The Container Tree Nursery Manual

Volume Three
Atmospheric Environment

Introduction

In this volume of the Container Tree Nursery Manual, we will discuss the four atmospheric factors of the container nursery environment-temperature, humidity, light, and carbon dioxide-which directly control the growth rate of a crop of tree seedlings. The other two important factors controlling seedling growth-water and mineral nutrients-are supplied by the growing medium. These latter factors are discussed in volume four of the manual: Seedling nutrition and irrigation.

As explained in volume one, plants are grown in container nurseries so that the various factors that affect seedling growth and development can be kept as close to optimum levels as possible. The **principle of limiting factors** (Blackman 1905) states that, when a process is governed by several factors, its rate is limited by the factor that is closest to the minimum requirement. The practical significance is that, although all four atmospheric factors (light, temperature, humidity, and carbon dioxide) are necessary for growth, one usually limits the system at any particular time (Kramer and Kozlowski 1979).

Although they are discussed separately, these four factors must always be considered together because they interact with each other in controlling the growth of tree seedlings (fig. 3.1.1). A good example of these interrelationships is the one between humidity and temperature. The humidity in the air is typically measured by the relative humidity, and this value changes drastically with changes in temperature.

Perhaps the best example of the extreme complexity of the interrelationships of the four atmospheric factors is the physiology of a typical leaf (fig. 3.1.2). The two gases (carbon dioxide and water vapor) and light are involved in photosynthesis, respiration, and transpiration:

Photosynthesis uses carbon dioxide and produces oxygen.
Respiration uses oxygen and produces carbon dioxide.
- Transpiration is the loss of water vapor through stomata.

All three physiological processes are regulated by the temperature of the leaf and the functioning of the stomata (singular = stomate), which respond to the concentrations of carbon dioxide and the intensity of light as well as to levels of humidity and temperature. Stomata open in response to favorable light, carbon dioxide, and moisture levels, and stay open until transpirational losses of water vapor cause the guard cells to lose turgor pressure. The transpirational demand is primarily a function of temperature and humidity. Photosynthesis requires the stomata to remain open as long as possible to allow carbon dioxide to enter, but while the stomata are open, water vapor is lost (Roberts 1990).

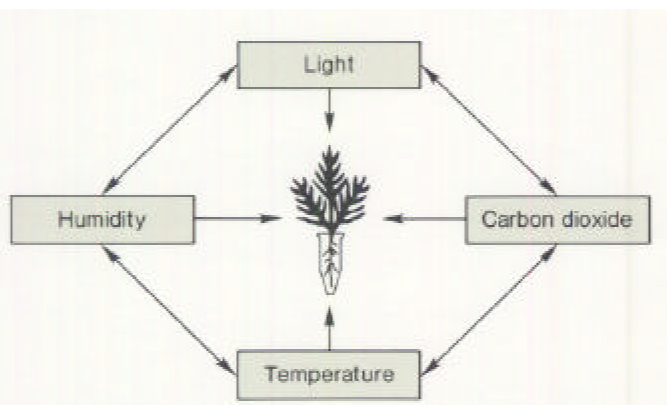


Figure 3.I.1—*Atmospheric factors affecting tree seedling growth.*

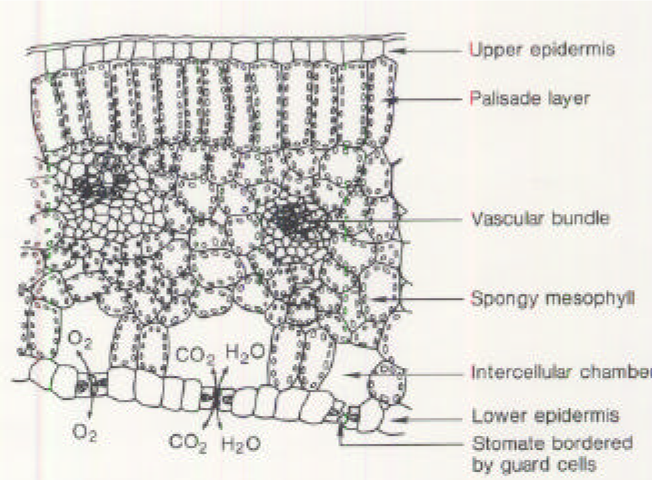


Figure 3.I.2—*Cross section of a typical leaf, showing the various types of tissues and cells and the sites of gas exchange (from Hartmann, Flocker, & Kofranek. © 1981. Plant science: growth, development, and utilization of cultivated plants. p. 32. Reprinted by permission of Prentice Hall, Englewood Cliffs, NJ).*

This basic example illustrates both the extreme complexity of the physiological processes that control plant growth and the interrelationships that exist between them and the limiting factors of the environment.

For convenience's sake, each of the four atmospheric factors will be discussed separately, but the organization in each of the following chapters is the same to permit easy comparison:

- **Introduction**-Discusses the basic concepts, terminology, and units of measurement.
- **Role in Tree Seedling Growth and Development**-Explains how these concepts can be applied in container nursery management.
- **Optimum Levels**-Analyzes the recommendations in the literature and relates what other container nurseries are doing.
- **Modifying the Factor in Container Tree Nurseries**-Discusses how container nursery growing structures and environmental control equipment can be used to keep the factor at optimum levels.
- **Monitoring and Control Systems**-Explains the types of monitoring equipment and environmental control systems that are available and have been used in container nurseries.

When applying any recommendations, the reader is cautioned to remember that all six environmental factors are always inextricably interrelated. A prudent nursery manager will consider the implications before changing any of the environmental factors that affect seedling growth, and if possible, should try any proposed change on a small scale first.

Literature Cited

Blackman, F.F. 1905. Optima and limiting factors. Annals of Botany 19:281-295.

Kramer, P.J.; Kozlowski, T.T. 1979. Physiology of woody plants. Berlin: Academic Press. 811 p.

Roberts, B.R. 1990. What are stomates and how do they work? Journal of Arboriculture 16(12):331.

The Container Tree Nursery Manual

Volume Three
Atmospheric Environment

Chapter 1
Temperature

Contents

3.1.1 Introduction

Temperature is one of the most familiar aspects of our environment, and it has a pervasive effect on tree seedling growth. It directly affects the numerous chemical reactions involved in plant metabolism and also controls other growth-related processes such as transpiration. Temperature affects plant growth in several different ways, ranging from minor changes in growth rate to severe injury or even death. Because they are succulent when rapidly growing, container tree seedlings are particularly vulnerable to temperature stresses.

Temperature is the most frequently controlled and easily measured environmental factor when plants are produced under container nursery conditions. A greenhouse is the most basic cultural modification to control the growing environment, and completely enclosed structures contain heaters, vents, fans, evaporative pads, and sophisticated environmental controls to maintain ideal growing temperatures. Before discussing the horticultural applications, however, it is instructive to review the basic concepts of heat and temperature.

3.1.1.1 Heat versus temperature

Heat is the common name for **thermal energy** and represents the total kinetic molecular energy of a substance, whereas **temperature** indicates the average energy. When heat is applied to a substance, and there is no change in physical state (such as ice to water), the molecular motion increases and the temperature rises. If the same amount of heat is applied to two different substances, however, each would exhibit different temperatures because they have dissimilar molecular structures or densities and thus different capacities to absorb heat (Schroeder and Buck 1970). For example, a cubic meter of air at the same temperature as an equal volume of water does not contain the same amount of heat. From a heating standpoint, temperature indicates the direction but not the amount of heat transfer (Hanan and others 1978).

Thermal energy is measured in calories in the metric system, or British thermal units (Btu) in the English system. One calorie is the amount of heat necessary to raise the temperature of 1 g of water 1 °C, and 1 Btu is defined as the amount of heat required to raise the temperature of 1 pound of water 1 ° F. Temperature scales are based on the freezing and boiling points of water, 0 and 100 °C or 32 and 212 ° F; conversion tables for Centigrade and Fahrenheit are provided in the appendix. Air temperature, and often the temperature of the growing media, are normally monitored in container tree nurseries (see section 3.1.4 for more information).

3.1.1.2 Heat exchange in the container nursery environment

Heat is transferred from one place to another by three processes: **radiation, conduction,** and **convection.** In the container nursery environment, heat transfer can occur by solar and thermal radiation, through solids and liquids by conduction, and through liquids or gases by convection (fig. 3.1.1). In conduction and convection, heat is directly transferred by contact or mass flow of matter, whereas in radiation the energy form changes from thermal energy at the source, to electromagnetic energy for transmission, and then back to thermal energy upon reception (ASHRAE 1989).

In a container nursery all heat, except geothermal or nuclear waste heat, originates from the sun: either directly as solar radiation or indirectly from organic fuels such as wood, natural gas, or coal. The surfaces in a greenhouse heat up when electromagnetic radiation from the sun penetrates the transparent covering, is absorbed, and is converted to thermal radiation (fig. 3.1.1). This "greenhouse effect" applies especially to growing structures cov-

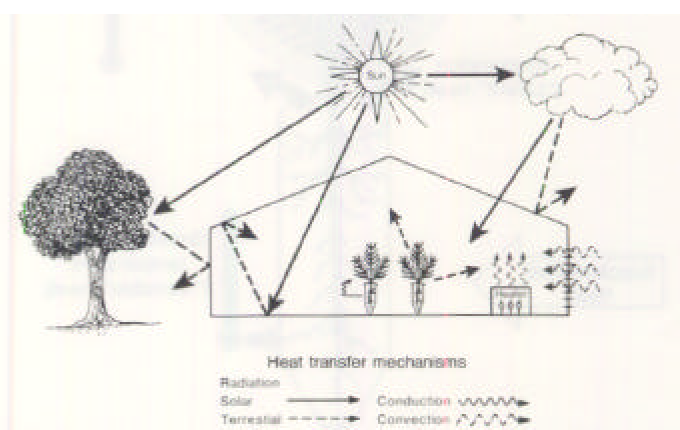


Figure 3.1.1—*Thermal energy exchange in a greenhouse environment.*

ered with glazings that are transparent to solar radiation but opaque to thermal radiation. Thermally opaque glazings include glass, fiberglass, acrylics, and polycarbonates; other greenhouse coverings, such as polyethylene and polyester films, are transparent to thermal radiation and the only reason the greenhouse heats up is air exchange with the ambient environment is restricted (Mastalerz 1977). (See chapter 3 in this volume for a more detailed discussion of solar radiation.)

Actually, temperature regulation in a traditional greenhouse is not a simple task. Greenhouses get too hot during periods of sunny weather, and growers must utilize vents or evaporative coolers to provide cooling. In the temperate zones, nurseries must supplement this direct solar heat during periods of cloudy and cold weather.

Heat from solar radiation and supplemental sources is dissipated as both sensible and latent heat in the microclimate around a tree seedling (fig. 3.1.2).

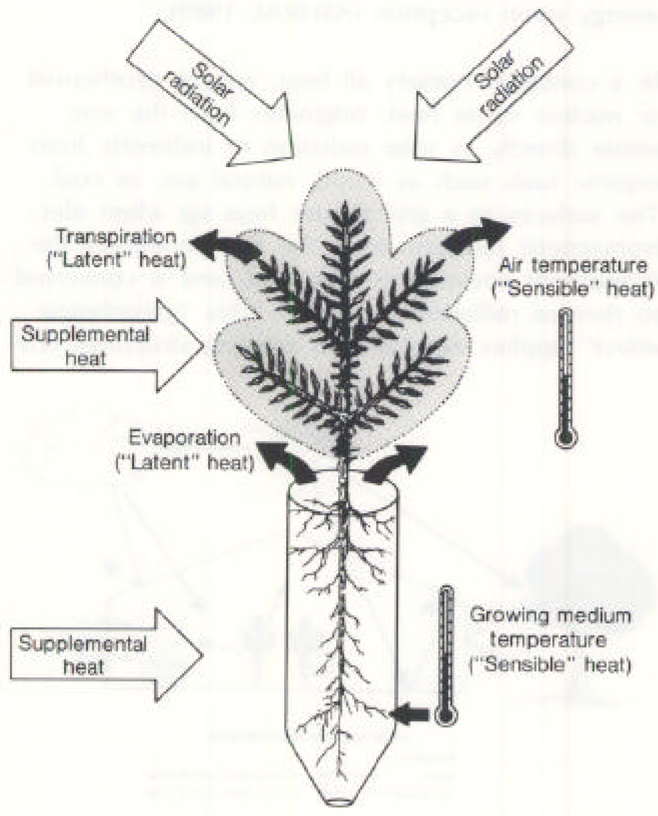


Figure 3.1.2—*Thermal energy exchange in a greenhouse microenvironment.*

Sensible heat is heat that causes an increase in temperature, of either the air or the growing medium. **Latent heat,** on the other hand, is heat that is required for a phase change such as that between liquid water and water vapor or ice, and is emitted or absorbed with no change in temperature (Stathers and Spittlehouse 1990). Both evaporation and transpiration consume latent heat in the greenhouse environment because transpiration is essentially bioregulated evaporation.

3.1.2 Role of Temperature in Tree Seedling Growth and Development

Plant growth is the end product of many different physical and chemical processes. Temperature has a direct effect on plant metabolism because the rate of a biochemical reaction increases by a factor of 2 to 3 for each 10 °C (18 °F) rise in temperature, up to the point where the enzymes are damaged. Each reaction has a different rate at any given temperature, however, and so an increase in temperature does not necessarily affect a complex process such as photosynthesis, which involves a series of reactions, in the same relatively simple way as a single reaction.

Temperature also affects other plant processes that control growth. Plants respond to temperature in a complex, buffered manner because of their high water content. Water has the highest specific heat of any common substance, and so plant foliage changes temperature much more slowly than the air around it. Water changing from a liquid to a gas requires a large amount of heat energy, and so transpiration helps cool the leaf and maintain temperatures that are most favorable for photosynthesis. Leaf shape has evolved to maximize interception of sunlight for photosynthesis, while dissipating the resultant heat through reradiation and transpiration.

3.1.2.1 Cardinal temperatures

The growth of tree seedlings, like that of all living things, is restricted to a discrete temperature range. The best temperatures for growing a particular seedling will vary according to species, ecotype, and stage of development. These ideal temperature ranges can be defined by **cardinal temperatures: minimum, maximum,** and **optimum.** These values are not rigid constants, however, but can shift as the plant matures or adapts to environmental conditions (Larcher 1975).

The general response to temperature is generic for most plants. For most temperate and boreal zone conifers, little seedling growth occurs below 10 °C (50 ° F), although basic processes such as photosynthesis and respiration continue very slowly at lower temperatures. Growth remains slow up to 15 °C (59 °F), and steadily increases through the optimum range of 18 to 30 °C (64 to 86 °F). Temperatures above 30 °C (86 °F) adversely affect growth (Kramer and Kozlowski 1979). Although the response varies both between shoots and roots and between species (fig. 3.1.3), seedling growth follows a typical bell-shaped curve over the range of temperatures that would normally be encountered in a container nursery.

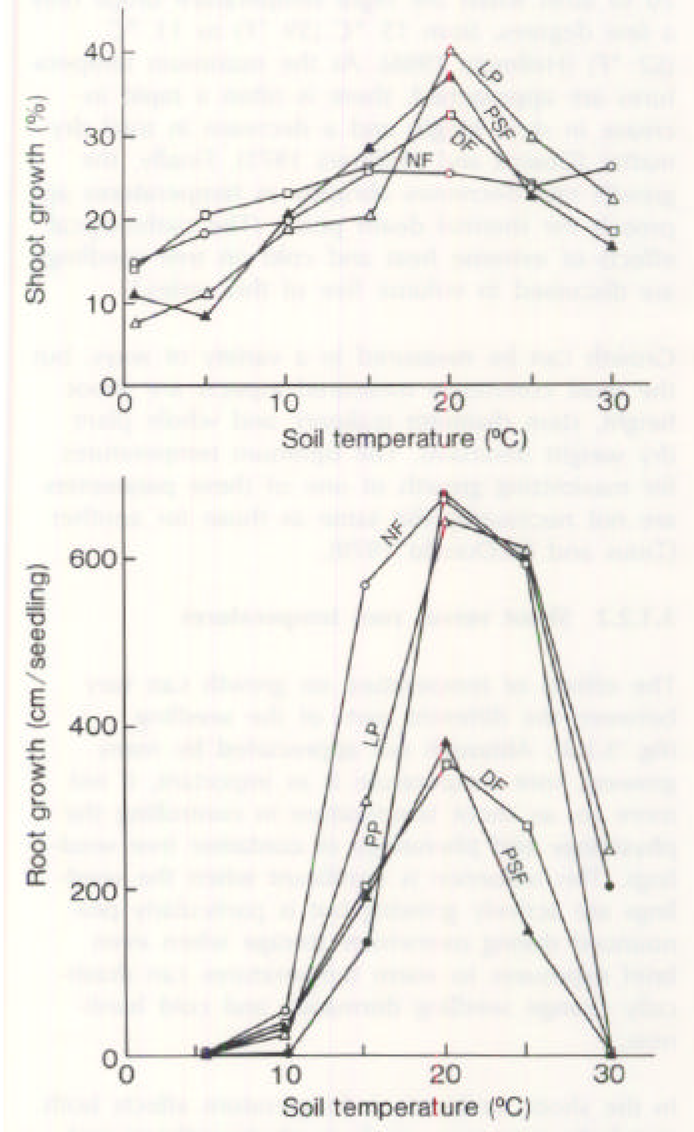


Figure 3.1.3—*Soil temperature influences both root and shoot growth, and the response varies between different species. NF = noble fir, LP = lodgepole pine, PP = ponderosa pine, DF = Douglas-fir, PSF = Pacific silver fir. (Modified from Lopushinsky and Max 1990.)*

The effects of temperature on seedling growth are most pronounced near the minimum and maximum values (fig. 3.1.3). As the lower limit of growing temperature is approached, the growth rate gradually decreases. There are exceptions: for example, the height growth and dry matter production of redwood seedlings abruptly decreases 70 to 80% when the night temperature drops only a few degrees, from 15 °C (59 °F) to 11 °C (52 °F) (Hellmers 1966). As the maximum temperatures are approached, there is often a rapid increase in stem length and a decrease in total dry matter (Downs and Hellmers 1975). Finally, the growth rate decreases abruptly as temperatures approach the thermal death point. (The pathological effects of extreme heat and cold on tree seedlings are discussed in volume five of this series.)

