The Container Tree Nursery Manual

Volume Three
Atmospheric Environment

Chapter 3
Light

Contents

3.3.1 Introduction

The nature of light has fascinated humans for thousands of years, but it was not until a little more than a century ago that its true nature began to be understood. Light is the most complex and variable of the environmental factors that affect plant growth and is arguably the most important (Smith and Whitelam 1990). In addition to its biological importance, light has both practical and economical implications for container tree nurseries. Light is a subjective phenomenon, and so container nursery managers must remember that their own response to light is not the same, in terms of wavelength (color) or intensity, as the response of their tree seedlings (fig. 3.3.1).

3.3.1.1 Biophysics of light

Light is defined as that part of the electromagnetic spectrum that is visible to the human eye. Our planet is bathed in a wide variety of electromagnetic waves from both natural and artificial sources. This radiation can be described by either wavelength or energy terms (fig. 3.3.2). Because shorter wavelengths carry more energy than longer wavelengths, cosmic rays are deadly whereas television and radio waves pass harmlessly through most objects. The electromagnetic spectrum ranges from very long wavelength AM radio waves (1 km), to visible light (10-9 m), to extremely short wavelength cosmic waves (10-15 m)(fig. 3.3.2).

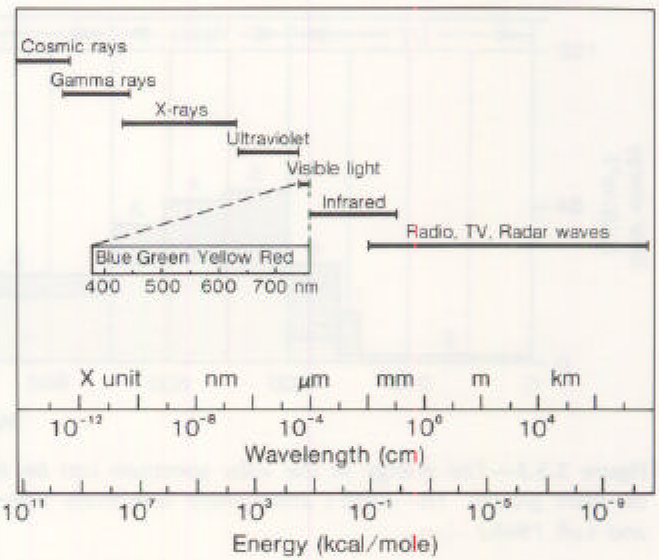


Figure 3.3.2—*The electromagnetic spectrum ranges from cosmic rays through visible light, from infrared radiation to radio and television waves (modified from Withrow and Withrow 1956).*

The term **sunlight** is the common name for electromagnetic radiation that originates from our sun, some 150 million km (93 million miles) away. All materials above absolute zero, which is -273 °C (-469 °F), emit some electromagnetic radiation, and the wavelength of this radiation is a function of the temperature of the source. The sun, with its surface temperature of 6,000 °C (10,800 °F), produces a wide range of electromagnetic radiation; 99% of which is between 200 and 2,000 manometers (nm) in wavelength (fig. 3.3.3).

The earth's atmosphere selectively screens out most ultraviolet radiation and also some visible wavelengths (fig. 3.3.3). Because clouds absorb and reflect so much visible sunlight, the total amount of solar radiation that is available for growing plants is affected by the latitude and number of cloud-free days (fig. 3.3.4). Because of this geographic variation, many horticultural greenhouses are located in the southwestern part of the United States, where skies remain sunny throughout the

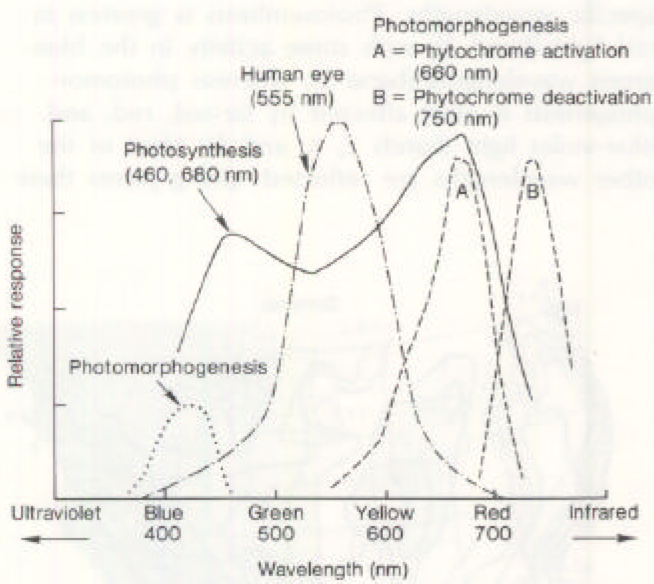


Figure 3.3.1—*The sensitivity of the human eye to solar radiation differs considerably from that of plants, which respond in various ways to different wavelengths.*

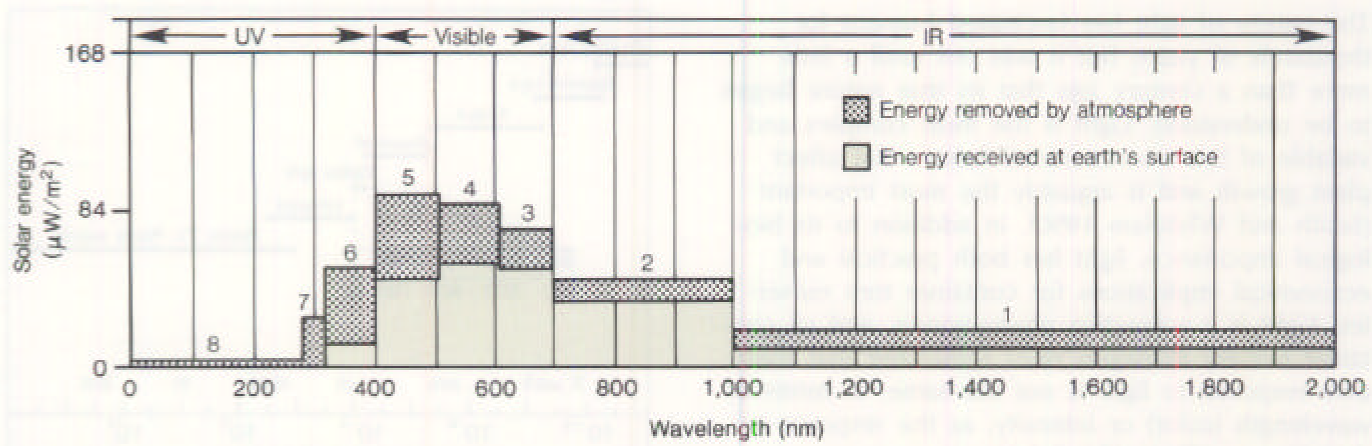


Figure 3.3.3—*The energy in the solar spectrum can be divided into 8 bands (table 3.3.1) which relate to their effects on plant growth. The earth's atmosphere selectively filters out much of the harmful radiation. (Adapted from Reifsnyder and Lull 1965.)*

year. (The effects of climate on container nursery location are described in more detail in volume one of this series.)

3.3.1.2 Definitions and units

The various types of electromagnetic radiation originating from the sun can be distinguished by their wavelengths. Although any units of length can be used, the wavelength of solar radiation is commonly measured in nanometers (1 nm = 10^{-9} m). English conversions for these units are available (Bickford and Dunn 1972) but are almost never used. The portion of the electromagnetic spectrum that has biological significance can be roughly separated into **ultraviolet radiation (UV** = < 400 nm), **visible light** (400 to 700 nm), and **infrared radiation (IR** = > 700 nm) (fig. 3.3.3).

The wavelengths that have significance to horticulture have been divided into 8 bands, based on their biological effects (table 3.3.1). Two specific physiological processes that are important for plant growth can be manipulated culturally by light of specific wavelengths. Photosynthesis is greatest in red light (band 3), with some activity in the blue-green wavelengths (band 5), whereas photomorphogenesis is most affected by far-red, red, and blue-violet light (bands 2, 3, and 5). Most of the other wavelengths are reflected, giving plants their

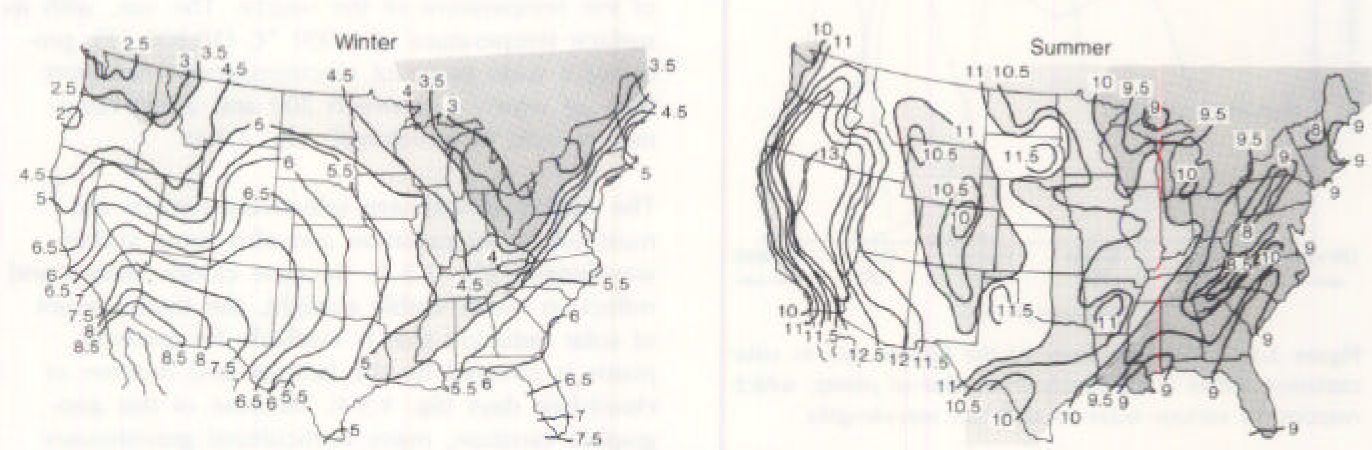


Figure 3.3.4—*The amount of solar energy that is available for raising container tree seedlings is affected by cloud cover, as reflected by the average daily hours of sunshine for the United States (from USDA 1941).*

Table 3.3.1—*Eight separate bands in the electromagnetic spectrum were delineated by the Dutch Plant Irradiation Committee to describe the different biological effects of sunlight*

Band	Wavelength (nm)	Visibility/ color	Biological effects
1	> 1,000	Invisible (IR)	No specific biochemical effect—absorbed and converted into heat
2	700 to 1,000	Invisible (IR)	Shoot elongation
3	600 to 690	Red	Strongest absorption of chlorophyll and photosynthetic activity*; also the region of strongest photoperiodic effectiveness
4	500 to 590	Orange Yellow Green	Low photosynthetic effectiveness*
5	400 to 490	Blue Violet	Moderate chlorophyll absorption and photosynthetic activity*; non-phytochrome photomorphogenesis
6	315 to 390	Invisible (UV)	Fluorescence
7	280 to 314	Invisible (UV)	Germicidal activity
8	< 280	Invisible (UV)	No specific biochemical effect; absorbed by the atmosphere

IR = infrared, UV = ultraviolet.
* The wavelengths from 400 to 700 nm (bands 3 to 5) are also collectively known as photosynthetically active radiation (PAR).
Source: modified from Reifsnyder and Lull (1965).

characteristic green color. However, for practical purposes, plant scientists combine the wavelengths from 400 to 700 nm into one term: **photosynthetically active radiation (PAR).**

Radiant energy can be measured in many different ways, and numerous terms and units have been used. The choice depends on use; for horticultural purposes, radiation should be measured in terms of power (watts) or photon energy (micromoles) within the PAR spectrum. Although they also describe light with power units, lighting engineers use units that reflect the sensitivity of the human eye within the visual spectrum (lux). Three systems are commonly used to describe and measure light (table 3.3.2):

Energy units- micromoles per second per square meter (µmol/s/m2)--measure the rate of radiation energy (photon flux density) per unit area. Simply stated, energy units describe the amount of power (in the case of sunlight, solar power) that is intercepted by an object (Bickford and Dunn 1972). The amount of energy per unit varies inversely with wavelength: 1 mole of red light (670 nm) carries 42,000 calories compared to 1 mole of blue light (470 nm), which has 60,000 calories (Reifsnyder and Lull 1965). Energy units are always in the PAR wavelengths unless otherwise stated. One mole of photons is also called an einstein (ASHRAE 1989).

Radiation units-watts per square meter (W/m2)--also measure radiation energy per unit area, but the specific wavelength and time interval also must be stated. Radiation units are often used by ecologists and plant scientists to describe the total amount of solar radiation that is received at a given location. In horticulture, radiation units are most useful for describing the intensity of artificial lighting because lamps are rated in watts.

