed, management creates goals and objectives to accomplish the firm's mission. Next, management develops a plan, executes that plan, and measures the results to see how the end product fulfills the original vision. The plan becomes the road map outlining what work is going to be done to meet the firm's goals and objectives. Management *organizes*, *directs*, *coordinates*, and *controls* the firm's resources to execute the plan. For greenhouses, this means effectively managing the company's *land, labor, money, materials, technology*, and the *environment*. Perhaps most important for the manager is to effectively manage his or her *time* in achieving these objectives with maximum efficiency. Finally, management measures the result to determine how effectively the goals were met. Management is not just about getting from point A to point B; it is about bringing together the firm's resources in the optimum combination to get there using the best possible path while taking into consideration the operating environment. The operating environment consists of things like the economy and federal, state, and county regulations as well as local ordinances. The measurements not only determine how effectively the objectives were met but also form the basis for the next planning stage. Management becomes a continuing cycle: plan, execute, and measure.

Management.about.com, (accessed February 24, 2011) an excellent online resource for managers, says management is the art of making people more effective than they would have been without the manager and the science of how it is done. Mary Parker Follett, considered to be the mother of scientific management in the early 20th century, said that management is "the art of getting things done through people." Management gets things done in the *right way* by the *right people* at the *right time*, using the *right combination of resources*.

BUSINESS PLAN

It has been said that managers who fail to plan, plan to fail. A plan is necessary for management to be effective. An effective manager guides others in following that plan. Without a plan the manager's actions can

Table 1
DIMENSIONS OF THE PLANNING PROCESS

The owner	Personal motivations and priorities
	Skills and abilities
	Financial resources
The industry	Statistical data
	History, trends, and future directions
	Industry strengths, weaknesses, opportunities and threats
The business	Business description
	Business SWOT
	Business objectives
	Strategies
	Methods of operation

seem random to the people being managed. This leads to confusion and disappointment. Success in a greenhouse requires both technical and business management skills. Managers who are evaluating whether or not to adopt a new system, technology, or technique must evaluate not only the impact on the technical aspects (environmental controls, pest management, fertilization, etc.) but also on the bottom line. Some greenhouse businesses that had good technical managers have failed because of poor business management, and other businesses have failed that had good business managers but did not have good technical managers. To survive in the long run, the manager must manage all aspects of the business well. Long-term survival of a business today also requires planning. The planning should reflect upon and analyze a range of issues relating to the owner, the industry, and the business itself (Table 1).

What Is a Business Plan?

A business plan is a systematic evaluation of a venture's possibility for success. It is a written summary of the proposed business venture, its operational and financial details, its marketing opportunities and strategy, and its managers' skills and abilities. A business plan is a reflection of its creator. The real value is in the process of creating it. It may help the creator realize that a business idea just will not work, or provide a plan to succeed with an idea that will work. While a business plan does not guarantee success, it does increase the chances of succeeding in business. It is a road map for managing a business successfully.

A business plan serves two essential functions:

1. It is the guide for the business. It charts its future course, defines the strategy for building it, and helps the business stay focused on its objectives.
2. It can be used to obtain capital from lenders and investors. It helps define the potential returns relative to the costs and risks.

What Should Be in a Business Plan?

A business plan should include a description and definition of who is involved, what consumer needs will be met, what the saleable product or service is, and the market environment in which the business operates. It also should contain an analysis and plan for how the product or service will be produced and marketed. Also important is a list of what resources are needed to achieve the plan, when they are needed, and a summary of anticipated results.

EXECUTIVE SUMMARY

The executive summary appears at the beginning of the business plan, but it should be written last. The focus of the executive summary depends on the purpose of the plan. If the business plan is being presented to lenders or investors, it should include highlights that will encourage them to consider financing the business. It should briefly describe what the manager plans to do, including expansion plans, market opportunities, and financial trends and projections. If the plan is primarily for internal management, then the executive summary should summarize the plan and communicate with family members (or board members if it is a corporation) and employees where the business is going. The executive summary should be no more than two pages and should summarize the big points from each section. The plan should match the firm's mission or vision. The executive summary is the *elevator pitch*. It should be clear, complete, and precise and convey that the manager believes in the future of the business. Anyone should be able to understand the entire business concept and the company's competitive advantage from reading the executive summary.

The executive summary answers the following questions:

- What is the current status of the business?
- What products or services will it provide? Are they unique or different?
- How large is the market and who are the customers who will be buying the product or service?
- Why will they buy this particular product or service? What is its competitive advantage?
- Who is on the management team? Do they have experience, motivation, relevant intellectual capital, and a proven track record?
- What key assets are in place?
- What are the market share and financial projections for the next three to five years?
- What does the venture need to accomplish these projections?

The following is an example for Mrs. Greenjeans Greenhouse, a company that is owned by Mary Wilson. Mary went back to college after her children were in school and received a B.S. in horticulture from a major land-grant university.

EXECUTIVE SUMMARY FOR MRS. GREENJEANS GREENHOUSE

Mrs. Greenjeans Greenhouse is a small greenhouse business located in a fairly rural area in Anywhere, USA. I, Mary Wilson, have a B.S. degree in horticulture and am the manager and owner of the greenhouse. This spring will be my first crop. My husband, John, has a degree in economics and earns enough money at his job as a financial advisor to keep the family going while I get the business up and running. He is helping with the business plans. Our two children, a daughter Linda, who is 14 and in 9th grade, and a son, Dan, who is 15 and in 10th grade, are helping out with the business a few hours after school each day.

The greenhouse facility is 25,000 square feet and is 30 years old. The business specializes in bedding plants and sells mostly to local retail garden centers. The previous owner of the business, Bill Smith, had reduced production to only bedding plants in the spring. I plan to produce bedding plants, but to also expand production to include poinsettias, hanging baskets, perennials, and garden mums so that I have crops almost year-round. This will improve cash flow, keep customers coming back for products all year, and help keep the same employees most of the year. I plan to produce my own plugs and rooted cuttings in the winter so that I can ensure the top quality demanded by the retail garden center market. I plan to sell extra flats of plugs and rooted cuttings to other producers. In addition to bedding plants, I will produce perennials for spring sales to garden centers. In the summer and fall, I will grow my own poinsettia stock plants, finished poinsettias, and florist mums. In addition to producing plants in the greenhouse, I will also produce garden mums for fall sales on about one quarter of an acre outdoors.

BUSINESS DESCRIPTION[1]

The business description introduces the company and helps people who are unfamiliar with the business understand what the greenhouse produces, the size of the operation, and how the products are marketed. It should include the business type and size; the history, current status of the business, and plans for the future; the location; the facilities; and the ownership structure.

Business Type and Size

The *business type* defines the primary business of the company. Examples are ornamental plant production for sale to mass merchandisers, direct-to-customer sales of ornamental plants and other products. It answers questions like what crops or other products will the greenhouse produce and sell? What is the size of the business in terms of the number of acres owned, acres rented, area in production, size of the greenhouse, and size of facilities? What services will be offered? Examples include post-sale services such as product delivery; online ordering; product information through Web sites, blogs, Facebook, Twitter; and/or 1-800 numbers.

History, Current Status, and Plans for the Future

This section of the business plan briefly describes when the business started, how it started, how long the current owner has owned or managed it, and important events and changes. If this is a business still in the planning stages, the business plan should describe the business the owner envisions. This section answers the following questions: What is the uniqueness of the business and its products and services? Who are the owner and key personnel? What are the financial capabilities? Are there any special business relationships? What are the key strengths to build upon, and weaknesses to correct or overcome? Are there any plans for expansion or changes in size, sales, and profitability? What are the future plans, timetables, resources and personnel required, or technical gaps to be filled? What major challenges will the business face over the next five years?

Location and Facilities

The business description should include the *location* of the business and why that location was chosen. Multiple production locations or sales outlets, if they exist, are described. It can include a legal description of the land, and if it is rented, it should list the parcels, the acres, and the landlords. It should also describe the size, type, and quality of the *facilities* and any retailing or other activities that require significant infrastructure.

Ownership Structure

The legal organization chosen for a business has risk, finance, tax, and estate planning ramifications. Greenhouse owners should consult an attorney and an accountant to select or change to a legal structure that best suits their needs. Figure 1 shows the percentages of New Jersey greenhouses using various legal structures. Most greenhouse businesses have legally organized as sole proprietorships, while others have organized as subchapter S or C corporations, limited liability companies, partnerships, or some other structure. A growing number of greenhouses are incorporating as limited liability companies (LLCs) because an LLC offers some financial protec-

[1]From Minnesota Institute for Sustainable Agriculture (MISA) (2010).

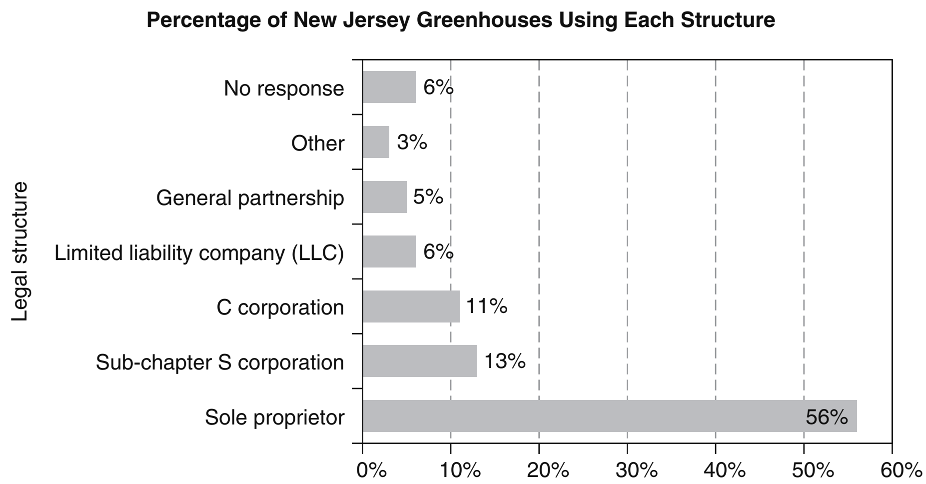

Figure 1
Percentage of New Jersey greenhouses using various types of legal structures.
(Data from Brumfield et al., 2008.)

tion, tax advantages, and other benefits such as being able to gradually pass shares and ownership of the business on to heirs in advance of retirement. The description of ownership structure should explain who owns the business, what proportion each owns if there is more than one owner, and how the profits are shared. It should include the proposed business name and indicate if it is registered. The advantages and disadvantages of various legal business arrangements are described below.

Sole Proprietorship In a sole proprietorship, the business is owned and controlled by one person. The primary advantage of a sole proprietorship organization is that the owner is independent and free to make all business decisions without an obligation to partners or shareholders. The disadvantage of a sole proprietorship is that the owner is personally liable for any debt, taxes, or other financial and regulatory charges.

Partnership Partnerships may be formed between two or more family members or third parties. Each partner is liable for all partnership obligations. One of the primary advantages of a partnership may be the infusion of business capital and other assets by one or more partners. For example, one partner may be good at merchandising and marketing, and the other may be good at growing plants and managing the physical facility. Each partner pays taxes individually based on his or her share of income, capital gains, and losses. There are two types of partnership: general partnerships and limited partnerships. In a general partnership, one or more partners are jointly responsible or liable for the debts of the partnership.

Corporation Corporations are owned by one or more shareholders and are managed by elected directors. A corporation must be established in compliance with statutory requirements of the state of incorporation. The corporation, not its shareholders, is responsible for corporate debts and other obligations. One disadvantage of corporate organization is that owners are considered employees of the business and are therefore subject to labor laws and taxes. For many corporations, the most important tax decision hinges on whether or not to elect to be treated under the provisions of *subchapter S* of the Internal Revenue Code. In general, *S corporations* do not pay any federal income taxes. Instead, the corporation's income or losses are divided among and passed through to its shareholders. The shareholders must then report the income or loss on their own individual income tax returns. This concept is called *single taxation*. If the corporation is taxed as a *C corporation*, it faces *double taxation*, meaning both the corporation's profits and the shareholders' dividends are taxed.

Limited Liability Company This organizational form offers owners limited liability like a corporation—investors are liable only for their investment in the business—but it may be classified as a partnership for tax purposes. Two or more business partners may form an LLC.

Land Trust A land trust is a legal entity that allows a land owner to transfer property to a trustee. While the trustee is the legal owner of the property, the beneficiaries are given possession and management of the land. This type of legal organization can be beneficial for estate planning purposes as it allows the beneficiaries to avoid probate upon death of the owner.

Cooperative A cooperative is a legally incorporated business entity capitalized by its member patrons or owners. Dividends are paid out to its patrons. A cooperative is taxed on income at corporate rates, but patronage refunds are often tax-deductible to the cooperative. Some producers use cooperative organization to acquire and provide machinery and equipment maintenance, as well as marketing and advisory services.

BUSINESS DESCRIPTION FOR MRS. GREENJEANS GREENHOUSE

Mrs. Greenjeans Greenhouse is wholesale floricultural business specializing in selling unique, high-quality plants to retail garden centers. The production facility is a 25,000-square-foot glass greenhouse. I plan to produce bedding plants, but to also expand production to include poinsettias, hanging baskets, perennials, and garden mums so that I have crops almost year-round. This will improve cash flow, keep customers coming back for products all year, and help keep the same employees most of the year. I plan to produce my own plugs and rooted cuttings in the winter so that I can insure the top quality demanded by the retail garden center market. I plan to sell extra flats of plugs and rooted cuttings to other producers. In addition to bedding plants, I will produce perennials for spring sales to garden centers. In the late summer and fall, I will grow my own poinsettia stock plants and finished poinsettias. In addition to producing plants in the greenhouse, I will also produce garden mums for fall sales on about one-quarter of an acre outdoors. The greenhouse sits on a 30-acre tract of land that also includes a small barn, not currently in use.

Mrs. Greenjeans Greenhouse is a new business just starting up with myself, Mary Wilson as owner/manager. The greenhouse facility is 30 years old and was purchased from Bill Smith, who retired. By the time he retired, Bill had reduced production to only bedding plants, which he sold in the spring to garden centers. I have a B.S. degree in horticulture and will be the manager and owner of the greenhouse. This spring will be my first crop.

My husband, John Wilson, has a degree in economics and earns enough money at his job as a financial advisor to keep the family going while I get the business up and running. He is helping with the business plans. Our two children, a daughter, Linda, who is 14 and in 9th grade, and a son, Dan, who is 15 and in 10th grade, will help out with the business a few hours after school each day.

Because of the growth of mass merchandisers who sell plants at low costs, I plan to produce high-quality plants and unique varieties that are not available in the mass market. I plan to sell my products to the retail garden center market, whose customers are serious gardeners looking for quality, service, and uniqueness.

Mrs. Greenjeans Greenhouse is located in fairly rural area just outside of a small town, Anywhere, USA, on a major road. The area contains upscale, Victorian homes where beds of annuals and hanging baskets are prized.

Mrs. Greenjeans Greenhouse has a 25,000-square-foot glass greenhouse with a 2,000-square-foot headhouse and loading dock. There is also a small barn that can be used for storage or possible retailing activities.

Mrs. Greenjeans Greenhouse is a partnership with Mary and John Wilson as owners. It has been registered with the state. I (Mary) utilized inherited assets to purchase the business, so I was able to provide 75 percent of the start-up capital. It is my intention not to make that inheritance a gift to my marriage, and accordingly have consulted a law firm to insure that in the event of divorce or my premature death, those assets will remain mine or protected in my estate. I am also the full-time manager. John and I are in agreement that, since I am providing 75 percent of the capital and John is providing 25 percent, the same percentages should apply to the proprietorship. This formula will then be the same that applies to all other aspects of the business structure, such as taxes, profits, and liabilities (as well as unforeseen circumstances that might arise and resolve themselves as liability issues).

STRATEGIC PLAN: BUSINESS AND INDUSTRY PROFILES

Strategic planning is a tool that looks at the big picture. Each firm possesses a unique bundle of resources. Strategic planning helps determine how to use these resources to develop basic and core competences that will give the business a competitive advantage. It considers future competitive forces in the industry. It describes where the owner wants the business to go and how he or she plans to get there over the next 5 to 10 years. Typical components of a strategic plan include (1) mission statement, (2) goals and objectives of the business, (3) industry analysis/situation (external opportunities and threats), (4) the firm's competitive position (internal strengths and weaknesses), (5) business strategy, and (6) implementation plan.

Mission and Vision Statements

To set goals and standards, a firm needs a vision and a mission. The vision looks at the future and asks *what kind of business does the firm want to be*. It is a source of inspiration and provides clear decision-making criteria. Some questions the owner can ask to help develop a clear company vision are What values do I hold that I will not compromise? What characteristics do I want to portray to people? What principles do I stand for? How do I want to be seen or thought of when I interact with people? What do I want in life?

The mission focuses on the firm's present. It lists the broad goals for which the firm was formed. Why does the firm exist? What is its purpose? What does the firm do? Why does it do it? For whom does it do it? It identifies the company's products, services, and customers. A mission statement should focus less on what activities happen in the greenhouse and more on what the business will accomplish for its customers, employees, and owners. In a market-driven economy, a good mission statement describes *what consumer need will be filled*. How the firm's products and services will do this better than the competition is the customer value proposition. This market-driven approach to business is different from the production-driven approach taken by many managers in the past. When times were less competitive, managers could produce high-quality plants and then find a market for them. Now, firms must first identify a market need and then grow products that satisfy that need, at a price customers are willing to pay and will still return a profit to the business.

A mission statement should be short enough so people can easily remember it. The mission statement is the mechanism for making clear to everyone the company touches the answers to the following questions: Why am I here? Where am I going? and How can we beat or avoid competition? A mission statement can be used to unify the people involved in the business around a common direction and understanding of the purpose. It can be used as a foundation or measuring stick for making decisions.

MRS. GREENJEANS GREENHOUSE'S MISSION STATEMENT

Mrs. Greenjeans Greenhouse will produce and distribute unique high-quality greenhouse products to serious gardeners within a 200-mile radius around Anywhere, USA. We will pursue continued market penetration through a commitment to quality and value.

Goals and Objectives

Goals and objectives help define what the business will become. While goals can be broad or general in nature, objectives should be clear and concise. Goals should give the business a future target. Objectives should be SMART (specific, measurable, attainable, relevant, and time-bound). Because the strategic plan should be frequently monitored and corrected, goals may need to change to reflect a new and revised strategy. Goals can be defined by discussing questions such as the following among family members and business partners:

- Why are we in business?
- Are we in business because we like being our own boss?
- What do we want to accomplish in our lives and business?
- What level of profits do we need?
- Are we purely profit motivated, or do we also make investments for community status or other reasons?
- How large should the business become?
- How will we provide employment and financial security for family members?
- How will we increase our family's wealth?
- Do we enjoy growing plants?
- Are we people oriented or technology oriented?

Objectives are usually expressed in financial terms. Managers should try to think of objectives for each of the following functions: financial, marketing (product, price, place, and promotion), profit, personnel, production, sales, customer and public relations, advertising, accounting, collection, purchasing and inventory control, legal, and security objectives. Many of these functions cannot be clearly separated from each other and will overlap. When developing objectives, managers should consider how they will impact the long-term profitability of the business. Some examples of specific objectives that are measurable with a specific time period are as follows:

- Increase return on investment 20 percent within the next three years.
- Increase sales by 50 percent over the next five years.
- Reduce labor costs by 20 percent over the next five years.
- Maintain the same level of sales, but look for ways to reduce costs by 5 percent next year through inventory management and mechanization.
- Establish a Keogh plan (A Keogh plan is a retirement plan tailored to the self-employed; see IRS Pub. 560.) for our employees and increase contributions to owners' retirement accounts to $10,000 per year by next year.
- Provide full-time employment for all family members within the next three years.
- Provide two weeks of paid vacation per year for all family members within five years.
- Increase production by 25 percent within two years.
- Grow the business to a size that will, in the long term, provide cash flow for three families at $40,000 per family.
- Reduce debt by $25,000 per year.
- Be in a position to transfer full ownership to my children when I retire within 10 years.

GOALS AND OBJECTIVES FOR MRS. GREENJEANS GREENHOUSE

The goal of Mrs. Greenjeans Greenhouse is to begin operating a 25,000-square-foot greenhouse and sell bedding plants to local retail garden centers next spring and continue with hanging baskets, garden mums, perennials, and poinsettias for year-round production. The first objective is to write a business plan within the next three months. The second objective is to contact an attorney to review the business plan and draw up new wills for Bill and Mary in the next three to six months. The third objective is to have sales of $200,000 the first year.

Opportunities and Issues Analysis: SWOT Analysis (Strengths, Weaknesses, Opportunities, and Threats)

Firms face external opportunities and threats that are beyond their control. Shifting economics, increased global competition, changing government regulations, and new technology are some of the reasons it is more difficult to make a profit in the greenhouse industry today than in the past. Firms also have strengths and weaknesses that are internal to their businesses, such as location, skills of key employees, and cash flow position. Building a successful business requires magnifying strengths and overcoming weaknesses. Managers can identify competitive advantages by matching internal strengths of the business to external opportunities. They can try to overcome internal weakness and external threats by converting them into strengths or opportunities. An example of a conversion strategy is to find new markets. For example, many smaller growers who cannot compete on price with larger competitors have turned to direct marketing, where they can compete on non-price factors such as service. If the threats or weaknesses cannot be converted, successful managers try to minimize or avoid them. For example, as the market for poinsettias in 6-inch pots became hypercompetitive, some producers purchased pre-finished poinsettias for resale rather than growing them. Others try to find a unique product that others are not producing, like an unusual plant, or a variation on a common plant, like poinsettia trees instead of poinsettias in 6-inch pots.

Managers need to take a hard look at forces that are at work within the business and in the outside business climate in which they must work. A strategic planning tool called a SWOT (strengths, weaknesses, opportunities, threats) analysis matches profitable business opportunities with the firm's resources. It describes the firm's overall approach to the business and helps to identify objectives, evaluate whether or not they are attainable, and develop strategies to meet them.

Competitive Position: Internal Strengths and Weaknesses Greenhouse production is a very competitive business. Building a successful business plan requires magnifying strengths and overcoming weaknesses. For example, a manager who has skills in the technical aspects of the business but is weak in the business aspects may be able to hire someone to help evaluate the economic impact of his or her decisions. Likewise, a good business manager who does not know the technical aspects of the business may want to hire someone who has those missing skills.

Perhaps the biggest advantage of many U.S. and European producers is that they are close to the market, that is, located near densely populated consumer markets of high-income consumers. This gives them a comparative advantage over competitors who must pay shipping costs to reach their markets, and it also gives them direct access to the customers. Weaknesses for U.S. and European producers are high costs for land, labor, and other inputs. To overcome these economic weaknesses, producers must find ways to reduce costs or they must focus on their strengths or a combination of both.

To assess the company's competitive position, managers should consider strengths that can be utilized and weaknesses that must be overcome to compete in a global environment and/or with other producers in their local area. Following are some questions to ask:

- What production levels do you have now or do you want to achieve?
- Where is your business located? Is it near a major highway, in a metropolitan area near consumers, or on an isolated country road? Does it lend itself to direct marketing or wholesale marketing?
- How much land do you own? Can you rent or purchase other land for expansion?
- What machinery and facilities do you have and the age and condition of each? Can they be better used? Should you sell off excess and unused equipment?
- What is your financial condition?
- What is the cash position of your firm?

- What are the skills and limitations of the owner/manager?
- Does your strategic plan require greater competence or resources than the firm currently possesses?
- Do the firm's skills and resources limit the alternatives?
- Does the proposed plan exploit marketing and production opportunities?
- Do your personal preferences or sense of social responsibility limit the alternatives? (For example, do you not want to work on Sundays, a possibly high sales day for direct marketing?)
- Can you form alliances or partnerships with other businesses that could complement yours?
- What marketing channels are possible?
- How many employees does your business have and what skills and talents do they possess?
- What family members will be involved in the business and what are their unique talents and interests?
- Who will be the next generation of management?
- How does the layout of the greenhouse operation impact production efficiencies?
- Do you have an adequate, cost-effective water supply?

INTERNAL STRENGTHS AND WEAKNESSES FOR MRS. GREENJEANS GREENHOUSE

Mary Wilson is starting a wholesale greenhouse and plans to produce high-quality plants for garden centers. She is also considering some retail sales directly out of her greenhouse in the peak bedding plant and poinsettia season. She has evaluated the firm's competitive position by analyzing the strengths and weaknesses of her business.

Financial

Strength: The business does not have to support the family initially because of John's job.

Weakness: The net worth is tied up in the greenhouses, which will rapidly depreciate.

Marketing

Strength: The business is located outside a city that boasts three supermarkets, which could be possible wholesale customers.

Weakness: If the greenhouse moves more into direct marketing, this would be a new venture with no current customer base.

Profit

Strength: John's job provides money to live on, so the greenhouse has the luxury of building the business long-term.

Weakness: Initially the business will be wholesale, so sales are not high and profit potential is limited.

Personnel

Strength: The children can help out after school for now.

Weakness: Labor is the largest cost, and will become even higher in three to four years when the children go off to college and more labor will need to be hired.

Production

Strength: Greenhouses are surrounded by enough flat farm land that agri-entertainment options could be considered. The possibilities include pick-your-own pumpkins, Indian corn, haunted houses, corn mazes, and pick-your-own strawberries.

Weakness: Facilities are old and limit mechanization.

Sales

Strength: Mary took over an existing business, so there is a customer base from which to draw.

Weakness: The greenhouse is one-half acre, and the previous owner sold wholesale, and only during the bedding plant season. Therefore, unless new items are added to increase production to include other seasons, sales could be limited.

Facilities

Strength: A small barn is currently not in use, but has potential for a roadside stand. It is highly visible from a heavily traveled road, and lends itself to window boxes and other displays. The property has a functioning well that provides enough water for the greenhouse.

Weakness: Greenhouses are in fair condition at best and in need of modernization and repair.

Personal

Strength: The family is behind Mary's plan to start a greenhouse business.

Weakness: The new business will take time away from activities that the family did before.

Industry Analysis: External Opportunities and Threats We truly live in a world economy today where the market is constantly changing. External factors drive these changes or trends. Many of these changes pose threats to greenhouse producers. When consumer confidence is shaken, demand for greenhouse products can decline. Imports coming from countries with lower production costs make it difficult to compete. Oil prices are volatile and impact input costs such as heating and transportation. For many businesses, weather can be a bigger challenge than a weak economy. Rainy weekends keep buyers away, and product cannot move through the supply chain. Government regulations are increasing, also pushing up costs and consuming management's time. On the other hand, external changes or trends also offer new market opportunities. The increase of two-income couples, for example, means these consumers have little time for gardening but have disposable income to buy high-quality finished containers. The buy local and green movements offer marketing possibilities to innovative producers. The explosion of Web sites and social networking sites such as Facebook and Twitter gives producers new ways to compete, but also takes time and effort. Growers who adjust to the change early take the most risk, but often also reap the most benefits.

Producers should identify trends (driving forces) in the marketplace that will impact the greenhouse industry. Areas to consider are technological innovations, legislation and political changes, government regulations, globalization, cultural and demographic trends, labor availability, or changes to input suppliers and markets. A basic part of strategic planning is to understand these trends. A successful manager will structure the business to take advantage of opportunities to meet the company's

INDUSTRY ANALYSIS: EXTERNAL OPPORTUNITIES AND THREATS FOR MRS. GREENJEANS GREENHOUSE, ANYWHERE, USA

Cultural and Demographic Trends

Opportunity: The number of two-income families with high disposable income is growing. Consumers are becoming more sophisticated and recognize new and different plant material.

Threat: There are a growing number of two-income families with little time to garden.

Market/Globalization Trends

Opportunity: Consumers are looking for a "shopping experience" that lends itself to having urban consumers buy right from the greenhouse and see how the plants are produced.

Threat: The increase in the number of superstores and warehouse stores, which sell plant material from other states and countries with lower costs or more favorable exchange rates, is pushing prices down.

Input Costs

Opportunity: Low-cost producers make purchasing standard-sized plants, like 6-inch poinsettias, cheaper, thus allowing small producers to buy these cheaply for resale so that they can concentrate on producing specialty plants that command a higher price.

Threat: Profits are declining as labor, heat, and other input costs increase.

Technology

Opportunity: Communications technology is improving and becoming less costly.

Threat: As a small producer, it is difficult to compete with large, low-cost producers who are mechanized.

Regulations

Opportunity: Consumers may want to learn about biological pest control and buy plants produced using reduced pesticides.

Threat: Minor use pesticides that are used in greenhouses are being removed from the market or are coming under pressure and becoming more costly as registration costs are passed along to the producers.

Government Programs, Legislation, Political Changes

Opportunity: Demand is increasing for native, organic, deer-resistant, drought-tolerant, and environmentally friendly plants.

Threat: Consumers are reluctant to buy landscape plants because deer will eat them, the political climate is resistant to increased hunting to reduce the deer population, and local municipalities may impose watering restrictions because of drought.

objectives and prepare for threats that might inhibit the company's ability to achieve its objectives. The types of questions to ask include the following:

- Can current or emerging market trends become business threats or missed opportunities if you don't include them in your strategy?
- Is technology changing such that you will not be able to compete with low-cost producers who adopt the new technology unless you adopt it as well?
- Will government regulations force you to adopt new systems?
- How can you offer service, convenience, and value for today's busy and cost-conscious consumer?
- What is happening to your particular market channel locally, regionally, nationally, and internationally? What opportunity does this open up for your business? What threats or challenges does it create for your business?
- What changes are greenhouse businesses similar to yours making?
- Have others made positive changes that might work for your business or bad decisions that you know you want to avoid?

Business Strategy

After gathering all of the information in the previous steps, managers are in the position to develop and evaluate alternative strategies that will attain the objectives of the firm. To develop a business strategy, a manager can begin by answering questions like what do you want your greenhouse business to be in the next 5, 10, and 20 years? and will your strategy help you *do the right things* to succeed in the future of your industry?

Develop Strategic Alternatives An analysis of external and internal opportunities and threats can lead to identifying strategic niche markets that the firm is best able to fill by capitalizing on strengths. This strategy is much more likely to be profitable than competing strictly on price with large firms in the industry. However, in this highly competitive business climate, reducing costs is an important consideration no matter what type of competitive strategy the firm chooses. The key is to identify ways to give the firm a competitive advantage.

Producers in a purely competitive market are price takers (i.e., they must "take" the market price). To increase profits, price takers are limited to competitive strategies that reduce costs or increase sales, since they do not have the ability to raise prices if they expect to remain in business. Producers selling to the mass market may be in this situation. They will want to evaluate alternatives that reduce costs, and therefore increase profits. Strategies that price takes can consider are as follows:

- *Reduce costs*. Greenhouse firms can increase profits by reducing the costs of inputs while holding the selling price constant. (But, they must be careful not to let product quality slip by doing things like growing plants on spacing that is too tight.) This strategy includes mechanizing to save labor, using more intensive production technologies, planning purchases to take advantage of volume discounts and prompt-payment discounts, and more intensively managing the entire operation so that fixed costs are spread over more output.
- *Expand the operation*. This is usually done to increase sales, and assumes that there will be economies of scale or that fixed costs per unit will at least not increase. Expansion should be considered only after increasing the production efficiencies of existing facilities. Expansion should also carefully fit into the firm's mission and goals. Many greenhouse owners expand to a larger operation, and find they are not making much more money than when they were smaller, and they enjoy it a lot less. Bigger is not necessarily better!

- *Replicate*. This is another way of expanding. Add another retail outlet or another production facility when land nearby is not available for expansion, or if a second location better serves the business mission.
- *Specialize* or focus on one or only a few products or activities. Successful producers have focused on growing only plugs, herbs, outdoor cut flowers, and so forth. This concentrated focus allows for production efficiency and lower costs of production.
- Charge a *price premium* for high-quality products (even the mass market is now looking for higher-quality products and is willing to pay a slightly higher price for a better-quality product).
- *Integrate horizontally*. Add more crops or enterprises to more fully utilize fixed inputs, thus spreading the fixed costs over more units of output.
- *Integrate vertically* by going higher or lower in the marketing chain. Options include value-added marketing or adding a retail sales area or an agri-entertainment component to reach the final consumer. Another option is to go toward the input part of the marketing chain. Options include producing inputs, such as plugs, or adding a dealership to sell inputs such as greenhouse benches.
- *Diversify* by adding new enterprises or products (the opposite of specializing). Diversifying the crop mix spreads risks over more products, and adding new customers or markets spreads business risks over more markets.
- *Use pricing strategies* to increase sales such as multi-unit pricing. (This means giving discounts to customers who buy larger volumes to encourage larger purchases, that is, one garden mum to retail customers for $5, but five for $20).
- *Network* with other greenhouse owners to produce, purchase inputs, or market.
- Develop an *exit strategy or downsizing plan* for the business.