Growth can be measured in a variety of ways, but the most commonly measured aspects are shoot height, stem diameter (caliper), and whole plant dry weight (biomass). The optimum temperatures for maximizing growth of one of these parameters are not necessarily the same as those for another (Tinus and McDonald 1979).

3.1.2.2 Shoot versus root temperatures

The effects of temperature on growth can vary between the different parts of the seedling (fig. 3.1.3). Although not appreciated by many growers, root temperature is as important, if not more so, as shoot temperature in controlling the physiology and phenology of container tree seedlings. This influence is significant when the seedlings are actively growing but is particularly pronounced during overwinter storage when even brief exposures to warm temperatures can drastically change seedling dormancy and cold hardiness.

In the shoot, ambient air temperature affects both metabolic processes, such as photosynthesis and respiration, and biophysical processes such as transpiration. Because these foliar processes are all dependent on water and mineral nutrients transported from the root system, the temperature of the growing medium is just as important as air temperature. The water absorption rate of seedling root systems increases with temperature and so seedling transpiration is directly affected by the temperature of the growing medium (fig. 3.1.4). Because mineral nutrient ions are carried along with the transpirational stream from the roots to the foliage, the uptake of nitrogen and other essential mineral nutrients is also limited at low growing medium temperatures (Orlander and others 1990). High root temperatures, those greater than 25 °C (73 °F), can also adversely affect growth, probably because the roots cannot take up enough oxygen (Garzoli 1988). Research has shown that, where growing medium temperature is controlled separately from air temperature, both shoot and root growth are influenced by the temperature of the growing medium (Lavender and Overton 1972). One of the significant advantages that container nurseries have over bareroot nurseries is that root temperature can be more easily monitored and controlled.

Temperature affects both the type and rate of seedling growth in container tree nurseries. Tinus (1984) grew several species and ecotypes under typical greenhouse conditions and found that shoot height, caliper, and biomass all vary with different combinations of day and night temperatures (fig. 3.1.5). He concluded that, for some species, these responses were different enough to warrant

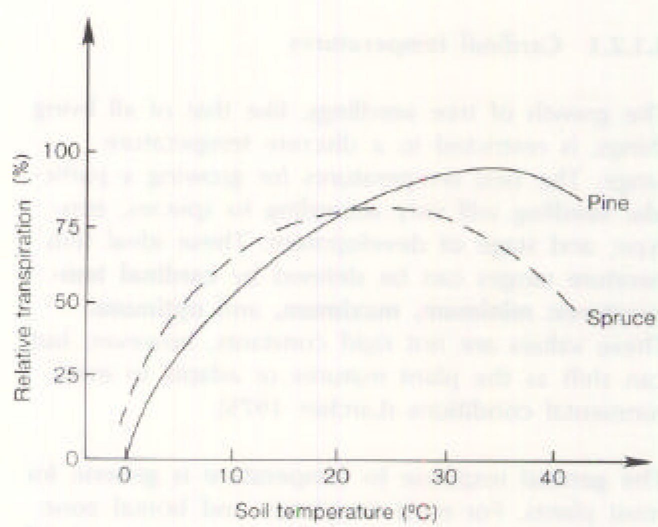


Figure 3.1.4—*Shoot physiology is dependent on the functioning of the root system. In this example, transpiration increases with temperature as the growing medium warms, until high temperatures cause severe moisture stress. Note that species respond differently. (Modified from Orlander 1985, as reported in Orlander and others 1990.)*

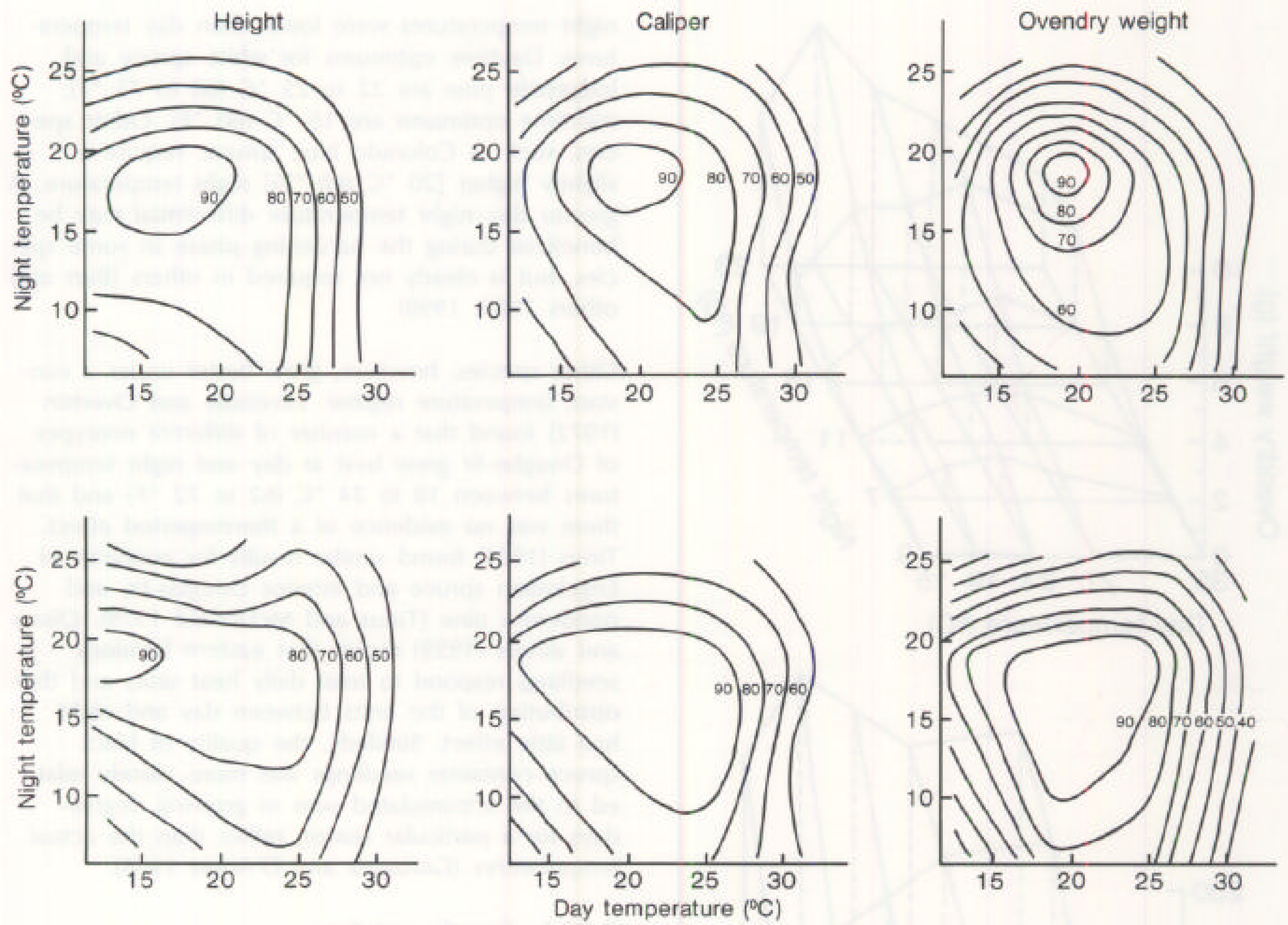
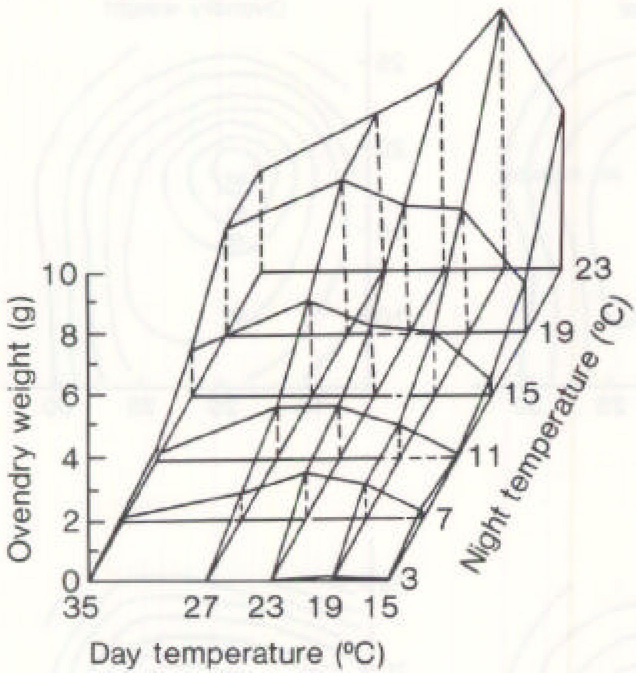


Figure 3.1.5—*Two ecotypes of Engelmann spruce, one from Lincoln National Forest in New Mexico* (**top**) *and the other from the Apache-Sitgreaves National Forest in Arizona* (**bottom**), *had different growth patterns of shoot height, stem caliper, and seedling biomass (ovendry weight) when grown under a range of night and day temperatures. Values are percent of maximum growth. (Modified from Tinus 1984.)*

separate growing environments. With most temperate zone conifers, high temperatures tend to produce spindly seedlings (Rook 1991); for example, Hellmers and others (1970) observed that high temperatures stimulated height growth of Engelmann spruce seedlings at the expense of dry matter production (fig. 3.1.6). This effect apparently does not apply to certain southern conifers, however. With loblolly pine, which produces from one to seven flushes of shoot growth during the year (depending upon a seedling's age and location), Mulroy (1972) found an inverse relationship with temperature. Flush number was increased and flush length shortened with increased temperature. Thus, these seedlings grew to about the same height under a wide range of temperatures.

3.1.2.3 Diurnal variation

Both day and night temperatures have been shown to affect seedling growth (figs. 3.1.5 and 3.1.6). Researchers have found that some tree species exhibit increased growth when night temperatures are kept lower than day temperatures; this day-night temperature differential is called the **thermoperiod.** Hellmers and Rook (1973) reported that radiata pine seedlings increased significantly in stem caliper and total and root dry weight when



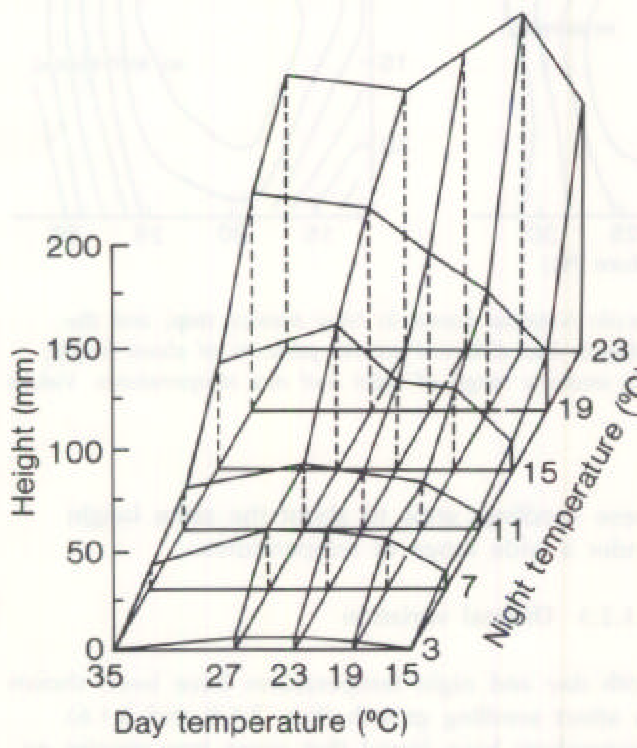


Figure 3.1.6—*Both seedling biomass (ovendry weight) and height of these Engelmann spruce seedlings increased significantly with growing temperatures. High temperatures stimulate excessive height growth, which often results in seedlings with poor root-to-shoot ratios. (modified from Hellmers and others 1970).*

night temperatures were lower than day temperatures. Daytime optimums for white spruce and lodgepole pine are 22 to 25 °C (68 to 73 °F); nighttime optimums are 16 °C (60 °F). Other species, such as Colorado blue spruce, require a slightly higher [20 °C (68 °F)] night temperature. A greater day-night temperature differential may be beneficial during the hardening phase in some species, but is clearly not required in others (Burr and others 1989, 1990).

Other species, however, grow better under a constant temperature regime. Lavender and Overton (1972) found that a number of different ecotypes of Douglas-fir grew best at day and night temperatures between 18 to 24 °C (62 to 72 °F) and that there was no evidence of a thermoperiod effect. Tinus (1984) found similar results for ecotypes of Engelmann spruce and interior Douglas-fir, and ponderosa pine (Tinus and McDonald 1979). Olson and others (1959) report that eastern hemlock seedlings respond to total daily heat units and that distribution of the units between day and night had little effect. Similarly, the quality of black spruce container seedlings was more closely related to the accumulated sum of growing degree-days for a particular season rather than the actual temperatures (Gonzalez and D'Aoust 1988).

3.1.2.4 Genetic variation

As shown in the previous sections, different species have different responses to temperature; in general, southern species and ecotypes have higher temperature requirements than those from further north. This intraspecific variation can exist even between species that occur in similar habitats. Lopushinsky and Max (1990) found that four different northwest conifers had significantly different root and shoot growth over a range of different soil temperatures (fig. 3.1.3). Different ecotypes of the same species can respond differently to temperature; the same authors found that ponderosa pine seedlings from a low-elevation seed source had shoot and root growth patterns that were different from those of seedlings from a high-elevation source (see also Tinus and McDonald 1979).

3.1.3 Optimum Temperature Levels

Seedlings grow over a wide range of temperatures, but somewhere within this range there are temperatures that promote optimal growth. The nursery manager needs to identify these optimum temperatures for different species and ecotypes at the various stages of seedling development, and determine how much variation can be tolerated while still producing the desired crop. Tree seedling growth in container nurseries can be divided into three stages:

- **Establishment phase**-the period from seed germination through primary leaf development and root extension throughout the container.
- **Rapid growth phase**-the period when seedlings grow in height and weight at an exponential rate.
- **Hardening phase**-the period after bud set when caliper and root growth continue (stage 1), and the seedling is cold hardened for outplanting (stage 2).

3.1.3.1 Establishment phase

The first stage in container seedling production is to promote rapid and complete seed germination, and the most critical environmental variables are moisture and temperature (Tinus 1982). Some temperate zone species require cold, moist stratification before their seeds will germinate and this process can take from 1 to 6 months depending on the species. Seeds of other species and more southerly sources require only a short presoak so that they can imbibe water (presowing seed treatments are described in detail in volume six of this series).

Minimum, optimum, and maximum temperatures for seed germination vary widely among seeds of different species and generally are lower for temperate zone species than for tropical species. Optimum germination (the highest percentage germination in the shortest time) is temperature-sensitive and varies somewhat between species and between genotypes within a species. However, germination temperatures between 22 to 24 °C (72 to 75 °F) are optimal for a wide range of species (McLemore 1966, Barnett 1979, Heidmann 1981).