Table 3.3.2—*Units and conversion factors for measuring light in container tree nurseries (choice of units will depend on the type of application)*

Energy units
- Preferred units:
  - micromoles per second per square meter (µmol/s/m²)
- Other units:
  - microeinsteins per second per square meter (µE/s/m²)
- Conversions*:
  - 1 µmol/s/m² = 1 µE/s/m²
  - 1 W/m² = 4.6 µmol/s/m²
  - 1 µmol/s/m² = 51.2 lx

Radiation units
- Preferred units:
  - watts per square meter (W/m²)
- Other units:
  - watts per square foot (W/ft²)
  - langleys per day (Ly/d)
  - calories per square centimeter (cal/cm²)
- Conversions*:
  - 1 W/m² = 2.07 Ly/d
  - 1 Ly/d = 0.484 W/m²
  - 1 W/m² = 10.8 W/ft²
  - 1 W/ft² = 0.093 W/m²

Illumination units
- Preferred units:
  - 1 lux (lx) = 1 lumen per square meter (lumen/m²)
  - 1 kilolux (klx) = 1,000 lx
- Other units:
  - 1 foot-candle (fc) = 1 lumen per square foot (lumen/ft²)
- Conversions*:
  - 1 lx = 0.09 fc
  - 1 fc = 10.76 lx

* Conversions between energy, radiation, and illumination units are quite complicated and will be different for each light source (see table 3.3.3). The spectral distribution curve of the radiant output of the source must be known in order to make the conversion. The above conversions assume a flat spectral distribution curve over PAR wavelengths.

Sources: ASHRAE (1989), Thimijan and Heins (1983), Hanan and others (1978), Hansen and Biggs (1979).

Illumination units--lux (Ix)—are a standardized measure of artificial light per unit area at a given distance from the source. They cover the visual radiation from 380 to 710 nm and peak at 555 nm, corresponding to the visual sensitivity of the human eye (fig. 3.3.1). The standard unit of illumination is the lumen. A lumen that is evenly distributed over an area of 1 ml is defined as 1 Ix; a lumen distributed over 1 square foot is 1 foot-candle (table 3.3.2). Although the sensitivity spectrum of the human eye is quite different from the needs of plants, the cheapest and most commonly used light-measuring instruments are calibrated in lux or foot-candles.

The best light unit to use in horticulture has been the subject of much debate. Both energy and radiation measurements are concerned with the same aspects of light but, for horticultural purposes, the use of energy units has been recommended as the most appropriate. When radiation units must be used, as when working with artificial lighting, the factors for converting to energy units will vary with the type of lamp (table 3.3.3). Complete conversion tables can be found in Thimijan and Heins (1983).

There are two common units for measuring energy that are numerically equal (table 3.3.2): micromoles or microeinsteins per second per square meter (µmol/s/m² or µE/s/m²). Although microeinsteins are commonly used by seedling physiologists (Kramer and Kozlowski 1979), micromoles are most widely recommended (Thimijan and Heins 1983) and will be used in this manual. Because illumination units (lux) are the most common way of measuring light in operational nurseries, light measurements will be given in both illumination and energy units. **The conversion between energy and illumination units varies with the light source, however (table 3.3.3). To avoid confusion and yet remain accurate, the value in micromoles will be followed by its approximate lux conversion in parentheses.** For example, there is considerably more light on a sunny day [2,000 µmol/s/m² (~108,000 lx)] than on one that is heavily overcast [60 µmol/s/m² (~3,200 lx)] (table 3.3.3). For those using the English illumination units of foot-candles, the conversion is simple because the two values differ by a factor of 10 (1 foot-candle = 10.8 lx).

The proper units must also be considered when purchasing alight meter or measuring light. For operational purposes, growers must use a light meter that will measure the relevant wavelengths. To measure the amount of sunlight or artificial light that is available for photosynthesis, PAR should be measured. For dormancy prevention, only red and far-red need be measured. (See section 3.3.5 for more information on types of light meters.)

Table 3.3.3—*Relative comparisons of light units for solar radiation and single lamps of some typical artificial lighting systems**

Light source	Radiation (W/m²)	Energy (µmol/s/m²)	Illumination (lx)	Approximate energy-illumination units conversion
Solar radiation (at sea level)				
Full sunlight	450	2000	108,000	54
Heavy overcast	15	60	3,200	54
Full moonlight	0.05	0.2	10	54
Artificial lighting†				
Incandescent (100W)	0.2	1.2	59	49
Metal halide (400W)	4.0	19.0	1,330	70
Cool-white fluorescent (40W)	0.3	1.3	103	79
High-pressure sodium (400W)	4.0	20.0	1,670	84
Low-pressure sodium (180W)	2.0	10.0	1,090	109

* For photosynthetically active radiation (PAR): 400 to 700 nm.
† Estimated values for a single lamp mounted 2 m above 3 m² of growing surface. Actual spacing will vary with the type of lamp and objectives of the grower. Under operational conditions, light intensities will be much higher because of overlap by adjacent lamps.
Source: modified from Thimijan and Heins (1983).

3.3.2 Role of Light in Tree Seedling Growth and Development

There are three main properties of light that affect plant growth: intensity, duration, and quality (Kramer and Kozlowski 1979). For the accelerated rate of growth that is desired in container tree nurseries, the source of light must provide enough radiant energy for photosynthesis. Light intensity is also a factor in preventing dormancy, although the required intensity is much less. The duration of light is primarily concerned with the daylength (actually, the length of the dark period is more important) that is required to prolong vegetative growth. Light quality refers to the fact that different wavelengths trigger different functions in plants; within the PAR range, however, light quality is considered to be less important than intensity and duration (ASHRAE 1989).

On a physiological basis, the effects of light on tree seedling growth and development can be grouped into two categories: the high-energy requirements of photosynthesis and the low-energy effects that are collectively known as photomorphogenesis (Kramer and Kozlowski 1979). Each of these responses is sensitive to specific wavelengths (fig. 3.3.1):

- **Photosynthesis**—Radiant energy (most PAR wavelengths but predominately red) is captured by the carotene and chlorophyll pigments and converted into the chemical energy needed for plant growth and metabolism, using carbon dioxide and water as raw materials.
- **Photomorphogenesis**—Radiant energy (far-red, red, and blue wavelengths) is captured by phytochrome and other pigments. Phytochrome is sensitive to the ratio of red to far-red light and acts as an environmental sensor to measure daylength. The phytochrome system controls seedling phenology, such as seed germination and bud set and also triggers other morphological reactions, such as the response to shade. Blue light is important to normal morphological development, particularly in regard to branching and shoot sturdiness.

3.3.2.1 Photosynthesis

Photosynthesis is one of the most important chemical process on earth- most life would impossible without it. Plants produce the basic building blocks of life such as carbohydrates, amino acids, and fats and also generate oxygen as a byproduct of photosynthesis. Oxygen is essential for the respiration of all organisms.

The majority of photosynthesis takes place in the foliage; chlorophyll, which gives plants their green color, is contained in chloroplasts in the leaves. Water is absorbed in the roots and transported to the leaves where it is combined with carbon dioxide in the presence of light to synthesize sugar. The products of photosynthesis are transported throughout the plant and are used in respiration, which is essentially the reverse chemical reaction of photosynthesis (fig. 3.3.5). Respiration, which occurs in the dark as well as the light, releases the chemical energy from the photosynthate for a wide variety of growth and maintenance functions (Kramer and Kozlowski 1979).

Net photosynthesis is measured by determining the amount of carbon dioxide that is removed from the air around a leaf or plant. The total photosynthetic rate is calculated by adding the amount of carbon dioxide that is evolved during respiration to that absorbed from the air. Plant growth is determined by the amount of photosynthate that is left over after respiration, and so the rate of net photosynthesis is more relevant to horticulturists than is the total rate (Mastalerz 1977). The rate of net photosynthesis is affected by several environmental variables (including availability of water and carbon dioxide) but is strongly controlled by temperature, which determines the rate at which photosynthate is used up in respiration (fig. 3.3.6)

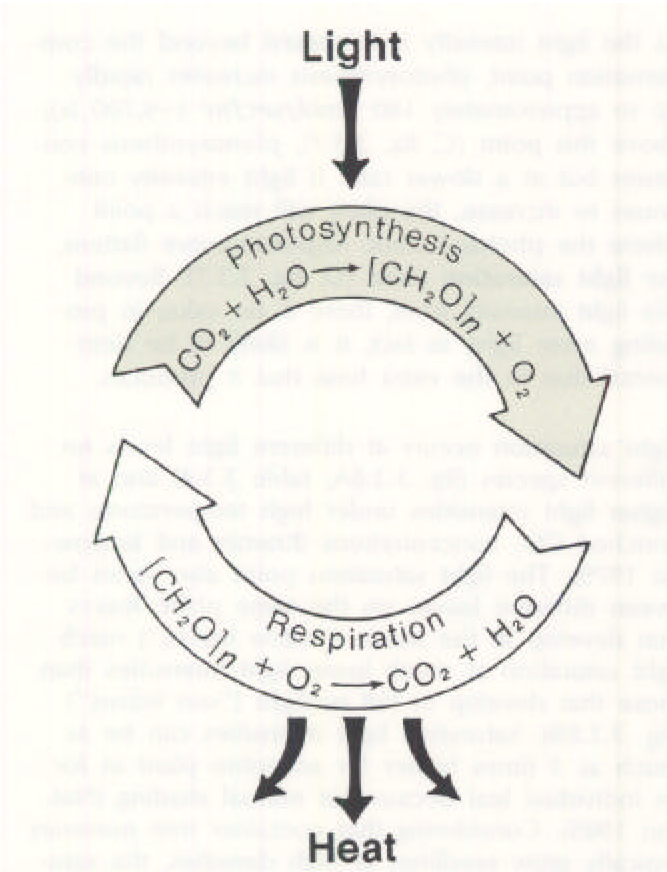


Figure 3.3.5—*Photosynthesis and respiration are actually reciprocal processes. In photosynthesis, green plants use light energy to convert carbon dioxide (CO_2) and water (H_2O) into carbohydrates (CH_2O), and release oxygen (O_2) to the atmosphere. All higher organisms burn these carbohydrates in the presence of O_2 to yield energy (heat), carbon dioxide, and water. (Modified from Gates 1971.)*

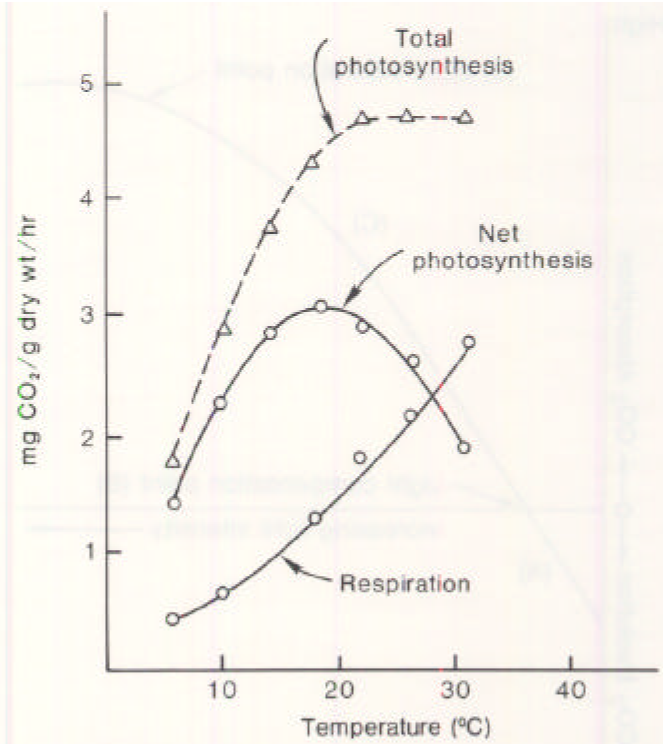


Figure 3.3.6—*Both total photosynthesis and respiration increase with temperature. The difference between these processes is known as net photosynthesis, and represents the amount of photosynthate that is available for growth and maintenance. (Modified from Mastalerz 1977.)*

Effect of light intensity. Photosynthesis increases curvilinearly with the intensity of the light (fig. 3.3.7). The response varies between species and is subject to the levels of other limiting factors, especially temperature, carbon dioxide (CO_2), and water. If the light intensity is too low (0 to 20 µmol/sec/m², or approximately 0 to 1,100 lx), the rate of photosynthesis will be less than respiration, and there will be a net loss of photosynthate (A, fig. 3.3.7). As light is increased to 20 to 50 µmol/sec/m² (~1,100 to 2,700 lx), photosynthesis will equal respiration, and there will be no net exchange of CO_2. This is known as the **light compensation point** (B, fig. 3.3.7), which is important because it determines the absolute minimum amount of light that must be supplied to keep a seedling crop alive.