Much of floriculture is not a completely competitive market; not every product has a clear market price. These markets provide an opportunity to differentiate the product. Strategies for product differentiation include the following:

- Look for *alternative crops* that are not so competitive.
- Find a *niche market* that competitors are not servicing.
- *Grade for quality* and charge premium prices for premium products.
- *Adapt to changes in consumer tastes and preferences*. For example, offer new varieties, service, and low-maintenance or drought-resistant plants.
- *Add service* to the product. This could include special containers and care tags.
- *Choose an ideal location*. This is a must for retail growers, but having easy access to major transportation routes also helps wholesale growers compete more cost effectively. Some existing producers have found that the best strategy is to sell existing facilities and move to a new location where they can take advantage of building newer, more efficient facilities.

Before greenhouse firms begin to look at expanding, diversifying, replicating, integrating, or adding new products, they should focus on the current operation, and look at cost-reducing options. If problems exist in the current operation, expanding will only make things worse. A better approach is to focus on the system and improve the profitability at the current level of production before considering getting bigger.

Some things managers should take into account when considering alternatives are as follows:

- What is the time period over which changes to the business will be made?
- Will they be done in increments or all at one time?
- What is the expected impact on the profitability, production levels, required labor, and markets if the plan is implemented?

ALTERNATIVE STRATEGIES FOR MRS. GREENJEANS GREENHOUSE

ALTERNATIVE A: YEAR-ROUND PRODUCTION

Instead of producing only bedding plants, we will expand production to include poinsettias, hanging baskets, perennials, and garden mums so that I have crops almost year-round. These will be wholesaled to garden centers, which pay a higher price than the mass market. I would also produce my own plugs and rooted cuttings in the winter so that I can insure the top quality demanded by the retail garden center market. I would sell extra flats of plugs and rooted cuttings to other producers. In addition to bedding plants, I will produce perennials for spring sales to garden centers. In the summer and fall, I will grow my own poinsettia stock plants, finished poinsettias, and florist mums. In addition to producing plants in the greenhouse, I will also produce garden mums for fall sales on about one-quarter of an acre outdoors.

Pros: This will improve cash flow, keep customers coming back for products all year, and help keep the same employees most of the year.

Cons: The previous owner produced only bedding plants, so a market would have to be created for the other products. Nearly year-round production will take much more management capability than producing only in the spring, and will leave less free time for family and other activities.

ALTERNATIVE B: RETAIL FARM STAND

Mrs. Greenjeans Greenhouse has a small barn that can be used for retailing activities. Bedding plants can be retailed directly out of the greenhouse, and garden supplies can be sold out of the retail stand. Easter and Mother's Day plants can be sold directly to the public. In the fall, mums, corn stalks, bales of hay, and so forth can be sold.

Pros: This alternative complements the production activity and creates a market that will command a higher price selling to garden centers compared with the wholesale market. Very little additional overhead costs will be required.

Cons: This will require more employees, more management, a focus on sales rather than production, and a parking lot.

ALTERNATIVE C: AGRI-ENTERTAINMENT

We could use the land surrounding the greenhouses to start an agri-entertainment business. We could sell admission for children to find their way through a corn maze. We could also sell pick-your-own pumpkins and Christmas trees. This will help draw in more customers to boost our garden mum sales.

Pros: We would be getting more money for less labor. We would have income from new crops and products such as cider, apples, pumpkins, squash, gourds, corn stalks, and bales of hay. This is a ready market for people celebrating the fall and Halloween and Thanksgiving holidays. This extends the cash flow season past the usual harvest when garden mum sales would die off. Combined with limited tree farming, it extends the sale into the Hanukkah/Christmas season. Christmas tree farming gives us a source to make door and Christmas wreaths.

Cons: More overhead would be required because agri-entertainment requires more supervision. Any time people are trekking over your property, there are more liability issues.

Select a Basic Strategy Once alternative strategies have been selected, they need to be evaluated. This is the stage when managers should do some kind of financial analysis. They will want to follow three basic investment criteria: (1) Larger benefits are preferred to smaller ones. (2) Early benefits are preferred to later ones. This takes into account the time value of money, that is, a dollar today is worth more than a dollar tomorrow. (3) Safety is preferred to risk.

In addition to financial analysis, managers will also want to analyze how these alternatives address the firm's other objectives. Some items to consider are as follows:

- Which alternative will best enable the firm to reach its desired objectives?
- Which alternative offers the greatest financial returns?
- Which alternative best matches the firm's skills and resources (financial, technical, personnel, etc.)
- Which alternative best meets the owner's personal preferences or sense of social responsibility?
- Which alternative minimizes the creation of new problems?

At this step, the manager and other members of the management team need to determine if the alternative strategies are consistent with the firm's mission and objectives. If they are not, they may want to develop a new mission statement or objectives at this point and follow the steps in the strategic planning process again. Or, they will want to eliminate or modify that alternative so that it is consistent with the firm's mission and objectives.

It is important to include the employees in the planning and evaluation process. Employees are often closer to problems than owners or managers. They often can contribute to recommendations and solutions to problems. Knowing that their opinion is valued can improve their job satisfaction and productivity as well.

After evaluating various strategies, the management team should select a basic strategy that is consistent with the firm's objectives. The basic strategy should include marketing, production, financial, and personnel plans. The *production plan* tells if the system is technically feasible. The *financial plan* tells if the system is profitable. The *personnel plan* tells if the right people can be found to make the system work. A *marketing plan* is the centerpiece of the business plan and is the engine that drives the entire business. The marketing plan is the complete assessment of all the factors surrounding the consumer needs that the business will fill. The starting point is a market analysis and the ending point is the marketing mix. The marketing mix includes the right *products* at the right *price*, in the right *places*, with the right *promotion*.

Selecting the final strategy may involve trade-offs among various objectives. One alternative may offer the greatest financial returns, but it may be inconsistent with other objectives. At this point, the manager must make a decision as to which objectives are most important. The final strategy may be a combination of more than one alternative strategy.

BUSINESS STRATEGY FOR MRS. GREENJEANS GREENHOUSE

ALTERNATIVE A: YEAR-ROUND PRODUCTION

We purchased an existing business that was producing only bedding plants. For now, we want to focus on that core, and add year-round crops that are produced in the greenhouse. In the future, we will again consider alternatives B and C, but this seems like too much of a leap at the present. We fear if we diversify too much, we will lose our core strengths.

Implement the Plan

Once a strategy has been selected, the next step is to implement it. The strategy describes "Where do I want to be?" The next step is "How do I get there?" The firm needs to identify *who* is going to do *what* by *when* for *whom* and for *how much*.

If the chosen strategy requires making major changes in the business, the implementation plan should describe what will happen during the transition period. If it involves expanding or changing the business, the plan may include a description of new facilities or land, a timeline for construction or purchases, a list of permits required and how to obtain them, a general overview of how the changes will be financed, and the impact on production levels during and after the changes. Many expansions do not meet their timelines, which results in increased financing needs. The implementation plan can include a timeline and a contingency plan for the possiblity that deadlines may not be met.

PRODUCTION AND OPERATIONS PLAN

The production and operations plan includes a description of what crops the firm will produce, how it will produce them, and what technology and equipment will be used. It can also include a list of the varieties that it plans to produce. Other business activities that may be related to the greenhouse should be enumerated. These may include activities such as growing other crops, that is, outdoor cut flowers or bio-fuels; selling production inputs to other producers; opening a roadside stand, farm stands, or CSA (community supported agriculture); or starting agri-entertainment ventures such as open houses, haunted houses, corn mazes, and pick-your-own outdoor cut flowers.

Cultural Records

Before growing a crop, one should decide which records to keep. One set will be financial, including costs of items such as plants, containers, root substrate, labor, and utilities. The other set of records is cultural in nature. Cultural records are maintained for the purposes of (1) providing a plan for duplicating successful crops and (2) giving an accounting from which the cause of errors in the culture of the crop can be determined and then corrected in the next crop.

Long before a crop is planted, a cultural schedule should be written, listing dates and labor budgets for operations such as root substrate preparation, planting, syringing, fertilization, pesticide application, pinching, pruning, chemical growth regulation, disbudding, harvesting, and cleaning up. This cultural schedule should be maintained in the general manager's office. The information should be duplicated on a cultural schedule record sheet to be hung in the greenhouse at the location of the crop being grown. The cultural schedule record sheet serves as a daily reminder to the production manager as to the various operations that must be performed.

When each operation is performed, the name of the performing employee and the date are entered on the cultural schedule record sheet in the greenhouse. Should an unscheduled operation or an alteration in a scheduled operation be necessary, a description of the operation is entered in the record. At the end of each day, the entries are verified and initialed by the manager overseeing the operations.

Gantt Charts: Planning and Scheduling for Labor Needs

Gantt charts can help managers work out the order in which tasks need to be carried out and identify the resources needed to grow and sell a crop, along with the times when these resources will be needed. When production is under way, Gantt charts help managers monitor whether or not the crop is on schedule. If it is not, they help pinpoint the remedial action necessary to put it back on schedule. The Gantt chart in Figure 2 depicts a portion of the production schedule for poinsettias showing the tasks required, the personnel in charge, and the dates for each task.

To use a Gantt chart, follow these steps:

1. List all production activities. The first step is to list all of the tasks that need to be completed to produce and sell a crop. For each task, show the earliest start date, how long the task will take, and who is responsible for each task.
2. Make a chart for the year and schedule the labor activities. Plot each task on yearly calendar, showing it starting on the earliest possible date.
3. Make a chart for each of your other crops and other greenhouse activities for the year and schedule the activities. Pay particular attention to which crops look the most profitable and also what crops or activities can extend into slack months.
4. Make a master Gantt chart. You may want to start by writing down how many employees you think are needed, then how many weeks, and, finally, how many hours of that labor will you have. Next, list what crops you intend to grow. Make a budget and a Gantt chart for each one.
5. Make a budget for each crop you intend to grow to match the hours of labor you expect to have. This will allow you to look at the big picture to see how much labor you anticipate needing in each month. Can you modify work schedules or crops and other activities to utilize available labor in slack months?

Task	Personnel	Start	End	Duration	Sec./pot
1. Order Cuttings	Production Mgr.	1/15	1/20	5 days	
2. Order Supplies-elle pots, trays, fungicide, growth regulator, 6-inch pots	Production Mgr.	4/15	4/20	5 days	
3. Hire Labor or reassign labor	Production Mgr.	6/1	6/15	2 wks	
4. Check mist lines & disinfect benches	Labor	7/1	7/6	5 days	
5. Stick Cuttings	Labor	8/1	8/6	5 days	
6. Pot to Final Container	Labor	8/15	8/22	1 wk	20
7. Water 3 times/wk for 6 wks.	Labor	8/15	9/25	6 wks	9
8. Drench for Pythium	Grower	8/22	8/29	1 wk	1
9. Pinch — 2 weeks after planting	Labor	8/29	9/3	5 days	3.5
10. Apply fungicides for botrytis	Grower	8/29	9/3	5 days	1
11. Apply Pesticides	Grower	9/12	8/20	5 days	4
12. Apply fungicides for botrytis	Grower	9/12	9/19	1 wk	1
13. Drench for Pythium	Grower	9/12	9/19	1 wk	1
14. Lower Temperature	Grower	9/21	9/26	5 days	
15. Natural Short Days	Grower	9/21	9/26	5 days	
16. Order Sleeves	Production Mgr.	9/21	9/28	1 wk	
17. Water 4 times/wk for 9 wks.	Labor	9/25	11/28	9 wks	18
18. Apply Growth regulator	Grower	9/28	9/12	1 wks	2
19. Space	Labor	9/28	10/12	2 wks	18.4
20. Apply fungicides for botrytis	Grower	10/10	10/15	5 days	1
21. Drench for Pythium	Grower	10/10	10/15	5 days	1
22. Apply fungicides for botrytis	Grower	11/1	11/6	5 days	1
23. Apply fungicides for botrytis	Grower	11/15	11/20	5 days	1
24. Drench for Pythium	Grower	11/15	11/20	5 days	1
25. Sleeve	Labor	11/15	12/21	5 wks	5
26. Collect from Greenhouse and Put on Racks	Labor	11/15	12/21	5 wks	47.8
27. Arrange in trucks	Marketing Mgr.	11/15	12/21	5 wks	
28. Delivery	Driver	11/15	12/21	5 wks	
29. Use Cost Accounting to Evaluate Results and plan for next year's crop	Finance Mgr & Production Mgr.	1/2	1/15	2 wks	
	Total Seconds				**136.7**
	Total Labor cost @ $10/hour			**$**	**0.38**

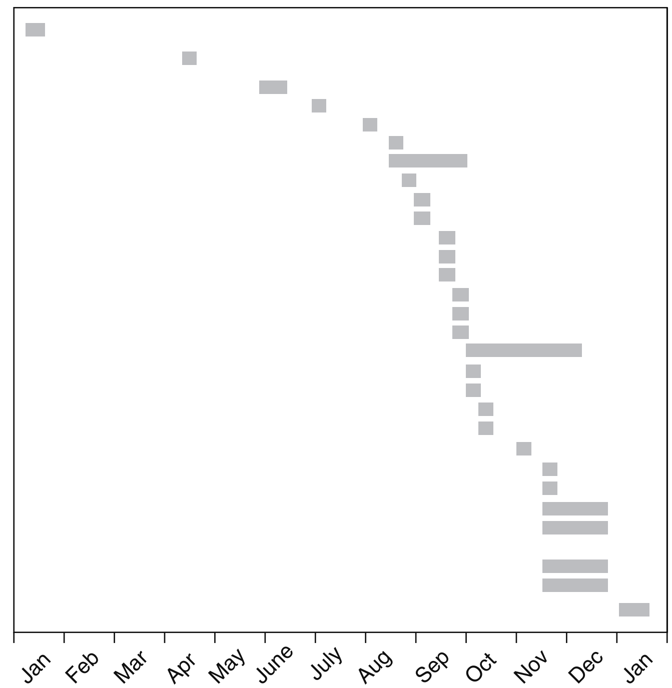

Figure 2

A Gantt chart showing a portion of the production schedule for poinsettias. The chart shows the tasks required, the personnel in charge, the start date, the end date, and the duration of the task. The entire chart would show the calendar for the entire year and a line would be drawn through the date for each operation to be executed.

Plant Environment Records

A second set of culture-related records contains the plant environment records, including temperatures inside and outside the greenhouse, solar radiation, root substrate nutrient analyses, foliar analyses, insect and disease occurrence, and visual observations. Temperature should be recorded in the greenhouse to determine whether the desired temperatures have been maintained. Deviations from both low-temperature and high-temperature phases have an adverse effect on plant growth and prevent efficient use of energy. Such records give an assessment of the quality of the heating and cooling equipment and indicate breakdowns. They can prevent the erroneous conclusion that the schedule is incorrect when the crop has matured at an unexpected time. To change the cultural schedule in this case would only lead to a second mis-timed crop. Recording thermometers with a seven-day record are available for this purpose. This is one more task at which a computerized greenhouse-control system excels. The computer can log temperature, relative humidity, light intensity, and any other parameter received from a sensor. The computer goes a step further by being able to tabulate or graph such data.

Inside temperatures indicate the condition of the temperature-control equipment, while outside temperatures reflect fuel and electrical consumption. A record of outside temperatures can be obtained from your local branch of the National Weather Service. Data are gathered at several points in each state and published. Greenhouse climate-control computer systems typically include an outside climate-monitoring station. Climate factors monitored include temperature, light intensity, rain, wind speed, and wind direction. For more sophisticated cost-analysis programs, the grower may want a record of daily minimum and maximum temperatures, heating degree days, and solar radiation. The winter-temperature and heating-degree-days data are useful in determining whether the fuel bill for one winter will be representative of successive years. These data also can be used to determine what proportion of the total fuel bill to allot to each crop grown during the heating season. This is important information for cost accounting. Summer-temperature data can be used in a like manner. Extremes in summer temperature result in crop delay and poor quality. Such records permit proper assessment of the cause.

Solar-radiation values indicate the amount of light reaching the earth's surface and thereby indicate when light is a limiting factor. When growth is limited by insufficient light, increases in temperature, fertilization, or CO_2 level are ineffective and a waste of money. Records such as those for solar radiation give an indication of which factor is limiting growth, thereby enabling the grower to decide whether alteration of environmental factors will be profitable.

Periodic root substrate tests and foliar analysis reports should be saved chronologically by crop. These are also valuable in determining factors that limit growth and thereby explaining exceptionally good or poor growth.These records are also used for establishing the fertilization program itself.

All states have agricultural extension agents who can identify insect and disease problems. Some states have insect and disease clinics where samples can be sent for identification. Whenever an insect or disease problem is identified, it should be reported in the plant environment records. Again, these factors explain poor quality and yield.

Production Records

The third set of culture-related records needed by the general manager is production records. These records are gathered throughout the growth period of the crop. The production manager should assess the condition of each crop weekly and enter this assessment into the production record. For a crop such as gloxinia, the width of a dozen typical plants might be measured and the average values entered into the record. The average height of a chrysanthemum crop could be measured and recorded. Visual observations also should be recorded, including such factors as form, leaf color, leaf size, stem thickness, and the appearance of chlorosis or necrosis.

These types of information allow for comparison of the present crop with previous crops. A problem such as phosphorus deficiency, which is not apparent to the eye in early stages, can be identified through smaller-than-normal growth measurements. By looking at a poor crop in retrospect, the grower can identify the stage of growth when trouble first occurred. The cultural records and plant environment records can then be checked to find the cause of the problem. In most cases, when the cause can be found, it can be corrected in subsequent crops. The production record should also include the number of blooms or pots harvested, the date, and the grade or quality. These records are needed for cost accounting and are used in the same manner as the growth measurements described earlier.

PRODUCTION PLAN FOR MRS. GREENJEANS GREENHOUSE

Mrs. Greenjeans Greenhouse is a small nursery located in Anywhere, USA. We purchased the business last year. The previous owner produced only bedding plants. We want to develop year-round production and sell primarily to retail garden centers. We hope to increase production and sales over the next five years by using the existing space more efficiently. The existing headhouse is the staging area for planting and preparing plants for delivery. It also has storage capacity for containers, chemicals, fertilizers, and bags of growing media.

The following table gives our production and price projections of each crop for the next five years. We plan to work closely with our county agent and use integrated pest management as much as possible.

Production and Price Projections for Mrs. Greenjeans Greenhouses

		Number of Units Produced				
Items	Price ($)	Year 1	Year 2	Year 3	Year 4	Year 5
Bedding plants	6.65	8,000	9,000	10,000	11,500	15,000
Hanging baskets	7.00	2,500	3,000	3,000	3,000	3,000
Perennials	10.00	1,000	1,000	1,000	1,000	1,000
Poinsettias						
4-inch	2.00	1,000	1,000	1,000	1,000	1,000
6-inch	4.00	2,100	2,100	2,100	2,100	2,100
7-inch	7.50	1,000	1,000	1,000	1,000	1,000
8-inch	12.00	400	400	400	400	400
10-inch	18.00	300	300	300	300	300
Hanging baskets	25.00	75	75	75	75	75

Risk Management Plan

Greenhouse production comes with many risks. In this scary economy, greenhouse owners are looking for ways to reduce both business and personal risks. They are reviewing their life, disability, health, crop, fire, wind, hail, and liability insurance. Crop insurance has steadily increased over the past few years. A minimum level of crop insurance, catastrophic (CAT) insurance, is available to all producers regardless of size at a small premium cost to the producer because CAT premiums are subsidized by the federal government. Higher levels of crop insurance (buy-up protection) are also federally subsidized, with nursery growers paying only 33 to 45 percent of the actual cost of the insurance (Harper and Brumfield, 2009).

Greenhouse businesses should implement financial management practices that can cut costs and improve the profitability at the current size, before getting bigger. Managers can consider ways to eliminate debt or restructure it. They should evaluate cash flow and their line of credit. With the focus on sustainability, they need to have pesticide management plans, consider integrated pest management (IPM), and look for more sustainable systems.

RISK MANAGEMENT PLAN FOR MRS. GREENJEANS GREENHOUSE

GENERAL
Mrs. Greenjeans Greenhouse grows all of our crops, except for garden mums, in the greenhouse; thus, most weather risks are controlled. However, weather can negatively impact our products. If spring rains occur, our garden center customers cannot sell plants and ask us not to ship them. Then the plants stretch and they end up being dumped or sold for a lower price than normal. Similarly, if the weather is cloudy, the crop gets behind and stretches. We feel that the other major risks are power failure, snowstorms, hurricanes, boiler failure, water pump failure, and ice storms. A big concern now is the high cost of fuel. We plan to buy and prepay for fuel in the summer when the prices tend to be lower so that we can reduce some of the price risk. We plan to take advantage of volume discounts when purchasing supplies, and have storage space available for supplies.

LIFE INSURANCE
Mary and John will each purchase a $250,000 policy. This will provide security for the family as well as the business. This will provide enough to reduce debt to a manageable payment, and will also provide enough funds to cover the increase in hired labor.

DISABILITY INSURANCE
Mary and John will each purchase a disability insurance policy because this is a bigger threat than death at our ages.

HEALTH INSURANCE
John has health insurance through his employer for the entire family.

WILL
We have an appointment with our attorney to draw up a new will for each of us to protect the other one from the risk of loss of cash flow and equity in the event of the death of the other.

HUMAN RESOURCES
I (Mary) am keeping employees who were hired by the previous owner. I will set up monthly meetings to emphasize the strategic plan and business goals. I also have an open door policy to listen to input from hired employees. I will provide employee training as needed for pesticide applications, worker safety, and other changes in operating procedures.

FIRE, WIND, AND HAIL
We have insurance on the greenhouse structure and other buildings to insure the business will continue in the event of a catastrophic loss.

SNOW
In the event of a snowstorm, we will open the curtains and set the thermostat to 75°F to save the crops.

IRRIGATION
Mrs. Greenjeans Greenhouse has four wells. If a pump on one well fails, we have a backup.

LIABILITY INSURANCE
We will provide coverage for personal injury to visitors or others on the property.

WORKERS' COMPENSATION
Mrs. Greenjeans Greenhouse will pay workers' compensation to provide benefits to workers injured on the job.

POWER OUTAGE
We have two backup generators in case of a power failure.

CROP INSURANCE
Mrs. Greenjeans Greenhouse has basic catastrophic crop insurance (CAT) and fire insurance on the crops 75 feet from the greenhouse wall. We are underinsured in the event of a total catastrophic loss, but we feel the chances of a total loss are very low. Because the crops we raise are so valuable, we are considering adjusted gross revenue (AGR) crop insurance to preserve income in the event of market failure or weather-related losses.

INPUT PRICES
We will take advantage of volume and quick paying discounts. We are using double-layer polyethylene-covered greenhouses to control heating costs.

ENVIRONMENTAL
Because of fear of losing pesticides labeled for greenhouse, we focus on integrated pest management and other ways of reducing pesticide use. We have installed screening to prevent entry of insects into the greenhouse.

Managers should also review their estate plans. Most do not plan to retire, but they do want to plan for an income stream in their later years. Rutgers Cooperative Extension's Later Life Farming Web site (http://laterlifefarming.rutgers.edu/. Accessed February 24, 2011.) helps producers deal with producing income in retirement or in later years as they cut back on some activities and turn the business over to others.

To develop a risk management plan, producers should describe how they will mitigate their risks by answering the following questions:

- Do we have fire, wind, and liability insurance coverage?
- Do we have crop insurance and, if so, what is the level of coverage?
- Do we have sales contracts for our crops? Explain the general contract terms and indicate whom the production contracts are with.
- Do we have production alliances or networking arrangements with other producers, cooperatives, suppliers, or companies?
- Are there other on-site issues? How do we manage pesticide and fertilizer storage and mixing; fuel storage; and concerns from neighbors?
- How are we addressing environmental issues?

MARKET ANALYSIS: MARKETING PLAN

Without customers, the business does not exist. A marketing strategy or plan is about defining the customer or target market and tailoring the product, pricing, distribution, and promotion strategies to satisfy that target market. Greenhouse businesses that are product oriented—those that try to sell what they can produce without first looking at customers' needs—risk growing plants and flowers that will not sell at a price that will produce a profit. Instead, most successful greenhouses are customer oriented—they design marketing strategies around the needs of their customers.

A marketing plan is the engine that drives the business. A marketing plan describes what the firm will market and how it is unique (product); how and when the firm will market the product (distribution and packaging), to whom (target customers), and for how much (price) the firm will sell its products; and how and what the firm will communicate to the customers (promotion). This includes what has been called the four Ps of marketing: *product*, *price*, *place* (distribution), and *promotion*.

Developing a marketing plan will help managers confidently answer the following questions:

- ***Markets:*** Who are the target customers and what do they value?
- ***Product:*** What product will be offered and how is it unique?
- ***Competition:*** Who are our competitors and how will we position ourselves to compete? Are there threats from new entrants?
- ***Distribution:*** How and when will we move our product to market? What market channel will we use?
- ***Packaging:*** How will we present the product to the customer?
- ***Prices:*** How will we price our product? What is the perceived value of our product to the consumer? Is our price in line with the market's perceived value?
- ***Promotion:*** How and what will we communicate with buyers or customers? Do we have a marketing strategy with appropriate promotional, advertising, and branding strategies in place?

Markets: Who Are the Target Customers and What Do They Value?

To fully define the target market and corresponding marketing strategy, the firm will need to identify the target market segment (who the customers are and what they value) and sales potential (how much customers are willing to buy). Target markets are most commonly characterized as either individual households (*direct marketing*) or businesses (*wholesale marketing*). Direct marketing tends to be more profitable than wholesale marketing because of value-added opportunities and the lack of middlemen. Developing *customer profiles* or segmenting the market can help determine if a market segment is large enough to be profitable. By identifying and targeting specific market segments, a firm can also develop more effective packaging, price, and promotion strategies.

Market Segments Markets can be segmented in a variety of ways. The most common form of segmentation is by demographics (age, gender, income, race, ethnicity, disabilities, mobility [in terms of travel time to work or number of vehicles available], education, home ownership, and employment status). A market can also be segmented geographically, for example, domestic and international subgroups, various neighborhoods where consumers live, or location of different stores owned by wholesale buyers. Another common way of segmenting markets is by psychographic characteristics (attributes relating to personality, values, attitudes, interests, hobbies, or lifestyles). Another important question to ask is, what are the customers' needs? This applies whether the product is going directly to the final consumer or to an intermediary. Do they need convenience? a particular size? Sunday delivery? unique products? high-value products? large volumes?

Size of the Market To begin a business, producers need to ask, How many potential customers are there? How often and how much will they buy? What is the total size of the market? Is the market emerging, growing, or shrinking? Will this market yield a high-enough volume of sales?

Analyzing USDA statistics, visiting potential buyers, and attending industry and university educational meetings to learn and network are good places to start answering these questions no matter what market channel is selected.

Wholesale deliveries are usually kept to a distance that a truck can deliver and return in one day, or about 200 miles. New producers will want to visit potential customers (usually another business). These customers will probably be willing to indicate how much they would be willing to buy short-term (one to two years) through either a written contract or a verbal agreement. Projecting long-term sales potential may prove more difficult. Projecting sales potential can be even trickier for direct marketers. As a general rule, 75 percent of direct market customers of a business will live within 20 miles of the business. Using this rule of thumb, a simple way to project direct market sales potential is to locate the business on a county map and draw 25- and 50-mile-radius circles around it. The manager can count how many towns or cities fall within the circles and add up the number of potential households in the nearby cities. These households represent the core potential customers. Then, with a feel for the number of potential customers, the manager can estimate the potential value of sales per household. This is the *sales potential.* The next step is to estimate the number of customers in each segment and project their weekly, monthly, or annual purchases. These sales estimates can come from household or county purchasing records (available at the public library), from the firm's own surveys of potential customers, from in-person interviews, or from secondary sources, such as New Strategist Publications' *Household Spending: Who Spends How Much on What*. Many businesses find it useful to hire a marketing consultant to develop surveys, lead focus groups, or conduct telephone interviews. The local Extension service or state Department of Agriculture may be able to assist in locating qualitative and quantitative information for a customer profile. They may have already done some studies that could be helpful. The Small Business Administration may also provide assistance. The Sustainable Agriculture Research and Education (SARE) program has a competitive grant program for farmers and may be willing to fund some market research for sustainable production (http://www.sare.org/). Accessed February 24, 2011.

Product: What Product Will Be Offered and How Is It Unique?

The products that the business will offer should be described in terms of the value they will bring to the customers. What is it that customers are actually buying? What exactly does the product or service do for the consumer? What is the life cycle of the product? How will consumers use this product? Will special knowledge or service be required?

Another way to look at the product is what makes the product truly unique. What are the unique benefits the customer will receive from using this product? What is the real value versus perceived value to the consumer? Why would customers prefer this product to one produced by the competition? How does it compare in terms of quality, appearance, performance, price, versatility, durability, postharvest life, speed of installation, consistency, ease of use, ease of maintenance, knowledge required, and so forth? Why would customers prefer this product to some other alternative way to spend their money, such as wine, candy, food, or entertainment? Can it appeal to the environmentally conscious? Are there opportunities to add value through processing, packaging, and customer service? How might the product line change over time?

Recommendations for Approaching Buyers

1. *Become knowledgeable about the market*, by talking with other growers selling in that market. Try to find out individual buyers' expectations of volumes and prices to see if they match your situation before approaching the buyer.
2. *Prepare an availability sheet or a Web site listing products and prices*. Make sure that enough product is available to meet possible demand.
3. *Send the availability sheet to buyers* whose expectations best match what you have to offer. Buyers often prefer to see this sheet before they talk to a producer.
4. *Project a professional image* and be well informed about production, supply, and quality, and be confident in the business's ability to meet the buyer's needs.
5. *Work out the details of the sale with the buyer*, such as volume, size, price, delivery dates, and labeling requirements. Some buyers have a set of written requirements for growers.
6. *Keep in touch with the buyer*. Growers need to keep the buyer informed about potential problems so that buyers can look elsewhere for a product if there is a supply problem.

The Competition: Who Are the Competitors and How Will the Firm Position Itself?

Nearly every business or product has competition of some kind. Questions to consider are who are the competitors and what do they offer customers? where are they located? and what is their market share? who are the key "minor players"? A trip to the big box store, florist, garden center, farmers' market, or even a bit of time on the Internet to research what the competition is offering may help to answer these questions. The idea is to find out everything possible about the competitors' business or their buyers. One option is talk to current and potential competitors and their customers. What share of the market can the new product realistically capture? Where does the new product have an advantage over them? What are the strengths in terms of size, price, quality, speed, location, and service? Can the new product be produced with a new twist? Does the firm have access to markets that competitors cannot reach? Is the firm better at working with people—at attracting and keeping customers? Does the firm have better business skills? What competitors' weaknesses can be capitalized on? In other words, is there a niche? How much market share will the new product take away from competitors? How will competitors respond to the new product? Will they respond by changing price? Will they change their product?

Distribution of the Product or Service

Distribution refers to how and when to move the product from the greenhouse to the customer's home, store display, or wholesaler. Distribution strategies typically describe scope, market channel, packaging, and scheduling/handling. The *scope* defines how widely will the product be distributed? Will the distribution strategy be intensive, selective, or exclusive? *Intensive product distribution* typically involves widespread placement of the product at low prices. The aim is to saturate the entire market with the product. This strategy can be expensive and very competitive. Large-scale producers who market nationally or internationally often employ this method. *Selective product distribution* involves selecting a small number of intermediaries, usually retailers, to handle the product. If the product is large, for example, premium quality poinsettia plants, the grower may want to be selective about the stores that stock them and choose only upscale garden centers or florists, or retail directly out of the greenhouse. Selective distribution offers the advantages of lower marketing costs and the ability to establish better working relationships with customers and intermediaries. *Exclusive distribution* is an extreme version of selective distribution. In this case, the producer agrees not to sell to another buyer. In exchange, the buyer may agree to buy that product only from the producer. The producer works closely with a retailer to set market prices, develop promotion strategies, and establish delivery schedules. Exclusive distribution carries promotional advantages, such as the creation of a prestigious image for your product, and often involves reduced marketing costs. On the other hand, exclusive distribution may mean sacrificing some market share for the product.

The most common distribution strategies or market channels for moving product to the final customer are direct marketing and wholesale marketing.

Because flowers are a perishable product, *delivery schedules* will be critical. Moreover, for producers marketing through an intermediary, the ability to meet delivery commitments may determine their continued business. Retail buyers rely on delivery at the promised time so they know how much product they will have on hand to meet demand and so they can schedule workers to handle delivery and display. Since most greenhouses are seasonal businesses, delivery schedules will vary and will be most crucial for both producers and buyers during peak production periods.

Packaging

Product or service packaging can be both functional and promotional—serving to preserve the product for shipment and to advertise and differentiate the product. Wholesale buyers may require certain packaging as well as bar codes. Direct market producers will have more flexibility in packaging and point-of-purchase (POP) advertising materials. This can be a daunting yet exciting task. Producers should begin their research by visiting retail outlets where competing products are sold. They should make note of how products similar to theirs are packaged and labeled. Producers should think about what the customers will see, hear, and smell when visiting the greenhouse or retail outlet or communicating with the owner and staff. Customer needs, such as convenience, and intermediary requirements are important.