Most research results on seed germination are obtained under standard laboratory conditions with constant temperatures. Such results cannot be applied directly to operational greenhouse conditions, however, where temperatures fluctuate both diurnally and from day to day. Some germination tests have been conducted with fluctuating temperatures that are more representative of greenhouse conditions. Of four southern pines, longleaf pine seed was the only one that was adversely affected by temperatures alternating between 24 to 35 °C (75 to 95 °F) compared to a constant 24 °C (75 °F) that would be typical of an operational greenhouse (table 3.1.1). All species showed serious reductions in germination when grown under constant high temperatures [35 °C (95 °F)]. Short periods of high temperatures may not reduce seed germination of some species; for example, Dunlap and Barnett (1982) found that exposing loblolly and shortleaf seeds to periods of 35 °C (95 °F) up to 12 hours per day speeded germination without adversely affecting total germination. However, the germination rate of longleaf pine seed was reduced by this exposure to high temperatures.

After the germinant begins to emerge from the container (fig. 3.1.7), growers must carefully regulate temperatures to promote rapid seedling growth and development and minimize the potential for damping-off disease or abiotic injury. Tinus (1982) recommends that temperatures during the establishment phase be maintained at or slightly below the optimum because slightly cooler temperatures slow hypocotyl elongation and result in sturdier seedlings. A recent survey of operational container tree nurseries revealed that growers use a relatively narrow range of temperatures during the establishment phase (table 3.1.2). Daytime temperatures ranged from 21 to 27 °C (70 to 80 °F), whereas overnight temperatures were only slightly cooler [18 to 27 °C (65 to 80 °F)].

Obviously, because of the relatively high temperatures that are necessary, heated greenhouses should be used during the establishment phase and some nurseries have constructed special germination rooms (fig. 3.1.8). Even in the production greenhouse, the placement of the sown containers can affect seedling emergence; Hallett and others

Table 3.1.1—*With the exception of longleaf pine, the germination of four southern pines was not adversely affected by the fluctuating diurnal temperatures that are typical of an operational greenhouse; all species were significantly affected by constant high temperatures*

Species	Seed stratified	Germination rate (%)		
		Constant 24 °C	24 °C (18 hr) + 35 °C (6 hr)	Constant 35 °C
Longleaf pine	No	79 a	61 b	12 c
Slash pine	No	84 a	83 ab	71 b
	Yes	80 a	72 ab	66 b
Loblolly pine	No	88 a	89 a	27 b
	Yes	97 a	96 a	46 b
Shortleaf pine	No	78 a	76 a	42 b
	Yes	46 a	45 a	30 b

Means within species stratification treatments (across rows) followed by the same letter do not differ significantly at the 0.05 level.
Source: Dunlap and Barnett (1982).

(1985) reported that the emergence of black spruce seedlings varied considerably between heated and unheated growing structures, and at different locations within a heated structure (fig. 3.1.9).

(More information on the effects of growing structures on temperature is provided in section 3.1.4.1.)

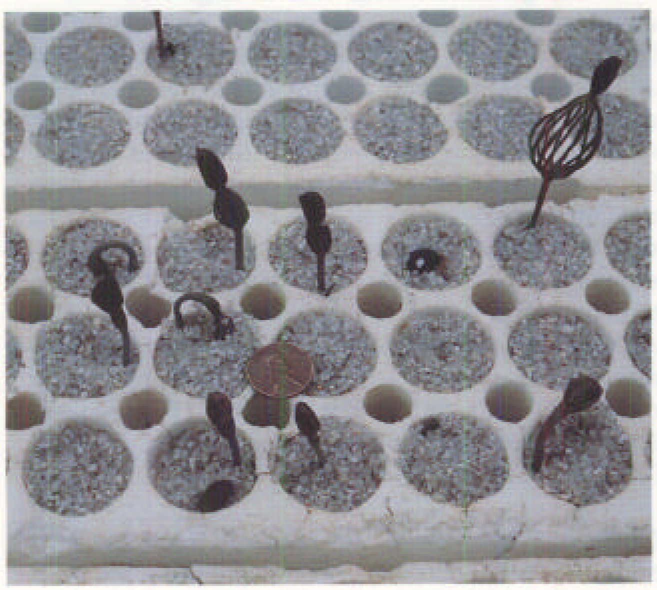


Figure 3.1.7—*During the establishment phase, temperature affects both the germination rate and total seed germination, as well as subsequent germinant emergence and growth.*

Figure 3.1.8—*Some container tree nurseries use specially equipped germination rooms to accelerate seed germination before moving the containers to the normal growing structures.*

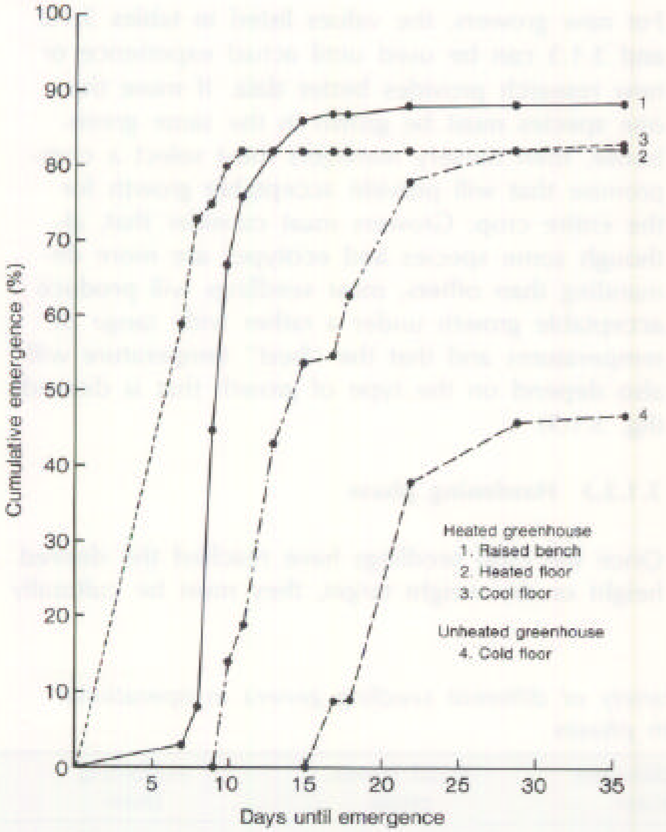


Figure 3.1.9—*The total emergence of black spruce seedlings was significantly greater in a heated than in an unheated greenhouse, and the emergence rate was much faster on a warm raised bench or floor than on a cool floor (modified from Hallett and others 1985).*

3.1.3.2 Rapid growth phase

Once the seedlings have emerged and become established in the containers, nursery managers must control the temperature in the growing area to promote rapid shoot expansion (fig. 3.1.10). The shoots of forest tree seedlings either grow continuously or in a series of sequential flushes, and temperatures in the growing area must be kept in an optimum range, or the seedlings may stop shoot growth and set a terminal bud (Kramer and Kozlowski 1979). Once this happens, it is often difficult to break bud dormancy without satisfying the chilling requirement, which can take months. In an operational nursery, premature bud set can be disastrous and can prevent the crop from meeting height standards within the crop schedule (Tines 1982).

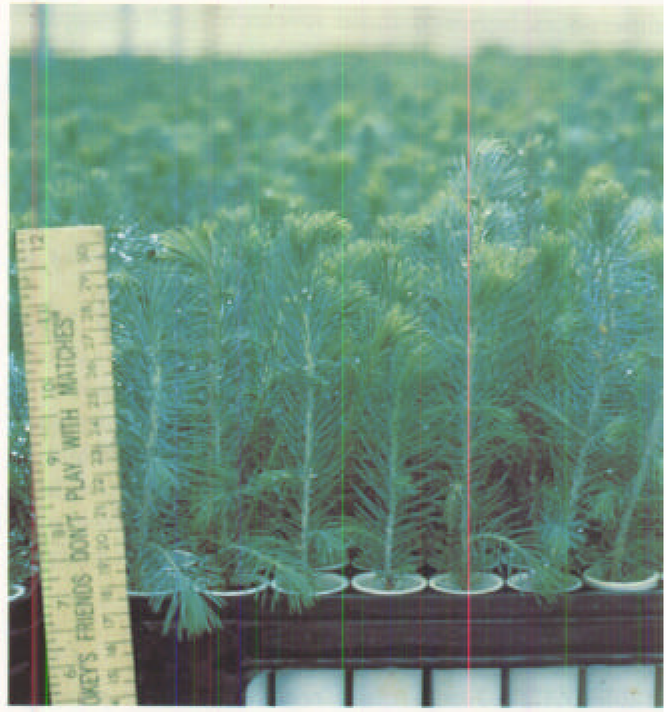


Figure 3.1.10—*During the rapid growth phase, the shoots of container tree seedlings grow at an exponential rate when air and growing medium temperatures are optimum.*

Recommended temperatures derived from growth chamber experiments (table 3.1.3) are within the optimum range for a variety of species. These temperatures consider not only biological requirements, but also the economic constraints of heating and cooling. These recommendations also indicate some differences in response between seed sources but not to the extent that different greenhouse temperature regimes are needed.

Tines (1984) and Barnett and Brissette (1986) have reported inconsistencies in optimum temperatures that are attributed to different ages and size of seedlings. For example, optimum day temperatures for Engelmann spruce reported by Hellmers and others (1970) were in agreement with data reported by Tines (1984) but optimum night temperatures were quite different. The optimum temperatures for container loblolly pine seedlings according to the work of Bates (1976) is a 29/23 °C (84/'73 °F) day/night regime. This is quite different from the data of Greenwald (1972), who studied loblolly seedlings more than 6 months old. The differences between these research results suggest that, as seedlings develop, there is a shift in the temperatures that are optimum for growth.

Nevertheless, selection of target temperatures need not be complicated. A survey of successful container nurseries showed that nursery managers are producing a variety of tree seedling crops under a relatively narrow range of temperatures (table 3.1.2). Daytime targets ranged from 21 to 27 °C (70 to 80 ° F) and target night temperatures varied from 16 to 24 °C (60 to 75 °F); these values agree with published data from Canadian container tree nurseries (Edwards and Huber 1982, Hallett 1982). These moderate temperature regimes reflect the operational realities of most container tree nurseries, including structural and equipment capabilities and the economics of energy use.

For new growers, the values listed in tables 3.1.2 and 3.1.3 can be used until actual experience or new research provides better data. If more than one species must be grown in the same greenhouse, then nursery managers must select a compromise that will provide acceptable growth for the entire crop. Growers must consider that, although some species and ecotypes are more demanding than others, most seedlings will produce acceptable growth under a rather wide range of temperatures and that the "best" temperature will also depend on the type of growth that is desired (fig. 3.1.5).

3.1.3.3 Hardening phase

Once the crop seedlings have reached the desired height or dry weight target, they must be culturally

Table 3.1.2—*Temperature regimes used to produce a variety of different seedling genera in operational container tree nurseries during the three principal growth phases*

Genera	Location	Day or night	Units	Establishment phase		Rapid growth phase		Hardening phase	
				Target	Range	Target	Range	Target	Range
Douglas-fir, fir, larch, pine, spruce	ID	D	°C	21	18–24	21	18–29	18/7	2–18
			°F	70	65–75	70	65–85	65/45	35–65
		N	°C	21	18–24	20	17–24	7/0	0–18
			°F	70	65–75	68	62–75	45/32	32–65
Cypress, juniper & redcedar, pine	TX	D	°C	21	20–27	21	20–27	Ambient	—
			°F	70	68–81	70	68–81	Ambient	—
		N	°C	21	20–27	21	20–27	Ambient	—
			°F	70	68–81	70	68–81	Ambient	—
Douglas-fir, eucalyptus, redwood, pine	CA	D	°C	21	16–32	27	16–38	27/16	7–35
			°F	70	60–90	80	60–100	80/60	45–95
		N	°C	21	16–27	18	16–24	16/7	5–27
			°F	70	60–80	65	60–75	60/45	40–80
Pine, spruce	ON	D	°C	22	20–28	20	18–30	10	15–20
			°F	72	68–82	68	64–86	Ambient	70–90
		N	°C	20	15–25	16	15–25	5	5–15
			°F	75	70–80	68	65–70	Ambient	50–70
Birch, maple	MN	D	°C	24	21–27	23	20–24	Ambient	21–32
			°F	75	70–80	72	68–75	Ambient	70–90
		N	°C	24	21–27	20	18–21	Ambient	10–21
			°F	75	70–80	68	65–70	Ambient	50–70
Oak, walnut	MN	D	°C	27	24–29	27	24–29	Ambient	21–32
			°F	80	75–85	80	75–85	Ambient	70–90
		N	°C	27	24–29	24	24–27	Ambient	10–21
			°F	80	75–85	75	75–80	Ambient	50–70

Source: Container Nursery Survey (1990)

Table 3.1.3—*Day and night temperature regimes for a variety of tree species and ecotypes, as determined by research trials*

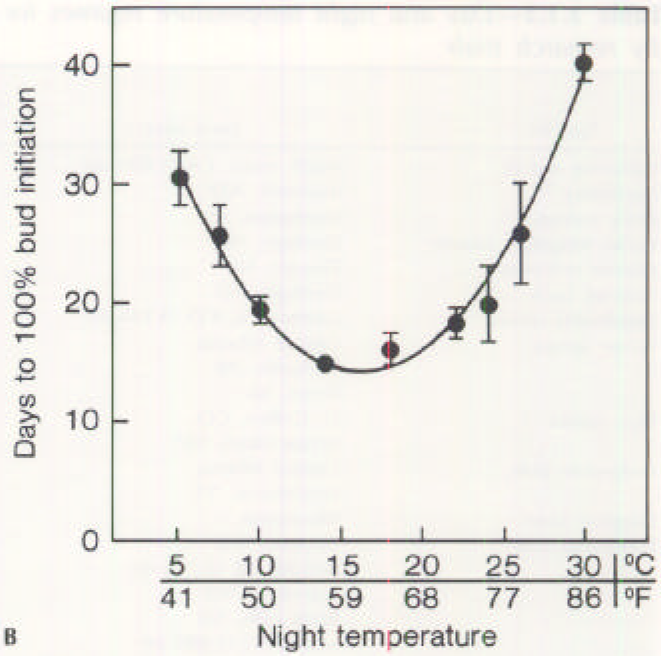
Species	Seed source	Day temperature Target	Day temperature Range	Night temperature Target	Night temperature Range	Authority
California red fir	North coast, CA (1,800 m)	17	16–19	5	4–10	Hellmers (1966a)
Hackberry	Bismarck, ND*	31	25–32	19	18–26	Tinus & MacDonald (1979)
Black walnut	Manhattan, KS*	28	26–30	22	19–28	Tinus & MacDonald (1979)
Rocky Mountain juniper	Denbigh, ND*	25	21–28	18	12–26	Tinus & MacDonald (1979)
Eastern redcedar	Towner, ND*	24	21–26	21	19–26	Tinus & MacDonald (1979)
Siberian larch	Denbigh, ND	25	24–28	22	16–26	Tinus & MacDonald (1979)
Engelmann spruce	Larimer Co, CO (3,140 m)	19	17–23	23	22–24	Hellmers et al (1970)
White spruce	Central Alberta	22	21–25	19	16–20	Tinus & MacDonald (1979)
	Fairbanks, AK	22	20–24	16	13–22	Tinus & MacDonald (1979)
	Kenai, AK	22	20–25	19	16–26	Tinus & MacDonald (1979)
Blue spruce	Ft. Collins, CO	20	18–25	22	19–26	Tinus & MacDonald (1979)
	Indian Head, SK*	22	18–25	19	17–23	Tinus & MacDonald (1979)
Lodgepole pine	Central Alberta	25	22–28	16	14–19	Tinus & MacDonald (1979)
	Whitehorse, YT	22	20–24	19	16–20	Tinus & MacDonald (1979)
Longleaf pine	Mississippi	23	17–26	17	17–23	Bates (1976)
Ponderosa pine	Ruidoso, NM	22	18–26	24	28–25	Tinus & MacDonald (1979)
	Safford, AZ (2,770 m)	17	16–19	22	21–23	Callaham (1962)
	Valentine, ND	22	20–25	24	20–25	Tinus & MacDonald (1979)
	Black Hills, SD	23	20–24	23	20–24	Larson (1967)
	Moon, SD (1,890 m)	23	20–27	22	21–23	Callaham (1962)
Radiata pine	Cambria, CA	20	19–23	5/20	4–7/17–23	Hellmers & Rook (1973)
Scotch pine	W. Ural Mtns., USSR	19	18–21	28	25–31	Tinus & MacDonald (1979)
	Central Russia	19	18–22	25	22–31	Tinus & MacDonald (1979)
Loblolly pine	North Carolina	26	23–29	20	17–23	Bates (1976)
Douglas-fir	Vancouver Island, BC	22	17–25	18	13–22	Brix (1971)
Bur oak	Devils Lake, ND	31	26–32	19	17–26	Tinus & MacDonald (1979)
Redwood	Klamath, CA	19	18–20	16	15–17	Hellmers (1966b)
Western hemlock	Vancouver Island, BC	18	17–20	18	13–20	Brix (1971), Owston & Kozlowski (1978)

* Location from which seed was obtained, not the origin of native stand.
Source: Tinus and MacDonald (1979).

induced to stop height growth and set a terminal bud (fig. 3.1.11A). During the hardening phase, stem caliper and root growth are encouraged and the seedlings are gradually hardened to tolerate handling, storage, and outplanting conditions. Temperature has a pervasive effect on seeding physiology, and thus bud development (fig. 3.1.11), dormancy, and cold hardiness are all affected by the temperature regimes maintained during the hardening phase. Other environmental factors also affect these processes, and so growers use one or more combinations of cultural treatments, including reducing temperature, shortening day length, decreasing nitrogen, and inducing moisture stress to initiate hardening.