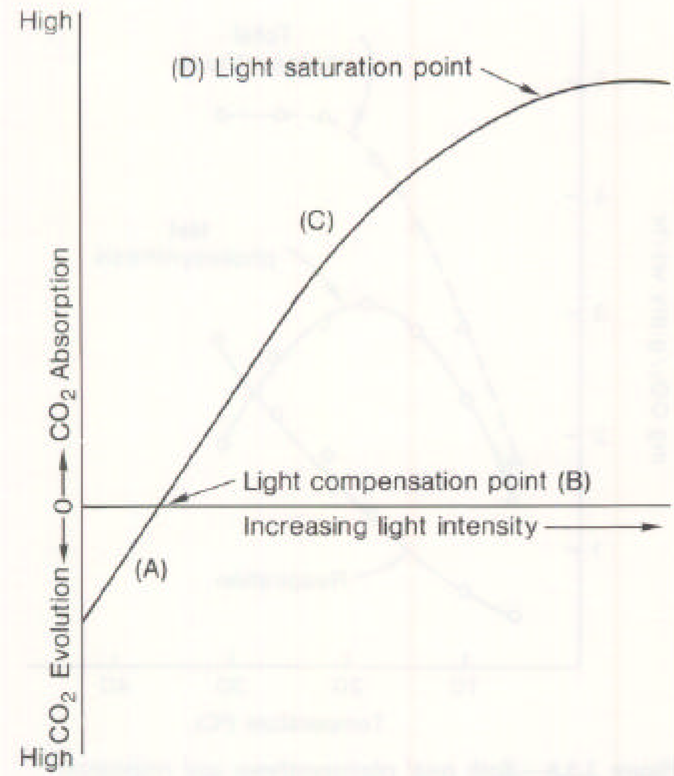


Figure 3.3.7—*Light intensity has a strong effect upon photosynthesis. Under low light, respiration is greater than photosynthesis and there will be a net loss of photosynthate* (**A**). *The light compensation point* (**B**) *is where photosynthesis equals respiration. With increasing light, the photosynthetic rate increases rapidly up to a point* (**C**) *when it begins to slow down. Beyond this point, the photosynthetic rate gradually decreases until the light saturation point is reached* (**D**)*; above this point, additional light does not increase photosynthesis and may actually be detrimental. The exact light intensities for the various points will vary with species. (From Hartmann, Flocker, & Kofranek. © 1981. Plant science: growth, development, and utilization of cultivated plants. p. 151. Reprinted by permission of Prentice-Hall, Englewood Cliffs, NJ.)*

As the light intensity is increased beyond the compensation point, photosynthesis increases rapidly up to approximately 180 µmol/sec/m² (~9,700 Ix); above this point (C, fig. 3.3.7), photosynthesis continues but at a slower rate. If light intensity continues to increase, the plant will reach a point where the photosynthetic response curve flattens, the **light saturation point** (D, fig. 3.3.7). Beyond this light intensity level, there is no value in providing more light; in fact, it is likely to be detrimental due to the extra heat that it produces.

Light saturation occurs at different light levels for different species (fig. 3.3.8A; table 3.3.4) and at higher light intensities under high temperatures and enriched $C0_2$ concentrations (Kramer and Kozlowski 1979). The light saturation point also varies between different leaves on the same plant; leaves that develop in the shade ("shade leaves") reach light saturation at much lower light intensities than those that develop in full sunlight ("sun leaves") (fig. 3.3.813). Saturation light intensities can be as much as 3 times higher for an entire plant as for an individual leaf because of mutual shading (Nelson 1985). Considering that container tree nurseries typically grow seedlings at high densities, the saturation light intensity would be much higher for a block of seedlings than for a single plant.

Extremely high light intensities can also cause "sunburn' (fig. 3.3.9), which is technically termed **photodamage or solarization** (Levitt 1980). Plants normally adapt to higher light intensity by a variety of physiological adjustments. Under stressful conditions, these mechanisms may become ineffective and the foliage can be photodamaged. Susceptibility to photodamage varies with seedling hardiness: dormant stock is least susceptible, and young succulent tissue is particularly sensitive (Gillies and Vidaver 1990). But even dormant, hardy plants can suffer photodamage. Excessive light intensity was found to cause chlorosis of Engelmann spruce seedlings that were shipped from the nursery to high elevation outplanting sites (Ronco 1970).

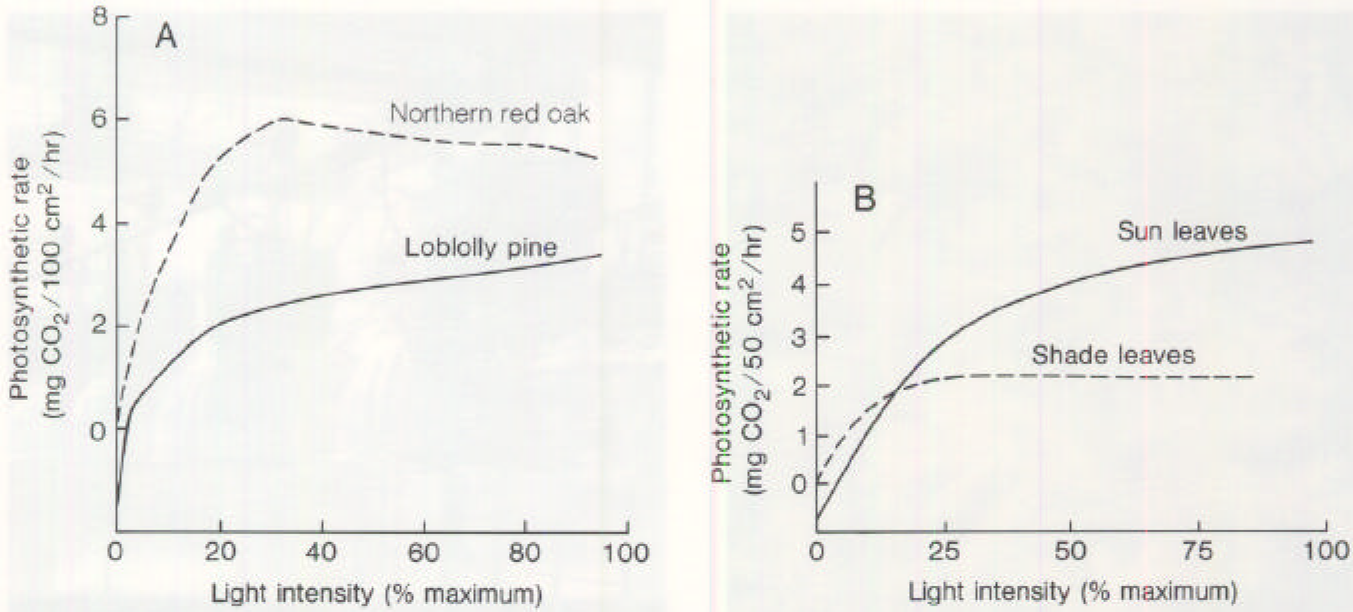


Figure 3.3.8—*The light saturation point (see fig. 3.3.7) occurs at lower light intensities for shade-tolerant species like northern red oak, than for shade-intolerant loblolly pine* (**A**). *The photosynthetic rate of sun leaves continues to increase with more light, whereas the shade leaves reach light saturation at relatively low light levels* (**B**). *(***A***, adapted from Kramer and Decker 1944;* **B***, from Boysen-Jensen and Muller 1929, as presented in Hanan and others 1978.)*

Use of artificial light. It is possible to compensate culturally for lack of sunlight with supplemental lighting, but high-intensity lighting systems are expensive to install and operate (fig. 3.3.10A). Supplemental photosynthetic lighting was used in only 5.4% of the forest nurseries surveyed in the United States and Canada. It is usually considered to be uneconomical, except under the following cir circumstances:

- During the winter at high latitudes, when sun light intensities are low and days are short. For horticultural crops, supplemental photosynthetic lighting is considered to be practical in nurseries above 40° latitude (Nelson 1985).

Table 3.3.4—*Saturation light intensities for various tree species*

Species	Saturation light intensity (μmol/s/m²)	Saturation light intensity (klx)	Authority
Siberian larch	100	NA	Environment Canada (1983)
Engelmann spruce	420	50	Ronco (1970)
Douglas-fir	550	30	Krueger and Ruth (1969)
Sitka spruce	550	30	Krueger and Ruth (1969)
Western hemlock	550	30	Krueger and Ruth (1969)
White oak	270	15	Kramer and Decker (1944)
Northern red oak	650	35	Kramer and Decker (1944)
Dogwood	650	35	Kramer and Decker (1944)
Blue spruce	400–1500	50–80	Tinus (1970)
Red alder	920	50	Krueger and Ruth (1969)
Loblolly pine	1,800+	100+	Kramer and Decker (1944)
Lodgepole pine	2,200+	120+	Ronco (1970)
Ponderosa pine	2,200+	120+	Tinus (1970)

NA = not available.

Figure 3.3.9—*The foliage of species grown under shade during the early part of the growing season becomes adapted to shade conditions. If the seedlings are moved to full sunlight without proper conditioning, they can become photodamaged. Injured foliage usually turns chlorotic or a bronze color.*

- When the crop is unusually valuable, as with tree improvement stock (Bongarten and Hanover 1985).
- When light-demanding species must be grown where overcast or foggy conditions are common.

(Specifications and other application information for photosynthetic lighting are provided in section 3.3.4.4.)

3.3.2.2 Photomorphogenesis

There are many different photomorphogenic responses by plants, but by far the most important is **photoperiodism,** which is the response of plants to the relative length of day and night. In horticulture, the terms **photoperiod** and **daylength** mean essentially the same thing and are used interchangeably. The ability to sense relative daylength is controlled by a light-sensitive pigment called **phytochrome** (Smith and Whitelam 1990).

A

B

Figure 3.3.10—*Relatively high amounts of light are required for photosynthesis and so high-intensity lamps must be arranged close together* (**A**). *Photoperiodic lighting* (**B**) *only requires relatively low light intensity, and so lights can be spaced further apart.*

The phytochrome system. Phytochrome is a blue-green pigment existing in two forms that respond to the ratio of red (R = 660 nm) to far-red (FR = 735 nm) light. Red light converts the inactive to the active form, and far-red light reverses the reaction. Daylight, which contains a high R: FR ratio, converts phytochrome to the active form; in darkness the active form slowly reverts to the inactive form. Photoperiodic lighting contains a high R: FR ratio, and so effectively shortcuts the natural system (fig. 3.3.11).

Phytochrome is present throughout the plant but is most abundant in meristematic tissues, such as seeds and vegetative or flower buds (Kramer and Kozlowski 1979). It functions at all stages of the life cycle and provides plants with invaluable information about the light environment. In addition to sensing daylength, the phytochrome system controls other important physiological functions such as seed germination, phototropism, and shade-induced responses (Smith and Whitelam 1990).

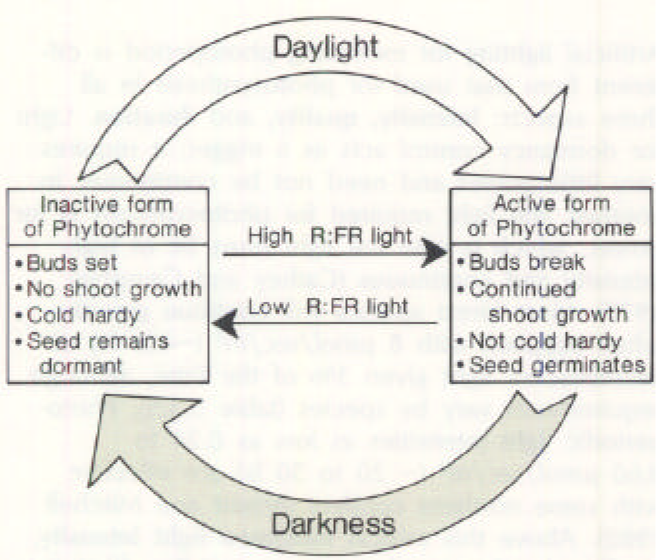


Figure 3.3.11—*Phytochrome is a plant pigment that is sensitive to the relative length of the dark period, and regulates many phenological and physiological activities. In container tree nurseries, artificial lighting with a high ratio of red to far-red light is used during naturally short days to keep seedlings actively growing. (Modified from Hanan and others 1978.)*

Horticulturists have identified a **critical daylength** for each of their commercial species, and traditionally divide their crops into long-day, short-day, and day-neutral types. Different cultural regimes have been developed for each group (Hartmann and Kester 1983). The situation is much simpler in container tree nursery culture because we are not interested in flowering, only in prolonging or terminating shoot growth.

Extending photoperiod. Photoperiodic lighting (fig. 3.3.10B) is the most common use of artificial lighting in horticulture (Bickford and Dunn 1972). Container seedling growers use photoperiodic lighting to extend daylength in all types of growing environments, from open compounds to fully controlled greenhouses. In a recent survey, 82% of the forest nurseries in the United States and Canada used artificial lighting to regulate photoperiod.

Photoperiod extension is critical to achieving the accelerated growth rates that are possible in container tree nurseries, especially when seedlings from more northern latitudes or higher elevations are grown at more southerly or lower elevation nurseries (Arnott and Mitchell 1982). Under natural conditions, shoots grow only during the long days of summer and set buds and become dormant when the days become shorter in the fall. Extending photoperiod is operationally important when seedlings cannot be reared to the desired size during the normal spring to fall growing season, and becomes particularly valuable when multiple crops must be produced in one season.