Values and goals, as well as target market preferences, will also affect the greenhouse owner's packaging choices. For instance, more and more biodegradable containers are available. By potting in biodegradable pots, or establishing a program to recycle plastic pots, producers will be able to satisfy an environmental concern for themselves and their customers—namely, to minimize their impact on the land through reuseable or biodegradable packaging.

Pricing: How Is Product Price Determined?

Prices charged will always have an important effect on sales programs. The pricing strategy depends on the market channel. In some markets (especially wholesale markets), producers will be price takers. In other words, the market, rather than the seller, sets the price. In other markets, producers can set their own prices. Even price takers can still *do things to obtain a higher price*. To have more control over pricing, producers will need to differentiate their product.

In general, prices are set by determining how much it costs to produce the product and adding a fair price for the benefits that the customer will enjoy. The cost of production becomes the *price floor*, that is, the lowest price. The *price ceiling* is the *value* consumers place on the product, that is, how much they are reasonably willing to pay for the product. Most customers will be willing to pay a price somewhere between the price floor and the price ceiling. To stay in business for the long run, the price has to cover costs. A place to begin developing a pricing strategy is to calculate the cost to produce the product. The costs include all the fixed and variable costs—including production, marketing, and promotion—as well as a return for the owner's time and investment. Examining what others are charging for similar products will give an indication of the price customers are willing to pay. Another source of prices for flowers and plants is the floriculture crop summary published every year by USDA (USDA, 2010).

With prevailing market prices and costs of production in hand, managers are ready to begin developing a pricing strategy. Common pricing strategies for differentiated products are discussed below. Each has advantages and disadvantages. Depending on the business goals, vision, target market, and product strategy, the firm may want to consider more than one pricing strategy. While pricing will be determined in part by the competitor's price, a small or mid-sized producer selling in a local market should not place too much emphasis on price competition. Competing on price can be intense, and larger firms will probably have lower costs. Instead, it will probably be easier to find ways to differentiate the product from the competition and compete on quality, value, and service. Still, price is an important consideration. In choosing a pricing strategy, managers should think through their rationale. Are they trying to undermine the competition by offering a lower price? Do they want to set a high price that reflects an image of quality? Are they simply looking to cover costs and reduce volatility?

Product Pricing Strategies for Differentiated Products

1. ***Competitive pricing*** Competitive pricing strategies are common among large companies and are aimed at undermining competition. Predatory pricing, where a company sets its price below cost to force its competitors out of the market, is a typical competitive pricing strategy. Although these strategies may work well for large commercial companies, they are not recommended for small-scale, independent businesses. Price wars are not easily won. However, the greenhouse industry is considered a mature market. Supply has exceeded demand for the last few years, and several well-capitalized players offer similar products. The ability to compete on the basis of price may be very important.

2. ***Cost-oriented pricing*** The cost-oriented pricing strategy is probably the most straightforward. Based on production costs, the manager makes a subjective decision about whether to price the product at 10 percent, 50 percent, or 100 percent above current costs. Of course, marketing research should be done to determine whether or not customers are willing to pay the cost-plus price that is established.

3. ***Flexible or variable pricing*** Flexible pricing strategies involve setting a range of prices for the product. Flexible pricing is common when individual bargaining takes place. Prices may vary according to the individual buyer, time of year, or time of day. For instance, growers who sell at farmers' markets often establish one price for their products in early morning and by day-end are willing to lower their prices to move any excess product.

4. ***Penetration or promotional pricing*** A penetration pricing strategy involves initially setting the product price below the intended long-term price to help secure the market. The advantage of penetration pricing is that it will not attract competition. Before pursuing a penetration pricing strategy, producers should thoroughly research prevailing market prices and calculate their costs to determine just how long they can sustain a below-cost, penetration price.

5. ***Product line pricing*** A line of products may be marketed within a limited range of prices for all of the products in that line. For instance, a line of products may be promoted and priced as "affordable" while another line may be a premium line with higher prices.

6. ***Relative pricing*** Relative pricing strategies involve setting the price above, below, or at the prevailing market price.

7. ***Price skimming*** The price skimming strategy is based on setting a high market-entry price to recover costs quickly (to *skim the cream off the top*) before lowering the price to the long-term price. This pricing strategy is possible only when there are few or no competitors. The primary disadvantage of the skimming strategy is that it attracts competition if prices remain too high for too long. Once competitors enter the market, producers may be forced to match their lower prices.

8. ***Contract pricing*** Contracts are arrangements between the buyer and the seller in advance and usually include the price, payment conditions, grower responsibilities, storage, and shipping arrangements. The advantage of pricing on contract is that the producer knows in advance what price will be paid for the product.

Following are common pricing mistakes:

1. ***Pricing too high relative to customers' existing value perceptions.*** If customers think the plant is worth $5 and the price is $6, they simply will not buy it. Producers must be aware of the value consumers place on the product.
2. ***Failing to adjust prices from one area to another based upon fluctuating costs and the customer's willingness and ability to pay from one market to another.*** Some growers have successfully marketed to more than one market by offering different products and price structures. For example, they may grow plants in larger pots with more cuttings per pot for their retail greenhouse, and sell plants in smaller pots with fewer cuttings to the mass market.
3. ***Attempting to compete on price alone.*** This results in a highly competitive market, and buyers will switch suppliers for someone selling only a few cents cheaper. Even in a price-competitive market, it pays to build relationships with the customers.
4. ***Setting prices too low with the intention of raising the prices later.*** Businesses with this strategy will struggle from the outset just to cover costs. It positions the

company as lower in quality versus most of the competitors (whether or not it is true), and makes it difficult to raise prices later.

5. ***Discounting prices.*** This communicates that price is overinflated. It is much better to couple any price discounts with an equal reduction in services or product offered, in quantity purchased, or in payment terms. For example, reduce the price, but make all sales final (remove the 100 percent guarantee on the discounted product). Or producers can offer volume discounts, or discounts for early payment. This way, they have shown flexibility in meeting the needs of their buyer, yet have maintained their pricing integrity.

Promotion: How and What Will We Communicate to Our Buyers or Customers?

Promotion is a must to gain product recognition among customers. Promotional strategies should be built around a *message* or the firm's *unique product value proposition*. The image the business wants to send to buyers should be incorporated into everything the firm does. This image should be clear on business cards, invoices, landscaping, building design, signage, brochures, Web sites, social media contacts, and vehicles.

A business may use a *brand* or logo to identify the products of the business and to distinguish them from those of competitors. Although the establishment of a brand can be expensive, particularly for small businesses, many direct market greenhouses are concentrating their promotional efforts on image advertising—promoting the concept of *locally produced*, *eco-friendly*, or *quality* products.

The best approach to advertising is to think of it in terms of media and which media will be most effective in reaching the target market. Then an advertising budget can be allocated to each medium. The advertising budget should include not only the cost of the advertising but also projections about how much business the advertising will bring in. Advertising media options include the Internet—Web sites, blogs, Facebook, YouTube, and Twitter; television; radio; newspapers; magazines; telephone books/directories; billboards; bench/bus/subway ads; direct mail; newsletters; and cooperative advertising with wholesalers, retailers, or other businesses. Some low-cost product promotion alternatives are POP displays, demonstrations, coupons, rebates, frequent-buyer clubs, publicity, and samples. Every business should also include some marketing material such as business cards, brochures, and pamphlets. Another avenue for promotion is free publicity, such as press releases, product launches, special events, including community involvement (e.g., America in Bloom), articles, and use of testimonials. Tradeshows can be an incredibly effective promotion and sales opportunity—if a firm attends the show that attracts its target customers and the promotion plan is in place.

Promotional activities are limited only by the imagination. Teaching a course, sponsoring a community event, or conducting an e-mail campaign can all fit into an advertising and promotion plan. Sporadic, unconnected attempts to promote the product or service are bound to fail; the goal is to plan and carry out a sequence of focused promotion activities that will communicate the unique product value proposition to potential customers. No business is too small to have a marketing plan. After all, no business is too small for customers. And a business that has customers needs to communicate to those customers about its products and/or services.

Marketing Strategy

Most producers have more than one market for their products, whether it is a direct market right out of their greenhouse, garden centers, big box stores, or customers at a farmers market. Price takers have very little control of the market price. Price takers can reduce business risk through product diversification and by adding new customers or markets, and they can use pricing strategies to increase sales, such as multi-unit pricing. To differentiate their products and receive a higher price, producers can (1) find a market niche that local competitors are not serving, (2) grade according to quality and offer higher-quality products for premium prices, (3) adapt to changes in consumer tastes and preferences, (4) add service to the product, or (5) if it is possible, choose an ideal location.

MARKETING PLAN FOR MRS. GREENJEANS GREENHOUSE

Mary Wilson is the Owner and Marketing Manager for Mrs. Greenjeans Greenhouse. Our aim is to serve an upscale market niche for gardening and indoor plants. We will strive to offer high-quality products. Our direct customers will be local garden centers within a four-hour radius (200 miles) of our greenhouse. We do not want to sell farther than our delivery trucks can deliver and return in one day. We will attempt to sell even closer and encourage garden center customers to pick up the product from our greenhouse. We want to give our garden center customers products that are not offered at the big discount stores. We are striving for a high-quality differentiated product. The final consumers of our products are homeowners and renters who are involved with their home and landscape. These customers will be a little more educated and have a higher income than customers who purchase from other market channels. We are competing for discretionary dollars. We compete with other garden centers, but we also compete with other luxury products such as candy and wine. We feel since we will be the "new kid on the block" we will have to strive to have a little better product and something that our competitors don't have. We plan to constantly look for ways to add a little extra value (such as making sure our pots are clean and won't soil the final consumer's car). Mary will visit all of the garden centers within the marketing area to establish a relationship with them. She will also develop flyers to mail out to her customers, letting them know what products will be available for the next season. She will strive to establish written contracts with them so that we can plan our production schedule around the marketing plan. This is not very common in the greenhouse industry, so we will offer discounts for contracts that are made before the beginning of the production season. We will develop a Web site, open Facebook and Twitter accounts, and tweet our customers weekly during the season to remind them to check out our Web site for our product availability.

We grow high-quality, unique blooming plants and bedding plants. We select varieties that will perform well in the landscapes and home of our customers. We look for disease, insect, and deer-resistant plants, unique colors, and unusual varieties to perform well for our customers and stand out from the competition. If some of our products are not top quality, we will sell them to local greenhouses who sell to the mass market. We want to protect our primary market by keeping the quality and prices high.

Mrs. Greenjeans Greenhouse also looked up information about the green industry from USDA and the National Gardening Survey. U.S. expenditures for floriculture and environmental horticulture were $15.9 billion in 2009. The green industry, also called the environmental horticulture industry, includes cut flowers, flowering potted plants, foliage plants, bedding plants, sod, ground covers, nursery crops, and bulbs. It does not include food crops produced in greenhouses. The green industry represented 5.6 percent of agricultural cash receipts in 2009. Thus, it was ranked the 6th largest commodity group in the United States in cash receipts in 2009, behind beef, corn, soybeans, dairy, and broilers. Environmental horticulture is the top commodity in Florida, New Jersey, and Oregon. From 1986 to 1990, the growth in grower cash receipts for the green industry was a phenomenal 10 percent per year. From 1991 to 1995, this growth rate slowed to 3.4 percent per year. After years of rapid growth, it appears the industry is now a mature market. U.S. wholesale value for all floricultural crop categories were down 6 percent in 2009 to $3.69 billion for the 15 states surveyed annually (see tables). However, tremendous opportunity for growth still exists in the green industry with per capita sales of only $13.65. While sales for most crop categories were down in 2009, the wholesale value for annual bedding plants increased by 1 percent in spite of the recession. The trend is back to gardening. The National Gardening Association found that 71 percent of U.S. households participate in some type of gardening activity and 30 percent participate in flower gardening. Two million more households participated in gardening activities in 2010 compared to 2009, from 81 million households in 2009 to 83 million households in 2010. While people spent more time gardening, they spent less money on gardening activities. The average annual amount spent on gardening activities decreased by $81, from $444 to $363. Unlike other agricultural commodities, which are limited by the size of a person's stomach, the growth potential for the green industry is almost unlimited. We want to tap into the reasons people garden: to improve or maintain the appearance of their property, to save money by gardening themselves rather than hiring services for it, because they enjoy gardening, to grow fresh and nutritious food, for exercise, to make their outdoor space more livable, and to be more self-reliant.

Total and U.S. Per Capita Consumption Floricultural Crops for 15 States Surveyed for Sales Over $100,000

Crop	2008 1,000 US dollars	2009 1,000 US dollars	% Change	Per Capita ($)
Annual bedding plants	1,308,664	1,316,676	1	3.24
Herbaceous perennials	545,126	491,739	−10	2.63
Flowering hanging baskets	668,170	632,356	−5	1.12
Foliage plants	510,311	454,340	−5	2.43
Cut flowers	417,098	359,227	−14	1.92
Cut cultivated greens	91,748	73,956	−19	0.40
Propagative floriculture materials	383,836	357,660	−7	1.91
Total or Average	$3,924,953	$3,685,954	−6	$13.65

Source: *Floriculture Crops 2009 Summary* (USDA, 2010 based on only the top 15 states).

Percentage of U.S. Households That Participate in Garden Activities

Activity	Percentage
Gardening	71
Lawn care	48
Grow indoor houseplants	31
Flower gardening	30
Landscaping	27

Source: National Garden Survey, National Gardening Association, 2007 (http://www.garden.org).

The Number and Percentage of People Who Say They Participated in Do-It-Yourself Lawn and Garden Activities

Reason	Millions	%
To maintain the appearance of my property	53	64
To improve the appearance of my property	50	63
To save money by doing more myself	47	57
To enjoy the activity	47	57
To grow fresh and nutritious food	25	48
For exercise	37	45
To make my outdoor space more livable	37	44
To be more self-reliant	27	32

Source: National Garden Survey, National Gardening Association, 2007 (http://www.garden.org).

Changes in Gardening in the United States from 2009 to 2010

Change	Percentage
Spent more time on lawn and gardening activities	20
Spent less money gardening	16
Spent more time food gardening	22
Spent more time flower gardening	19
Spent more time container gardening	19
Spent more time on lawn care	14
Spent more time on yard and landscape maintenance	13
Spent less time on lawn and gardening activities	10

Source: National Garden Survey, National Gardening Association, 2007 (http://www.garden.org).

MANAGEMENT AND PERSONNEL PLANS

Most greenhouses start small with the founder making all of the key decisions, and most communication is done by one-on-one conversations. This centralized control is particularly useful for a new business as it enables the founder to control growth and development. As the business grows, the owner must delegate more and more responsibilities to others. This is often a difficult transition because the founder of a business often feels that no one else can run the business as well as he or she can. While this may be true, if the business is to grow, the manager will have to learn to divide the responsibilities of running the business into various tasks and delegate these tasks to others. As the business grows, an organizational structure can allocate responsibilities for different functions to different individuals, departments, teams, or divisions. The most prevalent structure in the past was *hierarchical*, with a fixed chain of command and enforcement of rules and regulations to serve one common aim. Through the forces of globalization, competition, and more demanding customers, the structure of many companies has become flatter, less hierarchical, more fluid, and even virtual. In these newer organizational structures (flat, matrix, team, network, and virtual) decisions are based on dialogue and consensus rather than authority and command. There are few or no levels of middle management between staff and managers. The idea is that well-trained workers will be more productive when they are more directly involved in the decision-making process, rather than when they are closely supervised by many layers of management. Team organization synergizes individual competencies, empowers employees to make their own decisions, and creates an atmosphere for excellent customer service.

Management Team

The size of the management team can range from one person in a small firm to hundreds or thousands of managers in multinational companies. In large firms, the board of directors develops the company objectives and the chief executive officer (CEO) manages the firm's resources to meet those objectives. Some business analysts and lenders consider the quality and experience of the managers when evaluating a company's worth.

Labor Management

The verb *manage* comes from the Latin *manu agere*, "to lead by the hand." Skilled managers can accomplish much more through leading others than they can through their own single efforts. This means that labor is one of the most valuable resources in the business. And hiring and motivating employees is a critical management function.

Management functions are not limited to managers and supervisors. Every member of the firm has some management and reporting responsibilities. Successful managers listen to employee feedback and incorporate it into their plans. Leading greenhouse producers know that a satisfied employee needs to feel that he or she is part of the team. The strongest investment a company can make is in its employees. This is especially important since labor is one of the largest costs of production, accounting for about 33 percent of sales. Listening to employees and implementing their ideas shows how much they are valued; reduces turnover, absenteeism, and sick days; lowers labor costs; and can lead to innovation and competitive advantages for the greenhouse.

Seven Essential Steps to Encourage Top Performance

1. Set clear standards and goals. Establish desired behaviors and set goals to be rewarded.
2. Expect the best. If standards and expectations are high, yet achievable, people will strive to meet them. If they are low, people will meet that level of performance too.
3. Pay attention. Catch people doing things right and reward them—immediately. People want attention and like being told exactly what they are doing well. Managers who pay attention and reward behavior will get more good performance.

4. Personalize recognition and rewards. Different things are important to different people. Make your rewards meaningful to the person receiving it. If you don't know—ask!
5. Tell the story of success. Turn good examples into stories. Share the stories with other employees and off-farm individuals. People like hearing stories about themselves.
6. Celebrate. Recognize and reward people publicly. Host pizza parties or lunch or dinner. Invite industry people in to hear you boast about employees. Celebrate in some way even small team successes or goals accomplished.
7. Set the example. Walk the talk. Make recognition part of your job. Don't delegate recognition! Don't assume people know their efforts are appreciated. If you are positive and upbeat and appreciative, others will be too.

To set goals and standards organization needs, employees need to know the company's vision which tells them what kind of business you want to be and the company's mission that tells them why the company exists (the Purpose).

Managers need four key leadership traits. (1) Vision: Leaders have a sense of what is important. (2) Energy: Leaders are exciting and enjoyable to be around. (3) Power source: This can come from their position, the task, personal power, relationship power, or from knowledge and how to use it. (4) Direction: Leaders have a plan. A vision without a plan is just a dream.

Good managers create governing ideas or a governing philosophy. Do develop a governing philosophy; ask questions like What do I want people to say about me when I am gone? What values do I hold that I will not compromise? What characteristics do I want to portray to people? What principles do I stand for? How do I want to be seen or thought of when I interact with people? and What do I want in life?

Managers need to convey a sense of shared vision. A vision is a force in peoples' hearts, a force of impressive power. A shared vision answers the question, What do we want to create? It emerges from personal visions: The firm will not have a vision until individuals have visions. Personal visions derive power from caring for the vision; shared visions derive power from the common caring. Truly shared visions take time to emerge. Managers must create a culture where each individual can create his or her own vision.

Figure 3 depicts the steps in performance management of employees. It begins with the company's governing ideas, which come from the company's vision and mission. Then goals help the company achieve its mission. To meet these goals, managers

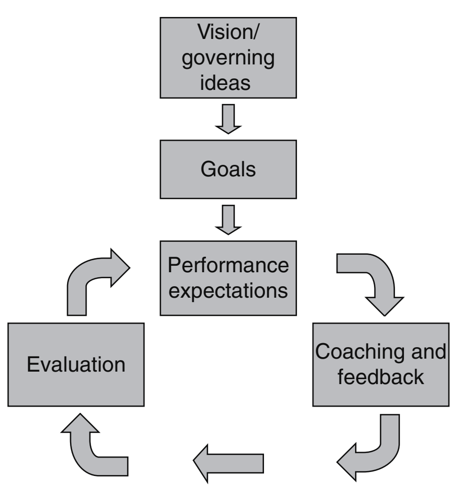

Figure 3
The steps in performance management of employees. It begins with the company's governing ideas, which come from the company's vision and mission.

develop performance expectations. They provide coaching and feedback to help employees meet these expectations. They evaluate employees' performance, and adjust the performance expectations if necessary.

Performance expectations are defined as conditions of satisfactory work. They should be discussed with employees and agreed upon before the work begins. They should be consistent with the mission, objectives, and goals of the organization. Performance expectations should be attainable and measurable. Adequate resources need to be available and tasks need to be done when they are expected.

The keys to being a good manager are to (1) like what you do, (2) be self-motivated, (3) look ahead to what needs to be done, (4) prioritize, and (5) get along with people. To motivate people to perform, (1) develop a standard operating procedure (SOP) and encourage suggestions to improve it, (2) provide regular, constructive feedback on employee performance with regard to the SOP, (3) minimize employee turnover, and (4) encourage employees to be part of the team.

Five Stages of Team Building and Reducing Turnover

1. Recruit and hire the right people.
2. Give the proper orientation and training starting from day one.
3. Provide appropriate ongoing training.
4. Develop individuals to successfully take on higher and higher levels of responsibility.
5. Motivate employees and yourself to continue in spite of occasional setbacks.

Once the right people are in place, take the following steps to get them to perform: (1) Tell them what to do. (2) Show them what to do. (3) Let them try. (4) Observe performance. (5) Praise progress or redirect. To increase efficiency, make sure the right people are in place who are willing to learn new skills, will work as part of a team, and perform to his or her ability. Managers need to make sure that employees have the right tools and are doing the right jobs. Managers need to match the employee's stage of learning with a particular leadership style (Table 2).

Managers become supporters and transfer ownership for work to those who do the work. They create the environment for ownership where everyone wants to be responsible. They coach to develop capabilities. Managers should learn fast and encourage others to do so too. Coaching rather than authoritative management makes everyone feel part of the team and want the business to succeed. Coaches catch

Table 2
Stages of Learning and Leadership Styles to Use with Employees at Each Stage

Stage of Employee Growth	Employee Skill Level	Leadership Style Needed	Manager's Role
Beginning	Are excited and enthused. The job seems easier than it really is.	Directive	Tell what, when, where, and how to do it.
Some Experience	Have little knowledge or skill. Have not mastered the task. Need to know *why*.	Coaching	Give direction and support.
More Proficient	Have technical capabilities to perform at a high level. Lack confidence.	Supportive	Encourage, but give little direction. Say "You have what it takes to get the job done."
Proficient and Self-confident	Have mastered the knowledge or skill. Have confidence to perform consistently and proficiently.	Delegating	Turn responsibility over to the employee.

employees doing something right and compliment them. They give at least four compliments for every constructive criticism. They ask questions about what is going well rather than what is going badly. They first focus on the positive and the innovative, before they criticize the negative. They ask, How are you? How are things going? What can I do to support you?

An increasingly popular tool for business managers is an employee manual. This manual provides direction for managers to be fair and balanced in their dealings with employees.

Tips on Developing an Employee Handbook Some company policies need to be in writing—for example, policies on sexual harassment and discipline—so that employees know what is expected of them. The following can form the basis of an employee manual.

1. The manager should draft the employee handbook with input from others in the business.
2. The employee handbook should be reviewed and fine-tuned by a lawyer.
3. The employee handbook should include a disclaimer stating clearly that the manual is in no way a legal contract.
4. The Small Business Administration's Web site, at http://www.sba.gov. Accessed February 23, 2011 and listed in the references. (search for "employee handbook"), has a template of what to include in a handbook as well as several relevant articles on creating an effective employee handbook and human resources management program.
5. Every employee should receive a copy of the handbook and sign a statement saying that he or she has read it.
6. Management should review it every six months or so and update it as needed.

Working Conditions Working conditions are as important as the manager–employee relationship for encouraging good performance. Consider your own feelings when walking along a street in a town with no trees or plantings and with noisy traffic passing a few feet away versus walking along a pedestrian mall landscaped with lawns and planters and overhung by trees. Without realizing it, many greenhouse ranges develop into a harsh, repelling environment that brings about negative feelings in the employees. How much stimulation is there to plant seedlings neatly and at the precise depth when all around are weeds, trash, and unrepaired greenhouses?

Facilities. The greenhouses, headhouse, restrooms, and surroundings should be orderly and clean. This is an important part of insect and disease control. It is also important to proper management. A harmonious environment suggests a state of finesse, which can be achieved with a little encouragement by the manager.

A job is not finished until it is cleaned up. Tools, empty cartons, and so forth should always be in their proper places. Greenhouse aisles, the headhouse, and areas around the greenhouse should be clear. Aside from the negative messages that messes impart, they also present hazards and a physical barrier to efficient operation.

A program of preventive maintenance should be in place for all equipment to ensure that jobs will always be done on schedule. A little paint on a tank before it rusts, grease on a bearing before it freezes, or a tune-up on a rototiller before it stops will prevent breakdowns that could snowball into stoppage of many other operations.

Each human has an internal rhythm. When the pace of his or her work is geared to this rhythm, efforts are minimized and productivity is maximized. Disruptions in the form of ambiguous orders, undue changes in orders, and equipment breakdown break the work momentum. This is fatiguing and depressing to the employee.

Work facilities should be respectable. Human dignity dictates that bathroom facilities be provided. If the very being of an individual does not command respect, why should his or her productivity be any different? A pleasant area for eating and taking breaks should also be provided. A brief repose at mid-morning, noon, and mid-afternoon benefits the firm as well as the employee. A tired employee is not productive.

Many other aspects of the physical facilities warrant attention. Worthwhile improvements are those that prevent needless fatigue and facilitate work efficiency. Rubber mats on the floor and, under some circumstances, chairs are an asset to progress. Convenient centralization of tools and supplies also increases efficiency. The range layout as a whole should be formulated with efficiency in mind. A flat site and ridge-and-furrow greenhouses rather than separate structures permit automation and minimize walking effort. Service buildings on the north side, midway along the greenhouses, minimize travel distance. Permanently plumbed pesticide lines, local steam outlets for pasteurization, and central fertilizer proportioning equipment improve efficiency. Conveyor systems for moving flowers, potted plants, and supplies to or from production areas should be considered.

Product Quality. The demand for low-quality products is small. The profitability of such production is low at best. Some years ago, it was stated in the *Florist and Nursery Exchange* that Larry Taylor of Denver Wholesale Florist found on a year-round average that it took 1.8 standard-grade (second) carnations, 3.5 short-grade blooms, 7.5 design-grade blooms, or 11 split-calyx blooms to equal the profit of one fancy-grade (first) carnation. Aside from market price, product quality is important to personnel management. It affects the same principle of the employee relating to the firm. When a person knows that he or she is part of a quality production scheme, the incentive exists to try to meet these standards in his or her own work.

Education. Most people take pleasure in learning. It is flattering to an employee when the firm thinks enough of him or her to provide an education along with the job. Actually, there is a mutual advantage, since employees who understand the why and what of their tasks have the potential to be better workers. They are in a position to reason out better ways of doing the job and solving a problem when the job is not proceeding smoothly.

Education in a small firm need not consist of anything more than the manager talking with employees as they work. They should be given an appreciation of the various cultural procedures involved in a crop and how they interrelate. Employees should be aware of the quality standards required by the market. They should know the problems that can arise from mistakes such as insect or disease establishment, excessively high or low temperatures, improper photoperiod control, incorrect planting depth, nutritional disorders, and overwatering. Worthwhile employees welcome such knowledge and use it to better themselves within the firm and to assist the manager in meeting his or her responsibilities.

Larger firms, in addition to the procedure just discussed, sometimes use training sessions for their employees. These may be held on the premises of the firm and be conducted by management within the firm or by instructors hired from outside. Outside services are available for topics such as management and marketing. Visits from university personnel, allied-trade representatives, or competitive greenhouse operators can be a valuable source of information. If possible, the general manager should arrange an opportunity for key personnel to meet with such individuals.

Numerous educational meetings are sponsored each year by state and national flower grower associations, national floral marketing associations, state universities, local county extension services, and floral hardgoods suppliers. These meetings are an excellent educational opportunity for the owner and his or her key employees. Topics at these meetings may focus on a specific topic such as plant production or may encompass a broad range, including production, transport, marketing, business management, and personal development. A few examples of meetings around the world include the Ohio International Floral Short Course; the New England Greenhouse Conference in Massachusetts; Grower Expo in Chicago; the Far West Show in Oregon; The Canadian Greenhouse Conference; AgriFlor in Mexico; ProFlora in Colombia; International Flower Trade Show and NTV in Amsterdam; The IPM Show in Essen, Germany; Flormart/Miflor in Italy; Hortus Hungaricus; Agriflor Kenya; and Hortiflorexpo in China.

Most of the organizations mentioned publish newsletters containing current floral news items as well as articles on technical subjects. Growers should definitely get on the mailing list of the local Cooperative Extension Office and the horticulture department at their local state university. They should join their local flower growers' association as well as a national growers' association to expand their sources of information and ideas. Information derived from these organizations should be passed down through the firm by one or another of the methods discussed earlier. Several trade magazines also exist for the industry with educational articles for managers as well as employees.

Management Plan

Many people go into the greenhouse business because they like growing plants. They often prefer to focus on the labor tasks of growing plants rather than the management tasks that lead to a profitable greenhouse. The owner of a small greenhouse often finds it necessary to be a laborer as well as a manager. Indeed, working alongside employees and performing some of the labor tasks can be a valuable tool to build esprit de corps. It can motivate employees to pull together in pursuit of the common purpose of accomplishing the firm's goals effectively and efficiently. However, greenhouse managers should never lose sight of the need to manage and must guard against spending too much time performing labor tasks rather than managing.

To develop the management plan, a business needs to do the following:

- Define the business operational areas by function. Figure 4 shows an organizational chart depicting the different business operations or managers required to manage a greenhouse and their functions. In smaller greenhouses, one person will perform the duties in more than one of these business operations.
- Determine what skills, education, and experience are necessary for each key position on the management team.
- Describe the experience, skills, education, goals, interests, and wages or salary of each person currently in the workforce.
- Identify key persons for each management position and briefly describe their management role and their qualifications.
- Identify areas where skills are lacking and those that depend on one person. Identify people in the firm who could be trained as the primary person or as a backup.
- If additional part-time and/or full-time employees are needed, determine how these personnel will be recruited, hired, compensated, motivated, and retained.
- Give job descriptions for managers and employees, compensation plans, incentive plans, information on employee handbooks, and training procedures.
- List expertise that is not available among the owners or the current employees. The firm may want to hire a consultant for specific tasks, such as a business consultant to help develop the business plan, an accountant to prepare income tax returns, or

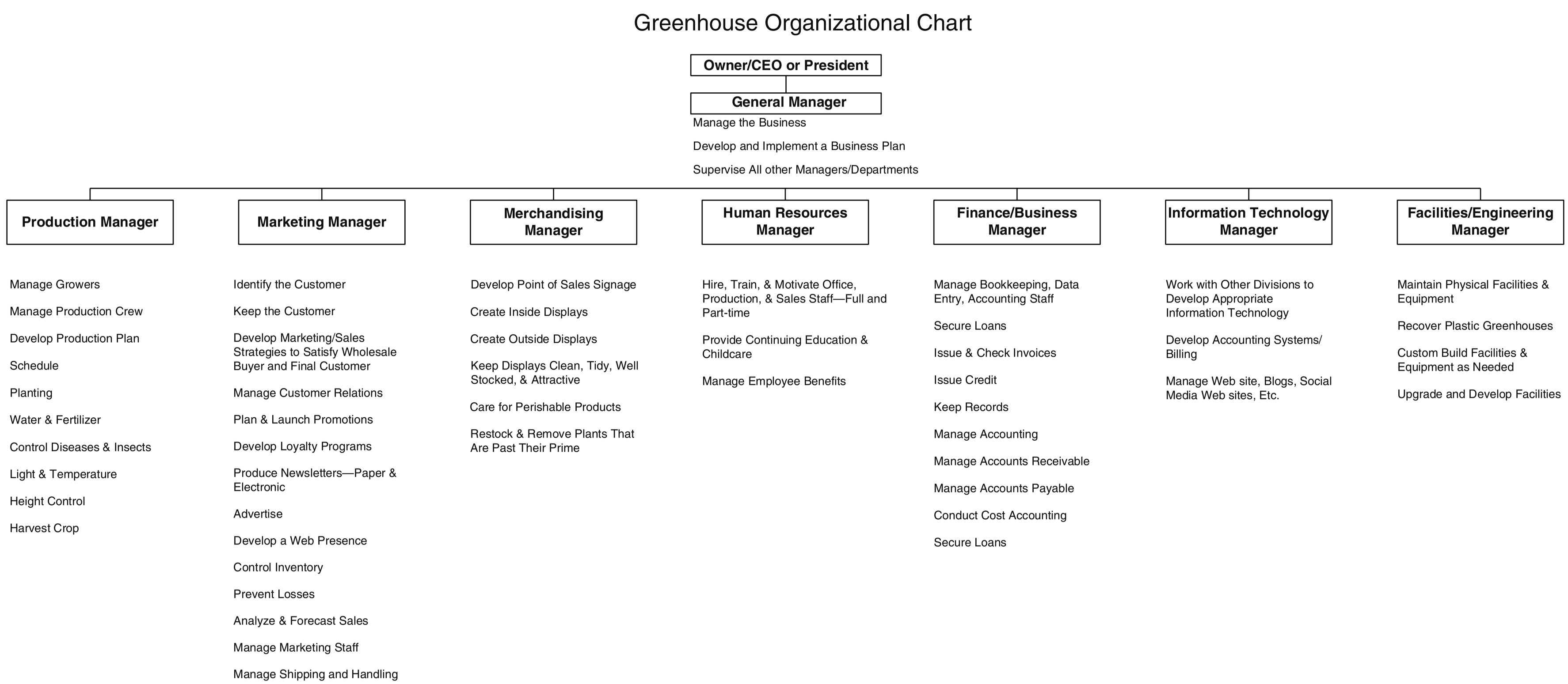

Figure 4

A typical managerial structure of a greenhouse business, showing the functions of each manager of a division. The owner, or the CEO or president, carries the full responsibility for managing the business. Often the owner serves as the general manager. In smaller greenhouses, the general manager performs the duties of all the other managers. As the business grows, additional managers will be hired to perform the managerial duties of the division managers. One person may be responsible for functions in more than one division. Some wholesale greenhouses will not have a merchandising division while others will have merchandisers in the retail stores.

a lawyer to prepare wills and documents to establish a partnership or corporation. It may also contract specific tasks such as IPM scouting.