For crops grown for more than one season, temperate zone species require a cold treatment before shoot growth can resume (Kramer and Kozlowski 1979). The chilling requirement is more pronounced in northern or continental climate species and ecotypes, but there is usually some requirement for cool temperatures in southern and maritime species. For example, Garber and Mexal (1980) reported that about 7 weeks of cool temperatures were needed before bareroot loblolly pine seedlings would resume normal growth. The exact age or stage of development when the chilling requirement becomes necessary is not known for most species. (The use of low temperatures in developing cold hardiness and in meeting chilling requirements are described in greater detail in volume six of this series.)

Container nursery managers routinely use cooler temperatures, especially at night, to help induce



A B

Figure 3.1.11—*Seedlings must be induced to stop height growth and set a terminal bud* (**A**) *at the beginning of the hardening phase. Temperature can have a significant effect on bud development. For example, the rate of bud initiation of white spruce seedlings* (**B**) *was optimum at ~15 °C (59 °F).* (**B**, *Odlum 1991.)*

shoot dormancy and set terminal buds (table 3.1.2). The response to cooler temperatures is varied, however, and interacts with photoperiod in some species. Lodgepole pine seedlings wll continue height growth over a wide range of temperatures as long as an extended daylength is maintained whereas other species, such as bur oak, may set a terminal bud in response to cool nights regardless of the photoperiod (Tinus 1982). For Scotch pine, the length of the shoot growth period was substantially shorter with warm nights; warm days had a much smaller effect (table 3.1.4).

Many nurseries move their crops from the greenhouse or remove the covering at the beginning of the hardening phase; thus, some of the temperatures reported in table 3.1.2 reflect outside ambient conditions. Even in enclosed growing structures, ambient temperatures are not precisely controlled unless damaging temperature extremes are encountered. Crops that must be left in enclosed facilities are hardened by lowering the temperature in two stages. The first stage reduces day and night temperatures to a level that is suboptimum for rapid height growth but warm enough for cali-

Table 3.1.4—*Days to terminal budset for Scotch pine seedlings raised under 16 different day/night temperature regimes (day temperatures of 15 to 30 °C and night temperatures of 5 to 20 °C)*

Temperatures		Days to terminal budset			
°C	°F	5 °C (41 °F)	10 °C (50 °F)	15 °C (59 °F)	20 °C (68 °F)
15	59	116	120	99	83
20	68	102	104	95	70
25	77	104	99	87	64
30	86	102	101	101	64

Source: modified from Thompson (1982).

per and root growth to continue and for the metabolic changes to occur that result in the onset of hardening. These temperatures are maintained for 4 to 6 weeks. The second stage of hardening requires temperatures just above freezing, especially at night, for 4 to 6 weeks. During this time bud chilling requirements are met, cold hardiness develops, root growth potential rises, and the seedlings become resistant to mechanical damage. The hardening process will proceed most quickly if temperatures during these two stages are kept close to their optimum. Operationally, however, it will often be cheaper to reduce the temperature incrementally, which happens naturally in a crop hardened outdoors, where temperatures eventually reach, or fall below, freezing.

3.1.4 Modifying Temperature in Container Tree Nurseries

The primary purpose of a greenhouse is to control temperature. A greenhouse without temperature control is usually too hot in the day and too cold at night; this is why the seedling environment must be heated or cooled. The recommended targets in tables 3.1.2 and 3.1.3 refer to the temperature setpoints on the heating and cooling systems, and the range gives the temperatures within which the greenhouse should operate most of the time. When temperatures go outside the range, growth is slowed but usually no permanent harm is done unless damaging hot or cold temperatures are exceeded for an extended time. If temperatures are allowed to remain outside the ranges during the establishment or rapid growth phases, seedlings may be stressed into a temporary state of dormancy. When this stressed condition persists, the entire crop production schedule may be seriously delayed. During the hardening phase, bud set or cold hardiness may be delayed or even reversed, leaving the crop in poor condition to be cold stored or outplanted. However, a certain amount of temperature fluctuation is permissible and even desirable. Within this recommended range, a greenhouse is cheaper and easier to operate if its temperature is allowed to fluctuate a few degrees rather than being held to very close tolerances.

In a properly designed greenhouse, stable night temperatures are relatively easy to maintain, because there is no incoming heat load from the sun. However, ambient night temperatures are almost always lower than optimum and supplemental heat is required in the greenhouse. Many species have surprisingly high nighttime optimum temperatures and maintaining them can be expensive, especially during cold weather. One strategy is to lower the night temperature from the optimum to a temperature at which both the growth rate and the cost of heating are acceptable. Another option is to avoid rearing seedlings during the coldest months of the year. (Crop scheduling is discussed further in section 3.3.3.1 and in volume six of this series.)

Even container seedlings grown in outdoor compounds have a significant benefit over bareroot seedlings in that the small volumes of growing media in containers warm much faster than field soil. This feature can also be a hazard, however, because container seedling root systems must be protected against both hot and cold temperature extremes.

3.1.4.1 Growing structures

Producing a uniform growing environment within an enclosed greenhouse is a more complex problem than most people realize. One of the primary reasons to grow seedlings in a transparent growing structure is to trap solar radiation and convert it to thermal energy (fig. 3.1.1), but this free source of heat energy can also create problems:

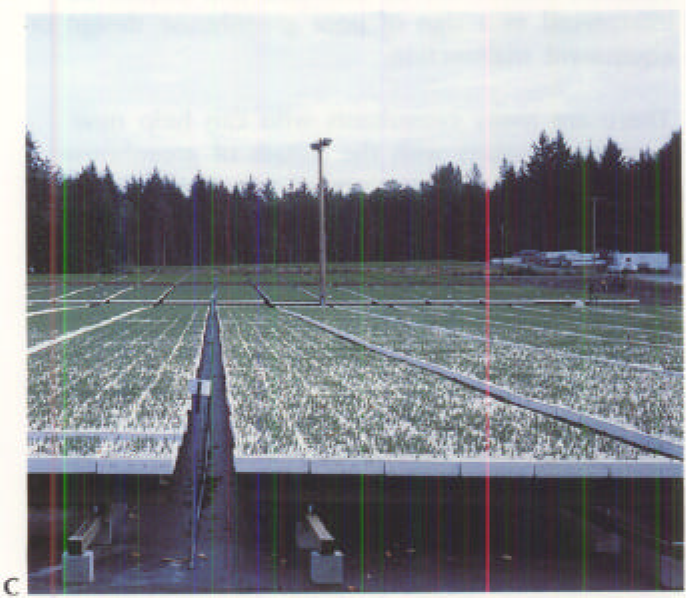
1. Heat builds up very rapidly on sunny days, even in the winter.
2. Cooling occurs rapidly in poorly insulated structures at night and during cloudy weather.
3. The high humidities that are maintained in enclosed growing structures significantly affect the heat budget of a container nursery because of the latent heat consumed in evapotranspiration or released during condensation.

The type of greenhouse or other growing structure can vary with the growth stage of the seedlings. Enclosed, heated greenhouses are routinely used during the establishment phase to speed germination and early seedling growth. Even the location within a heated greenhouse is important; many nurseries grow their container seedlings on benches and some provide underbench heating. Underbench heating increases temperature uniformity within the greenhouse. Hallet and others (1985) found that the emergence rate for black spruce seedlings was significantly faster in heated than in unheated greenhouses and was most rapid when the sown containers were placed on raised benches or directly on a heated floor (fig. 3.1.9).

Some container nurseries even have special germination rooms that are kept uniformly warm, humid, and light to stimulate rapid germination (fig. 3.1.8). Matthews (1982) stated that, in British Columbia, well-insulated greenhouses are modified to serve as germinators by installing efficient heating systems and special mist irrigation equipment. Sown containers are stacked 12 high on pallets and moved into the germinators for approximately 7 days. He concluded that germinators improve both the rate and percentage of germination and may also reduce total heating costs. Other nurseries move their seeded containers directly into the production greenhouse.

Most container tree nurseries still grow their seedlings in some sort of greenhouse during the rapid growth phase, and all growing structures have specific design features to help control temperature. **Fully controlled greenhouses** are equipped with heating and cooling equipment to control temperature throughout the growing season (fig. 3.1.12A). **Semicontrolled environments,** often called shelterhouses, have roll-up side and end walls that can be raised to promote cross ventilation (fig. 3.1.12B). Shelterhouses are particularly useful during late spring and early summer when solar radiation is most intense and during the hardening phase when low night temperatures are desired. In recent years, some forest nursery managers are growing their stock in uncontrolled environments, sometimes called **outdoor growing compounds** (fig. 3.1.12C), in which temperature cannot be controlled. (More information on types of growing structures can be found in volume one of this series.)


B


C


A

Figure 3.1.12—*The type of growing structure has a significant effect on the degree of temperature control that can be achieved and the cultural methods that can be used. A fully controlled environment* (**A**) *has heating, cooling, and forced air circulation capabilities. A semicontrolled environment, such as this shelterhouse* (**B**), *has forced air heating but also features roll-up sides that allow the grower to regulate temperature with cross ventilation. In recent years, container tree seedlings have been grown in outdoor "growing compounds"* (**C**) *that have no temperature control at all.*

3.1.4.2 Temperature modification equipment

Although greenhouses are not as sophisticated as growth chambers, modern environmental control equipment can regulate the indoor climate very well. However, most growers cannot afford and do not need truly precise control and thus must be content with some fluctuation in environmental conditions, including temperatures outside the permissible range for a small portion of the time (usually less than 5%). Daytime temperatures will fluctuate more than those at night because solar radiation load varies tremendously. Nighttime temperatures in a well-designed greenhouse will be quite stable and very close to the setpoint. Poor control of temperature can cause serious problems during critical periods in the crop cycle such as germination and emergence. Excessive temperature variation should not be tolerated and should be interpreted as a sign of poor greenhouse design or equipment malfunction.

There are many consultants who can help new nursery managers with the details of greenhouse design, layout, and equipment selection. Hiring a greenhouse consulting service may be too expensive for a small nursery operation, however. The other option is for the nursery developer to learn as much as possible about the types of structures and equipment. Without the services of a knowledgeable consultant, a basic understanding of the calculations for heating and cooling a growing structure is essential. Armed with this knowledge, the developer can critically review construction proposals provided by manufacturers from both a technical and an economical standpoint.

A critical first step is to visit other local nurseries, especially those with a similar crop, and see what structures and equipment they are using. Most growers will gladly point out both the good and bad points about their facilities, and especially what they would do if they had to build their operation over again. They should also be able to evaluate the reliability and competence of local greenhouse distributors and consultants. Nursery developers should deal with distributors who carry a full line of greenhouses and equipment to assure several choices of component combinations and prices. Economics of design and frequency of sale of a given structure or equipment model often can affect prices drastically. Whenever dealing with greenhouse suppliers or consultants, nursery managers should be sure to point out the unique requirements of a tree seedling crop compared to other horticultural crops, such as the long growing cycle and the need to harden the seedlings adequately. The temperature control system for a growing structure is usually designed around a particular crop and a specific growing season but with enough flexibility to change crops or growing schedules to some extent.

Other aspects of the nursery (benches, containers, etc.) must be considered in the design of the original growing structure and selection of environmental control equipment. For example, raised benches are often used in container tree nurseries to allow for underbench heating and ventilation. However, if the containers will be grown on special pallets that will be handled with forklifts, then the floor area must remain clear of obstructions and the heating and cooling equipment situated overhead.

Several good technical references are useful guides in designing a heating or cooling system. These publications contain good discussions of the basic principles and tables of environmental and engineering specifications, as well as step-by-step worksheets and examples. The Greenhouse Climate Control Handbook (Acme 1988), ASHRAE (1989), and Ball RedBook (Ball 1985) are particularly useful. Good information can also be found in various greenhouse books (Hanan and others 1978, Langhans 1980, Nelson 1985, Garzoli 1988, Aldrich and Bartok 1989).

3.1.4.3 Cooling

In many parts of North America, cooling a greenhouse is more of a problem than heating it, especially in the spring and summer, when the maximum amount of sunlight is available and most tree seedling crops are grown. Efficient cooling presents a serious technological challenge (Garzoli 1988). The sunlight that is so necessary for photosynthesis generates excess heat that can adversely affect plant growth. On a clear day, solar radiation will generally provide more thermal energy than is lost through the structure, even if the outside temperature is below freezing (Hanan and others 1978). In addition to cooling, adequate ventilation is often necessary to control excessive humidity. (The effects of humidity are discussed in chapter 2 of this volume.)

Greenhouse cooling and heating systems typically consist of a series of successive stages. The first stage of most cooling systems mixes the hot air in the structure with cooler air from the outside. The cooling capacity of a ventilation system is expressed as the rate of air exchange and is measured in the number of air changes per hour, which is the number of times that the volume of air in the greenhouse can be exchanged for outside air in 1 hour. Two site factors affect the efficiency of cooling with air exchange: 1) intensity of solar radiation, because air warms as it moves across the greenhouse from the intake vents to the exhaust vents, and 2) elevation, because the lighter air at high elevations is less effective in removing solar heat. As an example, an air exchange rate of 2.4 $m^3/min/m^2$ (8 cubic feet per minute per square foot) of greenhouse space is considered to be adequate for a greenhouse located at elevations below 300 m (1,000 feet), with an interior light intensity of 53.8 klux (1,000 $\mu mol/s/m^2$) and a temperature rise of 4 °C (7 °F) from the cooling pads to the exhaust fans (Nelson 1985).

Three basic types of greenhouse cooling systems are used: **convection ventilation, fan ventilation,** and **evaporative cooling.** They may be employed singly but are often used in combination. A fourth method-refrigerated cooling-is rarely used because it is uneconomical except in special situations.

Convection ventilation. This basic type of greenhouse cooling uses the least amount of energy; it operates on the fact that hot air is lighter than cooler air. Vents at the top and sides of the greenhouse are opened, which allows hot air to escape by convection and be replaced by cool air from the side vents (fig. 3.1.13A). The vents can be either manual or automatic, and thermostatically controlled vents can provide a reasonable degree of temperature control when the outside air remains cool.

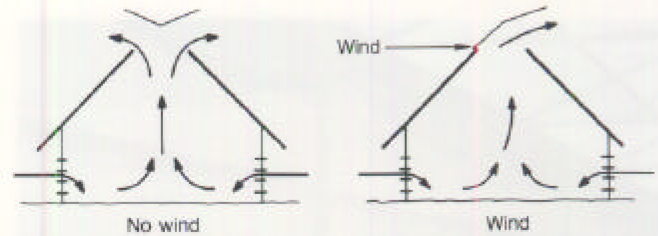


Figure 3.1.13—*Convective ventilation utilizes top and side vents to create a convective column to draw in cool air on the sides and let hot air escape out the top* (**left**). *In winds greater than 10 km/h (6 miles per hour) the vent on the windward side should be closed and the vent on the leeward side opened wide to increase airflow* (**right**). *(Modified from Langhans 1980.)*

With convection ventilation, the degree of temperature control depends upon four factors: type of growing structure, location and position of vents, wind speed and direction, and the temperature differential between inside and outside. The curved roofs of some growing structures, such as polyethylene-covered quonset houses, do not have conventional ridge ventilation or vents on the side walls (Garzoli 1988). Taller greenhouses generally ventilate better than those with low profiles because they generate a better convection column. Shelterhouse structures are specifically designed to promote good natural ventilation, and their roll-up sides can be operated either manually or automatically (fig. 3.1.12B). Some greenhouses are now equipped with Poly-vent° walls, which create a rigid side wall when inflated and collapse to allow good cross ventilation when deflated (fig. 3.1.14).

Vents must be properly located and operated for effective natural ventilation. Under calm conditions, all vents should be wide open and the greater the temperature differential between inside and out, the greater the airflow. When the wind speed exceeds about 10 km/h (6 miles per hour), the side vents and leeward roof vent should be opened to their widest position and the roof vent on the windward side should be closed (fig. 3.1.13B). This causes a slight lowering of the air pressure right above the leeward vent and increases airflow (Langhans 1980). Cooling with convection ventilation is widely and effectively used in container tree nurseries in the Pacific Northwest and the

Figure 3.1.14—*Greenhouses with Poly-vent® sides can deflate the panels to generate good cross ventilation during hot weather. During the winter, the sides can be inflated to provide heat insulation.*

Canadian Maritimes, where temperatures rarely exceed 38 °C (100 °C) at mid-day in the summer.