Species show variable responses to photoperiod extension. The need for photoperiod lighting will depend on the following three main factors:

Location of the nursery. Nurseries in tropical and subtropical climates usually do not provide photoperiod lighting because most of their crops grow year round. Growth chamber experiments have demonstrated, however, that some tropical species will exhibit accelerated shoot growth when produced under extended daylength (Kramer and Kozlowski 1979). In temperate climates, container nurseries that produce species from a wide geographic area, and especially from high-elevation or high-latitude sites, should plan on supplying photoperiodic lighting (fig. 3.3.12A).

Species and ecotype. Species, such as Engelmann spruce, that only grow on high-elevation sites will always require photoperiodic lighting. The degree of response increases with elevation; for example, some subalpine species exhibit premature budset even under conventional photoperiodic lighting (fig. 3.3.12B). The response of seedlings of species that grow over a wide geographic range (for example, Douglas-fir) will depend on the specific seed source; seedlings from low-elevation, coastal sources grow perfectly well without lights, whereas seedlings of ecotypes from high-elevation or interior locations cannot be grown without them. It is prudent to use photoperiodic lighting when growing a mixture of species and ecotypes, or when the response of all seed lots is unknown, because nonresponsive species are not harmed and operating costs are minimal. Once seedlings set a dormant terminal bud, it is difficult and/or time consuming to get them to resume shoot growth.

The cropping cycle. Nurseries that grow more than one crop per year will usually need photoperiodic lights to keep their crops from setting bud prematurely in the fall; this is even more important for late fall or winter crops. On the other hand, nurseries that do not have rigid time constraints, and therefore do not need to maximize growth rates, can grow perfectly acceptable seedlings without photoperiodic lighting. Sensitive seedlots may exhibit an unacceptable amount of height variation, however (fig. 3.3.12C).

Other factors. Response to photoperiodic lighting is also a function of seedling age. For example, Scotch pine showed no response at 6 weeks but exhibited a strong photoperiod requirement by 18 weeks of age (fig. 3.3.13). The precise age at which different species become sensitive is not known. Most container nurseries should begin photoperiod control at germination. A few species, such as mountain hemlock, are so sensitive that they will set a premature bud if they germinate in the absence of photoperiodic lighting (Arnott 1991). If the photoperiod lights fail for as little as one night, then some species will set a premature terminal bud (Arnott and Simmons 1985) (fig. 3.3.12D). When seedlings have been growing under photoperiodic lighting for extended periods, the critical daylength for continued accelerated growth may need to be lengthened. Even with a 24-hour photoperiod, most temperate species grown for an extremely long time will eventually set bud (Kramer and Kozlowski 1979).

Effects of extended photoperiod are also affected by temperature. Spruce seedlings subjected to the same photoperiodic lighting grew significantly larger in a heated greenhouse than in an unheated shelterhouse (Arnott and Mitchell 1982). The same researchers found that cool night temperatures produced smaller seedlings and delayed formation of a terminal bud even under photoperiodic lighting.

Artificial lighting for extending photoperiod is different from that used for photosynthesis in all three aspects: **intensity, quality,** and **duration.** Light for dormancy control acts as a trigger; it requires very little power and need not be continuous. In contrast, the light required for photosynthesis is for power, which is why the light must be of high intensity and continuous (Cathey and Campbell 1977). Most forest species will continue growth when supplied with 8 µmol/sec/m² (~430 lx) of incandescent light given 3% of the time, although requirements vary by species (table 3.3.5). Photoperiodic light intensities as low as 0.24 to 0.60 µmol/sec/m² (~ 20 to 50 lx) are effective with some northern conifers (Arnott and Mitchell 1982). Above this **critical minimum light intensity,** seedling height growth increases rapidly with intensity and then appears to taper off (figure 3.3.14), and there is no additional benefit from providing more light. The critical minimum intensity varies

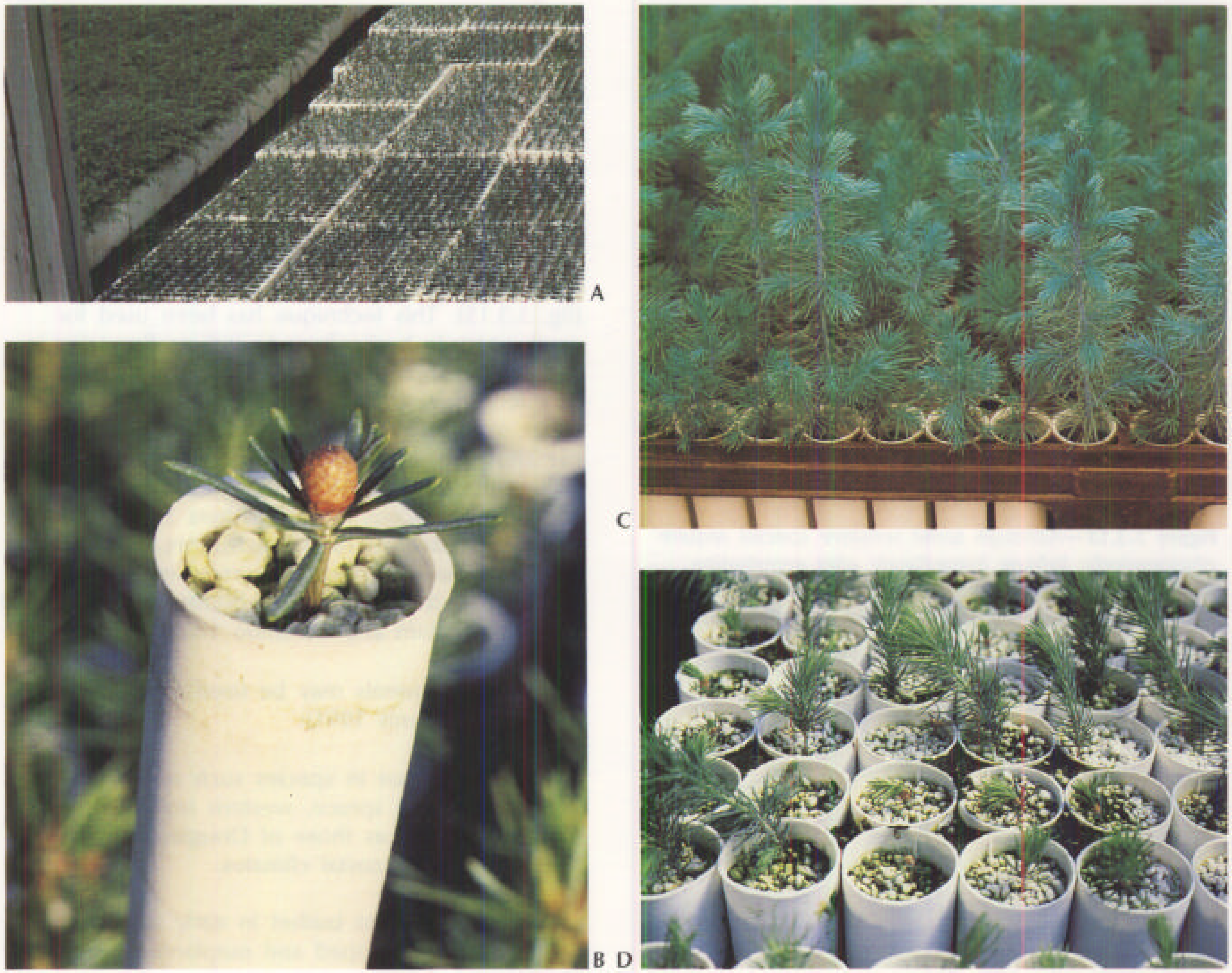


Figure 3.3.12—*Container nurseries that grow species or ecotypes from high latitudes or high elevations* (**A, lower right**) *must provide photoperiodic lighting for these seedlots or they will grow much slower that the rest of the crop* (**A, upper left**) *or even set a terminal bud very early in the season* (**B**). *Sensitive species or ecotypes can be grown without photoperiodic lighting, but they will exhibit extreme variation in shoot growth rates* (**C**). *When photoperiodic lighting is provided, a power failure for even one night can set terminal buds and result in irregular growth rates* (**D**).

with seed source: four different interior spruce seedlots had critical minimum intensities ranging from 0.24 to 0.96 μmol/sec/m^2 (~20 to 80 lx) (Arnott and Mitchell 1982). Upper limits at which no additional growth response were noted ranged from 1.0 μmol/s/m2 (~100 lx) for Engelmann spruce to 8.6 μmol/s/m^2 (~800 lx) for white spruce (Arnott and Macey 1985).

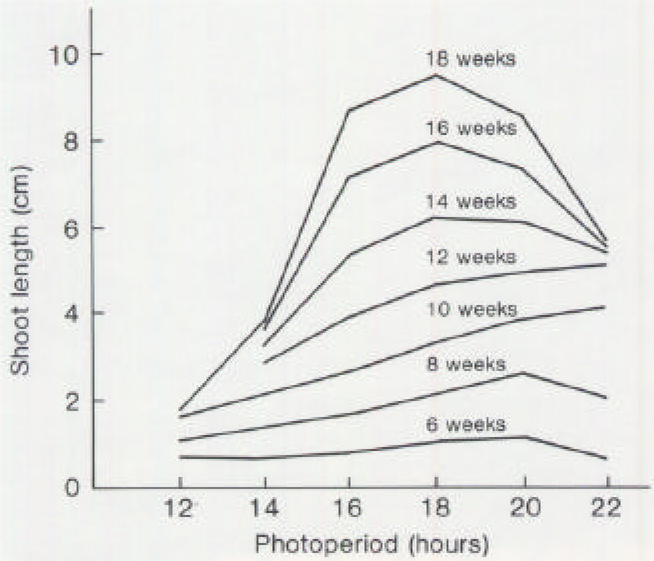


Figure 3.3.13—*Although some sensitive species require photoperiodic lighting immediately after germination, Scotch pine seedlings did not respond until around 8 weeks and the response increased over the growing season (adapted from Thompson 1982).*

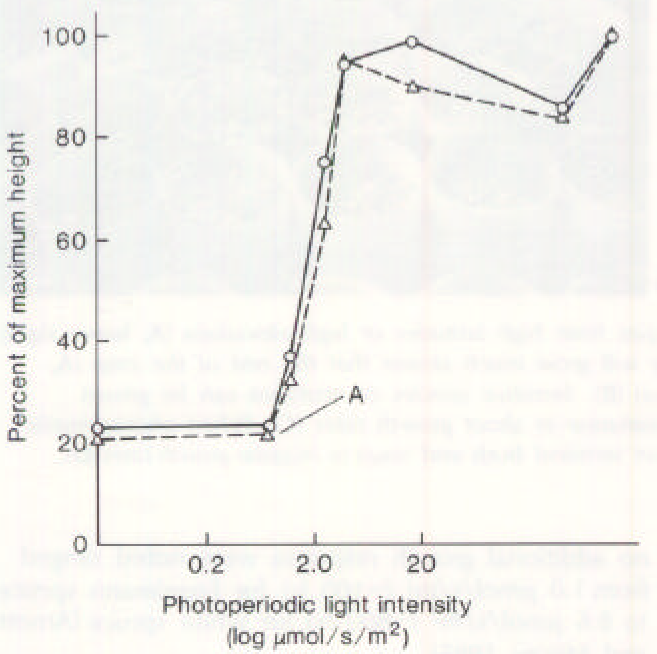


Figure 3.3.14—*Crops that are sensitive to photoperiod, such as these two ecotypes of white spruce, have a critical minimum light intensity* (**A**) *that must be satisfied; for many forest species, a full response can be obtained at light levels as low as 8 µmol/s/m² (~ 430 lux) (modified from Tinus 1976).*

As for light quality, the objective is to keep the phytochrome in the active form by using lamps that generate a high ratio of red (660 nm) to farred (735 nm) wavelengths (fig. 3.3.11). (See section 3.3.4.5 for operational applications of extending photoperiod.)

Shortening photoperiod. **Short-day treatments,** also known as "blackout," are produced by excluding daylight for several hours during the day (fig. 3.3.15). This technique has been used for many years in horticulture to induce flowering in short-day plants (Mastalerz 1977). During the naturally long days of summer at higher latitudes, container seedling growers have found it effective to use short-day treatments to stop height growth, induce budset, and promote cold hardiness in conifer crops (Colombo and others 1982). These treatments have afforded much more control over growing schedules because nursery managers can rapidly and uniformly induce budset at any time of the year (Odium and Colombo 1988).

Short-day treatments may be used for several purposes (van Steenis 1991):

- Inducing budset in species such as western hemlock, Sitka spruce, western redcedar, and ecotypes such as those of Douglas-fir from low elevation and coastal climates.

- Forcing premature budset in early season crops that must be shipped and outplanted during the summer.

The short-day technique has proven especially valuable at high latitudes where termination of photoperiodic lighting or other stress treatments may not be sufficient to trigger terminal bud set and initiate the hardening phase. In Canada, switching off photoperiodic lighting is not particularly effective because of the natural long days. Furthermore, moisture stress, which is also used to arrest seedling shoot growth, significantly reduces seedling biomass and adversely affects the size of the terminal bud (O'Reilly and others 1989, Grossnickle and others 1991).