- Describe any changes in the labor situation expected in the near future either because someone is leaving or because changes in the operation will require more people or different skills.
- Describe any long-term transition plan that may be required for transferring management responsibilities to the next generation, a partner, or an employee.

MANAGEMENT TEAM FOR MRS. GREENJEANS GREENHOUSE

The general manager is Mary Wilson. Mary is responsible for general business management, production management, labor management, marketing management, and capital purchases. The assistant manager is John Wilson, who will make decisions in the absence of the general manager and will be in charge of financial management and accounting. The production staff are Mary and John's children, Linda and Dan Wilson. Linda will monitor for insects, monitor for weeds, and perform other tasks as required. Dan will check watering needs after school, water as needed, and perform other tasks as required. Part-time production staff will be hired seasonally to (1) fill flats and pots with media, (2) seed plug flats, (3) transplant bedding plant flats, (4) move flats to the production area, (5) move finished flats to sales area, clean flats, and load marketing trucks, and (6) perform other tasks as required.

We will develop position descriptions. The positions will start at minimum wage, and increase with good work performance. The positions will be advertised at the local high school and placed in the local newspaper. Mrs. Greenjeans Greenhouse will hire a management consultant to help develop an employee handbook to cover benefits, working hours, leave policy, and wage concerns.

Mrs. Greenjeans Greenhouse will use the following service providers for business and professional needs: accountant Tim Jones and attorney Robert Smith.

FINANCIAL PLAN

Financial analysis and planning is an important part of describing the business to someone else. Financial projections give some indication of where the business is headed in the next few years and describe the financial ramifications of changes that are implemented in the future. It helps the firm evaluate alternative business investments. The financial section should also describe the assumptions used in making financial projections. These assumptions might include projected prices that will be received in the future, input costs, or production levels. These projections should be kept and compared against actual business performance.

Financial Projections

- The income and expense projection (income statement) provides the framework for determining what profit the business can expect to obtain and the expected fixed and variable expenses at the projected level of sales.
- The cash flow statement indicates how much to borrow and when.
- The balance sheet presents the company's financial position including assets, liabilities, and net worth.
- Breakeven analysis and financial ratio analysis compare the projections with industry norms and establish return-on-investment requirements.
- Benchmarks are used to monitor and evaluate progress in meeting established goals.

Projected Production and Sales

This section describes the firm's financial condition during the past few years. It is effective if a few financial indicators or measures are used to describe the firm's situation. It should include projected sales for each of the products the business plans to produce. As the business grows, it will also have its own historical data. A new business will not have any data for the historical trend (unless the business was purchased), and the manager must attempt to project sales.

REVENUE PROJECTIONS FOR MRS. GREENJEANS GREENHOUSE FOR THE NEXT FIVE YEARS

Items	Year 1 ($)	Year 2 ($)	Year 3 ($)	Year 4 ($)	Year 5 ($)
Bedding plants	53,200	59,850	66,500	76,475	99,750
Hanging baskets	17,500	21,000	21,000	21,000	21,000
Perennials	10,000	10,000	10,000	10,000	10,000
Poinsettias					
4-inch	2,000	2,000	2,000	2,000	2,000
6-inch	8,400	8,400	8,400	8,400	8,400
7-inch	7,500	7,500	7,500	7,500	7,500
8-inch	4,800	4,800	4,800	4,800	4,800
10-inch	5,400	5,400	5,400	5,400	5,400
Hanging baskets	1,875	1,875	1,875	1,875	1,875
Florist mums	1,200	1,200	1,200	1,200	1,200
Hardy mums	7,875	7,875	7,875	9,000	9,000
Plugs	96,000	104,000	108,800	112,000	112,000
Rooted cuttings	25,000	25,000	25,000	30,000	30,000
Total revenue	$240,750	$258,900	$270,350	$289,650	$312,925

Projected Profitability: Income Statement

An *income statement* (also called profit and loss statement, P&L statement, or operating statement) documents the firm's profitability. Profitability is the measure of how much income the business is making in relation to the resources used to produce that income. Net income is one measure used to quantify profitability. Net income is the revenue minus the expenses including depreciation. Profitability should usually be the major factor considered when making most financial decisions. Over time, profits generally drive the solvency and liquidity of a business.

The costs incurred in the greenhouse business can be grouped into two categories: variable costs and overhead costs. *Variable costs* are costs that vary with the level of production and can usually be allocated to a particular crop. Examples of variable costs are the costs of petunia seeds and bedding plant flats; both relate specifically to petunia production. *Overhead* or *fixed costs* are those costs that are incurred regardless of the level of production and are common to all crops. These costs include depreciation of the greenhouse structure, equipment, and other facilities and costs such as interest, repairs, insurance, taxes, and salaries of overhead personnel (i.e., the manager, salespeople, growers, secretaries, bookkeepers, etc.). The total cost of production is the sum of variable and overhead costs.

Table 3 shows an income statement developed from figures from a 2003 survey of northeast greenhouse growers, where the average size was 138,759 square feet, average sales were $2.2 million, and net returns were $211,152 or 9.5 percent. Figure 5 shows graphically the cost of the average northeastern greenhouse. By 2008, the price of fuel oil had tripled. Table 3 also shows the same income statement, but with energy prices raised to 2008 levels and other costs and prices held the same. The net losses are $37,534 or −1.7 percent. Doing a what-if analysis shows that by taking these 2008 costs but inflating prices of crops by 5 percent the net returns become positive (Table 4).

The profitability section of the business plan describes projected income over the next few years. It should take into consideration major changes planned for the business. It usually includes a pro forma income statement.

Table 3

Income Statement Data from a Survey of Northeast Greenhouse Growers in 2003 Entered into the Rutgers Program: Greenhouse Cost Accounting for Indoor and Outdoor Plants

	Values from Income Statement			
	2003 Actual		2008 Fuel Increase	
	$	% of Sales	$	% of Sales
Sales	**$2,219,560**	**100**	**$2,219,560**	**100**
	Directs Costs			
Seeds, cuttings, or plants	490,863	22.1	490,863	22.1
Pots or containers	140,984	6.4	140,984	6.4
Marketing containers	38,567	1.7	38,567	1.7
Growing medium	4,689	0.2	4,689	0.2
Fertilizer and chemicals	43,163	1.9	43,163 1.9	
Sales commissions	2,875	0.1	2,875	0.1
General wages (including benefits)	729,233	32.9	729,233	32.9
Other	37,468	1.7	37,468	1.7
	Overhead Costs			
Overhead salaries (including benefits)	2,895	0.1	2,895	0.1
	Utilities			
Heating fuel/machinery fuel	77,566	3.5	232,698	10.5
Electricity	40,352	1.8	40,352	1.8
Telephone	5,894	0.3	5,894	0.3
Water	464	0.0	464	0.0
Depreciation	92,642	4.2	92,642	4.2
Interest	8,080	0.4	8,080	0.4
Repairs	43,829	2.0	43,829	2.0
Taxes	26,131	1.2	26,131	1.2
Insurance	37,546	1.7	37,546	1.7
Advertising	11,277	0.5	11,277	0.5
Dues and subscriptions	100	0.0	100	0.0
Travel and entertainment	7,431	0.3	7,431	0.3
Office expense	9,589	0.4	9,589	0.4
Professional fees	19,444	0.9	19,444	0.9
Truck expense and equipment rental	46,954	2.1	140,762	6.3
Land rental	2,112	0.1	2,112	0.1
Miscellaneous	87,956	4.1	87,956	4.1
Total expenses	$2,008,104	90.5	$2,257,094	101.7
Net returns (profit)	$ 211,456	9.5	(37,534)	−1.7
Greenhouse area (ft^2)	138,759		138,759	
Greenhouse space used for production (%)	82		82	
Weeks in operation (52 if a full year)	40		40	

Source: Brumfield, 2009a.

Table 4

Ratios Using Actual 2003 Data from Northeast Greenhouses[1]

Ratio	Actuals, 2003	Fuel Increase, 2008	Fuel increase, 2008; Price increase 5%
Net Income	$211,456	$37,534	$73,444
Gross Margin	65.8%	65.8%	67.5%
Profit Margin	9.5%	−1.7%	3.2%

[1]Shown are changes to ratios by inflating fuel to 2008 prices, and inflating fuel prices to 2008 levels and increasing prices by 5 percent.

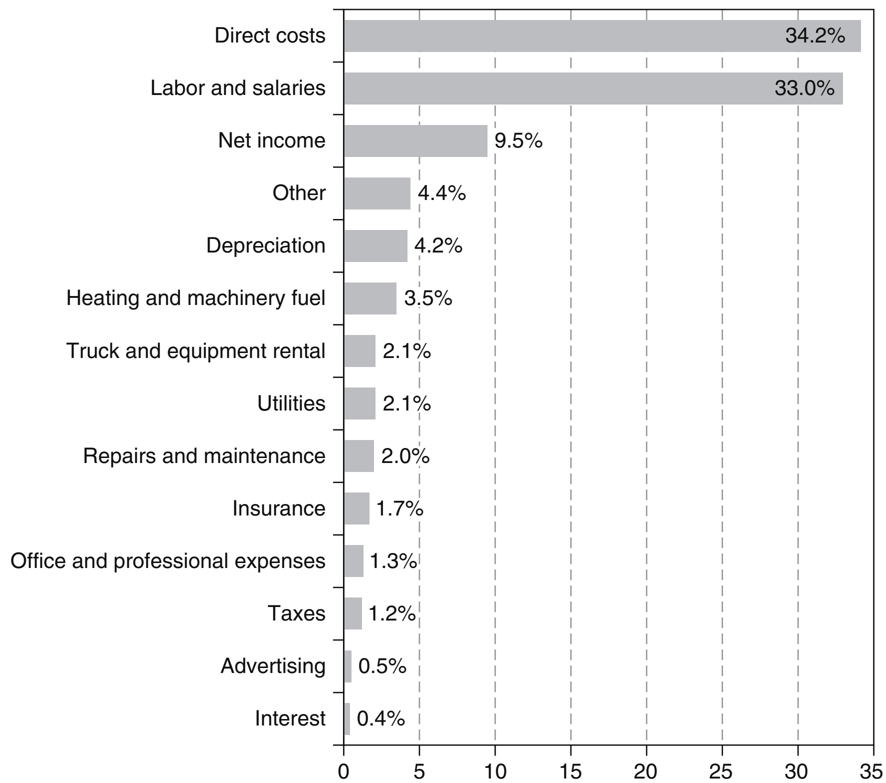

Figure 5
The relationship of expenses for typical flowering potted-plant greenhouse firms in the United States. Production and marketing expenses are combined within categories. Labor includes wages, salaries, and benefits. Materials include items such as plant material, seeds, pots, root substrate, labels, and pot sleeves.
(Data from Brumfield, 2009a,b.)

INCOME STATEMENT FOR MRS. GREENJEANS GREENHOUSE

Based on the historical data regarding price and production, Mrs. Greenjeans Greenhouse plans to increase its production by 10 percent every year and increase price by 5 percent every year. The following is the pro forma income statement for above projected sales and price data.

PRO FORMA INCOME STATEMENTS FOR MRS. GREENJEANS GREENHOUSE FOR THE NEXT FIVE YEARS

	Year 1 ($)	Year 2 ($)	Year 3 ($)	Year 4 ($)	Year 5 ($)
Sales	240,750	258,900	270,350	289,650	312,925
Labor	85,000	98,000	104,000	118,000	130,000
Heating	10,000	11,000	12,000	13,000	14,000
Materials	76,300	77,000	78,000	79,000	80,000
Rent and depreciation	16,000	16,500	17,000	17,500	18,000
General maintenance	3,000	3,500	4,000	4,500	5,000
Insurance	2,000	2,100	2,200	2,300	2,400
Office expenses	1,000	1,100	1,200	1,300	1,400
Auto and truck expense	1,000	1,000	1,100	1,200	1,300
Interest	5,000	5,100	5,200	5,300	5,400
Advertising	74,255	85,764	99,058	114,412	132,146
Freight and trucking	5,000	5,000	5,000	5,000	5,000
Bad debt	69,255	80,764	94,058	109,412	127,146
Taxes	17,314	20,191	23,514	27,353	31,786
Meetings/conventions	1,000	1,100	1,200	1,300	1,400
Professional fees	800	900	1,000	1,100	1,200
Dues and subscriptions	200	250	300	350	400
Total expenses	$222,900	$239,750	$250,600	$268,950	$285,300
Net Income	$ 17,850	$ 19,150	$ 19,750	$ 20,700	$ 27,625

Balance Sheet

A balance sheet indicates the amount of equity the owner has in the business and the structure of assets and liabilities. It shows how funds are invested in the business (assets) and the financing methods used (liabilities and owner's equity). Unlike the income statement, which represents a period of time, the balance sheet, represents a single moment in time. It is used to help understand the firm's financial situation, especially solvency or net worth.

Net worth indicates the equity position of the firm (assets minus liabilities). Net worth is important in evaluating the risk position of the firm and in considering future borrowing capacity. Net worth growth is usually one of the major goals of a business. Table 5 shows a balance sheet based on a survey of greenhouses in the northeast in 2003 showing the average net worth of over $750,000.

A balance sheet is included in the business plan if the plan is being developed to be shown to lenders, potential investors, or partners. A balance sheet will probably not be included in the plan if it is being developed to communicate the direction of the business to those employees to whom the owner wishes not to disclose the entire financial situation.

Table 5
Balance Sheet from a 2003 Survey of Greenhouses in the Northeast

Assets	
Current Assets	**Year End ($)**
Cash/checking/savings	128,362
Accounts receivable	86,364
Other stock and certificates	616
Prepaid expenses	3,707
Wholesale inventory held for sale	182,666
Retail inventory held for sale	9,091
Other current assets	38,996
Total Current Assets	$449,802
Long-Term Assets	**Year End ($)**
Buildings and improvements (Owned) and land	504,180
Machinery and equipment (Owned)	276,784
Leased machinery and equipment	1,335
Total Long-Term Assets	$782,299
Total Assets	$1,232,101
Liabilities	
Current Liabilities	**Year End ($)**
Accounts payable	115,408
Operating debt	4,013
Other current liabilities	123,219
Total Current Liabilities	$242,640
Long-Term Liabilities	**Year End ($)**
Leased structures	1,335
Leased machinery and equipment	562
Other long-term liabilities	229,409
Total Long-Term Liabilities	$231,306
Total Liabilities	$473,946
Net Worth	
Net Worth (Owner's Equity)	$758,155

Source: Brumfield, 2009a.

MRS. GREENJEANS GREENHOUSE BALANCE SHEET

Assets	
Current Assets	
Cash on hand	$ 10,000
Accounts receivable	—
Plant inventory	50,000
Supply inventory	20,000
Total Current Assets	$ 80,000
Long-Term Assets	
Machinery/equipment	$ 75,000
Buildings/fixtures	200,000
Land	100,000
Total Long-Term Assets	$375,000
Total Assets	$455,000
Liabilities	
Current Liabilities	
Accounts payable	$ 10,000
Short-term notes	7,000
Taxes	2,800
Total Current Liabilities	$ 19,000
Long-Term Liabilities	
Mortgage	$175,000
Long-term notes	25,000
Total Long-Term Liabilities	$200,000
Total Liabilities	$219,000
Net Worth	
Net Worth	$235,200

Cash Flow

Financial liquidity is usually evaluated using a cash flow plan. Cash flow planning is a projection of all sources and uses of cash during a specified planning period. Cash flow plans are an important tool for evaluating the liquidity of a farm business, the annual operating loan needs, and the ability of the business to repay loans. A cash flow projection should also indicate potential financial problems and alert the manager and lenders to possible changes that might be made. Profitable firms can still fail because of cash flow problems. Producers must buy inputs and grow crops and livestock before they are sold and have a cash inflow. Lenders usually want to evaluate the projected cash flow when making loan decisions. And owners will want to have a line of credit or operating loan to cover short falls.

Cost Accounting

Profit for any business can be calculated by the simple formula *Profit = Sales – Costs.* Greenhouse managers know the profitability of their entire business from their income tax records at the end of the year. However, because most greenhouses produce many crops, they often do not know which crops are making money, which ones are losing money, and which crops are making the most money. The profit formula for determining the profitability for each crop becomes

$$\text{Profit per crop} = (\text{Number of units sold}) \times (\text{Sales price per unit} - \text{Total costs per unit})$$

PRO FORMA CASH FLOW STATEMENT FOR MRS. GREENJEAN'S GREENHOUSE

Mrs. Greenjeans Greenhouse will need nearly $50,000 in operating credit in the first year of operation in January. This will be needed to purchase supplies and plant material to begin plug, cutting, and bedding-plant production. Because of a beginning cash reserve, and early sales of plugs, we should not have to borrow in subsequent months or in subsequent years. But we will still obtain a line of credit to protect us against unforeseen problems such as insect or disease damage, weather-related disasters, or other problems that reduce sales.

Pro Forma Cash Flow Statement for Mrs. Greenjean's Greenhouse

	Total cash inflows	Total cash outlays	Surplus or deficit	Beginning cash balance	Cash available	Needed to borrow
January ($)	0	58,317	–58,317	10,000	–48,317	–48,317
February ($)	70,000	10,817	59,183	–48,317	10,866	0
March ($)	51,000	20,817	30,183	10,866	41,049	0
April ($)	2,075	19,117	–17,042	41,049	24,007	0
May ($)	20,000	19,617	383	24,007	24,390	0
June ($)	39,825	11,813	28,012	24,390	52,402	0
July ($)	17,000	2,817	14,183	52,402	66,585	0
August ($)	3,000	22,817	–19,817	66,585	46,768	0
September ($)	2,000	7,817	–5,817	46,768	40,951	0
October ($)	5,875	10,317	–4,442	40,951	36,509	0
November ($)	4,975	11,617	–6,642	36,509	29,867	0
December ($)	25,000	11,817	13,183	29,867	43,050	0
Total ($)	240,750	207,700				–48,317

The process of assigning production costs to each crop and subsequently calculating the profit of each crop is called cost accounting. Cost accounting can be used by managers to analyze various production, financial, and marketing strategies.

For example, once managers know the costs of producing each crop, they can (1) look at ways to increase sales of the profitable crops, (2) find ways to cut costs on the less profitable crops, (3) decide whether or not to drop unprofitable crops, and (4) consider producing new crops.

Greenhouse businesses are caught in a cost-price squeeze: Prices are going down because of a weak economy and oversupply, while the costs of labor, pesticides, fuel, and other inputs are going up. Going back to the profit equation above, greenhouses have two basic ways to increase their profit margin: (1) increase sales or (2) decrease costs. They can increase sales by, for example, increasing the number of units sold, increasing prices, increasing inventory turnover, changing the production schedule, changing the product mix, reducing the age of accounts receivable, and integrating horizontally or vertically. They can decrease costs by, for example, mechanizing, decreasing overhead, reducing shrink, and increasing volume to spread overhead over more units.

Costs vary from grower to grower due to size of operation, location, managerial practices, time of year, availability of labor, product mix, market channel, and volume of production. The bottom line is that every firm's costs are different, so every greenhouse business needs to have its financial team calculate the costs for the business. In spite of the very competitive market, many greenhouse business owners still do not calculate their costs. Most of them are farmers at heart, and would rather grow plants than calculate costs. Some are afraid of what they may discover: Their favorite crop is not profitable.

Others think that it takes too much time or they are content with the status quo. But cost accounting is the *only way* to make accurate product mix and pricing decisions.

The tools needed for cost accounting are an income statement, production data, pencil and paper or a spreadsheet like the Rutgers Cost Accounting for Indoor and Outdoor Plants, and a desire to determine the most profitable crops. Cost accounting begins with cost information typically found on income statements. Table 3 shows an income statement based on typical costs from a survey of greenhouses in the northeast.

The next step is to gather production information for each crop (Table 6). Information needed is the number of units started, the space devoted to each unit, number of weeks each crop is in the greenhouses, the percent sold, and the sales price per unit—items that most managers know for each crop. Once this information is gathered, managers allocate as many costs as possible to individual crops. A business owner or manager may not know the various costs of producing a specific crop. For example, the *total* cost of seeds is usually known. However, the cost of petunia seeds may be unknown. If the cost of petunia seeds is known, it can be allocated as a variable cost to petunias; if it is not known, it is left as an unallocated overhead cost. Variable costs that cannot be assigned to a particular crop can be treated the same way as unallocated overhead costs. If the same crop is sold at more than one price, then that crop may be treated as two or more crops. For example, perhaps 20 percent of petunia flats are sold at $6.00 per flat to customers who buy more than 100 flats, and 80 percent are sold at $6.50 per flat to customers who buy fewer than 100 flats. Petunias can be treated as two different crops: petunia flats at $6.00 and petunia flats at $6.50. Total costs can be allocated on an 80 percent/20 percent basis. Another option is to enter the average price for petunias.

While the figures in Tables 3, 4, and 5 show actual results of surveys of northeast growers, Table 6 shows a hypothetical production schedule constructed to match the actual income from the 2003 surveys. The table shows the number of units started, the number of square feet used for each crop, the number of weeks it takes to produce a crop, the percent of the crop that is sold, and the sales price for each crop for a hypothetical greenhouse producing petunias, marigolds, and geraniums in flats; geraniums in 4-inch pots; poinsettias in 6-inch pots; and an acre of outdoor cut flowers.

Once as many costs as possible are assigned to a particular crop, the remaining unallocated costs will be added and assigned as overhead costs to each crop on a per-square-foot-week basis (Table 7).

Table 6
Cost Accounting Information for a Hypothetical Greenhouse Using 2003 Northeast Data

Item	Petunia Flats	Marigold Flats	Geranium Flats	Geraniums 4-Inch Pots	Poinsettias 6-Inch Pots	Outdoor Cut Flowers: Bunches
Number of units started	50,000	50,000	50,000	100,000	126,000	26,136
Square feet per unit	1.64	1.64	1.64	0.11	1	1 acre
Weeks to grow	8	6	13	6	15	15
Percent sold	0.98	0.98	0.95	0.95	0.95	0.95
Sales price	$ 7.93	$ 7.00	$ 11.73	$ 1.66	$ 5.46	$ 4.00
Labor	$ 3.37	$ 3.37	$ 3.37	$ 0.82	$ 1.00	$14,994
Seeds or plants	$ 0.55	$ 0.35	$ 3.75	$ 0.14	$ 1.54	$50,000
Containers	$ 0.73	$ 0.73	$ 0.73	$ 0.09	$ 0.18	$ 6,915
Growing media	$ 0.20	$ 0.20	$ 0.20	$ 0.02	$ 0.04	$ 0
Fertilizer and chemicals	$ 0.10	$ 0.10	$ 0.15	$ 0.09	$ 0.11	$ 393
Tags	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0.16	$ 0
Other direct costs	$ 0	$ 0	$ 0	$ 0.05	$ 0.20	$ 3,873

Table 7
INCOME STATEMENT SHOWING COSTS FROM THE GREENHOUSE PORTION OF THE ORIGINAL INCOME STATEMENT, THOSE COSTS AS A PERCENTAGE OF SALES, VALUES THAT HAVE BEEN ALLOCATED TO INDIVIDUAL COSTS, AND THE REMAINING UNALLOCATED COSTS THAT HAVE BEEN ALLOCATED TO EACH CROP ON A COST-PER-SQUARE-FOOT-WEEK BASIS

Item	Values from Income Statement ($)	Greenhouse Income Statement Costs as a Percentage of Sales	Values from Cost Sheet ($)	Unallocated Costs ($)
Sales	2,120,243			
Direct Costs				
Seeds, cuttings, or plants	440,735	20.79	440,540	195
Pots or containers	140,984	6.65	141,180	(196)
Marketing containers	31,198	1.47	30,200	998
Growing media	4,689	0.22	37,340	(32,651)
Fertilizer and chemicals	42,571	2.01	40,360	2,211
Tags	0	0.00	60,160	(60,160)
Sales commissions	0	0.00	0	0
Other	36,470	1.72	0	36,470
Salaries				
Overhead salaries	0	0.00		0
FICA	0	0.00		0
Unemployment insurance	0	0.00		0
Workers' compensation	0	0.00		0
Wages				
General wages	714,162	33.68	713,500	662
FICA	0	0.00		0
Unemployment insurance	0	0.00		0
Workers' compensation	0	0.00		0
Utilities				
Heating fuel/machinery fuel	77,566	3.66	60,160	17,406
Electricity	40,352	1.90		40,352
Telephone	5,394	0.25		5,394
Water	164	0.01		164
Overhead				
Depreciation	92,542	4.36		92,542
Interest	7,930	0.37		7,930
Repairs	43,779	2.06		43,779
Taxes	25,681	1.21		25,681
Insurance	36,946	1.74		36,946
Advertising	11,077	0.52		11,077
Dues and subscriptions	0	0.00		0
Travel and entertainment	7,331	0.35		7,331
Office expense	9,389	0.44		9,389
Professional fees	19,244	0.91		19,244
Equipment rental	46,904	2.21		46,904
Land rental	1,792	0.08		1,792
Contributions	0	0.00		0
Bad debts	0	0.00		0
Miscellaneous	87,681	4.14		87,681
Total Unallocated Costs				401,141
Greenhouse	**From Income Statement**	**From Greenhouse Crops**		
Greenhouse area (in square feet)	138,759			
Greenhouse space used for production (%)	82%			
Weeks in operation (52 if full year)	40			
Square feet weeks of utilized greenhouse growing space	4,551,295	4,170,000		
Unallocated cost/square foot of utilized growing space/week				$0.096
Net Returns	$195,662	9.23%		

This overhead cost along with the assigned variable costs are used to calculate the profit or loss for each crop and per unit (flat or pot) (Table 8). The costs per unit include the costs for labor, seeds or plant, container, growing media, fertilizer, chemicals, tags, other direct costs, total direct costs, overhead costs, loss of unsold plants, total costs, sales price, and profit or loss (Tables 6 and 8).

In the example, all crops are profitable (Table 8). Marigold flats are the most profitable crop per unit, and petunia flats are the second most profitable. In the unallocated costs column of Table 7, the overhead cost per square-foot-week is $0.096.

Differences in profit pictures exist between cost per square-foot-week and cost per unit in Table 8. Marigold flats are the most profitable crop per unit, but geraniums in 4-inch pots are the most profitable crop per square-foot-week. Geraniums in 4-inch pots have a lower profit per pot, because they are sold at the lower price per unit than the marigold flats. However, geraniums in 4-inch pots are the most profitable crop per square-foot-week because of more efficient use of space. Returns per square-foot-week of bench space may be the most informative way of comparing profitability among crops because of differences in use of space.

All crops are profitable in the 2003 example (Table 8). But, when the energy costs are increased to the 2008 level, geranium flats and poinsettias become unprofitable. If the fuel costs remain high and the prices increase by 5 percent, the net return becomes positive (Table 9), but poinsettias are slightly unprofitable, losing $0.01 per square-foot-week.

As shown in this hypothetical example, knowledge of the profitability of each crop helps managers make production and marketing decisions to improve their businesses. With rising fuel costs and competitive markets, managers need to pay close attention to the bottom line and how changes in costs impact it. Cost accounting allows managers to do what-if planning on paper instead of making bigger, real mistakes in the greenhouse.

Table 8
THE RESULTS OF COST ACCOUNTING PER UNIT, PER CROP, AND PER SQUARE-FOOT-WEEK

Item	Petunia Flats ($)	Marigold Flats ($)	Geranium Flats ($)	Geraniums 4-Inch Pots ($)	Poinsettias 6-Inch Pots ($)	Outdoor Cut Flowers: Bunches ($)
Costs per Unit						
Total direct costs	5.11	4.91	8.36	1.37	3.23	2.91
Overhead costs	1.26	0.95	2.05	0.06	1.44	0.17
Loss of unsold plants	0.13	0.12	0.21	0.08	0.25	0.16
Total costs	6.50	5.98	10.62	1.51	4.92	3.24
Sales price	7.93	7.00	11.73	1.66	5.46	4.00
Costs per Crop						
Square feet	82,000	82,000	82,000	11,000	126,000	43,560
Square feet-weeks	656,000	492,000	1,066,000	66,000	1,890,000	653,400
Overhead/ square foot-week	0.10	0.10	0.10	0.10	0.10	0.01
Sales	388,570	343,000	574,770	157,700	653,562	99,317
Direct costs	255,502	245,502	418,005	137,300	406,982	76,175
Total costs	318,607	292,830	520,551	143,649	588,794	80,524
Profit (loss) per crop	69,963	50,170	54,219	14,051	64,768	18,793
Profit (loss) per unit	1.43	1.02	1.11	0.15	0.54	0.76
Profit (loss) per square-foot-week	0.11	0.10	0.05	0.21	0.03	0.03

Table 9
Greenhouse Cost Accounting Program Information per Unit and per Crop Using 2003 Northeast Costs

Item	Petunia Flats ($)	Marigold Flats ($)	Geranium Flats ($)	Geraniums 4-Inch Pots ($)	Poinsettias 6-Inch Pots ($)	Outdoor Cut Flowers: Bunches ($)
			2003 Fuel Prices			
Sales	388,570	343,000	574,770	157,700	653,562	99,317
Profit (loss) per crop	69,963	50,170	54,219	14,051	64,768	18,793
Profit (loss) per unit	1.43	1.02	1.11	0.15	0.54	0.76
Profit (loss) per sq. ft-wk	0.11	0.10	0.05	0.21	0.03	0.03
			Everything Held Constant, but Energy Adjusted to *2008 Fuel Prices*			
Sales	388,570	343,000	574,770	157,700	653,562	99,317
Profit (loss) per crop	30,682	20,709	(9,612)	10,110	(48.084)	19,188
Profit (loss) per unit	0.63	1.42	(0.19)	0.11	(0.40)	0.77
Profit (loss) per sq. ft-wk	0.05	0.04	(0.01)	0.15	(0.03)	0.03
			Everything Held Constant, but Energy Adjusted to *2008 Fuel Prices and Sales Prices Increased by 5 Percent*			
Sales	407,999	360,150	603,508	165,585	686,240	104,283
Profit (loss) per crop	50,222	37,942	19,307	17,995	(15,406)	23,759
Profit (loss) per unit	1.02	0.77	0.39	0.19	(0.13)	0.96
Profit (loss) per sq. ft-wk	0.08	0.08	0.02	0.27	(0.01)	0.04
Price	$8.33	$7.35	$12.32	$1.74	$5.73	$4.20

Ratio Analysis

One method of assessing the financial health of a business is using financial ratios. Ratios are calculated using numbers from the balance sheet and income statement. The ratios fall into four categories: profitability, financial efficiency, liquidity, and solvency. The explanations of ratios in Table 10 use numbers from a 2003 survey of northeast greenhouses.

Profitability Ratios Profitability ratios measure the ability of the business to earn a good profit and generate a satisfactory return on investment. These ratios are typically a good indicator of management's overall effectiveness. The *net profit margin* is the most common. It is a measure of the operating efficiency of the business. It measures how effectively the business is controlling expenses relative to its value of output. A high profit margin indicates good cost control. The net profit margin is the profit per dollar of sales after paying the owner's salary and accounting for opportunity cost of capital invested.

Common problems with profit margin are the wrong pricing system, prices that have not been increased as costs have increased, costs that are too high relative to size of business, not enough sales for the resources allocated, high overhead costs, wasteful spending on inputs, and poor production. If costs are too high, questions to ask are as follows: Is the business overmechanized? Is labor being used efficiently? Does the firm have too much labor? Is it the right type of labor? Is there too much labor in slack periods? Is there a labor shortage in peak periods? What costs are the highest? Are these controllable? Are the costs necessary? Can the same function be done a better way? Would mechanization reduce costs? It is important to keep in mind that every dollar saved by cost control equals a dollar of *profit*.