Even with well-designed systems, there are some drawbacks to convection ventilation systems. Convective systems cannot reduce temperatures below the outside ambient environment, and will increase evapotranspiration in dry, sunny climates. Roof vents must be closed during unusually high winds or they may be damaged.

Fan ventilation. When convection ventilation is ineffective, exhaust fans can be used to increase the air exchange rate through a greenhouse. Fan ventilation is more efficient than convection ventilation because the laminar flow from a properly designed system cools only the area around the crop, not the air in the upper strata of the greenhouse (Langhans 1980).

A fan ventilation system consists of a series of vents for air intake on one end wall of the greenhouse and a combination of exhaust fans and vents on the opposing end (fig. 3.1.15). Greenhouse exhaust fans are generally of the propeller

A

B

Figure 3.1.15—*A fan ventilation system greatly increases the air exchange rate and hence the cooling capacity of a greenhouse. A typical system consists of louvered vents on one end wall (**A**) that open automatically when the exhaust fans on the other end (**B**) are turned on.*

type and must be able to function against the slight negative pressure that exists in a closed greenhouse. Special louvered intake vents are often used and are designed to remain closed normally, and to open only under the negative pressure created by the exhaust fans or when their opening motor is turned on.

The position of the fans and vents will depend on the type of greenhouse, its orientation, and the prevailing wind direction. Fans should be located to draw air across the longest dimension up to a maximum of 70 m (230 feet). This limitation is a compromise between efficient use of the tempered air and the temperature rise from the vents to the fan. It is more efficient to locate fans and vents on the end walls because fewer exhaust fans are needed, and it is much easier to create uniform conditions due to the laminar flow that is created. To be most effective, fans should be on the side opposite the normal direction of the wind and, where greenhouses are located close together, fans should not be positioned directly opposite one another. Other aspects of fan placement are covered in Nelson (1985) and Langhans (1980).

The capacity of fan ventilation systems can be measured in air exchange rates; obviously, the greater the exchange rate, the better the ventilation (table 3.1.5).

To achieve better air exchange and mixing, some greenhouses have installed **tube ventilation** systems, which use large-diameter, flexible plastic tubes with regularly spaced holes to draw cooler outside air into the warm top of a greenhouse (fig. 3.1.16). **Fan-jet ventilation** systems (fig. 3.1.17A) combine exhaust fans with a tube ventilation system to regulate air temperature and humidity efficiently within a growing structure (Langhans 1980). When the temperature or humidity is optimum, the system recirculates the air within the greenhouse (fig. 3.1.17B), but when they become too high, the exhaust fan removes inside air and the inlet louver opens to let in cooler outside air (fig. 3.1.17C).

There are also disadvantages to fan ventilation. The amount of air that can be economically drawn through a greenhouse with fan ventilation has a limit, and three air changes per minute is considered to be the maximum (Langhans 1980). If there is a power failure and greenhouse cooling is totally dependent on fans, the temperature can rise to damaging levels quickly.

Evaporative cooling. This popular greenhouse cooling system is based on the fact that a significant amount, 585 kcal/l (8,900 Btu/gal), of latent heat is absorbed when water evaporates. Therefore, when dry air from outside the greenhouse is

Table 3.1.5—*The amount of heat removed from a greenhouse cooled by ventilating with outside air and lowering the temperature of the incoming air with an evaporative cooling system is a function of the volume of air that can be moved through the greenhouse and the temperature difference between the outside and inside air**

Vol. of air moved		Heat removed (× 1,000 kcal)		
Air exchanges per minute	Fan rating (m^3/min)	5 °C difference (9 °F)	10 °C difference (18 °F)	15 °C difference (27 °F)
0.5	300	25	50	75
1.0	600	50	100	150
1.5	900	75	150	225
2.0	1,200	100	200	300
3.0	1,500	125	250	375

* Assuming a 600 m^3 (21,200 ft^3) greenhouse at sea level, and an inside temperature of 20 °C.
Source: modified from Langhans (1980).

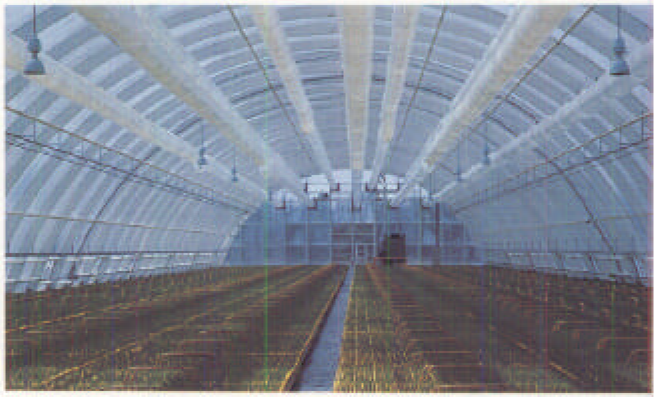


Figure 3.1.16—*Convection ventilation can be increased with tube ventilation systems, which introduce cool, dry air into the warm, humid top of the greenhouse. Any overhead equipment can, however, produce shadows that may reduce photosynthesis and affect growth if they persist in the same area.*

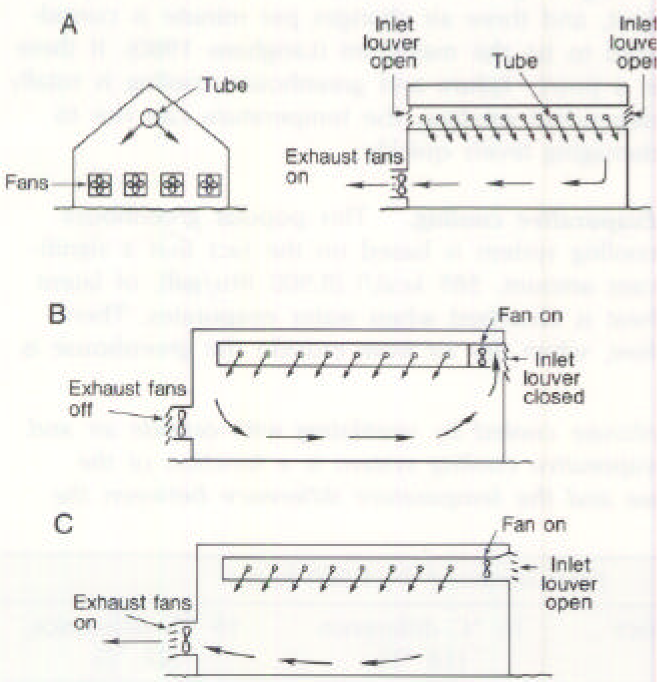


Figure 3.1.17—*Fan-jet ventilation systems (**A**) use louvered vents and exhaust fans in addition to ventilation tubes to promote better air exchange. With the inlet louvers closed (**B**), a fan-jet system recirculates air in the greenhouse; with the louvers open (**C**), the fans can be modified to introduce cooler, outside air. (Modified from Langhans 1980.)*

drawn by a fan through a water-soaked pad, it is cooled by the evaporating water, and the amount of heat removed can be substantial (table 3.1.5). The common home "swamp cooler" is a miniature version of an evaporative cooling system.

The potential for using an evaporative system to cool a container nursery structure depends on the water vapor pressure deficit of the outside air and the thermodynamic efficiency of the system. The drier the outside air, the lower the temperature to which that volume of air can be cooled (fig. 3.1.18). The procedure for evaluating the cooling potential utilizes a psychrometer and a psychrometric chart to determine the wet-bulb depression, which indicates the drop in temperature that can be expected through evaporation (Langhans 1980).

A typical evaporative cooling system consists of absorbent pads with a water pump and sump to keep the pads wet on one wall, and exhaust fans on the opposing wall to draw air uniformly through the pads and across the growing area (fig. 3.1.19A). The efficiency of an evaporative system is dependent on many design and engineering factors, such as type and thickness of the pad material and position of pads and fans and is expressed as the temperature of the air emerging

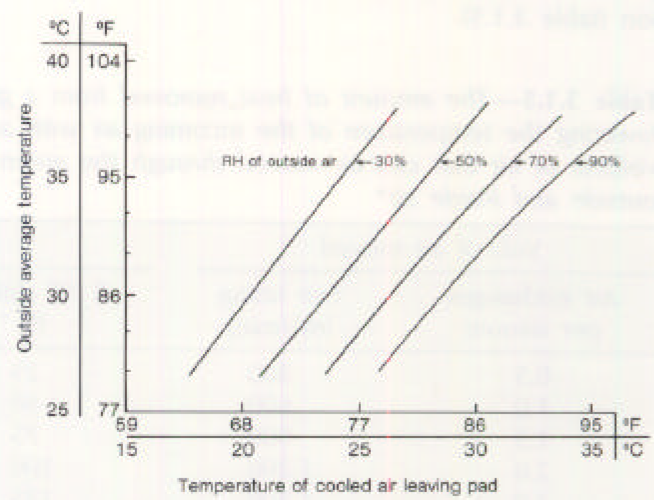
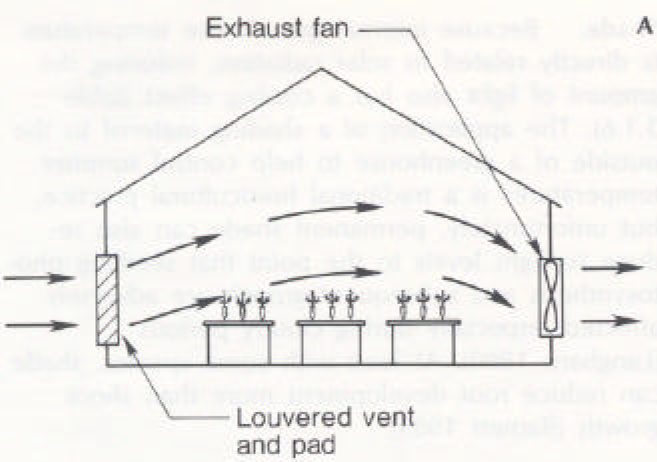
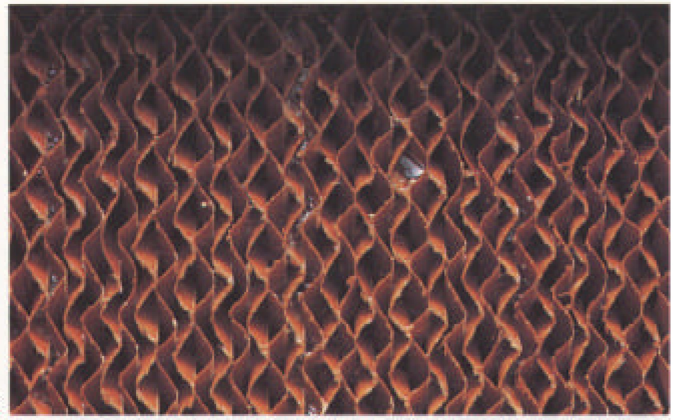


Figure 3.1.18—*Evaporative cooling systems are most effective in dry climates because the amount of cooling increases with the wet-bulb depression, which is a function of the relative humidity (RH) and temperature (modified from Aldrich and Bartok 1989.)*





C

Figure 3.1.19—*A typical evaporative cooling system* (**A**) *consists of a specially designed wet pad on one end wall and exhaust fans on the other. A recirculating pump system* (**B**) *keeps the pad wet* (**C**). *The latent heat of evaporation lowers the temperature of the air coming through the pads and the cool air is drawn across the greenhouse.*

from the wet wall divided by the wet-bulb depression (Nelson 1985). A well-designed system should be able to reduce the in-house temperature to approximately 85% of the wet-bulb depression, although the temperature can be expected to rise from 3 to 4 °C (5 to 7 °F) across the greenhouse due to solar reheating (Ball 1985).

Evaporative cooling systems are common in container tree nurseries in warmer and drier climates, and the most popular is the fan and pad system. Exhaust fans were discussed in the previous section on fan ventilation. Pads are typically mounted vertically (Fig. 3.1.19A/B) and are made of specially treated cardboard (fig. 3.1.19C), which can give 10 years of service. Aspen excelsior, which lasts only one season, was previously used. Horizontal pads, which contain porous gravel or lava rock that is kept wet by mist nozzles, have also been used successfully but are much less common (Nelson 1985).

Winter cooling*.* Due to the high solar radiation loads during clear fall or winter days, it is often necessary to introduce cool outside air into the greenhouse. Cold air can damage succulent seedlings, however, and so must be mixed with the warm, inside air before it is distributed throughout the greenhouse. It is sometimes prudent to introduce dry outside air after irrigation to avoid excessive humidity and the resultant condensation (fig. 3.1.20), which can cause disease problems such as grey mold.

The fan-jet system (fig. 3.1.17A and C) that was described in the previous section on fan ventilation has proven to be an effective method of mixing and distributing outside air throughout the greenhouse during cold weather. Several companies sell specially designed environmental control systems that can accommodate the demands of winter cooling.

Cultural techniques*.* In addition to the abovementioned structural and equipment options, container nursery managers can cool their crops with several cultural techniques including shading, irrigation, and seed mulches.

Figure 3.1.20—*One common use of "winter cooling" is to remove the warm, humid air that accumulates in closed greenhouses after irrigation. High humidity causes condensation on seedling foliage, which frequently encourages foliage diseases, such as grey mold.*

Shade. Because internal greenhouse temperature is directly related to solar radiation, reducing the amount of light also has a cooling effect (table 3.1.6). The application of a shading material to the outside of a greenhouse to help control summer temperatures is a traditional horticultural practice, but unfortunately, permanent shade can also reduce sunlight levels to the point that seedling photosynthesis and subsequent growth are adversely affected, especially during cloudy periods (Langhans 1980). At least with some species, shade can reduce root development more than shoot growth (Barnett 1989).

In horticultural applications, shade can be either seasonally fixed or movable. Shading compounds, including special shade paints, are considered fixed because they are applied for the entire growing season and may be difficult to remove. Because they function by reflecting a portion of incoming sunlight, only white colors are recommended and the amount of shade is controlled by the thickness of the layer (Hanan and others 1978). Shade paint usually weathers or washes away, or is designed to peel off with the first hard frost.

Fixed lath can also be used to produce permanent shade, and some container nurseries use special lath houses to both shade and protect seedlings during the hardening phase and for overwinter storage. Standard shadeframes are made from snowfence, which consists of strips of wooden lath connected by wires with alternate open spaces that produce 42% shade. Although some container nurseries produce seedlings in shadehouses, this amount of shade is generally considered to be too high for most species.

A variety of different brands of synthetic shadecloths can be used to generate permanent shade (fig. 3.1.21A). They are available in different materials or weaves that will generate any amount of desired shade, ranging from 25 to 90%. Although shadecloth can be mounted inside the growing structure, this is not recommended because it will absorb solar radiation and interfere with proper ventilation, thereby contributing to the heat load (Davis and Cole 1976). Mounting shadecloth outside is a better option because, if properly installed, it will not be damaged by wind or hail

Table 3.1.6—*Shading a growing structure can effectively lower both foliage and air temperatures*

Type of growing structure	Light intensity		Air temperature		Leaf temperature	
	µmoles/s/m²	ft-candles	°C	°F	°C	°F
Unshaded	1,370	70,200	36	97	40	105
50% Shadecloth	525	27,000	32	90	32	89

Source: Gray (1948).