Table 3.3.5—*Response of various species to photoperiodic lighting treatments*

Species & seed source	Growth response* Height	Growth response* Weight	Photoperiodic lighting Duration	Type	Intensity (μmol/s/m)	Intensity (lux)	Authority
Pacific-silver fir (British Columbia)	1.9	1.5	C	HPS	2.2	220	Arnott (1979)
Hackberry† (Bismark, ND)	1.2	1.8	I	INC	8	430	Tinus & McDonald (1979)
Black walnut† (Manhattan, KS)	1.1	1.1	I	INC	8	430	Tinus & McDonald (1979)
Rocky Mtn. juniper (Towner, ND)	1.6	2.3	I	INC	16	860	Tinus & McDonald (1979)
Eastern redcedar (Towner, ND)	1.9	2.4	I	INC	8	430	Tinus & McDonald (1979)
Engelmann spruce (southern BC)	5.0	6.6	I	INC	8	430	Tinus & McDonald (1979)
Engelmann spruce (southern BC)	1.7	1.7	C	HPS	1.0	100	Arnott & Macey (1985)
White spruce (central Alberta)	4.5	> 10	I	INC	8	430	Tinus & McDonald (1979)
White spruce (central BC)	2.3	2.0	C	HPS	8.6	800	Arnott & Macey (1985)
Blue spruce (Fort Collins, CO)	1.4	7.7	I	INC	8	430	Tinus & McDonald (1979)
Blue spruce (Indian Head, SK)	1.4	7.7	I	INC	8	430	Tinus & McDonald (1979)
"Interior" spruce (central BC)	4.0	5.5	I	INC	8	400	Arnott (1982)
Lodgepole pine (central Alberta)	2.3	2.6	I	INC	8	430	Tinus & McDonald (1979)
Ponderosa pine (Ruidoso, NM)	1.5	1.8	I	INC	8	430	Tinus & McDonald (1979)
Ponderosa pine (Valentine, NE)	3.1	3.6	I	INC	8	430	Tinus & McDonald (1979)
Ponderosa pine (Colorado Springs, CO)	1.5	2.3	I	INC	8	430	Tinus & McDonald (1979)
Bur oak† (Devils Lake, ND)	1.2	1.2	I	INC	8	430	Tinus & McDonald (1979)
Western hemlock (Oregon Coast)	1.7	1.6	I	INC	8	430	Owston & Kozlowski (1978)
Mountain hemlock (British Columbia)	2.3	1.7	C	HPS	4.0	400	Arnott & Macey (1985)

I = intermittent lighting, C = continuous lighting, HPS = high-pressure sodium lamps, INC = incandescent lamps.
* Response equals growth under recommended light treatment divided by growth with no light at night.
† *Hackberry* seems to maintain growth without extended photoperiod, but it should be used anyway. *Black walnut* responds to long photoperiod only under high CO_2. *Bur oak* requires hot days and warm nights to maintain growth, and the effect of photoperiodic lighting under these conditions is uncertain.

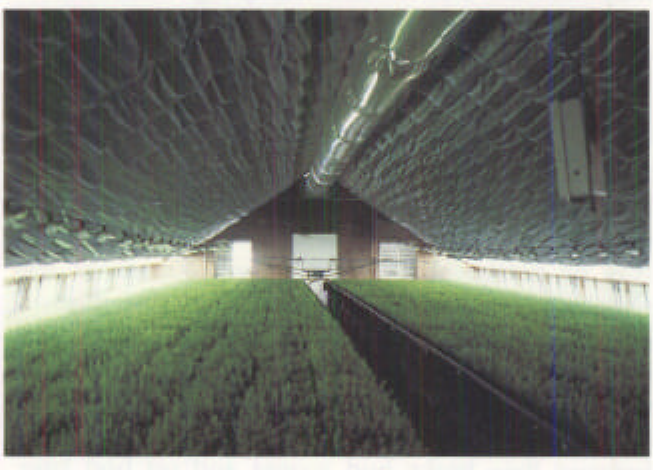


Figure 3.3.15—*In nurseries at high latitudes, some growers use blackout curtains to create short-day conditions during the naturally long days of summer. After a few weeks of short-day treatments, the seedlings stop shoot growth and set a terminal bud.*

The short-day technique is not normally required in nurseries at low latitudes; turning off the lights is usually sufficient. Seedlings that have been grown under photoperiodic lighting respond quickly to changes in photoperiod. During the rapid growth phase, growers can generate a "relative" short-day condition by switching off the photoperiodic lighting system when height growth reaches 85 to 90% of the target.

Short-day treatments are a relatively new technology in forest nurseries, however, and have potential hazards. For example, some nurseries have had problems with maintaining a firm bud after the short-day treatments have been terminated (fig. 3.3.16A). This can be caused by not applying the blackout treatment for the proper length of time, or by unusually warm temperatures that interfere with the dormancy process (Odium 1991).

A

B

C

Figure 3.3.16—*If short-day treatments are improperly applied, some species or ecotypes will break bud and grow lammas shoots after the treatments have been discontinued (***A***;* **B***,* **right***). The effects of short-day treatments can last until the following spring, when the treated seedlings (***C***,* **right***) flushed earlier than the control treatment (***C***,* **left***). (Courtesy of K. Odlum.)*

Not all species may respond favorably to these treatments. Recent research with western redcedar has shown that the short-day treatments must be applied too early in the season to be practical and may be detrimental to root growth (Krasowski and Owens 1991). The phenological effects of short-day treatments can persist for at least 1 year after outplanting. Black spruce seedlings that received short-day treatments had greater height growth than the controls during the first growing season because they broke bud sooner and set bud later (Odium and Colombo 1988). This potential advantage can be a liability because many of these seedlings suffered cold injury due to spring frosts. At the end of the first growing season, however, the short-day seedlings had developed new terminal leaders and were actually taller than seedlings from the natural day treatment (Odlum 1991; fig. 3.3.16C). Obviously, more research is needed on both the short-term and long-term effects of this technology. (See section 3.3.4.6 for more information on short-day treatments.)

Phototropism. Although not nearly as culturally important as photosynthesis or photoperiodism, phototropism concerns morphological responses to differences in light quality. Recent evidence indicates that these phototropic responses may actually be controlled by a phytochrome response to the ratio of red to far-red light (Smith and Whitelam 1990). In enclosed greenhouses, some species exhibit undesirable shoot elongation ("stretching") when grown in excessive shade. West coast growers have observed that Douglas-fir seedlings become tall and spindly when overhead structures or equipment cast permanent shadows on the growing area or the covering is old or dirty.

The shoot growth of many species naturally orients toward the sun or other predominant light source, and this tropism can become excessive in nurseries located at higher latitudes in the fall and winter (fig. 3.3.17).

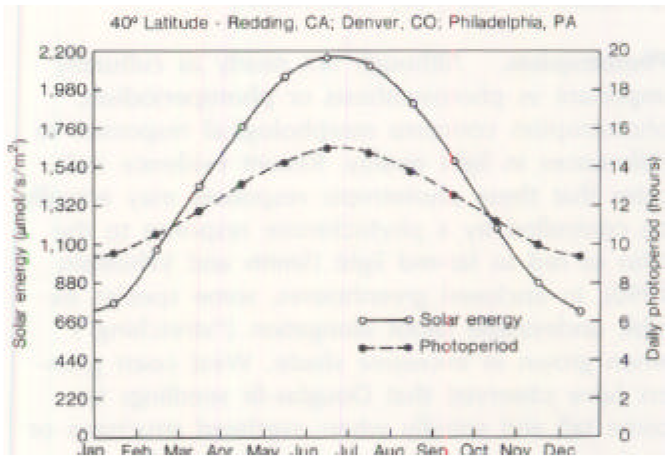
Figure 3.3.17—*Seedlings grown during late fall or early spring at high-latitude nurseries sometimes exhibit phototropism, a directional response to the sun which is low on the horizon.*

3.3.3 Optimum Light Levels

Light affects all phases of seedling growth and development, from seed germination through the accelerated growth that typifies container seedlings, to budset and hardening, and this influence in particularly significant in the container nursery environment. The intensity and duration of available sunlight should also be considered during nursery development, because both crop scheduling and the number of crops that can be grown per year will be affected.

3.3.3.1 Crop scheduling

Not only does daylength change with the season at high latitudes, but so does the intensity of solar radiation. In fact at higher latitudes, seasonal variation of solar intensity is almost as extreme as that of photoperiod (fig. 3.3.18). This seasonal change in solar intensity affects crop scheduling. Nurseries in the tropics routinely sow their crops without regard to the time of year. The potential for multiple crops decreases at higher latitudes, however.



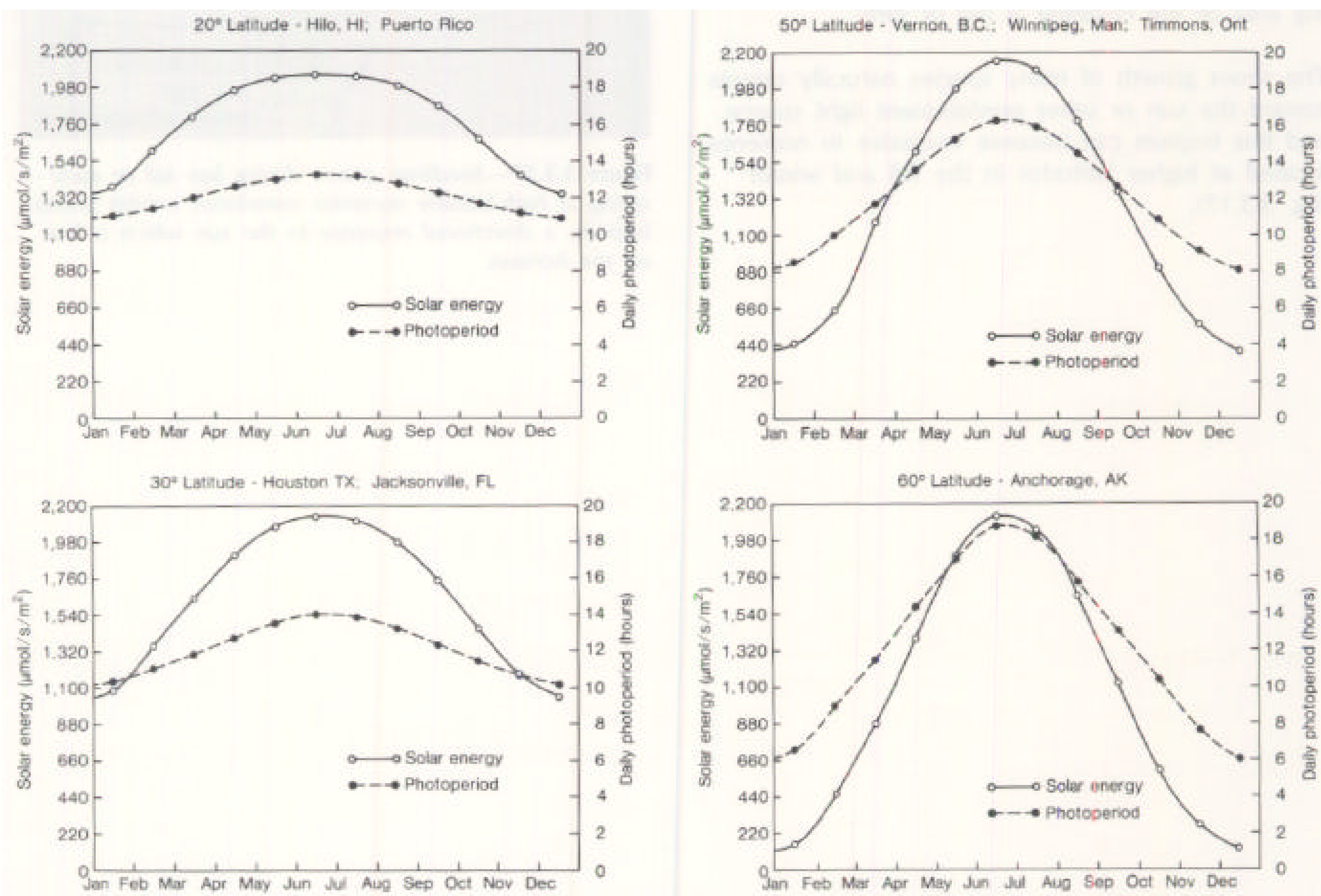


Figure 3.3.18—*Seasonal variation in the intensity of solar radiation, as well as daylength, increases with latitude. Although not as apparent as changing daylength, the variation in solar intensity is just as important to container nursery culture.*

In the temperate zones, container nursery managers growing one crop per year should schedule around the summer solstice (June 21 in the Northern Hemisphere) so that there will be sufficient sunlight for seedling growth throughout the crop cycle (fig. 3.3.19). Multiple crops should also be scheduled around the solstice. For container nurseries growing two crops per year, the first crop should be sown early enough that it can be removed from the greenhouse and the second crop sown by the solstice (fig. 3.3.19). Crops sown later in the year have increasingly less sunlight available for photosynthesis and this is even more significant in very cloudy climates (fig. 3.3.4). Decreasing solar intensity will be reflected in slower growth rates during the fall and winter (Downs 1985) and also affects other nursery production factors, such as the incidence of diseases like grey mold (Tuller and Peterson 1988). So, unless production demands require a second crop, it is more economical to raise just one "summer" crop in the temperate zone nurseries. (Crop scheduling will be discussed further in volume six of this series.)