The *return on assets* (ROA) ratio measures the profit-generating capacity of total assets of the business. It measures the firm's effectiveness in using all of the available

Table 10
Seventeen Key Ratios Calculated from Averages of a Survey of Northeast Greenhouses in 2003, the Formula for Each, an Explanation of Each, and a Recommended Level for Each Ratio

	Measure	Your Figure	Recommendation	Formula	Explanation
Profitability: The Ability to Earn a Good Profit and Generate Satisfactory Return on Investment					
1	Net income (profit)	$211,456	>$50,000 per family	Sales – Total costs	What remains after subtracting all the costs (including depreciation, interest, salaries, and taxes) from your sales. Also called bottom line, net earnings, net profit.
2	Gross margin	65.82%	>30%	(Sales – Total direct costs)/Sales	The amount of contribution to the business enterprise, after paying direct costs.
3	Profit margin	9.53%	10–15%	Net income/Sales	Profit per dollar of sales after paying the owner's salary and accounting for opportunity cost of capital invested.
4	Return on equity	27.89%	>10%	Net income/ Net worth	Measures how effectively you are using your reserves to produce income.
5	Return on assets	17.16%	>10%	Net income/ Total assets	Measures how you employ your assets to obtain sales revenue.
Financial Efficiency: How Well You Employ Your Assets					
6	Financial efficiency ratio	85.94%	<65%	(Total expenses – interest – depreciation)/ Sales	Measures how you employ your assets to obtain sales revenue.
7	Asset turnover ratio	180.14%	>25–30%	Sales/Total assets	How you are in utilizing your assets in generation of sales revenue. Higher is better. If low, it indicates the current level of investment needs to be used more efficiently or maybe some capital can be sold without adversely affecting operating efficiency.
8	Operating expense ratio	13.54%	<65%	(Operating expense – Depreciation)/Sales	For every dollar we took in, how much did we need to spend?

9	Depreciation expense ratio	4.17%	<15%	Depreciation expense/Sales	Provides a measure of the capital costs incurred by the firm.
10	Interest expense ratio	0.36%	<15%	Interest expense/Sales	Shows percent of your income needed to pay interest.
Liquidity: The Ability of the Firm to Meet Its Current Obligations Without Disrupting Normal Business Operations					
11	Current ratio	1.85	>1.5	Total current assets/Current liability	Measures the ability to satisfy current debts with current assets.
12	Working capital	$207,162	Positive, stable	Total current assets – Total current liabilities	Approximates the amount of funds available from within the business to purchase crop inputs and equipment necessary to produce products. In general, a lot of working capital = more success since you can expand and improve operations.
Solvency: The Ability to Meet Loan Payments					
13	Debt/asset ratio	38.47%	<30%	Total liabilities/ Total assets	Measures the percentage of the your total assets to which creditors have claims. Measures financial risk with debt financing. If = 0, the firm is out of debt.
14	Equity/asset ratio	61.53%	>60%	Total equity/ Total assets	What portion of the business *you* own.
15	Debt/equity ratio	62.51%	<70%	Total liabilities/ Net worth	What portion of the business *your lenders* own.
16	Working capital ratio	10.32%	>50%	(Current assets – Current liabilities)/Total expenses	Measures the return on your assets without regard to how the firm is financed.
17	Leverage factor	1.625	<5	Total assets/Net worth	A measure of the firm's riskiness. It is the ratio of your assets to your net worth.

total capital—both debt and equity. Return on assets shows how well the firm is using its assets to generate a profit.

Efficiency Ratios Efficiency ratios help explain why the business is making or losing money. While financial efficiency is related to profitability, it is quite different. The profit margin shows the return or loss for a given year. Financial efficiency seeks to understand the components of sales and determine if an operation is spending excessive amounts on operating expenses, interest, depreciation, and so forth. Therefore, it is important not only to understand the components that come together to determine profitability but also to understand why a business is or is not profitable. Financial ratios tell you how well the firm employs its assets.

Liquidity Ratios Liquidity ratios measure the capacity of the business to meet its short-term liabilities, either by using cash or by converting current assets into cash. Creditors and other lenders favor liquidity ratios that tend to reveal financial strength or weakness. The *current ratio* has long been the primary test for creditworthiness. It measures the ability to satisfy current debts with current assets. The higher the ratio the greater the protection for short-term creditors. A ratio of less than 1 or a declining trend can signal problems in liquidity.

Solvency Ratios Solvency ratios measure the extent to which a business is financed by debt and the firm's ability to meet loan payments. Lenders of long-term funds and equity investors have an interest in solvency ratios. The *debt-to-asset ratio* is a way of evaluating the degree of asset financing creditors provide. It measures the percentage of the firm's total assets to which creditors have claims. A higher ratio indicates greater financial risk and lower borrowing capacity. A ratio of less than 30 percent is considered strong.

Table 11 shows the impact of taking the costs of northeast growers in 2003 and inflating the costs of energy to the peak of 2008 prices. Net income, profit, return on

Table 11
Ratios Using Actual 2003 Data from Northeast Greenhouses, Changes to Ratios by Inflating Fuel to 2008 Prices, and After Inflating to 2008 Prices and Increasing Prices by 5 Percent

Ratio	Actuals, 2003	Fuel Increase, 2008	Fuel Increase, 2008, Price Increase 5%
Net income	$211,456	($ 37,788)	$ 73,444
Gross margin	65.8%	65.8%	67.5%
Profit margin	9.5%	–1.7%	3.1%
Return on equity	27.9%	–5.0%	9.7%
Return on assets	17.2%	–3.1%	6.0%
Financial efficiency ratio	86.0%	97.1%	92.5%
Asset turnover ratio	180.1%	180.1%	189.1%
Operating expense ratio	13.5%	17.8%	17.0%
Depreciation expense ratio	4.2%	4.2%	4.0%
Interest expense ratio	0.4%	0.4%	0.4%
Current ratio	1.9	1.9	1.9
Working capital	$207,162	$207,162	$207,162
Debt–asset ratio	38.5%	38.5%	38.5%
Equity–asset ratio	61.5%	61.5%	61.5%
Debt–equity ratio	62.5%	62.5%	62.5%
Working capital ratio	10.3%	9.2%	9.2%
Leverage factor	1.6	1.6	1.6

SOME KEY PROJECTED RATIOS FOR MRS. GREENJEANS GREENHOUSE

Profit Margin = Profit/Sales	7.41%
Asset Turnover = Sales/Total Assets	0.53
Return on Assets = Profit Margin × Asset Turnover	3.92%
Financial Leverage = Total Assets/Net Worth	1.93
Return on Equity = Return of Assets × Financial Ratio	7.59%
Debt to Asset Ratio = Total Liabilities/Total Assets	0.48
Current Ratio = Current Assets/Current Liabilities	4.04

assets, and return on equity all become negative under these conditions. If prices are increased by 5 percent while holding everything else the same, the net income, profit, return on assets, and return on equity all become positive again, though not as large as the 2003 levels. This shows that ratio analysis can be a useful management tool, especially when facing external threats.

When working with ratios, the following rules are important:

1. Ratio trends calculated consistently over time will provide better information.
2. Differing accounting policies, overall business size, and maturity of the business impact ratios.
3. Ratios supplement but do not replace sound business judgment. Ratios can be very useful in identifying areas of strengths and weaknesses, but because they are summary level in nature, many facts can remain buried if you don't take the analysis further.
4. Individual business ratios can be compared to industry statistics and trends.

Benchmarks

Managers can learn about the strengths and weaknesses of their business by benchmarking them against similar greenhouse businesses in their region and across the country. Benchmarking means comparing the firm's financial and production performance measures against averages for the industry. One challenge with benchmarking is determining what the critical success factors are. Which measures will really make a difference to the firm's profitability? The second challenge is finding industry data to benchmark against. Table 10 is a place to start, with 17 key ratios. Other places to look are cooperative extension publications, Web sites, and industry groups.

Capital Required

The most common reason for developing a business plan is to be able to present the firm's ideas for a new or expanded business to investors or lenders. After investors or lenders see the plan, they will want to know how much money is needed and how the money will be used.

Managers should think about what financial resources are needed for the following list: (1) equipment and facilities; (2) lease versus purchase; (3) suppliers: delivery schedules, beginning inventories, economic order quantities, cost of storage, and lead times for delivery, (4) start-up costs: overhead components, incidental costs, initial advertising and promotions, utilities installation costs, renovations, working capital start-up, timing and source of investment, insurance, licensing, and accounting fees;

BENCHMARKS FOR MRS. GREENJEANS GREENHOUSE

Mary and John Wilson of Mrs. Greenjeans Greenhouse found some information from 1994 published by PPGA. Since the information is expressed as a percentage of sales, they can still use this to see if they have strengths they can build upon, or weaknesses they need to correct. Overall, their expenses are very much in line with the national averages. Their projected profits are 2 percent higher than the national average. They hope that they can meet this goal, and this will help to give them a competitive advantage.

BENCHMARKS FOR MRS. GREENJEANS GREENHOUSE

Expense Item	All Greenhouses (%)	Mrs. Greenjeans Greenhouse (%)
Labor	33.8	35.3
Heating	3.9	4.2
Materials	35.3	31.7
Rent and depreciation	5.5	6.6
General maintenance	2.5	1.2
Insurance	1.6	0.8
Office/administration	0.9	0.4
Other utilities	1.6	1.7
Auto/truck	1.7	0.4
Interest	1.7	2.1
Advertising	1.0	0.8
Other items	5.1	7.3
Total expenses	94.6	92.6
Profit (sales less expenses)	5.4	7.4

Source: Professional Plant Growers Association, 1994.

(5) typical annual and monthly estimates, and (6) desired mix of financing: equity, long-term loans, short-term or working capital loans, equipment or facilities loans, leases or rentals.

Managers should describe how they will acquire and manage capital assets. Do they purchase, lease, or custom-hire to meet equipment needs? If they plan to rent land or buildings, they should describe the lease arrangements. They may want to include a summary of retirement or savings investments. If major changes are planned, they must describe how these assets will be managed.

Consider how well the machinery and equipment are matched to the size of the business. Good management of major assets has a large impact on profitability. Machinery and equipment are large expenditures that are motivating some producers to become more creative with alternative means of gaining access to assets.

CAPITAL REQUIREMENTS FOR MRS. GREENJEANS GREENHOUSE

Operating Line of Credit	$100,000
Long-Term Credit	
Emergency generator	$ 5,000
Seeder	$ 20,000
Total long-term capital to borrow	$ 25,000

Supporting Documentation

An appendix to the business plan should include other supporting documentation. Resumes of key people could be included. If the business was purchased from someone else, it should include any financial data that he or she has provided as well as a history of the business.

Reviewing Business Plans

A well-prepared plan is the road map to the future of the business. Business owners need to make the document work for them. They should skip sections that are not relevant, and add others if their business requires them. A business plan must pass three tests (Marshall, 2004):

1. The *reality test* proves that a market really exists for the products or services, and the firm can actually build it for the costs estimated in the plan.
2. The *competitive test* evaluates the firm's position relative to its key competitors and management's ability to create a business that will gain an edge over its rivals.
3. The *value test* proves investors or lenders will receive an attractive rate of return or a high probability of repayment.

A periodic review is imperative for the business plan to measure the firm's progress toward meeting its financial, marketing, and other goals. Greenhouse managers tend to be overly optimistic, underestimating costs, and overestimating returns. A review of the plan will help identify deviations from the plan early before they become serious problems. Early reviews will allow for modifications if needed. Several tools are available to determine the profitability of alternative strategies. However, profits may not be the only objective of the business. Other questions to ask are as follows: Is our current strategy consistent with the business and strategic plan? If it is not, should it be rejected, or should the plan be reevaluated?

After a firm has decided who its customers are, what consumer needs it will fill, how other business forces will affect the industry, and how the firm's individual strengths and weaknesses will be used and improved for business success, it has to implement the strategy. Having a strategic plan will help the firm to be proactive and to anticipate and take advantage of business trends. The firm will also want to continue to stay informed about its customers' needs and desires. The management team should keep focus on the strategic plan and share the mission and objectives with employees and customers. It is also a good idea to periodically review the firm's mission, goals, and objectives and change or modify them as external and internal situations change. But, also, management should be sure that the direction in which the firm is moving is consistent with the current mission and strategic vision of the firm.

SUMMARY

1. Management begins with formulating the company's mission or vision, developing a plan, executing that plan, and measuring the results to see how the end product fulfills the original vision.
2. A business plan is a systematic evaluation of a venture's possibility for success. It is the guide for the business. It charts its future course, defines the strategy for building it, and helps the business stay focused on its objectives. It can be used to obtain capital from lenders and investors and helps define the potential returns relative to the costs and risks.
3. A business plan should include the following:
   a. An executive summary, the elevator pitch to describe the business concept and the company's competitive advantage.
   b. A business description of who is involved, what consumer needs will be met, what the saleable

product or service is, and the market environment in which the business operates.

c. A vision statement that looks at the future and asks what kind of business does the firm wants to be.

d. A mission statement that tells why the company exists (the *purpose*), that is, what will the business accomplish for its customers, employees, and owners.

e. Goals and objectives to help define what the business will become. While goals can be broad or general in nature, objectives should be SMART (specific, measurable, attainable, relevant, and time-bound).

f. A strategic plan to match profitable business opportunities with the firm's resources.

g. A production and operations plan that includes a description of what crops the firm will produce, how it will produce them, and what technology and equipment will be used.

h. A marketing plan that defines the customer or target market and describes how the firm will tailor the product, pricing, distribution, and promotion strategies to satisfy that customer or target market.

i. A management plan that defines the business's operational areas by function and who will perform each function.

j. A financial plan that gives some indication of where the business is headed in the next few years and describes the financial ramifications of changes that are implemented in the future.

4. A strategic planning tool called a SWOT (strengths, weaknesses, opportunities, threats) analysis helps firms identify external opportunities and threats that are beyond their control, such as shifting economics, increased global competition, changing government regulations, and new technology, and their internal strengths and weaknesses, such as location, skills of key employees, and cash flow position. Building a successful business requires magnifying strengths and overcoming weaknesses and matching internal strengths of the business to external opportunities.

5. In addition to financial records, greenhouse managers need to keep cultural records to (1) provide a plan for duplicating successful crops and (2) give an accounting from which the cause of errors in the culture of the crop can be determined and then corrected in the next crop.

6. As the business grows, an organizational structure can allocate responsibilities for different functions to different individuals, departments, teams, or divisions. Team organization synergizes individual competencies, empowers employees to make their own decisions, and creates an atmosphere for excellent customer service. The size of the management team can range from one person in a small firm to hundreds or thousands of managers in multinational companies.

7. Labor is one of the most valuable resources in the business, and hiring and motivating employees is a critical management function. Management functions are not limited to managers and supervisors. Every member of the firm has some management and reporting responsibilities.

8. Managers need four key leadership traits: (1) Vision—Leaders have a sense of what is important. (2) Energy—Leaders are exciting and enjoyable to be around. (3) Power source—This can come from their position, the task, personal power, relationship power, or their knowledge and ability to use it well. (4) Direction—Leaders have a plan. A vision without a plan is just a dream. Managers need to convey a sense of shared vision.

9. Financial analysis describes the financial ramifications of changes that are implemented in the future. It should include the following:
    a. The income statement provides the framework for determining what profit the business can expect to obtain and the expected fixed and variable expenses at the projected level of sales.
    b. The cash flow statement indicates how much to borrow and when.
    c. The balance sheet presents the company's financial position, including assets, liabilities, and net worth.
    d. Breakeven analysis and financial ratio analysis compare the projections with industry norms and establish return-on-investment requirements.
    e. Benchmarks are used to monitor and evaluate progress in meeting established goals.
    f. Cost accounting assigns production costs to each crop and subsequently calculates the profit of each crop.
    g. Capital requirements for (1) equipment and facilities, (2) lease versus purchase, (3) suppliers, (4) start-up costs, (5) typical annual and monthly estimates, and (6) debt service.

10. A well-prepared plan is the road map to the future of the business. A periodic review is imperative for the business plan to measure the firm's progress toward meeting its financial, marketing, and other goals.

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Marketing

Robin G. Brumfield

When it comes to running a greenhouse business, many people seem to focus on working out the production and technical aspects, with little regard to marketing. Market success is not guaranteed. In today's competitive markets, just being able to produce a good product does not mean it can be marketed for a price that covers costs. The fact that no one else is producing a particular product does not mean that a viable market exists. Greenhouse owners not only have to be able to produce and sell plants and flowers, but they have to produce at a cost low enough and sell at a price high enough to generate a profit. Production decisions are an integral part of a marketing plan.

Marketing is one of the most important factors in determining the success of a business. Most of the decisions made by the producer are marketing decisions, which range from determining the most marketable varieties to produce to deciding how to deliver profitable, high-quality products to consumers. However, marketing does not begin after the crops are produced. Instead, a greenhouse manager must consider marketing strategies before he or she produces anything and must continue to do so long after an actual sale is made.

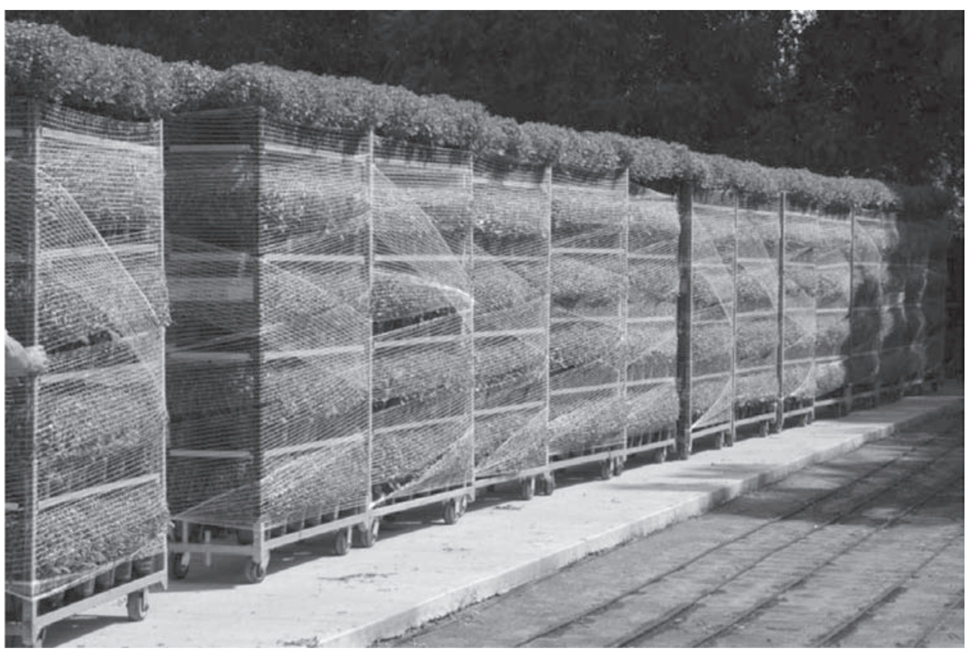
Planning prior to production entails a market-demand evaluation to ensure that the correct crops, sizes, colors, and so forth are grown to meet market needs. Cultural schedules are developed to finish the crop at a potentially profitable time. All too often, greenhouse managers become concerned entirely with maximizing the use of bench space and lose sight of the market demand and selling price of the crop. A properly planned crop paves the way to the more obvious steps of marketing beginning at harvest time.

PACKAGING

Potted plants are usually sold individually to full-service florists. Mass-market outlets commonly load plants into carts with multiple, adjustable shelves. Sometimes, the carts are shrink-wrapped to protect the plants (Figures 1 and 2). The carts are rolled into trucks to use all available space. This precludes the need for fixed shelving in the truck, which was common in the past. Carts are loaded into the truck in the reverse order in which they will be removed as the truck reaches each of its market desti-

Figure 1
Racks loaded with garden mums and pansies ready to load onto trucks to be taken to market.
(Photo courtesy of Ed Higgins, Ball Chrysanthemums, 380 Leatherman Road, Wadsworth, OH 44281.)

Figure 2
Racks loaded with plants and shrink wrapped and ready to be loaded onto trucks to be taken to market.
(Photo courtesy of Ed Higgins, Ball Chrysanthemums, 380 Leatherman Road, Wadsworth, OH 44281.)



nations. Full carts are left at the retailer's facility to be returned later when they are emptied.

Skill is required to harvest fresh cut flowers at the proper stage of maturity. It is sufficient to note that, with the exception of roses, a grower has a degree of latitude with regard to the stage of development at which a cut-flower crop must be cut. The exact stage depends on the length of time and type of handling in the market channel. European and Colombian carnations are often harvested in a tight stage (with guard petals upright) to facilitate shipping and lengthen vase life. Carnations grown for local consumption are generally harvested open (with guard petals horizontal or lower) to minimize handling time. Tulips, daffodils, peonies standard chrysanthemums, and several other crops can be similarly harvested in the bud stage.

Floral products are packaged in conventional unit sizes. Roses and carnations are packaged in bunches of 25, while the number is 10 for most other cut-flower crops except protea, which are packaged 5 to the bunch. Pompom chrysanthemums are bunched according to weight in some parts of the world, with 9 ounces (255 g) common and no fewer than five stems. The weight of the bunch varies with different growers. In some regions, they are packaged with five stems to the bunch rather than by weight. Generally, the stems are 30 inches (76 cm) long. Bunches of cut flowers are often placed in a plastic sleeve to protect the blooms, and the stem ends are bound with a rubber band or string. Bunches so wrapped have traditionally been placed in cardboard boxes for refrigerated storage or shipping. The standard box measures 48 by 20 by 12 inches ($122 \times 51 \times 30$ cm) and typically weighs between 40 and 60 pounds (18 and 27 kg). The trend today is away from this standard box and toward a half-box size. Half boxes reduce the weight and better conform to dimension requirements for truck and air containers. More recently, plastic containers have been replacing cardboard boxes for floral transport. The container shown in Figure 3 allows flowers to be packaged and shipped in an upright position. The ends of the stems are placed in flo-

Figure 3

A plastic container for shipping cut flowers in an upright position from producer to retailer. Stems are maintained in floral preservative throughout transit. A cardboard collar of varying heights can be positioned immediately below the plastic top to accommodate flowers of various heights.

(Photo courtesy of Pagter Innovations b.v., Vaartveld 14 4704 SE, Roosendaal, The Netherlands, E-mail: info@pagter.com; in USA: Pagter Innovations, Inc., 1544 West Thorndale Avenue, Itasca, IL 60143, Tel: 1-630-539-1400, E-mail: sales.na@pagter.com.)

ral preservative through the entire transit process. This particular container has a disposable cardboard collar between the plastic cover and the plastic base container. The cardboard collar is available in various heights to accommodate different flower heights. Flowers can be displayed in this container for sale at the retail outlet. The container is purchased by producers and travels all the way through the importer, auction, and wholesaler to the retail florist without removal of the flowers. This eliminates the time-consuming need to cut the stem ends and transfer them to new preservative solutions at the auction, wholesaler, and retailer levels. The retailer has the option of returning the containers to the producer for a refund. Trucks, cargo planes, and international passenger planes readily accommodate these containers. These containers are often used when initial shippers are sending direct to retailers.

GRADES AND STANDARDS

There has been considerable controversy over assigning grades to cut flowers and potted plants to quantify their size and quality. Opponents cite hidden factors such as the increased cost of handling. Proponents see grading as a means of discouraging poor quality in the marketplace and achieving financial remuneration for high-quality products. It could also go a long way toward nurturing consumer satisfaction.

Most cut-flower producers use a grading system. However, the system varies markedly. Those who ship to an auction conform to whatever system is in place for that auction. For instance, stem lengths are generally specified in even increments of 10 cm in European auctions, for example, 50, 60, 70 cm. In the United States, the lengths may be in inches, such as 30 inches (76 cm). Otherwise, the tendency is for each producer to set up his or her own grade specifications. Input into the specifications comes from the producer as well as the consumer. Standardized grading could give both the marketer and the consumer a means for judging and demanding the quality they prefer. It would give the grower a tangible objective and measuring stick for achieving a better product. Greater consumer satisfaction should lead to increased product demand. Higher-quality production and handling would help reduce flower losses in the market channel.

To this end, the Floral Marketing Association (FMA) in cooperation with the Society of American Florists (SAF) developed grades and standards for 21 types of cut flowers (FMA/SAF, 1996). An example set of standards developed for carnations by the SAF is presented in Table 1.

Table 1
SOCIETY OF AMERICAN FLORISTS STANDARDS FOR CARNATION GRADES[1]

	Blue Grade (fancy) (1)	Red Grade (standard) (2)	Green Grade (short) (3)
Minimum length[2]	22 in. (56 cm)	17 in. (43 cm)	12 in. (30 cm)
Minimum flower diameter[3]	Tight[4]—2 in. (51 mm)	1¾ in. (44 mm)	No requirement
	Fairly tight—2½ in. (64 mm)	2¼ in. (57 mm)	
	Open—3 in. (76 mm)	2¾ in. (70 mm)	

[1]Flowers in the blue, red, and green grades should be full, symmetrical, and free of insects, disease, and mechanical injury; they should also be free of bloom defects such as slab side, bullhead, blow heads, singles, sleepy appearance, splits, and discoloration. The stems should be of sufficient strength that they do not deviate more than 30° from the horizontal plane when held 1 inch (2.5 cm) above the minimum length of the grade with the natural curvature down. Any flowers with these defects are either sold at a lower price or discarded.
[2]Length is measured from the top of the bloom to the cut end of the stem.
[3]The flower diameter is the greatest dimension of the petals measured through the center of the bloom. The guard petals of open blooms are held horizontally when size is determined.
[4]*Tight*: Guard petals are up; center petals are up but fluffed. *Fairly tight*: Guard petals are horizontal; center petals are up and fluffed. *Open*: Guard petals are horizontal or lower; center petals are out or down.

Foliage plants in particular should be graded to protect the consumer as well as the grower of quality plants. Foliage plants are grown in a favorable environment relatively rich in nutrients and sunlight. They are then utilized, hopefully for many years, in a rather marginal indoor environment. The grower must provide a period of acclimatization in order for these plants to make the transition successfully. Acclimatization can be costly, since it entails a period of slow growth when nutrients and light are reduced. Growers who do not acclimatize their crops may realize a profit in the short run, but in the long run, the industry is hurt by consumer dissatisfaction. Standards for foliage plants should take into account such handling so that it is encouraged and rewarded. As early as 1977, a set of standards existed for foliage plants (Gaines, 1977). The current set of grades and standards for about 20 foliage-plant crops was completed by the FMA in association with the Florida Nursery Growers Association (FNGA) around 1995 (FMA/FNGA, 1995).

Standards did not exist for flowering potted plants until 1987, when the FMA and the SAF made the decision to promote the development of grades and standards. The first set of guidelines was released in 1989 and covered azalea, chrysanthemum, lily, and poinsettia. Today, there are grades and standards for 20 potted crops (FMA/SAF, 1995).

The standards are voluntary. Differences in tastes and preferences exist across regions. Desired potted-plant height is higher in the western regions of the United States than in the eastern regions. Consumers in California prefer an 18- to 20-inch (46- to 51-cm) potted mum, measured from the base of the pot to the top of the plant, whereas those on the East Coast prefer a 14- to 16-inch (36- to 41-cm) plant. Included in the standards are height, minimum width of the top of the plant, number and developmental stage of buds, condition of foliage and roots, strength of stems, and the presence of a care tag. When the grower has finished grading and packing cut flowers or potted plants, they are shipped to the wholesaler or retailer generally at the grower's cost. Foliage plants are an exception. They are often shipped by the grower at the retailer's expense or are picked up directly by the wholesaler or retailer.

THE MARKET SYSTEM

Market Channels

Greenhouse markets can be divided into two broad market channels: wholesale and retail. Each of them has advantages and disadvantages. A wholesale production greenhouse sells relatively large amounts of a variety of plants to a relatively small number of accounts. A retail greenhouse sells relatively small amounts of plants to a relatively large number of individual customers. Deciding which market channel to use for selling products to buyers is important. Managers will want to match their belief system, personality, resources, goals, assets, market potential of their products, and location with a market best suited to them. Many greenhouse firms pursue both wholesale and retail (direct), or more than one wholesale market or retail market. Diversifying in markets, just like diversifying in production, helps reduce risks by providing income stability. The market channel will also help determine the best crops to grow.

Advantages and Disadvantages of Wholesale Marketing The biggest advantage of wholesale marketing is larger potential transaction sizes and volume. Someone else does most of the marketing, allowing the greenhouse owner to focus on production. Promotional/educational costs are low. Strategic location is less important and potentially less expensive compared with firms catering to retail markets. Legal risks may be lower compared with retail marketing because customers will generally not be on the property. Wholesale marketing is a good choice if the greenhouse owner is not a people person and doesn't want to deal with the public. However, someone will still need to sell to wholesale customers. Wholesale marketing is suited to large greenhouses, which should receive economies of scale. Once a greenhouse becomes large, it is often difficult to sell everything directly, and wholesaling may become the second marketing channel if not the only channel. The wholesale growers can usually concentrate on a few enterprises so that they can do each one well and have benefits of economies of size.

Because the marketing function is being done by others, the price in the wholesale market is lower than that in direct marketing alternatives. Producers will have little control over the price, that is, they will be price takers. They will need to follow careful harvesting, packaging, labeling, trucking, and post-harvest handling procedures and adhere to strict grading standards of size and quality to meet competitive market standards. They may have to take the product to a distribution center market and incur some transportation costs.

Advantages and Disadvantages of Direct Marketing The prices are higher in direct markets than prices in wholesale markets. Direct market producers will have some control over the price based on being able to differentiate their product or service, that is, make their products different from their competitors' products so they can charge a higher price. Because direct market customers are looking for freshness rather than strict grades such as uniform size, retail greenhouses will probably be able to sell all sizes and grades for higher prices than they would receive in a wholesale market. The proclivity of the public to buy locally produced products creates an almost automatic loyalty. Consumers perceive products from a local grower to be fresher than products being shipped from distant markets. In some direct markets, transportation costs are low or nonexistent. Direct marketing is great for people who love dealing with the public or have employees who are "people persons." Greenhouse growers can spread depreciation, interest, taxes, insurance, rental, advertising, and other costs that are fixed in the short run over additional activities such as agri-tourism, on-farm stands, and pick-your-own facilities. Direct marketing may require minimal additional investment and may utilize excess capacity of labor, capital, land, and natural resources. Direct marketing is a revenue risk management strategy because of the higher prices received for the products. Bringing customers to the greenhouse is an excellent means of supporting the local community and keeping it alive and prosperous.

Direct marketing will require more promotional/educational costs in terms of money and time than wholesale marketing. To succeed, direct marketers will need to develop brochures, newsletters, Web sites, or other promotional materials. A sales area in the greenhouse or some type of farm stands will be needed. The sales costs for hiring and training sales employees are high. Traffic will probably increase and retail greenhouses will need to provide parking (retail from the greenhouse, roadside stands, pick-your-own, and CSA [community-supported agriculture] on the farm) unless the products are being delivered (farmers' market, CSA, drop off, Internet, and mail order). Retailing can result in more conflict with neighbors because of increased traffic. Legal liabilities and safety concerns increase with customers on site, requiring additional liability insurance.

Market Components

Retailers The end consumer can purchase floral products at one of at least six sources: full-service florists, garden centers, big box stores (large discount stores, do-it-yourself hardware stores, club stores), direct-to-consumer (directly from the greenhouse, mail order, wire, Web), farmers' markets, and CSAs.

Full-Service Florists. In earlier times, virtually all cut flowers, foliage plants, and flowering potted plants were purchased at full-service retail flower shops. These shops have always provided services of floral arrangement and delivery. Through the first two-thirds of the 20th century, full-service florists were characterized by nonspontaneous purchases. Eighty-five percent of cut-flower sales went into funeral and wedding orders. Traditional holiday sales made up much of the remainder, for example, Easter lilies at Easter, poinsettias at Christmas, and roses on Valentine's Day. Repeat customers consisted of only about 25 percent of the population at that time.

During the last four decades of the 20th century, the mass market came into being. Initially, full-service florists appeared to be doomed by the lower prices of the mass market. This, however, did not happen. It became apparent that full-service florists and mass-market outlets have some distinctly different roles that do not overlap. Where roles do overlap, full-service shops adopted some of the strategies of the mass market. These include simpler floral bouquets in addition to arrangements, selling individual flowers by the stem, including smaller plants in the line of potted plants, relocating to higher pedestrian traffic areas including malls and supermarkets, and embracing a higher degree of self-service. Due to these changes, full-service florists now access much more of the spontaneous purchase market than in the past.

Purchases, on average, cost more at full-service florists compared to the mass market. Floral products can be marked up to a retail price three or four times the wholesale price paid for them. This is acceptable to consumers because of the value that is added, such as customized arranging of flowers, top-end and/or offerings in the potted and cut-flower lines, fancier packaging, convenience of telephone or Web orders, delivery, and most important, the value impact perceived by the recipient. If it were not for these distinguishing features, mass-market outlets would have replaced the full-service florists. In 2005, approximately 40 percent of the total value of floral sales passed through traditional florist shops and their traditional counterpart, the garden centers (data collected by Ipsos-NPD for the American Floral Endowment). An earlier prediction by astute members of the floral industry that mass-market sales would help create a greater appreciation and desire for flowers and thereby enhance sales in the conventional florists' channel has come true. The mass market has "grown the market pie" by bringing in new consumers who are impulse buyers and/or buyers who are looking for the lower prices the mass market offers. Some of these consumers then move on to other outlets looking for variety, better quality, service, and information.