A

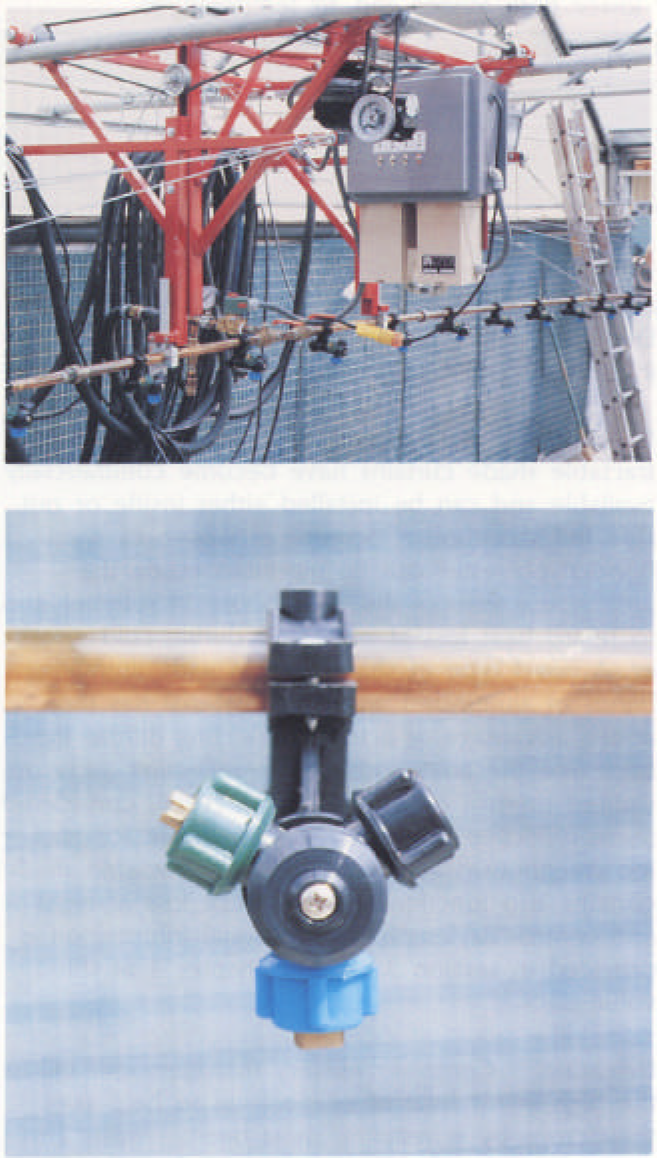

B

Figure 3.1.21—*Synthetic shadecloth, traditionally used to to cool greenhouses, is installed and left on throughout the summer months* (**A**). *When light intensity declines in the fall, shadecloth must be removed* (**B**).

and will dissipate the heat outside the greenhouse. Deploying and removing shadecloth are often labor intensive (fig. 3.1.21 B).

In the past few years, mechanically controlled retractable shade curtains have become commercially available and can be installed either inside or outside the greenhouse. Screens of woven or spun-bonded polyester can be mounted inside the greenhouse to cool the greenhouse in summer and to retard heat loss at night and during cold weather. A novel type of shade curtain with alternating bands of aluminized and clear material has the added advantage of actually reflecting diffuse light back into the greenhouse while reflecting away unwanted thermal radiation. Garzoli (1988) considered these reflective shade screens invaluable for cooling greenhouses across Australia. (Retractable shade curtains also function to retard heat loss at night and control daylength, so additional information is provided in section 3.1.4 and chapter 3 of this volume.)

Irrigation. Container nursery managers can utilize the high latent heat of evaporation to help cool their crops by scheduling short bursts ("mists") of irrigation during the hottest time of day. This is particularly effective during the establishment phase, when the young, succulent germinants can be easily damaged by high temperatures at the surface of the growing medium. Mist cooling can also supply the young seedlings with enough water without saturating the medium. Some nurseries have outfitted their moveable irrigation booms (fig. 3.1.22A) with multiple-position nozzles that contain a mist head in addition to the standard irrigation nozzle (fig. 3.1.22B). Older seedlings can also be cooled with irrigation, but this is usually done on a periodic basis to supplement the standard cooling system during unusually hot weather.



A

B

Figure 3.1.22—*Seedlings can be cooled by frequent, light irrigations. Some container nurseries have moveable irrigation booms* (**A**) *that are equipped with compound spray heads that contain a mist nozzle as well as the standard irrigation nozzle* (**B**).

Running water over the outside of a greenhouse will reduce internal air temperatures, and it can be applied with a sprinkler in emergency situations. However, research trials that selectively filtered out all of the thermal wavelengths of solar radiation by continuously running a film of water or dye solution over the surface of the greenhouse did not provide adequate cooling (Garzoli *1988).*

Seed mulches. Using a light-colored seed mulch after sowing (fig. *3.1.7)* will also help prevent damaging surface temperatures. Dark mulches absorb more solar radiation and quickly reach temperatures that can scald the succulent stems of young tree seedlings. Light-colored mulches in combination with mist cooling are particularly effective in preventing heat damage to the stems of young seedlings. (Heat injury is discussed in greater detail in volume five of this series.)

3.1.4.4 Heating

Even if greenhouses receive a surplus of free solar heat during daylight hours, they must still be equipped with heating systems to keep the crops warm at night and to supplement solar radiation on cloudy days. Heating systems have become quite efficient over the years, but a greenhouse is a difficult structure to keep warm enough to grow a crop. Growing structures are designed to capture as much sunlight as possible, but are inherently poorly insulated. In northern climates, the cost of fuel is usually a limiting factor and so container nurseries must be carefully designed so that they can be heated both efficiently and economically.

Calculating heating requirements. The basic concept in heating a growing structure is to add heat at the same rate as it is lost, and so the heating system must be matched to the properties of the growing structure. The majority of heat is lost by conduction through the supporting materials that hold the greenhouse cover and the covering material itself. Remember that heat losses are not the same for all covers. For example, fiberglass panels lose only 1 % of the total incoming radiation, compared to 4.4% for glass and *70.8%* for a single layer of polyethylene film. Adding a second layer of polyethylene to create an insulating air space reduces the heat loss by almost 40% (Nelson 1985). Cold air infiltrating through cracks and around doors also accounts for a considerable loss of heat. Greenhouse heating specialists take measurements of greenhouse surface area and apply coefficients of heat loss to compute a rough estimate of total heat loss for the structure. If a more accurate estimate of heating requirements is needed, other factors such as wind velocity must be considered (Langhans 1980, Acme 1988). The heating requirements for a container nursery will vary during the calendar year; they are highest in the winter when solar input is least and cloud cover is greatest, but become negligible during the summer months (table 3.1.7).

Types of fuels. The choice of a fuel to heat a greenhouse is critical because fuel can significantly affect operating costs if crops are to be grown during periods of cold weather. Although cost is often the most obvious consideration, other fuel and heating equipment factors must be evaluated: availability (particularly dependability of supply), convenience of use and storage, and cleanliness. Considerations related to the heating equipment include operating requirements, service requirements, and ease of control (ASHRAE 1989). Most common types of fuels have been used to heat greenhouses, but some locally cheap and abundant fuels, such as coal, may be unsuitable because of their air pollution potential. The following general discussion of common greenhouse fuels is presented in order of preference, based on the Container Nursery Survey (table 3.1.8). More specific information can be found in Langhans (1980), Nelson (1985), and ASHRAE (1989).

Gas. Natural gas is composed mostly of methane and ethane, depending on its geological source; for safety purposes, mercaptans are added to produce a noticeable odor. Where available, natural gas is a preferred fuel for heating greenhouses because the initial installation of heaters is easy and inexpensive, storage tanks are not required, and the gas burns hot and clean. Natural gas was used in 33% of the forest nurseries surveyed in 1984 (table 3.1.8). Air pollution is not a problem because the only byproducts of natural gas combustion are water vapor and carbon dioxide.

Table 3.1.7—*Monthly heating requirement for a greenhouse in State College, PA*

Month	Average degree-days	Percentage of total heating season
January	1,401	24
February	933	16
March	608	10
April	379	7
May	139	2
June	44	1
July	0	0
August	12	0
September	83	1
October	439	7
November	766	13
December	1,130	19
Total	5,934	100

Source: Pennsylvania State Department of Horticulture, as presented in Ball (1985).

Liquefied petroleum (LP) gases (propane, butane, and mixtures of the two) are commercially produced as byproducts of oil refineries or by stripping natural gas. They share most of the advantages of natural gas but are generally more expensive and must be stored in tanks (fig. *3.1.23).* Propane is the only practical LP gas for most forest nurseries because it can be used at below-freezing temperatures whereas butane cannot. In spite of its higher cost, propane was the second most commonly used fuel because it has the same characteristics as natural gas and can be transported by truck to remote locations (table *3.1.8).*

Oil. Heating (or fuel) oil is also commonly used in container tree nurseries (table 3.1.8). Heating oil comes in several grades that are determined by viscosity (which increases with the number of the grade) and other suitability factors. The heavier oils cost slightly less and have a higher heat content but must be preheated before they can ignite (ASHRAE 1989). Grade #1 is kerosene, which is not typically used for greenhouse heating; #2 is the common fuel used for unit heaters because it does not have to be preheated. Because of their higher viscosities, grades 4, 5, and 6 are only useful for the larger furnaces used in central heating systems (Bartok 1990). Their sulfur contents are also a consideration and are related to grade, ranging from an allowable maximum of 0.64% for #2 heating oil to 4.00% for #6. In addition to their air pollution potential, high-sulfur fuels are more corrosive to heating equipment.

Electricity. Electric heat is not a common source of heat in ornamental nurseries, but was the fourth most popular in the Container Nursery Survey (table 3.1.8). This popularity is probably a reflection of the fact that electricity can be easily transmitted to locations where few other fuel options are available. In addition to being the most efficient source of energy for heating (table 3.1.8), electricity has the advantage of being quiet, clean, and non-polluting. However, it is by far the most expensive energy source.

Figure 3.1.23—*Propane gas is a popular fuel for heating greenhouses in remote forest nurseries.*

Table 3.1.8—*Heating properties for commonly used fuels in North American container nurseries*

		Typical fuel value				
		Metric units		English units		
Heat source	Use in forest nurseries (%)	wt (kcal/g)	vol (kcal/l)	wt (Btu/lb)	vol (Btu/ft³)	Heating efficiency (%)
Natural gas*	33	14.3–15.4	10.4–21.8	23,600–25,500	890–1,860	65–87
Propane†	24	13.8	8,000	22,900	794,000	65–87
Fuel oil	24					
#2 Grade	—	10.6	10,100	17,500	1,038,000	70
#6 Grade	—	11.7	11,200	19,300	1,147,000	65
Wood	5	4.6	2,760	7,560	283,500	60
Coal	0	7.2	14,400	12,000	1,500,000	62
		Typical energy value				
		Metric units		English units		
Electricity	9	860 kcal/kwh		3,412 Btu/kwh		100
Solar radiation	2	1.4–3.3 kcal/day/m²		500–1200 Btu/day/ft²		N/A
Waste heat	3	Variable—see example in text				

* Natural gas consists of varying mixtures of methane and ethane, which have different fuel values.
† Propane is supplied as a pressurized liquid, but burned as a gas.
Source: modified from Nelson (1985) and Langhans (1980).

Wood. In some areas of North America, where wood is cheaply and readily available, wood is being used to heat container tree nurseries (fig. 3.1.24). Compared to other fuels, wood has a relatively low heat output (table 3.1.8), is bulky to handle, and creates a considerable volume of ash, which must be removed. However, wood is a good, relatively nonpolluting fuel when burned in a properly designed and maintained furnace. Wood pellets are a recent innovation that may prove practical for heating greenhouses, especially in areas where other fuels are unavailable.

Coal. Coal was a traditional fuel for heating greenhouses but is not commonly used in container tree nurseries (table 3.1.8). Where readily available, coal is generally the cheapest fuel but is bulky to handle and store. Some grades are high in sulfur and are therefore unsuitable because of air pollution concerns.

Since the fuel crises of the 1970's, container nursery managers have become much more cost conscious when it comes to heating fuels and many new options are being explored:

Figure 3.1.24—*Heating with wood is a natural alternative in forest nurseries because wood is readily available and inexpensive at many locations.*

Waste heat. A few forest nurseries have converted to using heat generated from other industries for growing tree seedlings (table 3.1.8). As an example, for every 1 billion kcal that are converted into electricity at generating plants, another 1 billion kcal are lost in the cooling water. This hot water could easily be used for heating greenhouses (Langhans 1980). One nursery reported that cooling water at 32 °C (90 °F) from a power plant supplied 750,000 kcal/h of heat for their greenhouses (Container Nursery Survey).

Solar heat. By their very design, all greenhouses use solar energy to supply at least part of their heating requirements. A few forest nurseries reported that solar energy was their main source of heat (table 3.1.8). Many different solar heating systems have been designed for greenhouses (fig. 3.1.25A), but they have not been widely adopted because of the low cost and availability of fossil fuels. However, container nursery managers can make minor structural modifications to capture the solar energy that is so abundant during the daytime and store it for use during the night (fig. 3.1.25B). Thermal insulating blankets are another simple design feature that are very effective in retaining captured solar energy. (See the following section on heat conservation for more details.)

Beaters and heat distribution systems. Once the type of fuel has been selected, the next step is to convert it into usable heat and the first decision is whether to use **central** or **unit heaters.** With a large central heating system, one or two large boilers are located in a single position (fig. 3.1.26A), and steam or hot water is piped to the various surrounding growing structures (fig. 3.1.26B). These systems require a larger initial investment-$16 to $32/m2 ($1.50 to $3.00 per square foot)-and thus are only economical for large-scale nurseries.

Unit heaters are much smaller and are located in each growing structure (fig. 3.1.27A), where they distribute the heat-hot air, water, or thermal radiation directly to the crop (fig. 3.1.27B). They are more practical for smaller nursery operations and cost approximately $2.70 to $10.80/mz ($0.25 to $1.00/ft2) (Nelson 1985).

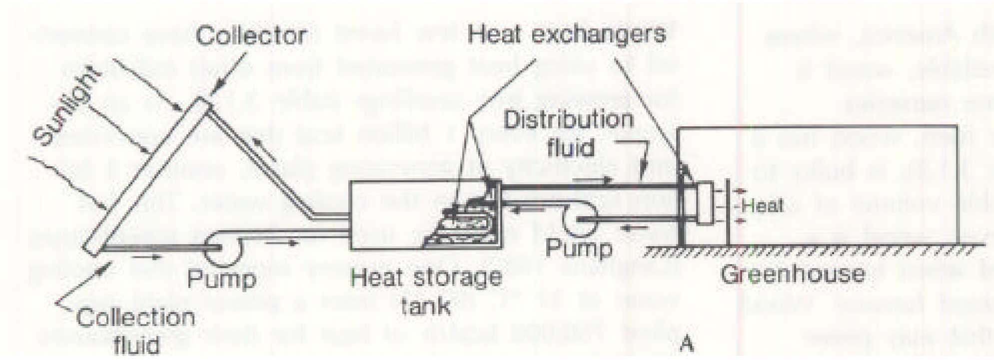


Figure 3.1.25—*Although many systems have been designed for greenhouses* (**A**), *few forest nurseries rely solely on solar heat. Container nursery managers can, however, modify their growing structures to capture solar energy and retard its loss at night. Black barrels filled with water are heated by the sun during the day and give off heat at night* (**B**). (**A**, *courtesy of D.H. Willits.)*

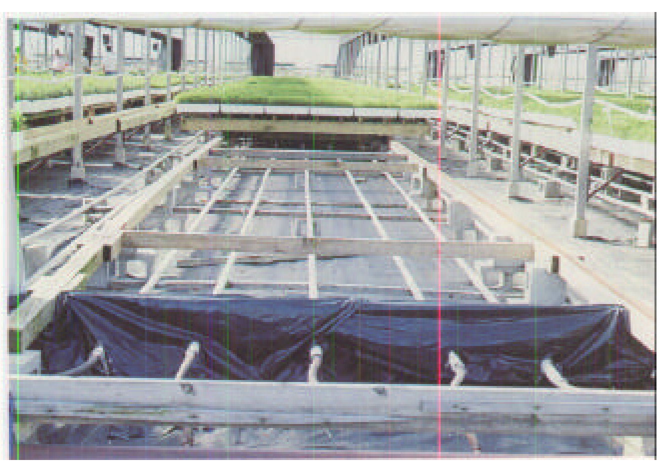
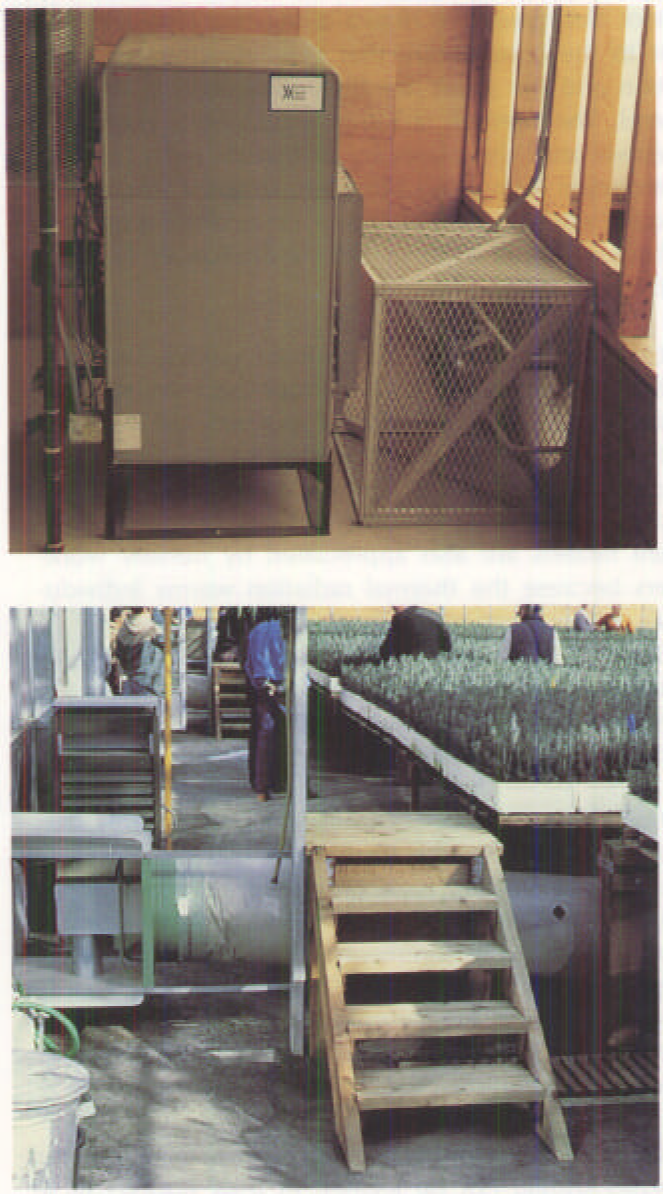


Figure 3.1.26—*Central heating systems use a large boiler* (**A**), *generally located in a separate building, to generate hot water or steam that is distributed through pipes to heat a number of surrounding growing structures* (**B**).