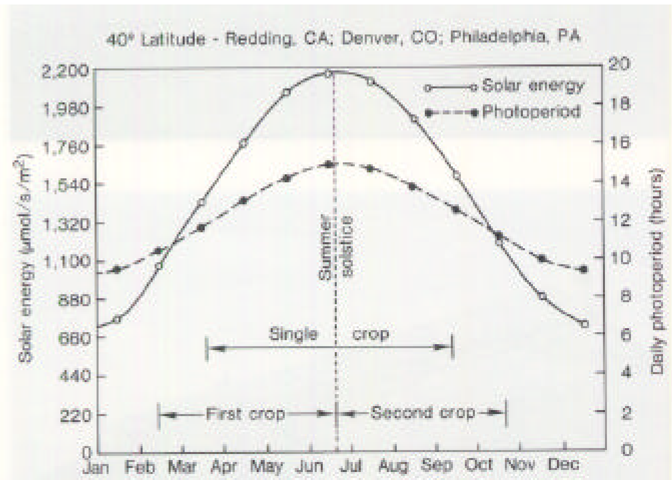


Figure 3.3.19—*Because supplemental photosynthetic lighting is usually uneconomical, growers should plan their crops around the summer solstice to take advantage of the greater light intensities. In the temperate zone, some nurseries are able to produce two or even three crops per year with careful planning.*

3.3.3.2 Establishment phase

The germination of most tree seeds is not dependent on light intensity levels, but both light quality and photoperiod can have significant effects on some species. For example, red light (660 nm) promoted germination of loblolly pine seed, whereas far-red light (730 nm) inhibited it (McLemore 1971). Both germination rate and total germination are promoted under 8- to 12-hour daylengths for most species (Kramer and Kozlowski 1979). Some exceptions do occur, however, as Douglas-fir seeds germinated better under a 16-hour photoperiod than an 8-hour one (Jones 1961).

The cotyledons of germinating conifer seedlings become photosynthetically active as soon as they emerge from the growing medium, and the development of the primary needles depends on the photosynthate from the cotyledons. Most germinants grow best at moderate light intensities, around 55 µmol/s/m² (~3,000 lx), and some reduction in light intensity may therefore be necessary to reach optimum germination in environments with high levels of solar energy. With most popular greenhouse coverings, a 50% shadecloth should create the desired light intensity. A less dense shadecloth (30 to 50%) may be necessary in cloudy climates. The proper light intensity varies with species, however; with red pine seedlings, primary needle development was severely retarded when light levels decreased below 120 µmol/sec/m² (~6,500 lx) (Kozlowski and Borger 1971). In southern pine nurseries, any shade is undesirable, but shadecloth is used for protection from hard rains.

Germinants emerge into an environment with high levels of solar energy that subject them to stress. Light, temperature, and moisture conditions are critical at this time, and growers must be especially vigilant to ensure that all environmental factors are kept at optimum levels. The type of seed covering can also affect light and temperature in the microenvironment around the germinant. Lightcolored grit or perlite covering the growing medium reflects a considerable amount of solar radiation. On the other hand, dark seed mulches absorb solar radiation and damaging temperatures can develop around the succulent stem. (Heat injury to container seedlings is discussed in more detail in volume five of this series.)

3.3.3.3 Rapid growth phase

After container seedlings become established, the light intensity should be gradually raised to the saturation point to maximize photosynthesis. If seedlings were shaded during the establishment phase, then the covering should be normally removed unless daytime temperatures would become damaging without it. This is often the case in the tropics or in arid climates during the summer.

The light saturation point varies with different species (table 3.3.4), making it best to grow crops with different light requirements in separate growing environments. If separate environments are not available, growers must design a light environment that is suitable for the majority of the crop species. Shading one section of a growing structure for shade-loving species is an option. It is most practical for greenhouses that are oriented perpendicular to the solar arc (that is, north to south), but even then the shaded area will gradually change during the growing season. Ideally, shading should be adjusted throughout the day and from one day to the next to optimize light intensity but, if the shading can only be applied and removed manually, this is impractical. Motorized shading systems are now available that can achieve this result (Vollebregt 1990) (see section 3.3.4.6).

Because light intensity is reduced by any type of covering, some growers move their crops out of fully enclosed greenhouses as soon as the seedlings are established in the containers (fig. 3.3.20A). Of course, this is only an option when ambient temperatures are mild. Brissette and others (1990) reported that even 30% shade seriously reduced growth of longleaf pine seedlings and recommended growing them in open compounds in full sunlight during the summer months. Even as far north as British Columbia, some container nursery managers are removing the polyethylene coverings of their greenhouses in midsummer to maximize light intensity (fig. 3.3.20B). This practice has been shown to improve seedling quality (Tuller and Peterson 1988) (see section 3.3.4.1 for more information).

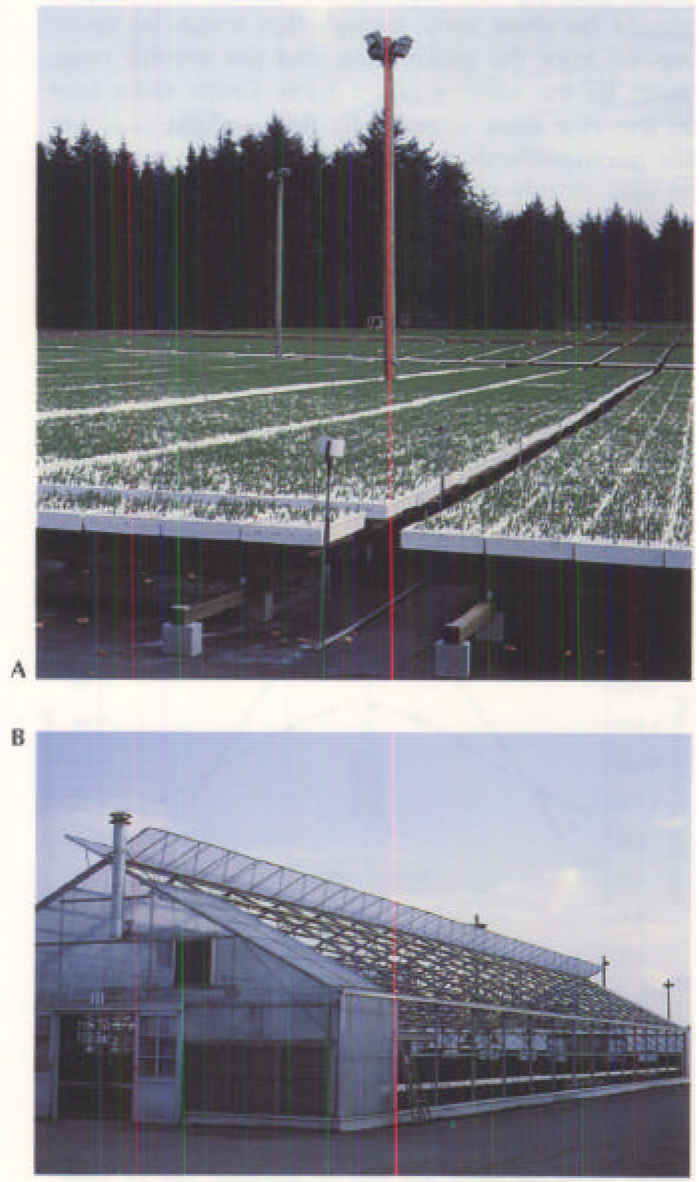


Figure 3.3.20—*Because any type of greenhouse covering reduces light intensity, some container nurseries are raising seedlings in open growing compounds that are equipped with photoperiodic lighting* (**A**). *Other growers remove the covering as soon as outside temperatures become favorable for growth* (**B**).

Photosynthetic efficiency also varies with the type of foliage. For example, primary needles of loblolly pine seedlings reached maximum photosynthesis at lower light intensities than did older seedlings with mature secondary needles (Bormann 1956). Mutual shading decreases photosynthetic rates when seedling crowns begin to overlap; this can occur relatively early in the growing season with large-leafed species or seedlings grown at close spacing. Large trees develop sun and shade leaves in response to light intensity (Kramer and Kozlowski 1979). Seedlings of shade-tolerant species, or any seedlings that have been raised under shade, can develop foliage that is not tolerant of high light intensity. These seedlings can become "sunburned" if exposed to full sunlight (see section 3.3.2.1).

Most nurseries keep their seedlings under extended photoperiod for the entire rapid growth phase to promote shoot growth and keep them from setting a terminal bud. Even a brief interruption during this period can result in bud set and have serious economic consequences (fig. 3.3.12D). When seedlings reach approximately 80 to 90% of their target height, growers shut off the photoperiodic lights to initiate the hardening phase.

3.3.3.4 Hardening phase

The objective of the hardening phase is to terminate height growth, set full buds, and stimulate caliper and root growth while gradually hardening the seedling to tolerate stress. Control of photoperiod is the predominant trigger that causes tree seedlings to cease height growth and set a terminal bud. Most forest species are very sensitive to changes in daylength, although species and ecotypes from southern latitudes and mild coastal environments are less affected (see section 3.3.2.2). In the United States, most container nursery managers shut off the photoperiodic lights to initiate terminal budset and induce dormancy. Because of the naturally long days in summer, some Canadian growers use blackout curtains to shorten the photoperiod. (This technique is discussed in section 3.3.4.6), and other cultural techniques for inducing dormany are discussed in detail in volume six of this series.)

Many container nurseries begin the hardening phase by removing the seedlings from the greenhouse and exposing them to ambient conditions; other nurseries simply remove the covering of the greenhouse. Growers should be cautious, however, when moving shade-tolerant species from a shaded growing area to full sunlight because they can become "sunburned" (fig. 3.3.9). Growers can prevent photodamage by minimizing plant stress and by making certain that sensitive species are gradually acclimated to high light intensity. Succulent foliage becomes hardened as it matures by developing a thicker cuticle and undergoing other morphological changes in the epidermis (Levitt 1980). Susceptible species should be moved from full shade gradually; first to an area with intermediate light intensity for several weeks, then finally to full sunlight.

3.3.4 Modifying Light in Container Tree Nurseries

Light is one of the most important cultural tools available to the container nursery manager, who can modify the intensity of natural sunlight or supplement it with artificial lights. The location and orientation of the growing structure is also important because persistent shadows can decrease seedling growth rates (fig. 3.3.21). (Locating container tree nurseries is discussed in more detail in volume one of this series.)

3.3.4.1 Effect of structural coverings

Solar radiation is modified, both in intensity and quality, from the time it enters the earth's atmosphere. The type of greenhouse and its physical location also affect the nature of incident sunlight. In spite of reductions due to solar angle and seasonal cloud cover, the solar radiation measured inside a greenhouse (fig. 3.3.22) still roughly follows the normal distribution pattern for solar energy over the growing season (fig. 3.3.19).

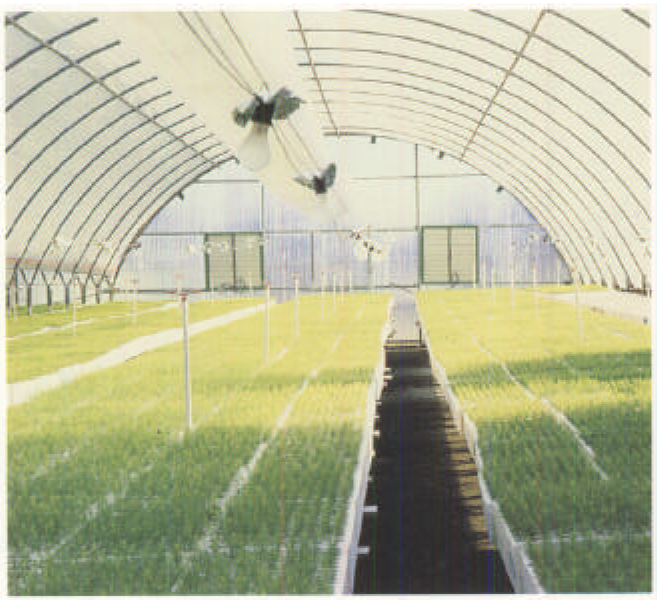


Figure 3.3.21—*Container nurseries should be located away from trees or other obstructions that can block sunlight for any appreciable part of the day or growing season. Persistent shade patches will reduce photosynthesis and can cause seedlings to become tall and spindly.*

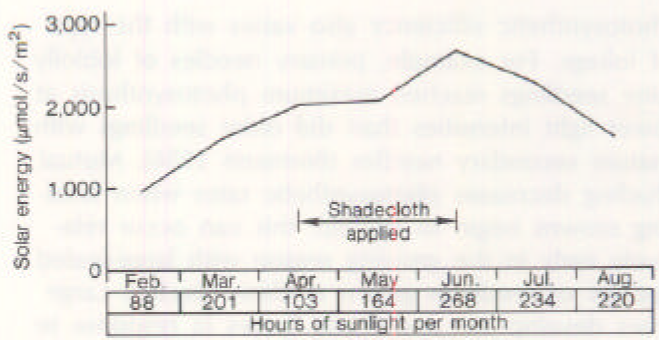


Figure 3.3.22—*The amount of solar radiation actually available to greenhouse crops is affected by the location, type of structure, and cultural practices. The average monthly sunlight within this glass greenhouse in Quebec followed the normal yearly pattern (fig. 3.3.19), except that shadecloth was used to reduce greenhouse temperatures during the early part of the growing season. (Modified from Gonzalez and D' Aoust 1988.)*

The degree of solar modification varies with the characteristics of the growing structure and the type, age, and cleanliness of the covering (Hanan and others 1978). Solar radiation in the PAR wavelengths was measured in two greenhouses in a forest nursery in British Columbia, one constructed of fiberglass panels and one of polyethylene film. The polyethylene covering transmitted all the measured spectra better than the fiberglass covering (fig. 3.3.23), and the average difference in the all PAR wavelengths was 12.2% (Tuller and Peterson 1988). Both the coverings reflected more of the shorter wavelengths, thus producing a light environment relatively higher in the red and infrared bands.