Garden Centers. Garden centers offer an important channel for marketing bedding plants, perennials, and flowering and foliage potted plants to consumers. As a whole, they are of limited importance for marketing fresh cut flowers. Their emphasis is on landscape materials, which typically includes woody ornamentals and herbaceous perennials. Garden centers are distinguished from floral departments in general mass merchandiser and do-it-yourself stores by the higher level of information and services they offer. On average, more in-depth cultural information is available. Such information may be disseminated individually to customers or through lectures. Services offered often include landscape plans, selection of appropriate plant material for a consumer's situation, and installation of plant material. In short, garden centers are more similar to full-service florists in terms of their relationship to mass-market outlets.

Big Box Stores. Not everyone places emphasis on prestige and service, nor can everyone afford the prices that a full-service florist must charge. During the mid- to late 1960s, floral mass-market channels began to develop in such places as supermarkets and mass merchandise stores. As was the case with so many other product lines, new methods increased the availability and decreased the retail price of floral products, making repeat purchases possible for a larger proportion of the public—some of the 75 percent of the population who had not been reached in the past. By 2003, the percentage of households in the United States purchasing floral products rose to a high point of nearly 60 percent (American Floral Endowment, 2004; U.S. Dept. of Commerce, Economics and Statistics Administration, Bureau of the Census, 2004).

The markup in mass-market outlets is generally 30 to 40 percent. Therefore, when a plant sells for $1, the mass-market outlet retains $0.30 to $0.40, while the grower receives $0.60 to $0.70. Many big box stores initiated pay by scan, which means that they are operating as a kind of consignment shop and do not pay the producer until the plants are sold. As a result, many wholesale greenhouses who supply products to the big box stores place merchandisers in the big box retail stores to prepare displays, stock the shelves, and perform other merchandising functions.

Mass marketing is the sale of floral products through cash-and-carry outlets in high-traffic locations. It breaks down into two main headings: big box stores and general retailers. The big box stores further divide into mass merchandisers such as Kmart, Walmart, Target, Bradlees, Caldor, and Shopko; home centers such as Home Depot (Figure 4) and Lowe's; and warehouse clubs such as Sam's Club, BJ's, and Costco. The general retailers include supermarkets, drug stores, hardware stores, and convenience stores. Some of these retailers focus more on one or a couple of the floral categories, while others carry all four groups: cut flowers, flowering potted plants, foliage plants, and bedding plants. All of these outlets offer flowering and foliage potted plants. Floral stems and bouquets are most often sold by the supermarkets and warehouse clubs. Bedding plants and perennials are more often offered by the home centers, mass merchandisers, and hardware stores. The objective is a high-volume business. Since purchases are usually spontaneous, prices must be sufficiently low to attract a customer's *discretionary dollars* (money remaining after the necessities of life are purchased). Thus, costly services such as floral arranging and delivery are often, but not always, avoided. Potted plants would most likely be sold in more common plastic pots, whereas in traditional flower shops they might be in more expensive decorative pots. While plants might be in the same size pots as sold by the traditional

Figure 4
Home Depot nursery and garden retail fall display.
(Photo courtesy of Lawrence S. Martin, 2908 West Turner Street, Allentown, PA 18104.)

florist, the plant may have been allotted less space and production time in the greenhouse during production. The result is a moderately smaller plant produced at a lower cost. Since the price received is different, growers often alter their production techniques, depending on the market they are servicing. For example, a poinsettia in a 6.5-inch (17-cm) pot might sell for $4.50 to a traditional florist but only $3.00 to the mass market.

Big box merchandisers purchase in large quantities. This gives them the ability to dictate to a large degree price and terms of sale. The need to meet quantity demand and achieve sufficient size to favorably negotiate with big box stores as they expand is a driving force for production greenhouse firms to grow larger. This explains in large part why the number of growers in the United States is diminishing while their average size is increasing. It also helps to explain why there are fewer firms in the mid-size category. They are too large to rely on smaller niche markets yet too small to negotiate with large mass markets.

General Retailers. As just mentioned, general retailers comprise a large array of retailers smaller than the big box stores and include supermarkets, hardware stores, drug stores, convenience stores, and arts and crafts stores. Like the big box stores, they are in continuous contact with the general population. They are likewise well positioned to capture impulse purchases as well as purchases for planned occasions. During 2005, general merchandisers sold 21 percent of the value of all floral products in the United States while big box stores sold 23 percent. By exposing greater numbers of people to floral products, these two groups of retailers generate many new customers that would not have been possible through traditional full-service florists. These are new customers who are not tradition bound. They purchase new crops; accept new colors, forms, and sizes; and are receptive to new retail outlets and ways of merchandising.

Direct-to-consumer. This is a small but growing segment of U.S. floral sales, which in 2005 amounted to 6 percent of the total. Consumers do not need to visit a retail shop to purchase flowers. A number of companies have established networks of florists around the world. These companies are referred to as wire and Web services. A customer can phone or visit a service company on the Web to see floral arrangements and potted plants that are available. When an order is placed, the central receiving office sends it on to a florist in the locality where the flowers are to be delivered. The local florist arranges the flowers or plants and delivers them to the designated recipient. Wire or Web services are provided by such companies as 1-800-flowers.com, AFS Florists, America's Florist, Florists' Transworld Delivery (FTD), Hallmark Flowers, National Flora, Teleflora, Martha Stewart.com, and ProFlora.com. The advent of 1-800-Flowers, the world's leading florist and gift shop, as well as Web sales is said to account for a sizeable proportion of the increase in cut-flower sales through traditional florists. Since its inception, 1-800-Flowers has been on the cutting edge of innovation, first with the use of the 1-800 number, then with a Web presence, and more recently, with partnership marketing. For Mother's Day 2010, 1-800-Flowers.com, Inc. teamed with Tropicana to offer up to $15 off a purchase of $49.99 or more by redeeming three Juicy Rewards points. (Visit Tropicana Juicy Rewards at http://www.tropicana.com/). This made the U.S. tradition of serving mom breakfast in bed alongside a vase of beautiful flowers a lot easier, and less expensive, to achieve. Another direct-to-consumer trend is for smaller greenhouses to retail their products directly out of their greenhouses. They often combine this with other activities such as Christmas tree sales, petting zoos, pumpkin sales, and corn mazes.

Other Retailers. The remaining 10 percent of floral sales in 2005 took place in a variety of markets. These included farmers' markets; street markets, CSAs; fund raisers at churches, schools, and community organizations; and home shows and flower shows.

Farmers' markets have been making a resurgence in the United States since the 1990s. Their numbers have grown to over 3,100. Consumers want to buy fresh farm products from their local farmers with whom they can build a relationship of trust. The primary reason consumers cite for purchasing from a farmer's market is quality; the second is to support local farmers.

Farmers' markets offer a regular outlet where producers can sell a wide range of farm products, including cut flowers and plants. Farmers' markets work well in the rural/urban fringe and help build goodwill for agriculture. If a farmers' market already exists in the locality, entry may be easy and limited only by space at a particular market and the fee to sell, which is usually nominal.

CSA is a partnership-marketing venture between farmers and consumers. Community members who join a CSA farm pay a local farmer an annual membership fee, usually between $300 and $600, to cover the production costs of the farm and in return receive a weekly share of the freshly picked harvest (usually organic) vegetables during the local season. Some farms also offer flowers, fruits, herbs, and other products. Here is an opportunity for flower producers to partner with CSA farmers. The partnership offers CSA farmers the opportunity to expand their offering to flowers without getting into the complex technology of floral field and greenhouse production.

A CSA operator sells individual shares in the farm before the planting season, thus receiving an infusion of cash to purchase inputs without having to finance the operation through credit. Ostensibly, the shareholders share in the risks of the production so CSA farms can shift some of the production, market, and financial risk from producers to consumers. Today, over 1,000 CSA farms operate in the United States and Canada, mostly near urban areas.

Wholesalers Wholesalers procure floral products from growers, auctions, or brokers and sell them to retailers or secondary wholesalers. They deal primarily in cut flowers, to a lesser extent in flowering and foliage potted plants, and rarely in bedding plants. If every retailer had several growers located nearby and collectively these growers offered the total required assortment of floral products, wholesalers would not be needed. Production, even within a given country, has specialized and concentrated into areas remote from the city markets. Unless it is very large, it is uneconomical for the retailer to negotiate the purchase of its numerous floral materials several times a week from distant areas. Wholesalers enjoy an economy of scale because they deal in larger volumes of product. This translates to better purchase terms and lower shipping costs. They also have a better opportunity for on-site inspection of producers. When the product channel is large, as when flowers are produced in one country and sold in another, two wholesalers may become involved in transactions. In this case, a larger wholesaler may receive the flowers at the point of entry into the receiving country and pass them on to a secondary wholesaler in a remote part of that country. This happens at rural ends of the market channel where sales are so sparse that the wholesaler at that end is not in a position to negotiate the procurement of product from a great distance away.

Often, the wholesaler is a commission wholesaler, one who takes flowers on consignment. This means the grower is paid for flowers that the wholesaler sells but not for those that he or she fails to market. The commission wholesaler sells the flowers at a wholesale price and then takes a commission of about 25 percent from this price, returning the remainder to the grower.

Recently, a trend has been developing for wholesalers to buy flowers outright from the grower or broker. This system is more expedient where flowers are mass-produced in one area and wholesaled a great distance away. Although the wholesaler appears to assume all the risk, this is not the case. Flower losses can be reflected in lower subsequent returns to the grower or higher prices for the consumer. The latter affects consumer demand, which hurts the grower.

Wholesalers sell flowers to retailers. Some retailers travel to the wholesale house to make their purchases; others are serviced by trucks operated by the wholesaler. Wholesale florists quite often stock supplies needed by retail florists, such as ribbon, net, vases, and wreaths, which are used in the daily operation of a full-service retail flower shop. The inventory may be larger, including plastic flower arrangements and giftware to be sold directly by the retail florist. Hard good inventory may exceed 50 percent of the total inventory at garden centers.

Most sales are made over the phone by salespeople employed by the wholesale florist. When the orders are filled, the remaining space on the truck is filled with flowers and merchandise that will probably be sold along the route. Each florist is generally serviced twice a week, often by more than one wholesaler. These truck routes serve a very valuable role for retail florists located in remote areas. The wholesale florist likewise plays a valuable role for the retail florist located near the source of flowers. The wholesaler brings together hundreds of items from numerous sources for the retailer's use. This saves the retailer considerable time and expense, as well as the problem of overstocking on items that must be purchased in case lots and soon become outdated. The wholesaler makes it his or her business to keep abreast of changing tastes in supplies, which further benefits the retailer.

Brokers A brokerage firm purchases flowers or plants from growers to fill orders it has received from smaller wholesalers or large retail floral outlets. Typically, the broker is located in the region of concentrated production, so that crops can be examined to match them to the various grade and quality levels demanded by clients. The wholesalers and retailers served are scattered at considerable distances from the production area. It is this distance between grower and wholesaler that creates the need for brokers. The broker serves as the eyes, ears, and legs of the wholesaler and retailer by maintaining on-site contact with producers. Due to distance, this contact is not possible for the smaller wholesaler or retailer. Because larger wholesalers are in a better economic position to establish a presence in the production area, they generally assume this role themselves. The broker system is popular in cut-flower production areas around the world, such as California, Colombia, Kenya, and Israel, as well as in the foliage plant production areas of Florida and California.

Auctions The Dutch have led the development of flower auctions to market flowers. Today, auctions fit into two roles. The first role is seen within individual countries where auctions, like brokers, are located in regions of concentrated floral production. These auctions bring together a wide range of cut flowers or potted plants into a single location where wholesalers and large retailers can efficiently purchase them for distribution to retail markets that may be located some distance from the region of production.

The Aalsmeer Flower Auction (*Bloemenveiling Aalsmeer*) located in Aalsmeer, The Netherlands, is the Wall Street of the flower industry. It is the largest flower auction in the world. The auction building of the flower auction in Aalsmeer is the third largest building in the world in terms of floor space, covering 990,000 m^2 (10.6 million ft^2). Flowers from all over the world are traded on a daily basis at the Aalsmeer facilities. In 2008 the auction merged with its biggest competitor FloraHolland. FloraHolland is a cooperative owned by its roughly 6,000 members, primarily from The Netherlands, but also from other countries.

Figure 5
Interior view of the Aalsmeer Flower Auction (Bloemenveiling Aalsmeer) in Aalsmeer, The Netherlands. This is the largest flower auction in the world, with approximately 6,000 members. Such auctions serve as a distribution channel between growers and wholesalers or large retailers.
(Photo courtesy of Ed Higgins, Ball Chrysanthemums, 380 Leatherman Road, Wadsworth, OH 44281.)

A typical Dutch auction functions as follows (Figure 5) (see also video at http://www.youtube.com/watch?v=V2CK2TatM_U). During the afternoon, flowers or plants are delivered by the grower to the auction, where they are set out on display. Early in the morning, wholesalers and large retailers peruse each lot to assess quality and condition. In so doing, they decide which lots they wish to purchase and how much they are willing to pay. A little later, around 6:30 A.M., wholesalers take their assigned seats in the auction room, as pictured in Figure 6. Each lot of flowers or plants is brought individually before the wholesalers. The clock at the front of the room indicates the identification number of the grower of the plants and the lot number of the plants. An auction employee holds the plants for all to see, and the auctioneer gives a brief assessment of the plants. The sale begins when the clock pointer, set on 100, is released and begins its descent in price. The value of each unit

Figure 6
One of many auction rooms in the United Flower Auctions in Aalsmeer, The Netherlands.
(Photo courtesy of Ed Higgins, Ball Chrysanthemums, 380 Leatherman Road, Wadsworth, OH 44281.)

on the clock's scale of 0 to 100 is denoted on the clock in euros. When the pointer comes down to the price a wholesaler is intending to pay, he or she presses a desk button that stops the clock and electronically records his or her identification number and the price on the clock at that point. The wholesaler finalizes the sale by indicating the quantity of the lot he or she wishes to purchase. By noon, all of the day's sales are made.

This system works rapidly. As many as 700 transactions can be made per clock per hour. The interests of both seller and buyer are served. If the buyer waits for an exceptionally low price, he or she may lose the chance to purchase the plants desired. If he or she bids too soon, a needlessly high price is paid. Each lot of plants is judged independently, and its price is established accordingly. The principle of supply and demand expresses itself in this system.

When sales are finished, flowers or plants are moved from their display area to loading docks where the trucks of the various wholesalers are waiting. Even this process is often mechanized. Carts are loaded according to purchaser and are moved automatically along tracks to the loading area. By mid-afternoon, the auction house is empty, and new flowers and plants arrive to begin another sales cycle.

Auctions add an extra link between the grower and the wholesaler in the distribution chain, but in so doing, they bring wholesalers into contact with hundreds of growers who would otherwise be difficult to reach. Dutch auctions charge a commission of 6 to 8 percent. This does not necessarily increase the retail price over that in a system without a flower auction, since the job of the wholesaler is made more efficient by the auction. Auctions operate under strict rules. Growers must be licensed to sell to an auction. Many require that growers sell all of their product through the auction. This is designed to prevent growers from selling their lower-quality product to the auction and prime quality products directly to retailers or wholesalers and also to stop growers from selling to the auction only when they have excess product.

Most auctions began as cooperatives of small- to moderate-sized growers. These growers felt a need to strengthen their presence in the marketplace for various reasons. Perhaps they felt that wholesalers were playing them against one another to keep purchase prices low. Others wanted to streamline the wholesaling process and keep the ensuing profits at home. Most felt the need to consolidate their small piece of the production pie into a larger entity that would improve demand and their market position. Today, most auctions are grower owned. Several other auctions exist in The Netherlands. Three major auctions in Canada are located in Montreal, Toronto, and Vancouver. Other auctions are located in the United States, France, Belgium, Italy, India, Korea, and Taiwan. Within Japan there are 100 or more small auctions. The massive floral wholesale center in Yunnan province in China includes an auction.

Most of the aforementioned auctions have continued to serve their geographical region—for example, the Vancouver auction services western Canada and northwestern United States. Also, these auctions have remained primarily under the control of the member growers. Some of the Dutch auctions have departed from this profile to the point where they serve a second role. They have become the expediters of the global flow of flowers. Over time, these Dutch auctions sought to increase their business and profitability by accepting flowers from foreign producers in countries such as Israel, Kenya, Zimbabwe, Thailand, and Colombia. As these auctions grew in size, they vertically integrated other functions into their responsibilities. Some took on the importer functions necessary to expedite movement of incoming flowers through customs and phyto-sanitary inspection prior to reaching the auction. With this growth, the size of management within the auctions grew. Grower–owners came to feel that, as individuals, their control was diminishing. They also sensed that this massive importation of flowers brought competition that hurt their production profits. On the other side of the coin, these auctions have been instrumental in the development of the current global flower distribution system enjoyed by growers in developing countries and retailers throughout the world.

Other smaller auctions also exist in The Netherlands and other countries. One such grower auction is in Kutztown, Pennsylvania. Like the Dutch auctions, it is grower owned. Unlike Dutch auctions, which is automated and starts with a high price, the Kutztown auction has an auctioneer who starts the bidding low. The auction continues with the price increasing until there are no bidders. This small auction allows local producers to sell their excess products. Producers can then focus on producing rather than selling their plants.

Importers The international flow of flowers necessitates an additional step in the market chain. When flowers cross the border into an importing country, an agent must record their type, quantity, and value so that tariffs and duties can be assessed by the importing country. These flowers and plants must be inspected for disease and insect presence to protect against the spread of pests into the importing country. Time and handling are required as packages are opened, repacked after handling, cooled during this interruption in shipment, and, finally, transported on to the addressee. These are the functions of an importer. Importing functions may be carried out by companies set up exclusively for this purpose. Alternatively, auctions and wholesalers may establish a department within their firms to perform this role.

The main ports of entry of cut flowers into the United States are Miami, where better than two-thirds of all imports are received; Kennedy airport in New York; Chicago; Los Angeles; and Seattle. Flowers passing through Miami are subjected to an additional inspection for drugs by the Drug Enforcement Agency. Over 100 importers handle the importation of flowers in Miami.

Exporters Exporters assume the tasks of procuring orders for flowers from wholesalers and large retailers in the importing country, shipping the flowers to importers in the receiving country, arranging for payment of taxes, filing claims for lost or damaged goods, and collecting payment. For these services, a charge of 15 to 20 percent of the sales price is usual. Wholesalers may take on these roles and serve in the dual capacities of wholesaler and exporter. Large flower producers sometimes serve the role of exporter. In order to do so, a grower must be able to meet the purchaser's quantity requirement throughout the year and supply the full range of cultivars of a given crop (e.g., roses) required by the purchaser.

Contract Growing Three possibilities exist for growers to market through contracts to other growers. These are finished plants, liners, and young plants. Occasionally, larger growers selling to big box stores need more plant material than they can produce and will contract with smaller growers to produce some of the order. A second possibility exists for producing liner plants for other growers who will finish these off for market. Potted mums and poinsettias are two such crops that fit this category. The first grower may take the plants through the stages of warmer temperatures, pinching, and application of growth regulator. Purchasing liners works for a grower who has a previous crop finishing after the time the next crop is due to be planted. The third category of contract growing involves serving the role of a rooting or seed germination station for a broker. The broker takes orders from growers for plug seedling trays or rooted cuttings. These are in turn produced by and shipped out from young-plant producers who are under contract with the broker.

The advantage of contract growing is that the product is sold before it is planted. An additional advantage can be minimization of the range of crops to be grown. These points allow the contract grower to focus attention on efficiency of production. A disadvantage can occur if the grower has only one contract, which is often the case, and it terminates.

Cooperatives Opportunities to join cooperatives are very limited. However, the possibility of initiating one is real. Motivation for a grower cooperative comes from the advantages of bringing several smaller growers together to pool their products. In such an arrangement each grower can specialize in the production of one or a few crops they grow well. This gives them the opportunity to achieve a higher level of production efficiency. It reduces the burden of marketing for each. It also allows the member growers to pool their purchases of production supplies for larger discounts.

Integration of Market Components

The arrangement of market segments for each major floral group, cut flowers, flowering potted plants, foliage potted plants, and bedding plants, has sizeable differences that sets it apart from the rest. It would be too complicated to discuss them together in a single market sequence. We will start with the simplest, bedding plants, and work toward the most complicated, cut flowers. Bedding-plant and flowering potted-plant market channels are simpler because these plants are typically limited to a one-day truck shipping distance of about 500 miles (800 km). Their heavy weight and large bulk preclude air transport.

Bedding Plants Bedding plants are the most universally produced floral commodity in the developed market regions of the world. The floral production industry in the well-developed market regions is based primarily on bedding plants, where vast quantities of floral imports occur, as in Germany. Due to their proximity to retail markets, bedding-plant growers generally sell directly to these outlets (Figure 7a). Growers negotiate sales and transport the product to retailers, most often with their own trucks. Occasionally this product passes through a wholesaler, broker, or auction. Retail outlets consist of garden centers, big box stores, and general retailers—particularly supermarkets and hardware stores. More and more small growers in densely populated areas sell bedding plants directly to consumers out of their own greenhouse, at farmers' markets, roadside stands, or garden centers. Some producers direct-market part of their product and wholesale part of it. Herbaceous perennials follow the same distribution channel as bedding plants.

Flowering Potted Plants Since flowering potted plants have greater value per unit weight than bedding plants, more marketing steps are feasible prior to trucking (Figure 7b). In the United States and Canada, plant production occurs homogeneously throughout market regions. This makes it easy for growers to sell directly to retail outlets. Wholesalers are used to only a small degree. In the European Union countries, flowering potted plants move directly to the retailer when production is in reasonable proximity to the market. Since there are major concentrations of production in Denmark and The Netherlands, an intermediate wholesaler step becomes important. In The Netherlands, many flowering potted plants are sold through the auction. Local retailers may purchase directly from the auction. Retailers located at a distance from the auction would more likely receive their plants from a wholesaler who, in turn, obtained them from the auction. Since national boundaries are close together in Europe and are often crossed, these wholesalers are more appropriately called exporters. Many of these wholesalers are known as Flying Dutchmen, who obtain orders from retailers throughout Europe. They purchase their plants from the auction to meet these orders and fill any remaining space on the truck with additional plants for speculative sales. As soon as the load is delivered, they return to the auction to refill and repeat the cycle. Retail outlets that handle flowering potted plants

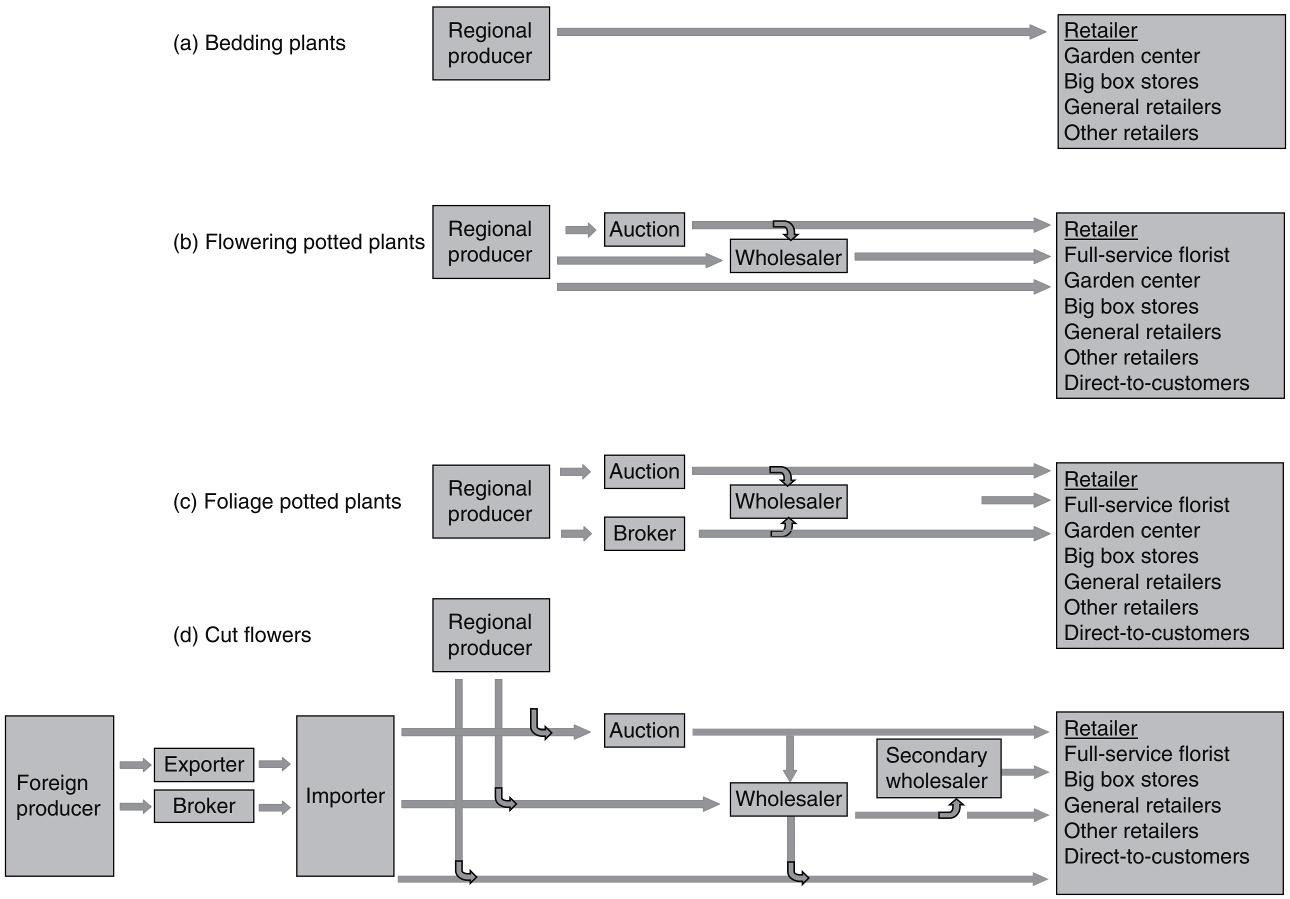


Figure 7
Channels through which (a) bedding plants, (b) flowering potted plants, (c) foilage potted plants, and (d) fresh cut flowers flow from the grower to the retailer.
(Illustration by Paul V. Nelson, Dept. of Horticultural Science, North Carolina State Univ., Raleigh, NC 27695–7609.)

include full-service flower shops, garden centers, big box stores, supermarkets within the general retailer category, direct-to-customer systems, and in the other category—farmers' markets and fund raisers.

Foliage Plants Foliage-plant production in North America is specialized in Florida, California, and south Texas. These are the regions where it is most economically feasible to provide the tropical conditions required for production of these plants; these regions have good access to domestic markets as well. As a result, production and retail markets are separated by great distances, and a more complex market channel is required (Figure 7c). Brokers very often negotiate the markets for the growers. Otherwise, much of the product passes through wholesalers. In Europe, production is concentrated in The Netherlands and in the southern countries. Again, distance is a problem. A wholesaler or a combination of auction and wholesaler is used. Foliage plants are retailed through full-service florists, garden centers, big box stores, general retailers, direct-to-customer services, and other retailers such as farmers' markets and street vendors.

Cut Flowers Approximately 68 percent of the cut flowers consumed in the United States are imported, with most of them coming from Latin America. Within the United States, about two-thirds of cut-flower production occurs in California. Within Europe, large numbers of cut flowers are produced in The Netherlands, France, Italy, and Spain. Additionally, large quantities are imported from Israel, Africa, and, to a lesser degree, Asia and South America. Although Japan produces cut flowers, it also imports them from Southeast Asia, Australia, and New Zealand. With this global movement of flowers, all segments of the market channel are utilized in the cut-flower trade (Figure 7d).

For the sake of simplicity, we will begin by discussing domestic producers. In the United States, traditional crops such as roses now come primarily from Ecuador and carnations come from Columbia. Cut-flower producers in the United States cannot compete in these commodities and have switched to specialty cut flowers that are new to the market, do not ship well, or are produced in small quantities and command a higher price than the major cut-flower crops. The Association of Specialty Cut Flower Growers was formed in 1988 to unite and inform growers in the production and marketing of field and greenhouse cut flowers (http://www.ascfg.org. Accessed February 23, 2011).

The producer can market directly to the retail outlet. Full-service florists generally purchase floral stems, while mass outlets purchase stems and bouquets. In the latter case, the grower becomes involved in a second business of assembling bouquets. This entails procuring a range of floral and foliage species, a task that discourages most small cut-flower producers from entering this market channel. Many cut-flower producers sell through a wholesaler or an auction. The wholesaler may sell directly to a retailer or, if the retailer is located in a distant, remote part of the market channel, the flowers pass through a secondary wholesaler to the retailer. As indicated earlier, the auction sells either directly to large retailers or to wholesalers.

Foreign producers selling flowers to other countries must use the services of an exporter for flowers leaving their country and an importer to get their flowers into the importing country. The exporter may be a broker. From the importer, the flowers enter the same three paths as they do from the domestic producer.

Consolidation for Enhanced Marketing

The business environment is in a constant state of flux. New businesses start every day, others close due to failed operations and consolidate or merge with other businesses. The floral industry is now a mature market, and has experienced considerable consolidation, mergers, shake-outs, and bankruptcies at all levels in the production/marketing chain. While each emerging company has its reasons for consolidation, common reasons include the following: (1) improve product quality by reducing time in the market channel, (2) amass and move sufficient product to meet the existing demand of a particular market, (3) facilitate changes needed to expand market demand, and (4) diversify business investments and potentially mitigate the risk involved with running business operations in a single industry. Organizations may also be able to generate capital through selling underperforming business facilities or production assets to a competing company in the business environment. Mergers occur when one company buys another in an attempt to consolidate market share and increase production output.

The most dramatic consolidation in the industry is in companies serving growers. Benary bought Bodger's seed lines, and a new company, Green Fuse, emerged to represent the vegetative lines. Paul Ecke Ranch, best known for its poinsettia cuttings bought, Oglevee Ltd., known for its clean geranium and other cuttings.

Perhaps the largest supplier to the greenhouse industry is the international company, Syngenta. Syngenta has a long history of mergers, acquisitions, and consolidations. It was formed in 2000 with the merger of two agribusiness companies, Novartis and AstraZenica, but it traces its history back to 1758, when Geigy was formed. The road to becoming Syngenta involved the merger and acquisition of many well-known agribusinesses, including Ciba-Geigy; Sandoz; ICI Americas, Inc.; Rogers Seed Company; Northrup King; Sluis and Groot; and Stauffer Chemical

Company. Since its formation in 2000, Syngenta has made a series of acquisitions of companies that supply inputs to the greenhouse industry. In 2006, it acquired Fafard, a leading North American producer of growing medium. In 2007, it acquired Fisher, a leading European supplier of geraniums and other plant material. In 2008, it acquired Goldsmith Seeds, a U.S. flower seed producer that breeds, produces, and sells a broad range of potted and bedding plants, including major crops such as cyclamen, impatiens, and petunias. In the same year, Syngenta acquired the chrysanthemum and aster divisions of Yoder Brothers, Inc. Syngenta has become a one-stop-shop for greenhouse producers, supplying growing media, chemicals, plant materials, and seeds. It also supplies information to producers, taking over some of the functions formerly provided by Cooperative Extension.

As the industry matures, industry consolidation continues at all levels and more growers leave the industry. To some degree, the box stores are forcing this by dramatically reducing their grower vendor base. Complexity and costs in the supply chain led to consolidation in all of the big box stores. Growers selling to Walmart are the latest ones to be scrambling for other vendors. When Walmart began selling plants a couple decades ago, a few growers saw an opportunity for growth and pounced on it. As Walmart's garden center business began to boom, more growers began growing for Walmart, creating a network of a few hundred growers. Recently, though, Walmart's grower network has dwindled to fewer than 40 select growers. Recovery hasn't been a smooth road for the growers pushed out of Walmart's network. Some are finding other opportunities, including becoming a contract grower to other growers who still sell to Walmart. Others are finding other niches and vendors. For those who are seeing gains in business, it is at the expense of other growers because the industry is flat as a whole. The most aggressive businesses are taking market share.