A

B

Figure 3.1.27—*Unit heaters are relatively small and are located in each growing structure* (**A**), *where they can be positioned to distribute heat directly to the seedling crop* (**B**).

Steam or hot water. A traditional system for heating greenhouses is to heat steam or hot water in a central boiler (fig. 3.1.26A), but new high-efficiency boilers are small enough to fit within individual houses. The hot water or steam is circulated through either plain or tinned tubing around the walls, overhead, under benches (Fig. 3.1.26B), or in the floor. Heat radiating from these tubes circulates throughout the greenhouse by convection, and so the location of the heating tubes is critical. ,Although steam is a more efficient way to transfer heat, it has more maintenance problems. Hot water systems ;generally provide more uniform temperatures (Langhans 1980). Large central heating systems are most efficient when operated at full capacity, and so must be properly matched to the size of the nursery operation. Steam or hot water heating was used by approximately 26% of the container tree nurseries surveyed in 1984.

Warm air. Many container nursery operations use small, self-contained unit heaters to heat individual growing structures with warm air (fig. 3.1.27A). These forced air heaters burn fuel in a lower combustion chamber and the hot gases rise through heat exchanger tubes and are exhausted through an outside stack. A fan in the rear of the heater blows through the heat exchangers and the warm air is either discharged directly into the greenhouse or into a fan-jet distribution system (fig. 3.1.27B). The latter is much preferred because direct discharge systems create problems with heat circulation, and warm air blowing directly onto the crop can cause excessive drying (Langhans 1980). Forced air unit heaters are the most common type (71 %) of heating system used in forest tree nurseries. The distribution tubes are often placed under the benches (fig. 3.1.27B) so that the warm air will rise through the seedlings, warming the growing medium and drying the foliage. Under-bench heating is particularly effective in reducing the incidence of certain fungus pests, such as grey mold.

Radiant heaters. In the past decade, some container tree nurseries (2%) have installed overhead radiant heating systems (fig. 3.1.28A), also called **infrared heaters**. These low-energy unit heaters consist of a series of small gas burners that are regularly spaced along a metal pipe (fig. 3.1.28B).

A

B

Figure 3.1.28—*Overhead radiant heaters* (**A**) *warm objects (seedlings and workers) without raising the temperature of the surrounding air. Gas is burned in combustion chambers located along the heat pipe, which is equipped with metal shields to reflect the infrared radiation downward* (**B**).

Hot flue gases are drawn along the pipe and heat it to the temperature that generates infrared radiation and the gases are then exhausted at the far end. The thermal radiation produced is directed down onto the plants by aluminum reflectors mounted above the hot pipe. Infrared heaters are quite energy efficient; some ornamental growers have reported a 30 to 50% reduction in fuel use (Nelson 1985).

One unique feature of overhead radiant heaters is that the plants are kept warmer than the surrounding air because the infrared rays are not converted to heat until they are absorbed by the plants. This practically eliminates condensation, which is one of the major causes of foliar disease. Overhead radiant heaters are also appreciated by nursery workers because the thermal radiation warms individuals without unnecessarily warming the air (fig. 3.1.28A). One drawback of the system is that, after seedling crown closure, the foliage absorbs all the heat and so the growing medium may remain too cool (Langhans 1980).

Heat conservation. During the energy crisis of the early 1970's, the increasing cost and scarcity of traditional heating fuels prompted an active research and development effort to reduce greenhouse energy requirements. Now, well-designed growing structures are much better insulated and equipped with energy-efficient heating systems. The following suggestions should be considered when designing a container tree nursery:

Select sheltered nursery sites. Container tree nurseries should not be located in frost pockets or in windy, exposed locations. Windbreaks can be effective in reducing conductive heat loss as long as they do not shade the growing area. (Site selection is discussed in more detail in volume one of this series.)

Maximize the capture of solar energy. Prevent shading within the growing structure by minimizing overhead piping and frameworks. Overhead heating or cooling equipment can create shade patterns that may reduce photosynthesis (fig. 3.1.16). Keep the greenhouse covering material clean and regularly replace weathered sections.

Insulate the growing structure. Insulation is particularly important in container nurseries because greenhouses can lose heat 5 to 10 times faster than an average residential house. Langhans (1980) discusses options that can significantly reduce heat losses. These are addition of 1) an extra plastic cover over the greenhouse to create an insulation air space, 2) retractable heat curtains, and 3) permanent insulation for north wall and roof areas.

An extra plastic covering is effective on structures constructed of either polyethylene sheeting or rigid panels. Houses covered with double layers of polyethylene are equipped with a small blower that maintains an insulating space of dead air between the layers, and energy savings of 30 to 40% over single layer structures have been reported. Approximately two-thirds of the nurseries in the Container Nursery Survey had energy-efficient double-layer coverings. (See volume one in this series for more information on growing structures.)

Retractable heat curtains can be extended out over the crop at night to reduce both radiation and convection losses (fig. 3.1.29A) while not interfering with needed sunlight during the day (fig. 3.1.29B). Almost any material that can be suspended on wires and pulled back and forth with a pulley system can be used as a thermal blanket. Sophisticated automatic systems are commercially available and can be installed in any type of growing structure without interfering with photoperiod lights or the irrigation system (fig. 3.1.29C). Retractable curtains are also used for shade cooling (see section 3.1.4.3) and photoperiod control (see chapter three in this volume).

Adding insulation, especially below bench height and on north walls (fig. 3.1.30A), can be effective in retarding heat loss. Tests have shown that a net loss of sunlight occurs through the north wall of a growing structure, and so covering the north wall and roof with reflective insulating material can retard heat loss while actually increasing photosynthetic active radiation; other inflatable insulating layers can be installed overhead (fig. 3.1.30B), or along the sidewalk (fig. 3.1.14).

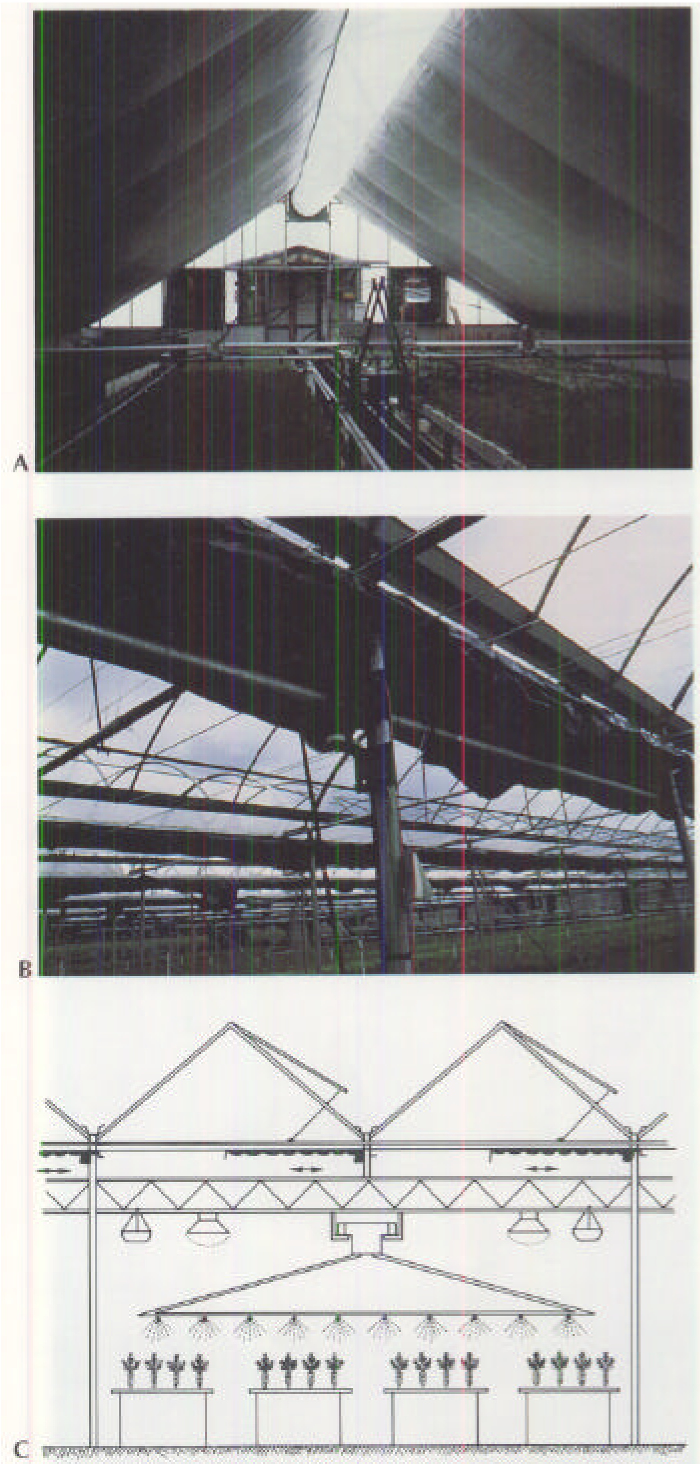


Figure 3.1.29—*Retractable curtains reduce heat loss through the greenhouse covering at night* (**A**) *without interferring with sunlight during the day* (**B**) *or with other environmental controls such as irrigation systems or photoperiod lights* (**C**) (**C**, *courtesy of Cravo Equipment Company).*


A

B


Figure 3.1.30—*Greenhouses can lose heat up to 10 times as fast as ordinary structures, and so insulation should be added along the north walls (**A**) and around the perimeter below bench height. Inflatable plastic ceilings can also be installed overhead (**B**).*

Be space efficient. Utilize greenhouse growing space effectively by keeping the structure filled with plants because the crop creates a thermal mass that will retain heat better than an empty structure. Minimize aisle and edge space and use moveable benches, if possible.

Modify cultural procedures to conserve energy. Maintain temperatures in the growing area to produce the most seedling growth for the least energy input. Because heating requirements are highest at night, lower the night temperature as much as possible. Langhans (1980) reported that lowering the night temperature a mere 3 °C (5 °F) will result in a 17% savings in heating costs; fuel savings as high as 50% are possible (table 3.1.9).

Design growing schedules around the solar calendar. Careful crop scheduling can result in considerable heat savings, especially when producing more than one crop per year. Growers should design their schedules so that trees are being hardened during the coldest months and winter crops consist of species that will tolerate lower temperatures. In some locations, crops may not be economical during the winter season because of the high cost of heating. (Crop scheduling is described in more detail in section 3.3.3.1 and in volume six of this series.)

Table 3.1.9—*Percentage fuel savings when greenhouse temperatures are lowered from 2 to 6 °C (5 to 10 °F)*

Outside temperature		Inside temperature reduction			
		18–16 °C	18–13 °C	16–13 °C	16–10 °C
°C	°F	65–60 °F	65–55 °F	60–55 °F	60–50 °F
−7	20	11	22	12	24
−4	24	12	24	14	28
−2	28	13	26	16	32
0	32	15	30	18	36
2	36	17	34	21	42
4	40	20	40	25	50

Source: Pennsylvania State Department of Horticulture as presented in Ball (1985).

3.1.5 Temperature Monitoring and Control Systems

Because temperature is so critical to tree seedling growth, growers should monitor air and soil temperature throughout the crop cycle. Successful growers use temperature-sensing devices to detect when conditions reach damaging levels, and alarms are activated when temperatures become either too hot or too cold. Many modern container nurseries have sophisticated environmental control systems that are continuously monitored by computer, but even the simplest facility should have certain instruments for monitoring and controlling temperature.

3.1.5.1 Sensing instruments

Growers have traditionally measured ambient temperature with standard glass thermometers. The "max-min" thermometer (fig. 3.1.31A) is an inexpensive instrument that should be used in all container tree nurseries. Not only can the current temperature be read, but the maximum and minimum temperature extremes are automatically recorded. A record of daily temperature fluctuations can be easily obtained by recording the values and resetting the instrument. A number of relatively inexpensive electronic thermometers are commercially available, and some have long probes that are useful for checking the temperature of the growing medium inside the container. Some of these instruments feature digital displays and data storage, yet are small enough to be carried in a pocket (fig. 3.1.31 B).

Because they are not inherently accurate, thermometers and other environmental monitoring equipment should be calibrated before initial use and at regular intervals. The most important source of error in measuring temperature is the effect of solar radiation. Thermometers should always be shaded when in use, and permanently mounted instruments must be placed out of direct sunlight. Some instruments are both shielded and aspirated, that is, a steady stream of air is drawn over the instrument with a small fan. (The proper location of environmental control equipment is discussed further in volume one of this series.)

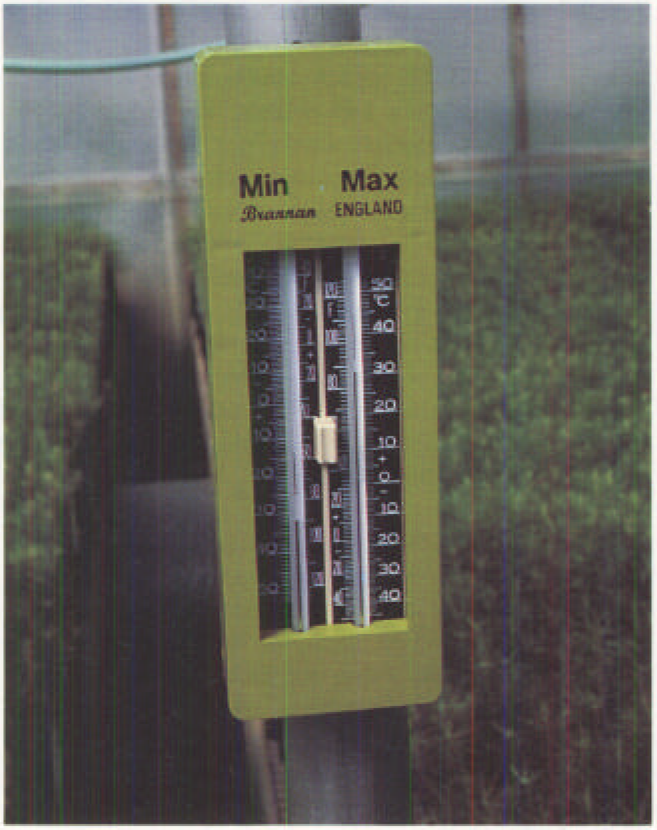
Another indispensable, yet inexpensive, piece of nursery equipment is the **recording hygrothermograph** (fig. 3.1.31 C), which continuously records both air temperature and relative humidity. The basic hygrothermograph contains a bimetallic strip thermometer, which measures temperature based on the differential expansion of two strips of different metals bonded together, and a hair hygrometer, which uses strands of human hair to record changes in relative humidity. This handy instrument contains a recording drum, and models can be purchased which record for either a week or a month between servicings. The drums are powered by either clock springs or batteries and so must be rewound or checked regularly.

Growers should plan to have at least one hygrothermograph for each growing structure. Hygrothermographs can be moved to various locations to check for hot or cold spots, or they can also serve as a standard while other locations are checked with thermometers. As with all temperature monitoring equipment, hygrothermographs should be kept shaded. Hygrothermographs must be calibrated regularly with an accurate thermometer and a sling psychrometer.

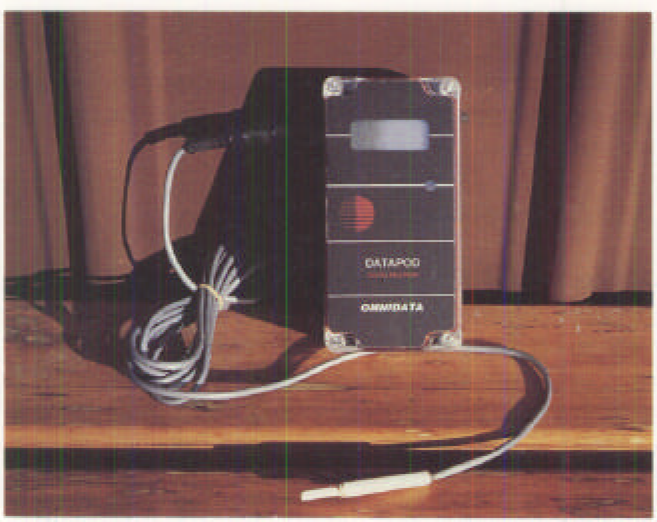
Most modern greenhouses are outfitted with sophisticated electronic control equipment that monitors temperature as well as many other environmental factors.