McMahon and others (1990), in a detailed survey of spectral transmittance of various greenhouse coverings and shading materials, found considerable variation between products (table 3.3.6). Both the intensity and quality of sunlight varied, not only between different structural and shade coverings, but also between similar products, such as brands of polyethylene film. Total light transmission ranged from 95 to 52% for the structural materials and from 45 to 21% for the shading materials. Although basically unaffected by the structural materials, the blue and red wavelengths were significantly changed by the shading materials. Both blue light and the ratio of far-red to red light can affect

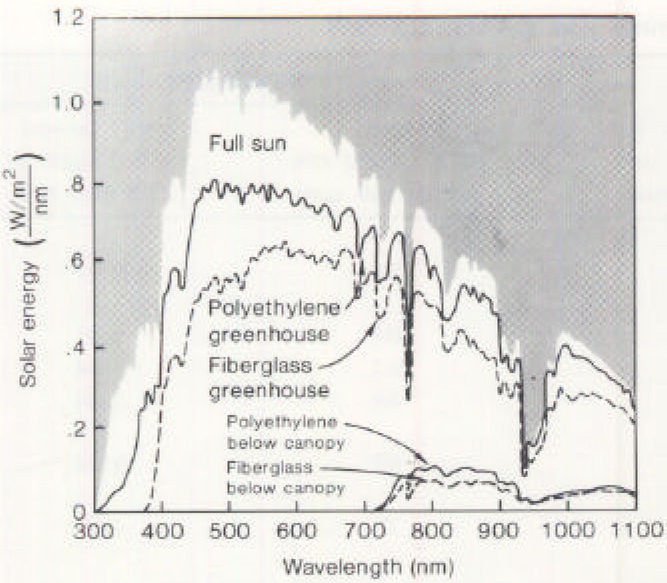


Figure 3.3.23—*The spectral distribution of solar radiation was proportionately less in a fiberglass greenhouse compared to one with a polyethylene covering. The sunlight that was transmitted through the seedling canopy was severely modified in both intensity and quality. (Adapted from Tuller and Peterson 1988.)*

plant morphology. Light with a high far-red to red ratio tends to produce larger leaves and longer internodes ("stretching") (McMahon and others 1990).

The condition and cleanliness of the greenhouse covering can have a profound effect on light transmission (fig. 3.3.24); Nelson (1985) estimates that accumulation of dust alone on the greenhouse coverings can reduce sunlight transmissions by as much as 20%. Hard plastic or fiberglass coverings should be cleaned regularly, and even polyethylene tarps can be hosed off with water. Cleaning or replacing the covering will affect not only the intensity of sunlight but also the temperature regime within the structure, and so cultural practices must be adjusted accordingly.

The season is also a factor because light transmission through greenhouse coverings varies with the angle of the sun. Garzoli (1988) measured the solar radiation transmission through a variety of greenhouse coverings with the sun directly overhead and at a 60° angle, which is the maximum

Figure 3.3.24—*Some types of greenhouse coverings need to be periodically cleaned or replaced. This old fiberglass covering had become yellow and covered with litter from an adjacent shelterbelt.*

solar angle at 37° latitude on the winter solstice in the Northern Hemisphere. Under these simulated winter conditions, light transmission decreased from 8.0 to 14.6% for common greenhouse coverings. (Properties of greenhouse coverings are discussed in more detail in volume one of this series.)

3.3.4.2 Shading the growing area

Heat buildup becomes more of a problem during the summer months, and many growers modify the light transmission characteristics of their greenhouses by applying a light-reflecting whitewash material or by installing shadecloth (fig. 3.1.21). Whitewash and shadecloth are considered "permanent" shading because they are typically left in place for most of the growing season. Shadecloth is preferable to whitewash because it can be removed seasonally without leaving a residue. Commercial shadecloths can produce from 20 to 90% shade and also are available in different colors. The transmission of both total PAR radiation and specific wavelengths is affected by the type of shading material (table 3.3.6), and the selective filtering of some shadecloth will affect plant growth (McMahon and others 1990).

Table 3.3.6—*Spectral transmittance of greenhouse coverings and shading materials*

Covering material	Photosynthetic light at 400–700 nm (% of full sun)	Photomorphogenic light	
		Blue at 400–500 nm (% of full sun)	Ratio far-red to red light at 730–660 nm
Structural materials			
Glass	93	93	0.97
Polyethylene film			
Monsanto 602®	88	83	1.01
Monsanto 703®	67	63	1.04
Monsanto Cloud-9®	52	48	1.04
Chambered acrylic panel			
Exolite®	95	92	1.02
Chambered polycarbonate panel			
Lexan®	78	75	1.04
Shading materials			
White latex paint	41	39	0.99
Black shadecloth (55% shade)	45	44	1.00
Green saran shadecloth (63% shade)	35	34	1.04
Green polyester shadecloth	21	27	5.58
Aluminized polyester shadecloth (80% shade)	21	18	1.06

Source: modified from McMahon and others (1990).

The proper choice of shading becomes an averaging process, however, because sunlight intensity changes during the day with the angle of the sun and the degree of cloud cover. Because of the labor involved, it is uneconomical to adjust the shadecloth manually to prevailing light conditions. With the advent of automatic retractable shading systems, however, growers have the option of adjusting the light intensity within the growing area to maximize photosynthesis or lower temperature several times a day (fig. 3.3.25). Although relatively expensive to install, automatic shading systems can greatly increase the amount of sunlight reaching the crop and therefore affect seedling growth rates. In an operational greenhouse trial, an automated shading system allowed the crop to receive 50% more hours of PAR than the crop in a house with permanent shade (Vollebregt 1990).

3.3.4.3 Types of lamps

The two most important biological factors to consider during selection of a horticultural lighting system are light intensity and light quality, together known as **spectral energy distribution,** because they will determine whether the system will be effective. Once these two criteria have been addressed, then a number of other operational aspects must be considered: energy efficiency, uniformity of light distribution, initial cost of the lamp and fixture, average lamp life, replacement cost of lamps, and resistance to corrosion. For horticultural applications, artificial lighting can be divided into incandescent, fluorescent, and high-intensity discharge lighting:

***Incandescent lamps**.* A **standard incandescent lamp** contains a tungsten filament enclosed in a glass bulb that is filled with nitrogen gas to prevent oxidation and evaporation of the tungsten at high temperatures (Bickford and Dunn 1972). A typical incandescent lamp produces radiation that peaks in the infrared band (fig. 3.3.26A) and so generates a relatively high amount of heat.

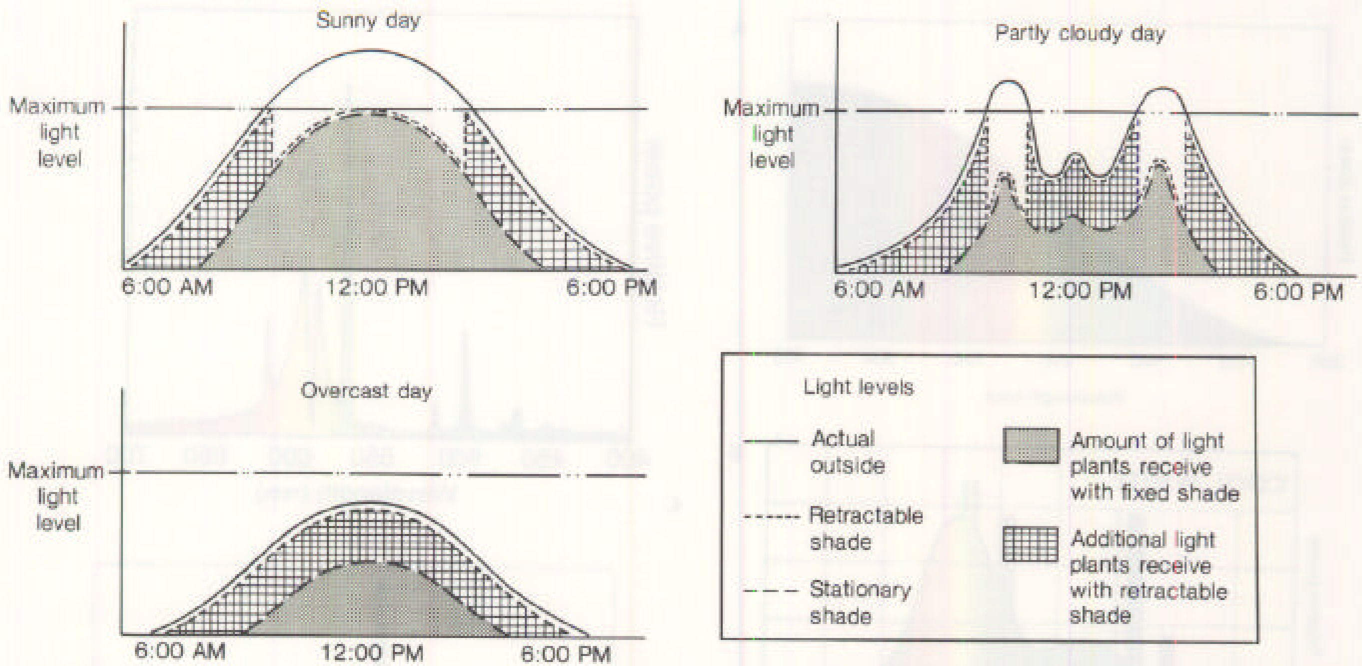
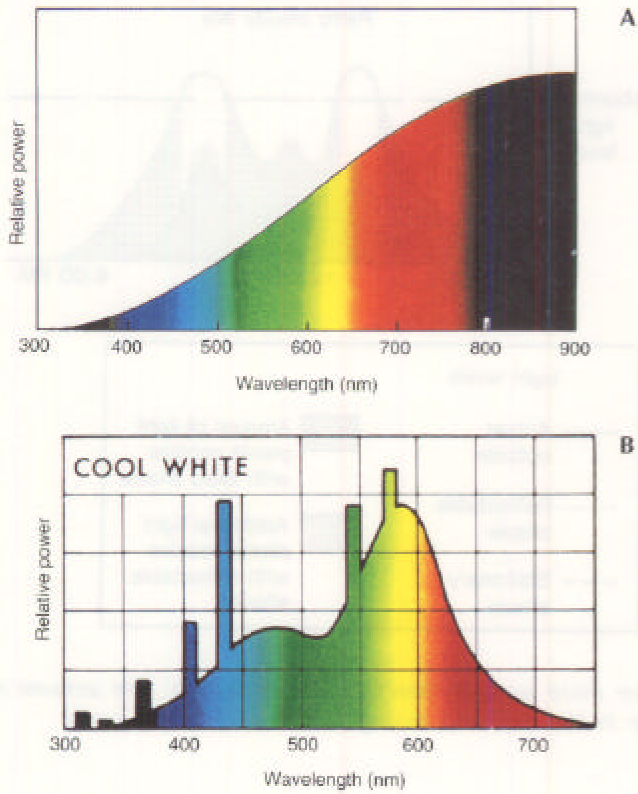


Figure 3.3.25—*Retractable shade systems allow plants to receive more sunlight than "fixed" shadecloth. The amount of additional light can be significant early in the morning and late in the day, and throughout the day under partly cloudy conditions. (Modified from Vollebregt 1990.)*

Incandescent lights are not recommended for photosynthetic lighting because they generate so much heat and are too expensive to operate at the required intensities. They can be balanced with fluorescent lights to better cover the PAR wavelengths, but this combination is only used in growth chambers. Incandescent lamps are the most widely used type of photoperiodic lighting in U.S. and Canadian nurseries, however (table 3.3.7), because they provide a usable spectral energy distribution, are cheap to install, and can be turned on and off frequently without loss of bulb life. Incandescent lamps gradually deposit tungsten on the inside of the bulb (a process called "blackening") which decreases the light output and their useful service life (Aldrich and Bartok 1989). Standard incandescent bulbs are the least efficient and have the shortest average life of all the common light sources used in horticultural lighting (table 3.3.8), which means that bulbs must be replaced frequently.