Yoder Brothers, Inc. is another company that has acquired and sold divisions over the years. Yoder Brothers, Inc. was founded in 1920 by two brothers, Menno and Ira Yoder. They expanded to other locations to become a large plant propagator as well as supplier of finished plants. Yoder Brothers acquired Blooms of Bressingham in 1995, to introduce exclusive Blooms perennials from England to North America. This expanded into a global activity, with business partners in many countries and introductions from breeders worldwide. Shortly afterward came the acquisition of Green Leaf Enterprises, one of North America's leading perennial growers. Yoder reorganized as Aris in 2008, with the sale of its chrysanthemum and aster product lines to Syngenta and continues to evolve to meet the changing horticultural market. Aris Horticulture, a company of 650 employees, now operates three business units: (1) Green Leaf Plants supplies starter plants and prefinished products for perennials, azaleas, tropical hibiscus, hydrangea, mandevilla, roses, exacum, gloxinia, lisianthus and penta; (2) Keepsake Plants produces finished potted plants, including azaleas, chrysanthemums, tropical hibiscus, hydrangea, and mandevilla, which can be found at retailers and mass merchants across North America; (3) Aris Horticultural Services sells a wide range of products and services, including those available through Green Leaf Plants and Keepsake Plants, and a complete line of brokered products from a large network of affiliated producers.

Ball Horticultural Company has grown through a combination of acquisitions and opening of its own new divisions. It has grown from a wholesale cut-flower operation started by George J. Ball in 1905 into a leader in all facets of floriculture, with distribution capabilities in all of the major world markets. Ball Publishing began in 1932, when George. J. Ball, a prolific writer, published the *Ball RedBook*, loaded with detailed production information. Now in its 17th edition, the *Ball RedBook* has sold hundreds of thousands of copies around the world. George J. Ball launched the *GrowerTalks* magazine in 1937 to give growers crop production articles in a timely fashion; in 1997, Ball Publishing launched the *Green Profit* magazine to provide retailers with crop and consumer trend information. In 2010, Ball acquired Kieft-Pro-Seeds, a well-known Dutch breeder, producer, and marketer of high-quality specialty annual and perennial seed to complement its PanAmerican Seed brand. Ball also acquired Darwin Plants and entered into an exclusive distribution relationship with Selecta.

Another company whose consolidation was driven by the big box stores is Color Spot. In 1995, Color Spot of California began to expand its production firm through purchase of other bedding-plant producers. By 1996, it was the world's largest bedding-plant producer, with 650 acres (260 ha) of production. In 2001, Tesselaar added Color Spot Nurseries, Inc. located in Fallbrook, California, as the Australian company's newest grower. In 2010, Color Spot had 13 production facilities between California and Texas, and purchased El Modeno Gardens in Irvine, California. Tesselaar does the marketing and Color Spot provides in-store merchandising, product displays, promotional planning, and product reordering services to its customers (Source: *GrowerTalks*, April 15, 2010).

Another example of a company that expanded through growth and acquisition to meet market demand is Hines Horticulture. Originally a woody ornamental producer, the company added a color plant division that produces bedding and related plants, and also acquired SunGro, a major soilless substrate formulator. In 2000, its new color plant division marketed approximately $125 million in the United States. Hines Horticulture announced in 2006 that it would sell all of its Florida assets in addition to its color facilities in Danville and Pipersville, Pennsylvania, and Utica and Newark, New York (Source: GPNmag.com, January-December 2006:3[1]). Hines filed for bankruptcy in August 2008 before its outstanding shares of stock were bought by Black Diamond Capital Management. In 2010, Hines Nurseries purchased all the assets—namely plant inventory and equipment—from Bordier's Nursery, the California business that had filed for Chapter 11 bankruptcy protection in December 2008. Bordier's had two locations: 120 acres in Irvine and 380 acres in Moorpack. Hines President and CEO Steve Thigpen, who had returned to Hines in 2009 after leaving his CEO post in 2000, gave several reasons why Hines acquired Bordier's: (1) The acquisition filled gaps in Hines' inventory. (2) Hines was able to take a competitor out of the marketplace. (3) Hines acquired not only Bordier's assets but also Bordier's customers (Source: *GrowerTalks*, August 31, 2010). In late 2010, Hines again filed for Chapter 11 bankruptcy and planned to lay off many of its employees because of its inability to extend its line of credit (*Greenhouse Grower*, October 8, 2010).

Consolidation can facilitate changes needed to hold on to or expand market demand. This is well illustrated by the Dutch group of freesia growers known as Unicum. In 1995, five freesia growers joined to address the problem of a saturated market and diminishing prices. Today, Unicum Freesia is a *growers' association* consisting of 21 growers all specialized in cultivating the flower, producing 160 million stems per year. Unicum Freesia has 60 hectares of growing space, which is approximately a third of the entire Dutch freesia market. Unicum began by investigating the causes behind the faltering market demand. It learned that large retail customer chains were frustrated by the lack of a channel to communicate their needs to the growers. They desired flowers with a scent. Scent was not a focus of the breeding program at that time. Because freesia producers acted independently, they lacked the numbers needed to adequately influence the goals of breeding programs. Retailers wanted a greater range of colors than the white and yellow colors requested by the auctions and wholesalers. Again, the message wasn't getting through from retailer to producer. Finally, they wanted a year-round supply rather than the spring and fall productions prevalent at that time. Unicum provided the ears desired by the retailers and the voice needed to negotiate changes in the breeding programs. Unicum growers work according to a set of fixed guidelines and use Unicum's own quality control system. This results in a consistently high-quality product. Unicum growers agreed to install cooling tubes in the soil to bring about production during the warm months to meet the year-round demand. The net result was greater demand for freesia and improved profitability. (Source: http://www.waitrose.com/shopping/homeandhousehold/blossomandbloom/flowergrowers.aspx. Accessed January 26, 2011.)

Consolidations of cut-rose firms have reduced the time the product is in the market channel. Rose cultivars today have an average life expectancy of 14 days from cutting to consumer discard. A rose produced in Ecuador could require 1 day from harvest to arrival by air in Miami; 2 to 3 days in the hands of the importer in Miami as it clears customs, is inspected for drugs, is repackaged, and is sold to a wholesaler; 2 to 3 days in a refrigerated truck en route to the wholesaler; 2 to 3 days in the hands of the wholesaler while it is being sold and delivered to the retailer; and, finally, 1 to 2 days at the retailer while it is being arranged and marketed. The total market channel time is 8 to 12 days, leaving only 2 to 6 days of consumer vase life. For the consumer, this ranges from totally unacceptable to minimally acceptable. Consolidations of firms have made it possible to move roses through the market channel in 2 to 3 days. Such improvements increase demand for flowers. Without consolidation of the players in the market channel, it is nearly impossible to ensure that at each step of handling, flowers will be held cool and in preservative solution and that needless delays will be eliminated.

A number of companies have formed out of consolidations over the past few years. Farm Direct is composed of a number of rose production farms in Ecuador, an import operation in Miami that also serves as a wholesaler to send flowers across the United States in climate-controlled airline containers, and secondary wholesaler departments with fleets of climate-controlled trucks at the terminal markets to deliver the flowers to the retailer. For rural areas, where the fleet of trucks is uneconomical, flowers are sent from Miami to the retailer via FedEx. Floral orders are taken through telemarketing. Then the orders are packaged individually for each customer at the farms. The whole distribution channel, from farm to retailer, can be navigated in two to three days. Because a single company controls this path, presold roses are shipped without devastating delays en route. In the alternative multi-company market channel, flowers experience delays moving between companies and at points where sales transactions are required. With one company in control, flower quality is further preserved because temperature, the most important factor during handling, can be controlled at all times. As a testimony to the success of this system, Farm Direct offers a full seven-day consumer guarantee to its retail florist customers. It ships over 2 million rose stems per month in over 100 rose varieties. It now offers a full range of other cut flowers, premade bouquets, wedding arrangements, fund-raising bouquets, greens and fillers, and fresh rose petals.

Other consolidated companies encompassing production farms have likewise formed. Virgin Farms and Rose Connection include Ecuadoran farms, and they package their flowers at their importer divisions in Miami. Virgin Farms focuses on the less accessible retailers in the mountain states of the United States and ships via FedEx. It adds to its 100 cultivars of roses other cut-flower types from Latin America and Holland and offers a 100 percent guarantee. Rose Connection began marketing roses originally to the Soviet Union and now ships all over the world from its own farms.

Paramount among the grower-encompassing consolidations is the one accomplished by the Dole Food Company, Inc. Dole purchased the largest producers of cut flowers for the U.S. market, consisting of over 2,000 acres (800 ha) of production in Latin America (including over 25 percent of Colombian cut-flower production) as well as some major U.S. importers and bouquet assembling firms. Dole sold under the brand names of the companies it purchased. Dole Fresh Flowers sold over $200 million in 1999 to supermarkets, E-commerce companies such as Calyx & Corolla, 1-800-Flowers, FTD.com, and PC Flowers. Sales were also made through its Web site, FlowerNet.com. Dole, which had been the largest importer of flowers to North America and the largest producer of cut flowers in Latin America, sold its flower interests and some of its banana plantations to pay down debt and reinvest in the business. (Source: http://www.humanflowerproject.com/index.php/weblog/comments/dole_wont_bring_you_flowers_anymore. Accessed January 26, 2011.)

USA Floral began in 1997 by purchasing 33 Miami importers, wholesalers, brokers, and bouquet makers. By 1998, it was the largest integrated distributor of floral products in the United States, with an estimated sales volume of $560 million. However, by 2001, the U.S. wholesale company faltered and ceased operations. This points out the extreme difficulty that has always plagued handling of perishable products across the distribution channel. Because flowers are a perishable product, quality losses in flowers blemish the brand name and threaten the survival of the consolidated firm.

The flower market is mature, and supply now outstrips demand. Thus, consolidations will continue, and some companies will no longer exist, others will be purchased by other companies, and some will contract for other growers. Fewer, large growers will be the primary vendors for the box stores as big box stores consolidate to deal with fewer suppliers. These large growers will be responsible for providing the complete assortment of products to the big box stores. This has required them to purchase product from other growers who become contract growers for them. This can be an opportunity for growers who have lost big box store accounts and for growers who would rather not be involved in marketing and merchandising. The caution for the contract growers is that since they are not performing the marketing function, their prices will be lower than before, and there is always the fear that if the larger growers expand their own production, the contracted growers will be left without a market. The whole industry will have to work together to reduce shrink and inefficiencies as consolidations continue and because pay-by-scan means growers are paid only when the product is sold to the final consumer. Companies who can anticipate change and plan for it will be the winners.

ECO-LABELS

In the early 1990s, German environmental and social action groups launched a campaign to alert the public about what they perceived as social injustices and environmental abuses occurring in the floral production industry in some developing nations that supplied the German market. Part of the message took form in the slogan "Blood sticks on flowers." The message had its impact on the public. Flower sales declined in Germany by 20 percent in the 1990s. Out of this background the Flower Label Program (FLP) was born in Germany. Grower members of FLPI must comply with the organization's standards covering human rights, pesticide use, and environmental protection (http://www.fairflowers.de/fileadmin/flp.de/Redaktion/Dokumente/Vereinsdokumente/FLP_Guidelines_Version_6_2009.pdf. Accessed February 25, 2011). Upon compliance, these growers are permitted to use the association's eco-label on their floral products. Membership includes European and developing-nation growers in countries such as Ecuador, Kenya, Zimbabwe, and South Africa. The heavy emphasis is on human rights. The FLP contracts inspectors from independent, nongovernmental organizations, whom it periodically sends out to inspect and rate grower members. The FLP certification on flowers entering the German market has gone a long way toward alleviating consumer concern.

A similar Dutch organization, Milieu Project Sierteelt (MPS), began in 1993 and now has 5,000 members in 38 countries who are eligible for the MPS eco-label. Grower members conduct a monthly audit of their production operations. Independent inspectors are sent out periodically to audit the producer to ensure compliance. Producers are rated on a scale from 0 to 100 and assigned grades of A, B, or C. A rating of 70 points earns a grade of A. Points are based on the following components: pesticide use, 40 percent; energy conservation, 30 percent; fertilizer nitrogen and phosphorus management, 20 percent; and waste management and recycling, 10 percent. Over 70 percent of floral produce marketed through the Dutch auctions is estimated to be produced by MPS-certified growers. Large European supermarket chains want proof for their customers that the flowers they sell have been produced in an environmentally conscientious manner. Consequently, many Dutch importers and exporters insist on MPS-certified flowers. In addition to marketing perks, member producers have experienced sizeable (up to 75 percent) reductions in chemical usage as a result of their adoption of the MPS guidelines.

In 1996, Colombian flower producers developed their Florverde program in response to pressure from the FLP and MPS programs. They desired to operate under a set of rules that applied more to the conditions in Colombia. By 2006, 72 Colombian producers were members of Florverde, representing 3,700 acres (1,500 ha; 60 percent of production for export). Florverde has inspectors who visit members on a six-month schedule to grade them on six areas: social worker standards, water, soil, integrated pest management, residues, and landscaping of the production premises. Member farms are also audited by an independent body.

The Kenya Flower Council (KFC) established a program for Kenyan flower growers. Standards address four main fields of environmental protection: good agricultural practices, employee health and safety, and social accountability. Producers are inspected on a six-month basis and can be awarded primary, silver, or gold standing. Four farms have received a Gold certificate. To reach gold status, farms must provide evidence of an established, full quality management system whose framework is comparable to ISO 14000 and applies strict rules in terms of environmental conservation, water, fertilizer and pesticide usage, health and safety, and social responsibility. Also, they must demonstrate the existence of projects to benefit the community, have a constructed wetland for waste water management, have a day nursery for workers' children, and provide three months' maternity leave. Four members have achieved Gold status. These standings allow producers to display the KFC label on their packaging and promotional literature. This eco-label has been positively accepted in European market channels.

Approximately 15 such programs exist worldwide. Some draw international membership while others focus on an individual country, such as Florverde and KFC mentioned above and the Ethical Trade Initiative (ETI) in the United Kingdom. EUREPGAP is a retailer-based program. It focuses on adoption of commercially viable farm assurance programs that promote minimization of agrochemical inputs. The desired outcomes are minimization of the negative effects of agricultural production on the environment; on occupational health, safety, and welfare; and on animal welfare. All of the programs share several common goals, including health and safety issues for the employees; fair hiring, wage, and benefits policies; protection of the environment; good agricultural practices; and community responsibility on the part of the member firm. A compelling force for joining these programs is the need to be compliant with the social conscience of the consuming public. Demands of the end consumer shape policies of the retailers, which translate into requirements passed on to the producer.

Currently, no single eco-label is accepted worldwide for flowers and plants. To this end, Union Fleurs, the international organization of the world flower associations, has established the Fair Flowers Fair Plants (FFP) program. Its goal is to establish a common platform for the world codes of conduct supporting flowers and plants grown in a sustainable manner. The FFP label is for all links in the chain, from producer through traders to retailers. The Fairtrade Labeling Organization (FLO), best known for its Fairtrade coffee and chocolate bars, strives to promote a more just distribution of revenues resulting from global trade while fostering sustainable development for the local communities. Its floral programs add a premium to the price of flowers (8 to 12 percent) to finance development programs for the community. In 2005, 113 million stems were certified from 6 farms; 83 million were under the Fairtrade label.

PROMOTION, ADVERTISING, AND BRANDING

Branding has been a hot topic in the floricultural industry for a number of years. Probably 25 percent of products sold in garden centers are branded with some name attached to them. With the increased drive toward consumer awareness and value, and with a changing consumer demographic toward value-added, branded products, brands will continue to grow. Some have considered branding to be simply developing a name or logo under which to sell plants. But creating a brand that is profitable to growers and retailers and truly solves consumers' problems and meets their wants and needs is not easy. The real job of plant marketers is much more than just "branding" plants. The real job is the long-term process of creating and building value for growers, retailers, and consumers. Increasingly, consumers seek out products they recognize and understand. In a consumer research study by Proven Winners at garden centers throughout the United States, 71 percent of shoppers aged 18 to 44 said they would seek out a "trusted" brand when buying plants compared to 36 percent aged 45 and above. This means that today's younger consumer—Gen X and Y—has been trained to rely on brands like no other generation. There is no doubt that branding is here to stay and will only get stronger. But only those who do the hard work of providing a strong value message will succeed. Some brands like Wave petunia provide true value to the consumer and have succeeded. Wave even has a fan club. Other brands like Flower Fields and Miracle Gro Plants are no longer on the national scene for various reasons.

Although cost is often perceived as a deterrent, those who do advertise generally find it profitable. Even a customer who enters the store without the intention of asking for a specific brand will often be drawn to a branded product because he or she has seen it in some sort of consumer advertising. Web sites, e-mail, e-newsletters, and social networking sites and blogs (e.g., Facebook, Twitter) are becoming increasingly popular. Traditional media ads in newspapers, on radio, particularly in connection with a gardening program, and on television are still used. Mailing lists in conjunction with loyalty programs and point-of-purchase (POP) material have provided a very successful avenue of communication with the consuming public for many retailers. Enabling quick identification of a product is key to selling to the time-starved consumer. POP materials that attract attention, provide information on product benefits, and help the customer make a buying decision allow the customer to shop and garden in less time.

Advertisement can occur on a very limited scale, such as Nelson the Florist striving to bring more customers into his shop, or it can take on a national or even international scope. Floral wire services collect a percentage of the gross wire sales of their member retail florists and use these funds for wide-range advertisement. The centralized program of the wire houses allows expensive but highly effective advertising media to be used. National television, major magazine ads, and billboard space can be used in conjunction with consumer information literature such as the booklet *Professional Guide to Green Plants*, sponsored by the Florists' Transworld Delivery (FTD) association. FTD's tips include "FTD Flower Care," "FTD Plant Care," and "Fun with Flowers" (visit http://www.ftd.com/flower-guide-ctg/product-flowers-flowerguide. Accessed February 25, 2011).

Brand names have been used as an effective advertising tool by some larger retailers and floral producers. Proven Winners is probably the most recognized brand in the industry for vegetative cuttings. Proven Winners began in the mid-1990s, when several growers with four unique plants met to develop the Proven Winners concept. Proven Winners has developed a complete marketing program to support its brand. It continues to offer new plant material, conduct market research, run ads, and offer programs like its free roadshows aimed at growers. It also runs ads targeted directly to the final consumer in magazines and on television. America's gardening guru P. Allen Smith is now the spokesman for Proven Winners. Proven Winners' Store-Within-A-Store concept is based on Proven Winners plants and POP being concentrated together in one space of the store to take full advantage of the Proven Winners consumer advertising campaign by creating a "home" within the store's brand and footprint. Home Depot has the Proven Winners brand as well as its own Viva brand and its gardening club and gardening newsletter in its retail stores. To address the fact that consumers today have less time and exposure to gardening than did prior generations, Proven Winners provided more than a quarter-million gardeners with its Proven Winners *Gardener's Idea Book* in 2009. In 2010 it offered to mail the *Gardener's Idea Book* to its retailers' customers with a customized promotional message for their store. The retailers provide the mailing lists and postage. More and more consumers have the do-it-for-me approach to gardening. Proven Winners has capitalized on this trend with its 30-second planter, which is a fully planted paper pulp insert that can be dropped into patio planters. Proven Winners' initial target market was growers who sold to independent garden centers. It has since marketed to growers who sell to Home Depot. Many retail growers and those selling to garden centers, however, believe that (1) royalties that Proven Winners charges (up to $0.18 or more per cutting) are high, (2) good alternatives exist, and (3) the brand has become a commodity now that it is closely associated with the mass market. They prefer to develop their own private brand to differentiate themselves from the mass market.

Hort Couture is hoping to be the brand for the retail garden centers and retail growers. Hort Couture is on the cutting edge of a new frontier in marketing. Hort Couture was launched in 2007 by Jim and Jennifer Monroe of Greenbrier Nurseries in West Virginia. The fashion-forward brand is designed for independent garden centers and grower–retailers like themselves. The idea was to give plants and gardening a more hip or chic image. The focus is more on container plantings than landscaping. The Monroes formed a joint venture with Gerry and Patty Raker of C. Raker & Sons in Michigan, to create a comprehensive supply chain alliance with key breeders, young-plant producers, brokers, and retailers. Gerry Raker thinks that other brands have not worked because the perspective was too narrow, with just one entity running the show versus a true collaborative partnership. He wants to take what he learned while building teams at Raker and spread it across all the companies in the supply chain. Hort Couture partners will ask each other questions like, What irritates you? What would you like to see? and What do you need? One progressive innovation that they are testing at Greenbrier Nurseries and Calloway garden centers in Texas are smart tags activated by smart phones that provide consumers a world of support and information driven by digital content. It could be as simple as receiving a printable coupon at the store with a smart phone or receiving a recipe that includes the herb or vegetable plant the consumer just purchased. Or, the consumer could bookmark the plant and later watch a video with planting and care instructions (Delilah Onofry, *Greenhouse Grower*, April 2010).

Ball Horticultural Company is an international breeder, producer, and wholesale distributor of ornamental plants that developed the Simply Beautiful and Circle of Life branded programs exclusively for independent garden centers. Simply Beautiful is Ball's brand for a complete marketing program for annuals aimed at both retail garden centers and their retail customers. Ball developed a Simply Beautiful quarterly e-newsletter and a comprehensive Web site to serve as a gardening resource to the final consumer. The Web site includes a plant search and garden center locator, and planting and growing information for home gardener. Gardeners can access specific variety information and combination recipes and create a customized shopping list to take to their favorite independent garden center. In 2010, 18,000 consumers received the quarterly Simply Beautiful e-newsletter. Today's consumer often gathers information about products before going to the store, and often visits the Web for additional product information after making a purchase. The Simply Beautiful Web site is referenced on every piece of in-store marketing, from Simply Beautiful pots and tags to bench cards, bench tape, and vertical signs. Ball branded plant varieties, including the Wave petunia family, Dazzler and Super Elfin impatiens, and Fiesta double impatiens. Ball Horticultural Company has partnered with garden centers to host Simply Beautiful container contests to benefit local charities. These initiatives were designed to not only provide a donation to charity but also to build momentum and demand from gardeners. Each contestant was given a set time limit to finish his or her creation, which was then judged on style, color, and creativity. For more information about the Simply Beautiful program, visit http://simplybeautifulgardens.com. Accessed February 25, 2011.

Flower Fields, a brand of vegetatively propagated annuals, was started by four major companies—Fischer USA, Goldsmith Seeds, Goldsmith Plants, and Paul Ecke Ranch. The rooted cuttings were planted and finished by numerous greenhouse firms and finally sold under the Flower Fields brand name. Now that Syngenta has purchased Fischer USA, Goldsmith Seeds, and Goldsmith Plants, and the chrysanthemum and aster divisions of Yoder Brothers, Inc., the actual flower field still exists in California, but the brand applies only to Ecke and is weak.

Branding of floral products can be even more powerful when two well-known brands form a partnership. One of the most popular brands in the United States today is Martha Stewart. Martha Stewart has partnered with 1-800-Flowers.com to offer her line of flowers and gifts. Vera Wang, one of the most popular designers in the United States, offers her Vera Wang Flowers through FTD.

Promotional Programs and Marketing Orders

While advertising is conducted for the purpose of generating sales of specific products or lines of products, *promotion* is conducted for the purpose of creating a widespread consumer interest in the overall products of the floral industry. Promotion is very generic in that specific products and firms are not targeted. It addresses all of the products in the total floral industry, or at the very least, in a division of the industry, such as cut flowers. Promotion increases business for all segments of the industry. As such, growers, wholesalers, transporters, retailers, and suppliers of allied goods for production and marketing should share in its cost. Attempts to conduct industry-wide promotion have not been supported broadly by the industry. Retailers tend to place more importance in promotion and advertising than the grower, wholesaler, and transport segments of the flower chain.

The American Floral Marketing Council (AFMC) was formed in 1969 as an independent committee affiliated with the Society of American Florists to boost flower and plant sales between major holidays. AFMC voluntarily collected funds from retailers, growers, wholesalers, and suppliers. At the peak of its monetary strength, in the early 1990s, AFMC was raising $5 million per year for promotion via nationwide radio advertising, billboards, decals on floral trucking company vehicles, and appearances by spokespeople on TV news programs and in radio and print interviews. The AFMC ceased operation and was merged into SAF in January 1995, when a national, mandatory promotion order, PromoFlor, was instituted by the U.S. Congress.

PromoFlor took advantage of the USDA option for a delayed referendum by the industry, who would fund the mandatory promotion order, and began its national advertising campaign featuring Buzz the Bee in 1996. It hoped that a successful program would garner support for the referendum. Under this marketing order, the U.S. Department of Agriculture oversaw collection of a mandatory 0.5 percent of sales from all flower handlers who sold $750,000 or more per year to retailers. This included growers, wholesalers, and bouquet makers. During its 30 months of operation, PromoFlor raised $10 million in promotional funds per year after the mandatory marketing order was imposed. Although an analysis by economist Ronald Ward, of the University of Florida, estimated a $6.62 return for each dollar invested in PromoFlor, the referendum was defeated in June 1997 by 58 percent of those assessed. The reasons given were its mandatory nature and that a limited segment of the industry was responsible for the promotions. In 2006, the Floral Industry National Marketing Campaign Feasibility Report by researchers at The Wharton School at the University of Pennsylvania analyzed returns on national mandated marketing orders and the potential for the floral industry. The study found that returns per dollar spent on nationally mandated programs were $5.80 for the beef industry, $15.50 for the pork industry, $4.30 for the egg industry, and $6.26 for the dairy industry. The study estimated potential net returns to the floral industry to be $122 million to $255 million over five years on potential advertising revenue of $15 million to $55 million. In spite of positive returns from national promotions, the greenhouse industry has rejected mandatory industry-wide marketing and promotional programs multiple times. Thus, each individual company must stand on its own merits and compete for its market position in a mature market. The successful, prosperous companies will be the ones that can match their strengths with market opportunities to satisfy consumer demand.

After the defeat of PromoFlor, SAF established a voluntary promotional program, Fund for Nationwide Public Relations, in 2001. The $400,000 annual budget of funds collected from nearly 2,000 florists, wholesalers, suppliers of hard goods, importers, and growers is used to build positive floral messages in the context of news. The Fund sponsors consumer research and public relations promotional programs. A good example are the studies conducted at Rutgers University by the team of Professor Haviland-Jones, director of the Human Development Lab, whose scientific findings confirm and extend what common sense has suggested for years: Recipients of flowers feel less depressed, anxious, and agitated, and demonstrate a higher sense of enjoyment and life satisfaction. Flowers stimulate formation of intimate connections with family and friends. A study of the impact of flowers on the lives of senior citizens demonstrated decreased depression, increased memory, and more social connections. The strategy is to use third-party experts as spokespeople to add credibility to the floral message. Press releases from these studies were picked up and disseminated by numerous local and national newspapers, magazines, radio stations, and TV stations. Local marketing kits released annually to SAF members help florists capitalize locally on the PR messages.

The Flower Promotion Organization (FPO), an alliance between Floral Trade Council, which represents U.S. growers, and Ascolflores, which represents Colombian growers, was created to expand consumer demand for fresh cut flowers, and ultimately expand the U.S. market for the entire industry. Its board of directors is comprised of eight growers, four Colombian and four from the United States. Efforts of the FPO promotional program, Flowers, Alive with Possibilities, are directed toward increasing the consumption of flowers for home decoration, gifting, and occasions. This program has been primarily funded with revenues from The Colombian Flower Council. These revenues stemmed from the settlement of a lawsuit involving antidumping duties on carnations and chrysanthemums. The U.S. and Colombian cut-flower industries agreed to redirect the time and resources previously spent battling legal proceedings into a multimillion-dollar consumer marketing campaign designed to boost demand for cut flowers, ultimately benefiting growers on both sides of the issue. Funds are contributed in proportion to the source of flowers marketed in the United States. The marketing campaign targeted six U.S. cities. As a result of the FPO promotion, the frequency of purchase of the target audiences increased 25 percent. Without funds to duplicate these efforts nationwide, FPO turned is efforts in 2004 to public relations. It teamed with SAF to research the power of flowers. This alliance funded the Home Ecology Study and the Flowers in the Workplace Study, both led by Dr. Nancy Etcoff, of Harvard Medical School and Massachusetts General Hospital. Funding was reduced in 2006, when the California Cut Flower Commission suspended financial support because of internal budget considerations and changes in its strategic directions. Columbian flower growers followed suit. The FPO continued operating from its reserves. FPO is also focused on enabling local market groups (wholesalers, retailers, and other industry groups) to use the FPO Alive with Possibilities message and promotional materials (POP, billboards, radio/TV spots, bus signs, print ads, press releases, etc.) for consumer promotion in all U.S. markets. For more information, visit the Web site http://www.flowerpossibilities.com.

The California Cut Flower Commission (CCFC) is a state government agency created in 1990 by a state marketing order to promote the sale of California-grown cut flowers and foliage. The CCFC is funded by a 0.5 percent assessment on California cut-flower growers whose annual sales exceed $500,000. In 2006, that represented about 70 growers. The focus of the organization is on marketing and promotions, government affairs, economic development, and logistics and transportation. Their Web site, http://www.ccfc.org, Accessed February 25, 2011, provides information for retailers and growers.

America in Bloom (AIB) is a very different approach to developing interest in the green industry. It is actually a community contest that promotes beautification through the involvement of a broad range of participants within a neighborhood, town, city, or county. The program was born in Europe, adopted in Canada in 1995 as Communities in Bloom, and debuted in the United States in 2001 as America in Bloom. Each community competes with other communities of similar size within their province or state. With time, the contest advances to the national level. Judges appraise community efforts in eight categories: tidiness, environmental awareness, community involvement, heritage, urban forestry, landscaped areas, floral displays, and turf and ground-cover areas. The program affects the bedding-plant segment of the floral industry directly. However, as with each of the previous promotional programs, promotion of any one area of floriculture automatically leads to enhanced interest in the other areas. Any individual or organization within a community can initiate formation of a committee to oversee and direct the program. Typically, the committee includes a member of the municipal council, who brings financial and technical help and coordinates planned activities, projects, and the contest budget with the municipality's affairs. Other members are selected from service clubs, horticultural societies, community groups, businesses, churches, schools, or other organizations that can bring resources of design, plant material, labor, or funds to the project. Activities have been as varied as the communities involved. They have included fundraisers such as plant exchanges, bingo, raffles, spaghetti dinners, and pancake breakfasts. Schools have worked planting experiences into their students' curricula. The mission reaches beyond public spaces, into personal life. Contests within the main contest can address the best residential or commercial landscape, best apartment building, storefront, farmhouse, street, or block. The result is a higher quality of life for the community and a deeper appreciation for gardening and landscaping. The true cost of running AIB is not known, since it includes donations of time, proceeds of fundraisers, and municipal expenditures. Its annual budget of just over $200,000 is used by the AIB task force to carry out the program.

The efforts of the aforementioned promotional organizations have been highly effective and are commendable. However, the industry as a whole is not doing much to promote flowers and plants. Floral sales are currently losing ground as other discretionary-product categories, such as cosmetics, candies, and hobbies, are gaining market share.

In a competitive market where supply exceeds demand, the industry needs to focus less on products and more on consumers. Successful growers need to understand what the consumer wants and why. Retailers need to build a strong relationship with consumers to build repeat business, not just the quick sale. Flowers are beautiful, but the industry also needs to understand those attributes of plants and flowers other than beauty that appeal to consumers. Flower growers have an obligation to share the overall marketing responsibility of the industry. Growers can take part in meetings of wholesaler and retailer organizations and consider current literature and popular attitudes. Wire services periodically feature specific cut flowers and plants in their promotional programs. Grower alerts are issued long in advance of the promotion date. Growers need to tune in to these ads so that they don't find themselves heavy on non-promotional items and short on those in demand. Through interindustry communication, it should be possible to use promotional programs to cope with inadvertent overproduction and periods of low market demand and to establish consumer demand for products and product forms, thus rendering larger profit to the grower, greater ease of handling in the market channel, and increased consumer satisfaction.

There are other ways growers can play a role in the overall promotional program. The entire industry depends on satisfying the consumers' ever-changing wants and needs. Growers must concern themselves with consumer satisfaction and loyalty. One way to help the final consumer succeed is by selecting plant varieties that stand up best in the region where they are marketed. Fuchsias are beautiful almost anywhere in the spring, but are a disappointment to consumers in hot climates when the heat of summer arrives. Such sales should be discouraged, and in their place, sales of crops adapted to the local situation should be promoted. The grower has a responsibility to make such decisions and to educate the retailer. It is the further responsibility of the grower to produce plants of high quality that are free of insects and disease. Whether consumers relate plant failure to the grower or to themselves, the main effect is the erosion of the desire to make a subsequent purchase.

No matter which market channel growers supply, they will increasingly become more involved with the consumer. Smaller growers are direct marketing their products right out of their greenhouses. In spite of the 2008–2010 recession and subsequent slow recovery, the trend to go green and buy local continued to grow. Growers who understand their consumers can take advantage of this trend as a new surge in gardening continues in the United States. As in the past, when the market is down, the demand for vegetable plants increased as consumers wanted to produce some of their own food. This also ties in well with Michelle Obama's program to fight childhood obesity by promoting organic vegetable gardening and more fruits and vegetables in schools along with exercise. With pay-by-scan, growers who sell to mass markets are also becoming more in tune with consumers' wants and needs. Many of them are putting their own employees in the big box stores as merchandisers who set up displays and maintain the plants. The grower basically is running a retail shop inside of the big box store.