3.1.5.2 Control equipment

A **mechanical thermostat,** which consists of a temperature sensor and a switch, can be used to activate everything from motorized vents to valves on mist irrigation lines. The temperature sensitivity of a thermostat is called the differential, which is expressed as the number of degrees between switching actions; most greenhouse thermostats have a differential of 0.5 to 2 °C (1 to 4 °F). The range of a thermostat is the temperature span within which the switch will operate, generally the range of 2 to 40 °C (35 to 105 °F). Thermostats provide a simple on-off control function, and multiple functions can be gained by using more than one thermostat (fig. 3.1.32A), which is referred to as staging (Aldrich and Bartok 1989). Mechanical ther-

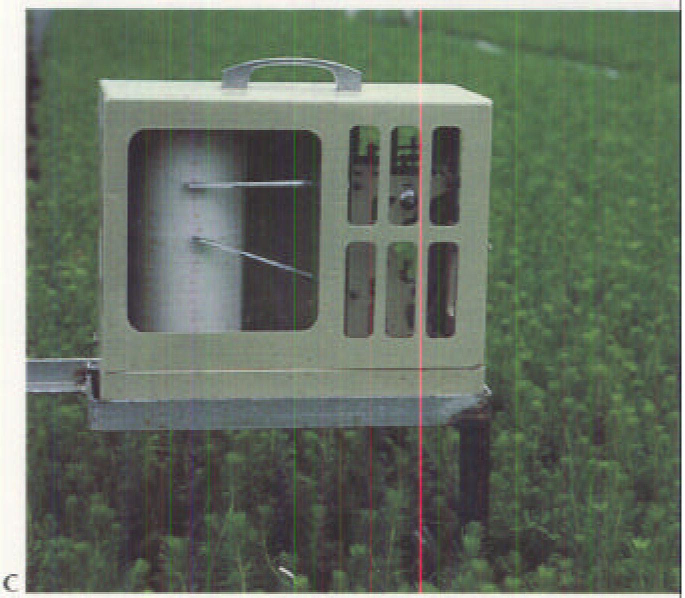


A



B

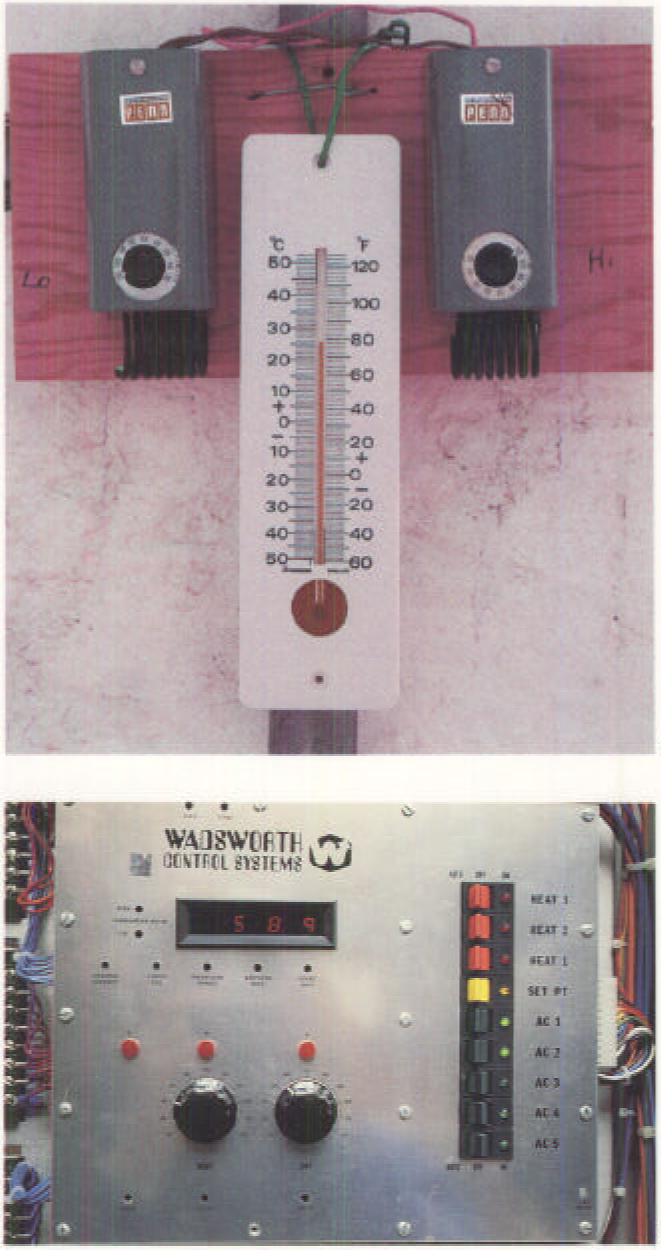
Figure 3.1.31—*Maximum-minimum ("max-min") thermometers* (**A**) *measure current air temperature and also mark the high and low readings for a given time period. New electronic instruments have probes that are small enough to measure and record the temperature of the growing medium within the container* (**B**). *Hygrothermographs* (**C**) *have been traditionally used in container nurseries to record both air temperature and relative humidity.*



C

mostats are inexpensive, but their accuracy and precision are not reliable and they must be calibrated regularly (Nelson 1985).

The next step in sophistication and cost is the thermistor, which is a solid-state temperature sensor that changes voltage output in response to temperature and activates a switch. Thermistors can be integrated into a circuit with a microprocessor or even a computer to form an "intelligent" control system (Nelson 1985). Sophisticated environmental control systems can sense and integrate several environmental variables at once and control both heating and cooling stages (fig. 3.1.32B). (More information on environmental control systems is presented in volume one of this series.)



A

B

Figure 3.1.32—*Thermostats* (**A**) *provide the simplest and most economical form of temperature control equipment. More sophisticated control systems* (**B**) *can precisely maintain a designated temperature, called a set point, through a series of heating and cooling stages.*

3.1.6 Conclusions and Recommendations

Although seedling growth occurs over a wide range of temperatures, container nursery managers need to identify those optimum temperatures for the different species and ecotypes that they will be growing. Optimum temperatures will vary with the stage of seedling development, and it is critical to learn how much temperature variation can be tolerated while producing an acceptable crop. Temperature guidelines are provided in tables 3.1.2 and 3.1.3. If more than one species must be produced in the same growing structure, then growers must accept a compromise temperature regime that will provide acceptable growth for the entire crop.

Approaches to temperature control in container nurseries will vary by type and location of the growing structure, availability of fuel sources, and type of temperature modification equipment. The information provided in this chapter can be used in the design of new growing structures or to improve the operation of existing facilities. Although economics will dictate which options are best, the nursery manager's objective should always be to optimize temperature regimes to the extent necessary to produce quality seedlings.

3.1.7 Literature Cited

Aldrich, R.A.; Bartok, J.W. Jr. 1989. Greenhouse engineering. Ithaca, NY: Cornell University, Northeast Regional Agricultural Engineering Service. 203 p.

Acme, 1988. The greenhouse climate control handbook: engineering principles and design procedures. Muskogee, OK: Acme Engineering and Manufacturing Company. 23 p.

ASHRAE. 1989. ASHRAE Handbook: fundamentals. Atlanta, GA: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. 792 p.

Ball, V. 1985. Ball RedBook: greenhouse growing, 14th ed. Reston, VA: Reston Publishing Company. 720 p.

Barnett, J.P. 1979. Germination temperatures for container culture of southern pines. Southern Journal of Applied Forestry 3(1):13-14.

Barnett, J.P. 1989. Shading reduces growth of longleaf and loblolly pine seedlings in containers. Tree Planters' Notes 40(1):23-26.

Barnett, J.P.; Brissette, J.C. 1986. Producing southern pine seedlings in containers. Gen. Tech. Rep. SO-59. New Orleans: USDA Forest Service, Southern Forest Experiment Station. 71 p.

Bartok, J.W., Jr. 1990. Fuel oil. Greenhouse Manager 9(8):91-92.

Bates, M.E. 1976. Growth responses of containerized southern pine seedling to temperature and light in controlled-environment greenhouses. Durham, NC: Duke University. 180 p. dissertation.

Brix, H. 1971. Growth response of western hemlock and Douglas-fir seedlings to temperature regimes during day and night. Canadian Journal of Botany 49:289-294.

Callaham, R.Z. 1962. Geographic variability in growth of forest trees. In: Kozlowski, T.T., ed. Tree growth. New York: Ronald Press: 311-325.

Davis, E.A.; Cole, F.D. 1976. Shade material for modifying greenhouse climate. Gen. Tech. Rep. RM-33. Ft. Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 6 p.

Downs, R.J.; Hellmers, H. 1975. Environment and experimental control of plant growth. New York: Academic Press. 145 p.

Dunlap, J.R.; Barnett, J.P. 1982. Germination characteristics of southern pines as influenced by temperature. In: Guldin, R.W.; Barnett, J.P., eds. Proceedings, Southern Containerized Forest Tree Seedling Conference; 1981 August 25-27; Savannah, GA. Gen. Tech. Rep. SO-37. New Orleans: USDA Forest Service, Southern Forest Experiment Station: 33-36.

Edwards, I.K.; Huber, R.F. 1982. Contrasting approaches to containerized seedling production: 2 The Prairie Provinces. In: Scarratt, J.B.; Glerum, C.; Plexman, C.A., eds. Proceedings, Canadian Containerized Tree Seedling Symposium; 1981 September 14-16; Toronto. Sault Ste. Marie, ON Canadian Forestry Service, Great Lakes Forest Research Centre: 123-127.

Garber, M.P.; Mexal, J.G. 1980. Lift and storage practices: their impact on successful establishment of southern pine plantations. New Zealand Journal of Forestry Science 10:72-82.

Garzoli, K. 1988. Greenhouses. Canberra, Australia: Australian Government Publishing Service. 185 p.

Gonzalez, A.; D'Aoust, A.L. 1988. Observations and measurements of containerized black spruce seedlings growing in a greenhouse. Inf. Rep. LAU-X-79E. Sainte-Foy, PQ: Canadian Forestry Service, Laurentian Forestry Centre. 70 p.

Gray, H. 1948. A study of the problems of heating, ventilation, and air conditioning greenhouses. PhD thesis. Ithaca, NY: Cornell University

Greenwald, S.M. 1972. Some environmental effects on the growth and monoterpene production of Pinus taeda L. and Ocimum basilicum L. Dissertation. Durham, NC: Duke University.

Hallett, R.D. 1982. Contrasting approaches to containerized seedling production: 3. The Maritime Provinces. In: Scarratt, J.B.; Glerum, C.; Plexman, C.A., eds. Proceedings, Canadian Containerized Tree Seedling Symposium; 1981 September 14-16; Toronto. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 129-138.

Hallett, R.D.; Cameron, M.D.; Murray, T.S., eds. 1985. Proceedings, Reforestation in the Maritimes Symposium; 1984 April 3-4; Moncton, NB. Fredericton, NB: Canadian Forestry Service, Maritimes Forest Research Centre. 188 p.

Hanan, J.J.; Holley, W.D.; Goldsberry, K.L. 1978. Greenhouse management. New York: SpringerVerlag. 530 p.

Hawkins, C.D.B.; Draper, D.A.; Eng, R.Y.N. 1988. Heating system, germination temperature and post germination fertilizer effects on white spruce nursery growth. In: Landis, T.D. tech. coord. Proceedings, Combined meeting of the Western Forest Nursery Associations; 1988 August 8-11; Vernon, BC. Ft. Collins, CO: USDA

Forest Service, Rocky Mountain Forest and Range Experiment Station: 50-53.
Heidmann, L.J. 1981. Overcoming temperaturedependent dormancy of southwestern ponderosa pine seed. Res. Note RM-406. Fort Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 4 p.
Hellmers, H. 1966. Growth response of redwood seedlings to thermoperiodism. Forest Science 12:276-283.
Hellmers, H.; Genthe, M.K.; Ronco, F. 1970. Temperature affects growth and development of Engelmann spruce. Forest Science 16:447-452.
Hellmers, H.; Rook, D.A. 1973. Air temperature and growth of radiata pine seedlings. New Zealand Journal of Forestry Science 3(3):271-285.
Kramer, P.).; Kozlowski, T.T. 1979. Physiology of woody plants. New York: Academic Press. 811 p.
Larcher, W. 1975. Physiological plant ecology. New York: Springer-Verlag. 252 p.
Langhans, R.W. 1980. Greenhouse management, 2nd. ed. Ithaca, NY: Halcyon Press of Ithaca. 270 p.
Larson, M.M. 1967. Effect of temperature on initial development of ponderosa pine seedlings from three sources. Forest Science 13:286-294.
Lavender, D.P.; Overton, W.S. 1972. Thermoperiods and soil temperature as they affect growth and dormancy of Douglas-fir seedlings of different geographic origin. Res. Pap. 13. Corvallis, OR: Oregon State University, Forestry Sciences Laboratory. 26 p.
Lopushinsky, W.; Max, T. 1990. Effect of soil temperature on root and shoot growth and on budburst timing in conifer seedling transplants. New Forests 4:107-124.
Mastalerz, J.W. 1977. The greenhouse environment. New York: John Wiley and Sons. 629 p.
Matthews, R.G. 1982. Contrasting approaches to containerized seedling production: 1. British Columbia. In: Scarratt, J.B.; Glerum, C.; Plexman, C.A., eds. Proceedings, Canadian Containerized Tree Seedling Symposium; 1981 September 14-16; Toronto. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 115-122.
McLemore, B.F. 1966. Temperature effects on dormancy and germination of loblolly pine seed. Forest Science 12: 284-289.
Mulroy, J. 1972. Some effects of temperature on growth and photosynthesis in loblolly pine (Pinus *taeda* L.) seedlings. PhD thesis. Durham, NC: Duke University.
Nelson, P.V. 1985. Greenhouse operation and management, 3rd ed. Englewood Cliffs, NJ: Prentice-Hall. 598 p.
Odlum, K.D. 1991. Hardening and overwintering container stock in Ontario: practices and research. In: Proceedings, 11th annual conference of the Forest Nursery Association of British Columbia. 1991 September 23-26; Prince George, BC. (In press).
Olson, J.S.; Stearns, F.W.; Nienstaedt, H. 1959. Eastern hemlock seeds and seedling response to photoperiod and temperature. Bull. 620. Storrs, CT: Connecticut Agricultural Experimental Station.
Orlander, G.; Gemmel, P.; Hunt, J. 1990. Site preparation: a Swedish overview. FRDA Rep. 105. Victoria, BC: Forestry Canada, Pacific Forestry Centre. 62 p.
Owston, P.W.; Kozlowski, T.T. 1978. Effects of temperature and photoperiod on growth of western hemlock. In: Atkinson, W.A.; Zasoski, R.J., eds. Contrib. 34 (May 1976). Seattle: University of Washington Western College of Forest Resources.
Rook, D.A. 1991. Seedling development and physiology in relation to mineral nutrition. In: van den Driessche, R., ed. Mineral nutrition of conifer seedlings. Boston: CRC Press: 85-111.
Schroeder, M.J.; Buck, C.C. 1970. Fire weather: a guide for application of meteorological information to forest fire control operations. USDA Agric. Handbk. 360. Washington, DC: USDA Forest Service. 229 p.
Stathers, R.J.; Spittlehouse, D.L. 1990. Forest soil temperature manual. Victoria, BC: Forestry Canada/BC Ministry of Forests. 47 p.
Thompson, S. 1982. Environmental control over the shoot growth of pine seedlings. In: Scarratt, J.B.; Glerum, C.; Plexman, C.A., eds. Proceedings, Canadian Containerized Tree Seedling Symposium; 1981 September 14-16; Toronto. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 177-181.
Tinus, R.W. 1982. Environmental control of seedling physiology. In: Scarratt, J.B.; Glerum, C.; Plexman, C.A., eds. Proceedings, Canadian Containerized Tree Seedling Symposium; 1981 Sep

tember 14-16; Toronto. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 75-82.

Tinus, R.W. 1984. Optimum temperatures for growth of southern Rocky Mountain Engelmann spruce and Douglas-fir seedlings. Res. Note RM442. Ft. Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 5 p.

Tinus, R.W.; McDonald, S.E. 1979. How to grow tree seedlings in containers in greenhouses. Gen. Tech. Rep. RM-60. Ft. Collins, CO: USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 256 p.