The consuming public has an underlying desire for information. This is often as important as the product itself. As retail garden centers, retail greenhouses, big box stores, and suppliers of cuttings and seeds continue to develop brands that convey value to the consumer, more consumers, especially those of the younger generation, will likely buy the product. Each plant or bouquet of flowers should have identification and post-consumer information. Growers who are not retailers must pass information along to the retailer as to how the product is to be handled during marketing. The grower should also supply information that the retailer can pass along to the consumer. POP information, information on smart phones, social media sites, e-mails, and newsletters are being used to provide information to consumers and to build a relationship with them. Everyone in the industry will need to work together to help the consumer succeed and to build consumer loyalty to floral products and shape the industry in the future.

Personal Brands

Everyone and every company has a brand. The brand is their reputation. A salesperson in a retail greenhouse or garden center or a merchandiser in a big box store has more impact on a company's reputation than anyone in management. They have the relationship with the consumer. They are the ones who take the time to listen to the customers and help them load their car with green-industry products. Businesses that do really listen to customer requests directly or via employee feedback, and actually implement their suggestions, can create consumer loyalty and profits. This was verified in a survey of over 2,000 companies, which ranked businesses from the most to the least successful, and compared the approaches of the "winners" or "most successful" with those of the "losers" or "less successful" to isolate the factors that make a difference (Coulson-Thomas, 2007). The results suggest that most of the critical success factors are attitudinal and behavioral. The "less successful" companies are unsure and unaware of the needs of others. They are cautious and fail to inspire and motivate and are reactive. They respond to events and often fail to anticipate the need for change. They confuse operational with strategic business issues. They fail to notice what is important and the biggest opportunities for performance improvement. On the other hand, winning companies tend to have a longer-term perspective. They are confident, positive, and proactive. They create compelling visions. They encourage innovation, trust people, and share information and opportunities with them. They understand their customers and concern themselves with increasing customer retention. Winners value relationships, empathize, ask for feedback, and are good listeners. Winners, then, transform and reinvent, and recognize that change can be stressful and can disrupt valued relationships. They find ways to alleviate stress when they can and accept it when they cannot. This applies not only to customers, but to valuing employees.

Since the greenhouse industry is now a mature market and very competitive, producers must focus on strategic planning to utilize their strengths. Producers try to understand their customers and retain them. Retail producers have frequent communication with customers, and wholesale producers work with retailers to determine what the customer wants. Many producers use surveys and social media and expend special efforts to determine consumer wants and then develop a product (and package) that satisfies those wants. This applies to both wholesale and retail markets.

Customer Loyalty Programs

Loyalty programs are structured marketing efforts that reward, and therefore encourage, loyal buying behavior—behavior that is potentially beneficial to the firm. Loyal customers will do three valuable things for a business: (1) buy more, (2) market the product, and (3) tell the company how to improve the business (Source: Denise Wymore: http://www.denisewymore.com/section.cfm?wSectionID=2170). Accessed February 25, 2011.

It costs five times more money to find a new customer than it does to get a current customer to come back and do more business (Kotelnikov, 2011). And loyal customers will not only return, they will tell other customers about the business. So, customer loyalty programs have become basic operating procedure in the United States.

The first loyalty program in the United States began in 1896 with Sperry and Hutchinson, who issued S&H Green Stamps to their customers. They had a simple concept: Consumers would buy products they normally buy, collect stamps for the purchase, and save them and redeem them for gifts in a catalog. At the height of their business, S&H printed three times as many stamps as the U.S. Postal Service, printed the largest publication in the United States (its catalog), and were the single largest purchaser of consumer products on behalf of their loyal customers.

Here are four types of successful customer loyalty programs today:

1. ***Membership Program.*** Membership programs usually charge an annual fee. Most programs provide special incentives to members as part of their membership. Shoppers' clubs like Costco, BJ's, and Sam's Club are membership-based retail stores. The YMCA and YWCA are good examples of membership programs.

2. ***Rewards Program.*** Rewards programs provide gifts and perks that are "earned" according to the amount of business customers do with a business. The airline, hotel, and supermarket industries all have well-known rewards programs, which offer free trips, free stays, discounts, or free turkeys based on how much customers spend with them.

3. ***Create a Community.*** We are all "tribal" and have a deep inner need to belong to a community. Belonging gives us security and helps us to understand our place in life. Local stores will offer donations to local charities based on a purchase. Many businesses donate a part of their sales to national charities if you buy a specific item. For example, the local gym may sell a tee-shirt with a pink ribbon at a higher price than other tee-shirts, and donate the funds to the Susan G. Komen for the Cure Breast Cancer Research Fund.

4. ***Partnerships or Coalitions.*** Marketing jointly or sharing data and allowing customers to choose between the rewards offered by the firm and those offered by its partner enhances business for partnerships. Domestic airlines often team up with international partners. Customers can use or earn frequent flyer miles in either of their programs.

Firms can implement a simple loyalty program by giving a frequent-purchase card to every person who buys from them. The card gets a stamp every time customers buy something, and customers get something when the card is full. This is simple to do, and customers do use them. The drawback is that unless someone personally talks with each customer who returns the card, the firm will not get valuable customer feedback.

Results of a study on customer loyalty programs found that nearly 80 percent of marketers have customer loyalty programs, loyalty program members constitute the best and most profitable customers, Americans hold 1.8 million loyalty club memberships, and the average U.S. household is enrolled in more than 14 loyalty and rewards programs but they are active in fewer than half of them (Chief Marketing Officer Council, 2010).

Customer loyalty, not customer satisfaction, is key to the success of an organization. A gap still exists between the percentage of people who say they're satisfied with a business and those who consider themselves *loyal* to that business—intent on maintaining the relationship and continuing it into the future. So to keep customers coming for additional purchases, it's vital to create a relationship with customers and to develop a loyalty program that they will actively use and rely on long term. Most companies focus on rewarding customers who make repeat purchases. Such reward programs help assure customer loyalty. However, if the product or service doesn't meet customer needs, no reward program will get them to return. For success in the long run, an organization must continuously improve and quickly identify and resolve problems to the customer's satisfaction—or more.

Tips for building a successful customer loyalty program follow:

1. *Don't Abandon Service for Savings Alone.* Discounts and savings are on the minds of most consumers, yet don't overlook other major customer-pleasing enhancements, such as quick or better service or improved customer handling. Nearly two-thirds of consumers have ended a relationship with a company due to poor customer service alone, and the majority of them take their business to a competitor. The best customers want personalized service and support that is accessible instantly—often by phone. This is where a small business can excel over larger competitors, whose customers may feel lost in a maze of automated self-service.

2. *Listen to the Customer: Make Communication a Two-Way Street.* Because of its cost efficiency, e-mail is the workhorse for the vast majority of loyalty campaigns. Printed mailings and statements are also used by many marketers to remind customers of benefits and rewards. And corporate Web sites are becoming increasingly important components in loyalty campaigns. For many types of businesses, it's smart to build interactivity into a company's site with customer-generated content, online customer service, or live chat with a representative. Starbucks has created a relationship-building environment at MyStarbucksIdea.com, with a reported 180,000 registered users who have played an instrumental role in helping revitalize the company.

3. *Avoid Loyalty Turnoffs.* Too much spam and junk e-mail tops the list of what consumers do not like about loyalty and rewards program membership. Daily or even weekly e-mails may be too frequent for many members, particularly if the offers or other communications are perceived as not relevant to their business or personal needs. However, weekly e-mails during the season to let customers know what is available or the special of the week may be appropriate. Other turnoffs include programs that have too many conditions and restrictions and rewards that lack real value.

4. *Personalize Contact with Individual Customers.* What customers really want is more discounts and savings based on relevant offers or individualized deals, and rewards that are easy to redeem from companies with which they have positive relationships. Customers want deeper engagement and personalized contact to build repeat sales (Gordon, 2010).

Consumer Value Proposition

A key in today's competitive market is listening carefully to consumers. Gone are the days when growers could produce their favorite crops and expect them to sell themselves. We have switched from a producer-driven to a consumer-driven market. Growers must find a niche where they have a comparative advantage, also called a *value proposition*. As competition increases, it becomes more and more important for firms to understand consumers' wants and needs and determine how their product or service meets those needs in a way that outperforms the competition.

Customer value proposition has become one of the most widely used terms in business markets in recent years. Simply stated, a value proposition conveys the value of a firm's product to its consumers. Customers may look only at price unless the business helps them understand—and believe in—the superior value of its products. The firm can do this by developing its consumer value proposition.

Types of Consumer Value Propositions. A Harvard Business School study classified the ways that businesses develop consumer value propositions: (1) all benefits, (2) favorable points of difference, and (3) resonating focus (Table 2).

All Benefits. When asked to construct a customer value proposition, most managers simply list all the benefits they believe that their products might deliver to target customers. The more they can think of the better. However, this approach requires the least knowledge about customers and competitors and, thus, results in a weaker marketplace effort, and its relative simplicity has a major potential drawback: benefit assertion, that is, managers may claim advantages for features that actually provide no benefit to their target customers.

Favorable Points of Difference. With the second type of value proposition, managers recognize that customers have alternatives and they focus on how to differentiate their products or services from the competition. Managers knowing that an element of their product has a point of difference relative to the next best alternative does not, however, convey the value of this difference to target customers. A product or service may have several points of difference, complicating the customer's

Table 2
Benefits, Differences, and Resonating Focus of Different Types of Customer Value Propositions

Value Proposition	All Benefits	Favorable Points of Difference	Resonating Focus
Consists of:	All benefits customers receive from your product	All favorable points of difference a product has relative to the next best alternative	The key points of difference whose improvement will deliver the greatest value to the customer for the foreseeable future
Answers the customer question:	Why should the customer purchase your product?	Why should the customer purchase your product instead of your competitor's?	What is most worthwhile for the customer to keep in mind about your product?
Requires:	Knowledge of your product	Knowledge of own product and next best alternative	Knowledge of the attributes of your product that deliver superior value to customers compared with next best alternative

understanding of which ones deliver the greatest value. While this approach looks at attributes of the product that have favorable points of difference relative to the competition, it does not seek to understand consumers. Without a detailed understanding of customer requirements and preferences, and what it takes to fulfill them, producers may stress points of difference that deliver relatively little value to their target customers.

Resonating Focus. The resonating focus value proposition acknowledges that consumers who make purchase decisions are often pressed for time. They want to do business with producers who fully grasp their critical issues and deliver a customer value proposition that's simple yet powerfully captivating. Producers can provide a customer value proposition by making their products superior on the few attributes that are most important to target customers. They need to demonstrate and document the value of this superior performance and communicate it to the customer. This is the most expensive and time-consuming consumer value proposition because it requires consumer value research.

Here are some steps to develop a value proposition (Narus et al., 2006):

1. Know the targeted customers and both their obvious and less apparent needs and desires.
2. Talk to current customers and understand the product's value from their perspective.
3. Know the competition. What product performance do your products and services provide that your competitors' products and services do not? Review existing competitive value propositions to develop an understanding of their relative strengths and weaknesses. Remember that whether you are a wholesale or retail producer, your products eventually compete for consumer dollars. The best alternative product for the consumer may not be another producer's potted plant. It may be other things that satisfy consumer needs. These alternatives can be such items as dinner out, wine, a movie, or a box of candy.
4. Research classic customer value propositions to learn from the success and failure of other marketplace offerings.
5. Brainstorm with both your employees and customers (current and potential) to develop a value proposition that states your product benefits clearly and accurately and brings sustainable brand recognition to your product. Some of the most successful greenhouse owners routinely brainstorm with their employees on ideas for new products that meet the needs of their consumers.

Generational Demographics

Consumers are often defined by their demographic or generational cohort, or people who have similar characteristics based on when they were born. The generations in the United States tend to be defined by the wars that were being waged during their formative years. These wars shaped their values. Knowing their values will help you as a producer to develop products and services that meet their needs and solve their problems.

The *Greatest Generation*, born 1925 to 1945, grew up during the Great Depression and World War II. Their values are thrift, cooperation, and patriotism.

They gave birth to the *Baby Boom Generation*, born 1946 to 1964. This is the largest generation in the history of the United States, and they are still in control. The Vietnam War led them to rebel against authority. Their values are consumption, experimentation, and keeping up with the Joneses.

Generation X or *Gen X*, born 1965 to 1979, is the smallest generation in U.S. history. They grew up during a period of relative peace after the Vietnam War. The end of the Cold War; the fall of the Berlin Wall; and a series of U.S. economic calamities, such as the 1973 oil crisis, the 1979 energy crisis, the early 1980s recession, Black Monday (1987), and the savings and loan crisis, instilled a sense of economic uncertainty and a reduced expectation of long-term job security. They value independence and individuality. Unlike their parents, who challenged leaders with an intent to replace them, Generation X tends to ignore leaders. From a marketing perspective, they are lost and ignored because the baby boomer market is so much bigger.

Generation Y, born 1980 to 1990, is also known as *Gen Y*, the *Millennial Generation*, *Generation Next*, *Net Generation*, *Millennials*, or *Echo Boomers*. They are an echo of the Baby Boom Generation and are the second largest generation in U.S. history. Compared to earlier generations, they display an increased use of and familiarity with communications, media, and digital technologies. They grew up with 9/11 and the wars in Iraq and Afghanistan. Their values are the same as those of the Greatest Generation: thrift, cooperation, and patriotism.

Question: How do you market to Gen X and Gen Y? Answer: You can't. They don't like *stalker* marketing, where marketers are going after them. They are very tribal, and will market for you or against you by word of mouth. They like to gather, and do it with technology, on Facebook, Twitter, MySpace, and blogs. The way to reach them is not to target an audience, but target a problem. To find out how to market to them, ask "What is your problem?"

Question: What problem did Blockbuster solve? Answer: People didn't want to go to movie theaters. They wanted to watch movies at home when they wanted. Question: What problem did Netflix solve? Answer: People didn't want to drive to Blockbuster and they didn't like late fees. Question: What is the problem with Netflix? Answer: People have to wait for the mail. Question: What problem did TiVo solve? Answer: People can download movies instantly. When developing a consumer value proposition, producers need to think of what problems or needs their customers have, and brainstorm ways to solve them (Denise Wymore, culture consultant).

Web Sites and Social Networking

In addition to building comprehensive Web sites and generating e-newsletters, growers are increasingly getting involved with social media via Facebook and Twitter. The idea is to build that one-to-one customer relationship and communicate more often. It's an attractive alternative or supplement to cost-intensive printed promotions and catalogs. This keeps the consumer more engaged with your business and products. Producers tie their Web sites to their social media sites to reach consumers and to get feedback from them. Many retail producers provide extensive care and diagnostic information as well as what crops are currently available on their Web sites.

Products must satisfy the consumer's needs: the features, service aspects, marketing season, and benefits to the buyer, whether that is the consumer who comes to a retail nursery to buy their perennials or the wholesaler who is buying annual vincas to sell to garden centers. As mentioned earlier in this chapter, with pay-by-scan, wholesale growers, who are paid only if their products sell, send their employees (called merchandisers) to the big box retail stores to display products, restock displays, and remove dead plants. Since the merchandisers see what products are moving and hear what customers are saying, they can provide valuable marketing information to the production and marketing managers.

U.S. demographics are changing. The number of mature consumers and tech-savvy younger customers who care about sustainability are increasing. The United States is becoming more ethnically diverse. For the first time in history, more women are in the workforce than men, more women are graduating from college than men, and single women under 30 have higher wages than men (Wiseman, 2010). These changing demographics are driving changes in consumer demand for green-industry products. Recession-worried consumers look for quality, variety, and value. Some consumers need or want good price deals and will search for lower prices. This means that in tough economic times, producers must supply the products that consumers want, and keep production costs low. An example of developing the product that would make it more convenient and add value in the eyes of the consumer are the mixed containers, once targeted to apartment dwellers, but now also popular with owners of single family homes. Customer service is key. The worse the economy, the better the quality must be.

MARKETING STRATEGIES

Some successful strategies employed by greenhouse managers in the United States follow.

Create and Exploit Your Competitive Advantage

To stay solvent and prosperous and remain in business, producers must maintain a solid base of satisfied customers. Customers are satisfied when the product or service delivers unique and/or superior value. The two main attributes that allow consumers to differentiate between the firm's products and those of the competitors' are *price* and *quality*. Firms that find the correct balance between these two attributes will have a successful product. If a producer is able to produce the same quality product as the competition and sell it for less, it has provided a price value to the consumer. Many growers that sell to the mass market compete on price. If a producer is able to produce a superior quality product for the same or a slightly higher price than the competition, it is adding more value. Many growers who sell in the direct market compete on value by offering differentiated products. All products must offer value through price and/or quality to succeed. Continued success in business is directly linked to a products' actual and sustained performance versus that of the competition. Greenhouse businesses need to define and exploit their competitive advantage by offering either the lowest cost product or the best quality product. This is true whether they retail or wholesale their products since ultimately, the product must satisfy the end consumer. Establishing a lasting business relationship will lead to future sales.

Find Your Market Niche: Match Strengths to Opportunities

When producers are competing against the big box stores' low prices, which are sometimes *below* breakeven costs, what can producers do? They can develop a market niche and help the customer differentiate their products from the competition. They can remind their customers of their higher product quality and value, years of service and knowledge, convenience, and selection. Producers must ensure that salespeople are courteous, engaging, knowledgeable, energetic, and helpful. They can remind consumers of the historic *win-win* relationship between the producers and the buyer. They can state that (1) they have been there when the customer needed them; (2) they did *not* gouge them with high pricing when availability of certain products in the market was low; and (3) they simply *cannot* meet the low prices charged by competitors for the quality products they provide.

Even in tough economic times, some opportunities exist for flower growers. Innovative producers find a market niche that competitors are not serving, and they take advantage of consumer trends. Buying local has become a national trend in the

United States. Producers located close to a consumer market are poised to take advantage of this opportunity. To be green and sustainable is to be strong, and producers that can become green and offer consumers a sustainable alternative can thrive. High energy costs can mean that greenhouse heating bills go up, but it also means that the fuel prices for competitors to ship into local market go up. For example, in 2008, energy costs were high, making shipping costs an issue for west coast producers shipping into the northeastern market. To make a profit, west coast producers needed to ship a full truckload of products. Northeastern U.S. producers could compete by sending small loads and making more frequent deliveries to better service their customers. An example of a greenhouse business that found a unique niche is one that began a line of pet greens to sell at pet stores.

Producers must pay attention to consumer demands and adjust as they confront difficulties. For example, as mentioned earlier, vegetable transplants are strong anytime there is a downturn in the economy, as home owners try growing some of their own food. This also ties in with the buy local and green movements. Vegetable transplant sales were up in 2009 in the northeastern United States. Unfortunately, just as many home gardeners were growing vegetables for the first time, they faced a double whammy. First, just as they had transplanted their tomatoes into their home gardens, they faced a frost late in May 2009 at the beginning of the growing season, which killed some of their plants. Then, toward the end of the season, they faced an epidemic of late blight. This may have discouraged many new home gardeners. To keep home gardeners from being discouraged, successful producers developed marketing programs to help these new gardeners succeed and suggested ways to prevent or deal with early frost, late blight, and other problems they may encounter.

Be an Optimist: Turn Weaknesses into Strengths

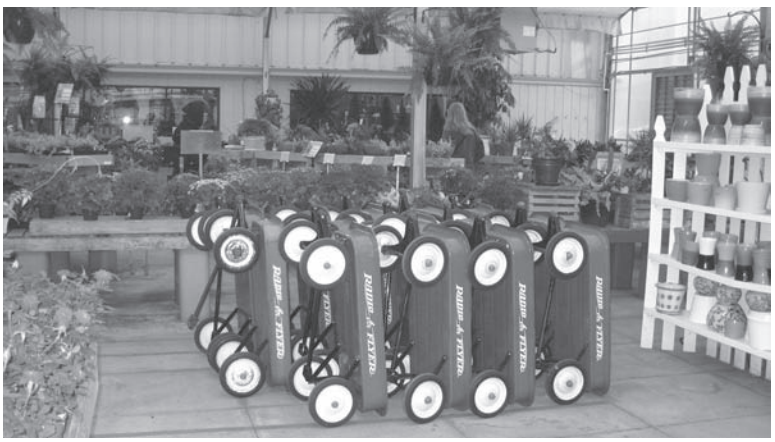
Producers can change products and marketing channels to fit the changing market. One example is a wholesale vegetable farmer who found that his farm that was once rural had become surrounded by bustling suburbs. Land became extremely expensive and labor costs high. But, rather than selling out to development, the farmer switched to year-round retail sales and added a greenhouse. The farm sells bedding plants; fresh, local, in-season produce; flowers, pumpkins, poinsettias, Christmas trees, and so forth. They offer variety that is *value added*.

Other examples are growers in the southern United States who have dealt with several years of drought and water restrictions. While the drought put some producers out of business, innovative growers sold rain barrels and low-water-use plants and developed POP materials to help home gardeners deal with drought (Figure 8).

Know Your Costs: Focus on Cost Control

Increasing costs of inputs are one of the biggest challenges to growers. Input costs—energy, labor, containers, soil amendments, fertilizer, chemicals, labels, tags, and plastic—are all increasing, but consumers expect price stability or reductions. This cost-price squeeze has the effect of reducing profit margins. Price and quality are the two main attributes that allow consumers to differentiate between your products and your competitors' products. Producers need to know their production and marketing costs so that they can establish a *price floor*. Equally important is knowing what customers want and how much they are willing to pay to establish a *price ceiling*. Managers need to do some cost accounting to determine the cost of production as well as sales and profit goals, and they need to develop a strategy to meet them.

(a)



(b)

(c)

Figure 8
Homewood Nursery and Garden Center in Raleigh, NC: (a) potting station for customer service, (b) carts for customer convenience, and (c) rain barrels to help customers deal with drought conditions.

Integrate Horizontally: Control More of the Market

The goal of horizontal integration is not to control all aspects of production, from raw materials to the final product. It is, instead, to be able to produce a large number of the same product or similar products and to control a large share of the market.

One way to integrate horizontally is to buy a second business, or expand to a second location to capture more of the market and create economies of scale. In a recessionary economy, successful firms can acquire struggling rivals cheaply. An example of this is greenhouses that successfully bought a bankrupt Frank's Nursery and Crafts garden center location; turned it into a second, profitable outlet for their products; and expanded their market in the process.

Horizontal integration brings many advantages to those businesses that are able to effectively expand. However, if a company expands horizontally too quickly without a solid plan, it can quickly be overwhelmed by several problems, including strained finances, excessive capacity, and excess inventory. Bigger is not always better. The expansion requires extra management and often a shift from the owner being an entrepreneur who had developed a small business and made all of the managerial decisions to a manager who must delegate responsibilities to others within the firm. Unused capacity from buying another business can lead to problems such as excessive overhead costs. Overproduction, without a market, can lead to increased inventory costs and excessive shrink, which can erode profits. On the other hand, with a carefully planned horizontal expansion, firms are able to sell more of their products, which is usually the goal of any company. Controlling a larger share of a given market gives a business greater power over the flow of products and resources from other companies. All of this added control, power, and productive ability add to the effectiveness of the business through economics of scale. With the proper planning, horizontal expansion can lead a business to great rewards.

Vertically Integrate the Business: Make Buying an Experience

Vertical integration has a goal of controlling all aspects of the production of a product or service. One of the most common forms of vertical integration in the greenhouse industry is to add a direct marketing component. An example of vertical integration is a greenhouse in an urban area where land and labor costs have soared. Rather than selling out to development, this greenhouse retails its products year-round. It sells fresh, local, in-season produce; flowers; pumpkins; Christmas trees; perennials; and so forth. It offers variety that is *value added* to high-income consumers who want to buy locally. Another advantage is that it can maintain its workforce most of the year. This allows it to better manage its labor, and not hire as many extra seasonal employees.

Often, adding direct marketing includes a degree of entertainment for the customer, making the greenhouse a destination. Small- and mid-sized greenhouses are increasingly diversifying and vertically integrating by adding agri-tourism activities to generate additional income. *Agri-tourism* is broadly defined as the business of establishing farms as travel destinations for educational and recreational purposes. Activities include hayrides, corn mazes, pick-your-own produce, farm stands, school tours, farm festivals, petting zoos, and winery tours. A Rutgers study found that more than one-fifth of New Jersey farms offer some form of agri-tourism, 43 percent of New Jersey's total farmland is engaged in agri-tourism, and 60 percent of farms involved in agri-tourism offer floral products (Schilling et al., 2006).

Consider Not Competing in the Lowest-Price Market

Big box stores are here to stay, are the price setters, and continue to push prices down. Some producers successfully compete in this market by controlling costs and inventory. Most, however, do not compete in the lowest-price market. Instead, they sell to independent garden centers, or directly to consumers. They focus on new and unique products or services with which they can offer their consumers value. They look for areas where they can outshine the competition in things like direct marketing, agri-tourism, new and unique varieties and enterprises, product appearance, and accuracy. For example, some of the most successful wholesale greenhouses, who sell plugs to other growers, guarantee a high number of plugs in each tray. Others offer performance and ease/cost of installation—this can include features like biodegradable pots. Other ways to compete are on ease/cost of training, versatility, ease/cost of use, durability, ease/cost of maintenance, speedy delivery, and trademarked lines—their own or industry-wide, quality, diversity of products, and a full range of product lines.

SUMMARY

1. Marketing is one of the most important factors in determining the success of a business. Most of the decisions made by the producer are marketing decisions, which range from determining the most marketable varieties to produce to deciding how to deliver profitable, high-quality products to consumers.
2. Packaging and grading.
   a. Potted plants are usually sold individually to full-service florists. Potted plants going to the mass-market outlets are loaded into carts with multiple, adjustable shelves and rolled into trucks to use all available space.
   b. Cut flowers are packaged in conventional unit sizes depending on the crop. Most cut-flower producers use a grading system. However, the system varies markedly across countries and markets.
3. Greenhouse markets can be divided into two broad market channels: wholesale and retail. Each of them has advantages and disadvantages.
   a. A wholesale production greenhouse sells relatively large amounts of a variety of plants to a relatively small number of accounts. The biggest advantage of wholesale marketing is larger potential transaction sizes and volume. Producers will have little control over the price, that is, they will be price takers.
   b. A retail greenhouse sells relatively small amounts of plants to a relatively large number of individual customers. Direct market producers will have some control over the price based on being able to differentiate their product or service. Costs will be higher for direct marketing than wholesale marketing for promotion, sales area, parking, and labor. Legal liabilities and safety concerns will increase with customers on site.
4. The end consumer can purchase floral products at one of at least six sources: full-service florists, garden centers, big box stores (large discount stores, do-it-yourself hardware stores, club stores), direct-to-consumer (directly from the greenhouse, mail order, wire, Web), farmers' markets, and CSAs.
5. Wholesalers procure floral products from growers, auctions, or brokers and sell them to retailers or secondary wholesalers. They deal primarily in cut flowers, to a lesser extent in flowering and foliage potted plants, and rarely in bedding plants.
6. The arrangement of market segments for each major floral group, cut flowers, flowering potted plants, foliage potted plants, and bedding plants, has sizeable differences that sets each apart from the rest.
   a. Bedding-plant growers generally sell directly to retail outlets and transport the product to retailers with their own trucks. Retail outlets consist of garden centers, big box stores, and general retailers—particularly supermarkets and hardware stores.
   b. In the United States and Canada, growers sell flowering potted plants directly to retail outlets, and wholesalers are used to only a small degree. In the European Union countries, flowering potted plants move directly to the retailer when production is in reasonable proximity to the market. In The Netherlands, many flowering potted plants are sold through the auction.
   c. Foliage-plant production in North America is specialized in Florida, California, and south Texas. Brokers or wholesalers very often negotiate the markets for the growers. In Europe, a wholesaler or a combination of auction and wholesaler is used.
   d. Approximately 68 percent of the cut flowers consumed in the United States are imported,

with most of them coming from Latin America. Within the United States, about two-thirds of cut-flower production occurs in California. Within Europe, large numbers of cut flowers are produced in The Netherlands, France, Italy, and Spain. Additionally, large quantities are imported from Israel, Africa, and, to a lesser degree, Asia and South America. Although Japan produces cut flowers, it also imports them from Southeast Asia, Australia, and New Zealand. With this global movement of flowers, all segments of the market channel are utilized in the cut-flower trade.

7. The floral industry is now a mature market, and has experienced considerable consolidation, mergers, shake-outs, and bankruptcies at all levels in the production/marketing chain.

8. Approximately 15 eco-label programs exist worldwide. All of the programs share several common goals, including health and safety issues for the employees; fair hiring, wage, and benefits policies; protection of the environment; good agricultural practices; and community responsibility on the part of the member firm. A compelling force for joining these programs is the need to be compliant with the social conscience of the consuming public. Demands of the end consumer shape policies of the retailers, which translate into requirements passed on to the producer.

9. Branding has been a hot topic in the floricultural industry for a number of years. Probably 25 percent of products sold in garden centers are branded with some name attached to them.

10. Although cost is often perceived as a deterrent, those who do advertise generally find it profitable. Web sites, e-mail, e-newsletters, and social networking sites and blogs (e.g., Facebook, Twitter) are becoming increasingly popular. Traditional media ads in newspapers, on radio, particularly in connection with a gardening program, and on television are still used. Mailing lists in conjunction with loyalty programs and point-of-purchase (POP) material have provided a very successful avenue of communication with the consuming public for many retailers.

11. While promotional programs and marketing orders have been highly effective, they have been consistently rejected by the industry.

12. In a competitive market, where supply exceeds demand, the industry needs to focus less on products and more on consumers. Successful growers need to understand what the consumer wants and why. Retailers need to build a strong relationship with consumers to build repeat business, not just the quick sale.

13. Since the greenhouse industry is now a mature market and very competitive, producers must focus on strategic planning to utilize their strengths.

14. Customer loyalty programs are structured marketing efforts that reward, and therefore encourage, loyal buying behavior. Loyal customers will do three valuable things for a business: (1) buy more, (2) market the product, and (3) tell the company how to improve the business. Tips for building a successful customer loyalty program follow:
    a. Don't abandon service for savings alone.
    b. Listen to the customer: Make communication a two-way street.
    c. Avoid loyalty turnoffs.
    d. Personalize contact with individual customers.

15. A key in today's competitive market is listening carefully to consumers. A value proposition conveys the value of a firm's product to its consumers. The steps to develop a value proposition are as follows:
    a. Know the targeted customers and both their obvious and less apparent needs and desires.
    b. Talk to current customers and understand the product's value from their perspective.
    c. Know the competition. What product performance do your products and services provide that your competitors' products and services do not?
    d. Research classic customer value propositions to learn from the success and failure of other marketplace offerings.
    e. Brainstorm with both your employees and customers (current and potential) to develop a value proposition that states your product benefits clearly and accurately and brings sustainable brand recognition to your product.

16. Consumers are often defined by their demographic or generational cohort, or people who have similar characteristics based on when they were born.
    a. *The Greatest Generation* was born 1925 to 1945, grew up during the Great Depression and World War II. Their values are thrift, cooperation, and patriotism.
    b. The *Baby Boom Generation* was born 1946 to 1964. The Vietnam War led them to rebel against authority. Their values are consumption, experimentation, and keeping up with the Joneses.

c. *Generation X* or *Gen X* was born 1965 to 1979, grew up during a period of relative peace after the Vietnam War. They value independence and individuality.
d. *Generation Y*, *Gen Y*, the *Millennial Generation*, *Generation Next*, *Net Generation*, *Millennials*, or *Echo Boomers* (born 1980 to 1990) grew up with 9/11 and the wars in Iraq and Afghanistan. Their values are the same as those of the Greatest Generation: thrift, cooperation, and patriotism.

17. In addition to building comprehensive Web sites and generating e-newsletters, growers are increasingly getting involved with social media via Facebook and Twitter. The idea is to build that one-to-one customer relationship and communicate more often.

18. Changing demographics are driving changes in consumer demand for green-industry products.

19. Recession-worried consumers look for quality, variety, and value.

20. Some successful strategies employed by greenhouse managers in the United States follow:
   a. Create and exploit your competitive advantage by offering either the lowest cost product or the best quality product. This is true for both retail and wholesale markets since ultimately, the product must satisfy the end consumer.
   b. Innovative producers find a market niche that competitors are not serving, and they take advantage of consumer trends.
   c. Producers can change products and marketing channels to fit the changing market.
   d. Producers need to know their production and marketing costs so that they can establish a price floor. Equally important is knowing what customers want and how much they are willing to pay to establish a price ceiling.
   e. Horizontal integration to control a larger share of a given market gives a business greater power over the flow of products and resources from other companies.
   f. Vertical integration has a goal of controlling all aspects of the production of a product or service. Another advantage is that it can maintain its workforce most of the year.
   g. Focus on new and unique products or services that can offer their consumers value. Look for areas in which you can outshine the competition, in things like direct marketing, agri-tourism, new and unique varieties and enterprises, product appearance, and accuracy.

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