A tremendous variety of standard and specialty incandescent lamps are available for many different applications (Kaufman and Christensen 1984). The standard incandescent bulb requires an external reflector to direct the light downward and provide more even distribution (fig. 3.3.27A); external reflectors cast unwanted shadows and may collect moisture, however. This problem can be avoided with specialized incandescent lamps that have internal reflectors to concentrate the light and focus it forward (fig. 3.3.27B-D). These flood lamps direct all wavelengths onto the crop. Both standard incandescent and tungsten-halogen reflectors can be coated with a transparent, slightly iridescent external ("dichroic") coating that reflects less of the infrared wavelengths forward (fig. 3.3.28). This is sometimes an advantage, because it raises the ratio of red to far-red light and makes these lamps more efficient for photoperiodic lighting.



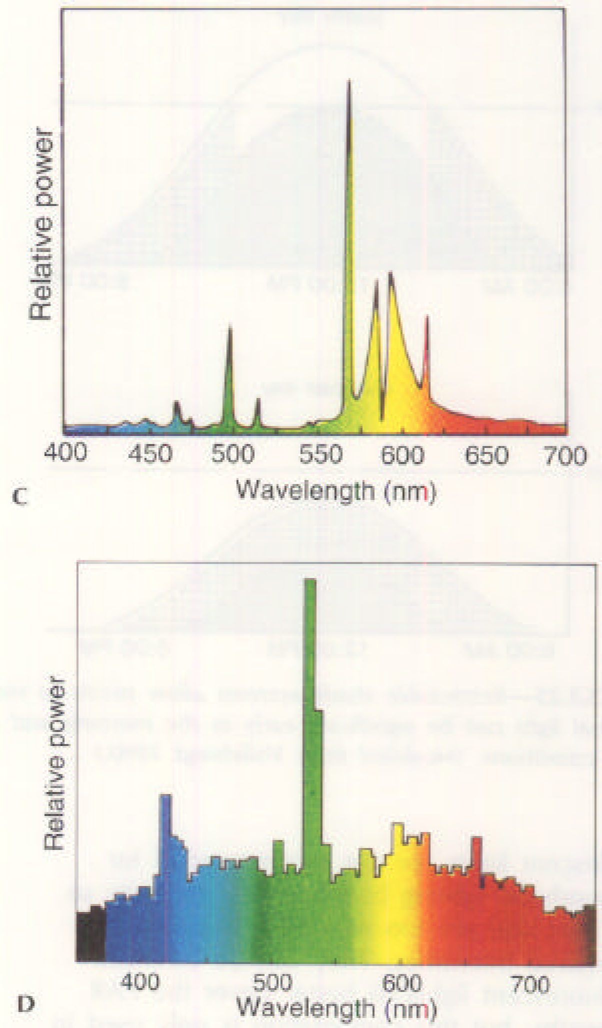


Figure 3.3.26—*The spectral energy distribution (SED) curves vary significantly among different kinds of artificial lighting. Incandescent lamps, including tungsten-halogen types, produce most of their light in the red and infrared wavelengths* (**A**). *There are several different types of fluorescent lamps, but their SED has a more balanced output* (**B**). *High-pressure sodium lamps* (**C**) *produce most of their light in the yellow wavelengths, which makes them good for photosynthetic lighting. The SED curves of metal halide lamps vary with the type of metal used and produce a balanced "white" light* (**D**). *(Reprinted from Kauffman and Christensen 1984: IES lighting handbook, 1984 reference volume, pp. 8-21 & 8-22, by permission of the Illumination Engineering Society of North America, New York.)*

Table 3.3.7—*Purpose of artificial lighting and types of lamps used in container tree nurseries in the United States and Canada*

Type of lamp	Light intensity*		Use (%)	
	$\mu mol/s/m^2$	lx	By class	Total
Photosynthetic lighting				5
High-pressure sodium	17.8–77.4	1,500–6,500	80	
Fluorescent	88.6	7,000	20	
No lamps				95
Photoperiodic lighting				82
Incandescent				
Standard	4.1–10.2	200– 500	54	
Tungsten-halogen	2.0	100	4	
Fluorescent	1.3– 6.3	100– 500	11	
High-intensity discharge				
Metal halide	5.7	400	1	
High-pressure sodium†	1.2–77.4	100–6,500	27	
Low-pressure sodium	3.7	400	3	
No lamps				18

* 39% of respondents were unsure of the light intensity at crop level, or only knew lamp specifications.
† Values are higher because these lights are also used for photosynthetic lighting.
Source: Container Nursery Surveys (1984; 1990).

Table 3.3.8—*Comparison of various light sources used in horticultural lighting*

Type of lamp	Electrical power (watts)		Illumination (lumens)	Efficiency (lumens/watt)	Average life (hr)
	Lamp	Total*			
Incandescent					
Standard	100	100	1,680	17	750
	200	200	4,000	20	750
Tungsten-halogen	75	75	1,400	19	2,000
	250	250	5,000	20	2,000
Fluorescent					
"Cool-White"	40	48	2,770	66	20,000
"Cool-White" VHO†	215	225	11,500	67	10,000
"Gro-Lux"	40	46	925	20	12,000
High-intensity discharge					
High-pressure sodium	400	425	45,000	117	24,000
	1,000	1,060	126,000	132	24,000
Low-pressure sodium	180	230	33,000	143	18,000
Metal halide	400	425	31,000	94	15,000
	1,000	1,060	100,000	118	10,000

* Includes ballast or auxiliary input.
† Very high output.
Sources: Aldrich and Bartok (1989); Kaufman and Christensen (1984).

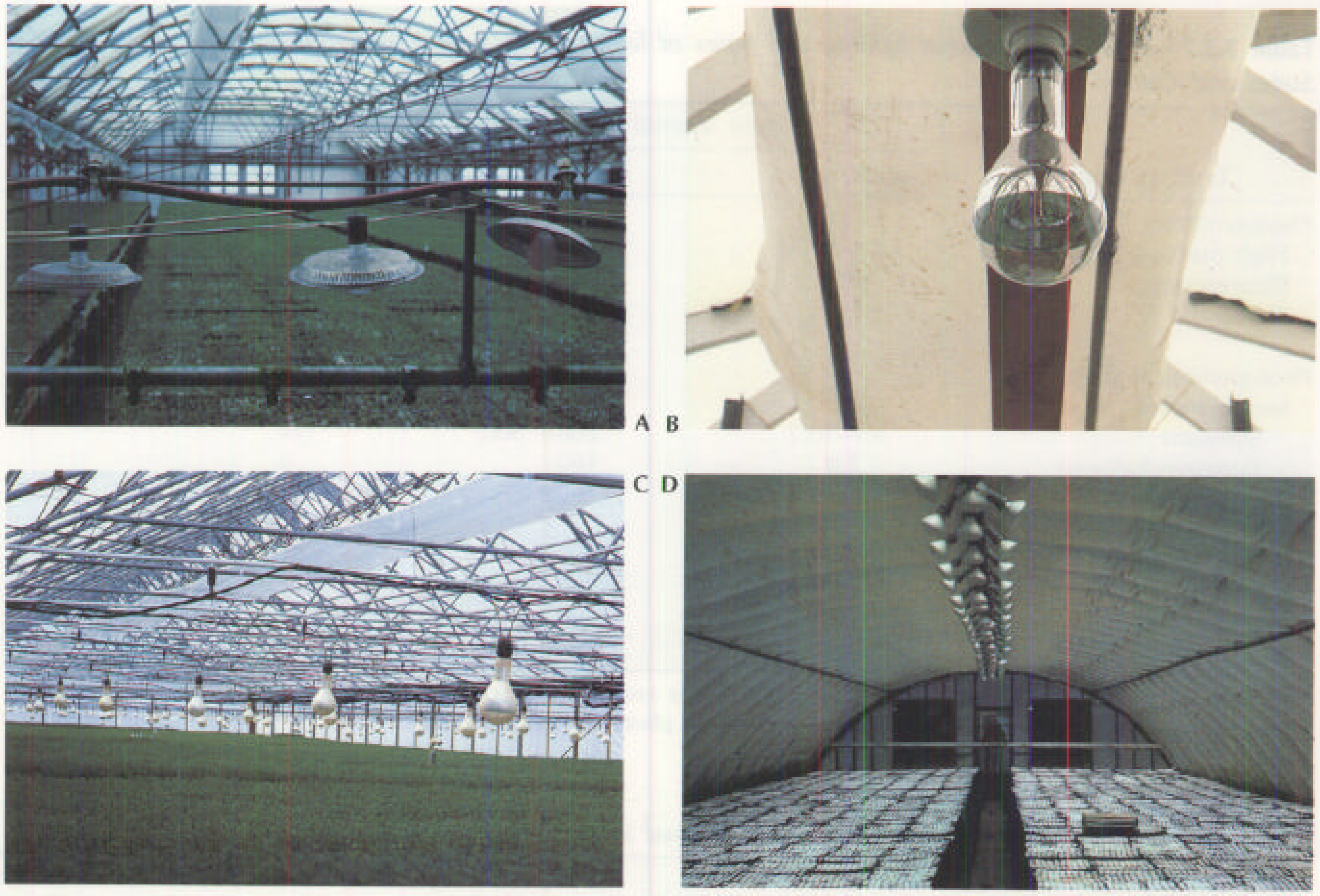
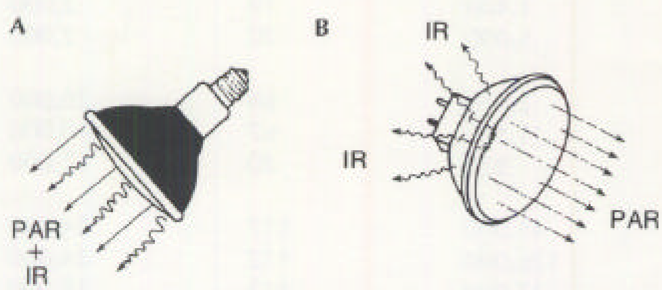


Figure 3.3.27—*Many different types of standard incandescent lamps* (**A–D**) *have been used for photoperiodic lighting in container tree nurseries. Some bulbs have internal reflectors* (**B–D**)*, which direct the light downward onto the seedling crop. Incandescent lamps are typically mounted in fixed overhead arrays that are used to provide intermittent lighting* (**C–D**).



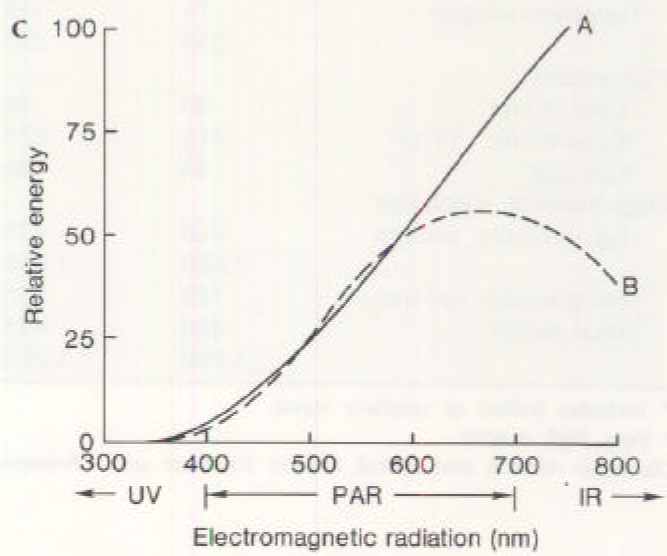


Figure 3.3.28—*Typical incandescent lamps* (**A**) *produce a high percentage of infrared radiation (heat), but can be purchased with a special dichroic coating on the back which reflects the photosynthetically active radiation (PAR) forward onto the crop, while transmitting infrared radiation (IR) out the back of the lamp* (**B**)*. Graph* (**C**) *shows the difference in spectra between the two lamps. (Modified from Bickford and Dunn 1972.)*

A relatively new addition to the incandescent class is the **tungsten-halogen** (also called "halogen quartz") lamp, which has the same spectral energy distribution as the standard incandescent lamp (fig. 3.2.26A) but has several distinct advantages, including longer bulb life and higher efficiency at the same wattage (Kaufman and Christensen 1984; table 3.3.8). The thin, tubular bulb is made of a quartz-silica glass, and a halogen gas (iodine or bromine) surrounds the tungsten filament and prevents the blackening that is typical of an incandescent lamp (Bickford and Dunn 1972). The small size of tungsten-halogen lamps enables them to be mounted in more efficient reflector fixtures (fig. 3.3.29). Like other incandescent bulbs, however, their energy efficiency is still relatively low compared to other types of lamps (table 3.3.8).

Fluorescent lamps. Fluorescent lamps produce light when a mercury arc excites fluorescent powders ("phosphors") that coat the inner walls of the bulb. Electrical current flowing between the electrodes on both ends of the lamp produces an arc in the mercury vapor, generating ultraviolet radiation and exciting the phosphors to emit light (Kaufman and Christensen 1984). Fluorescent lamps contain a complex electric circuit including a ballast, which provides enough voltage to start the electric discharge. Because the ignitor in the bulb wears out with use, lamp life is shortened if they are turned on and off frequently (Bickford and Dunn 1972).

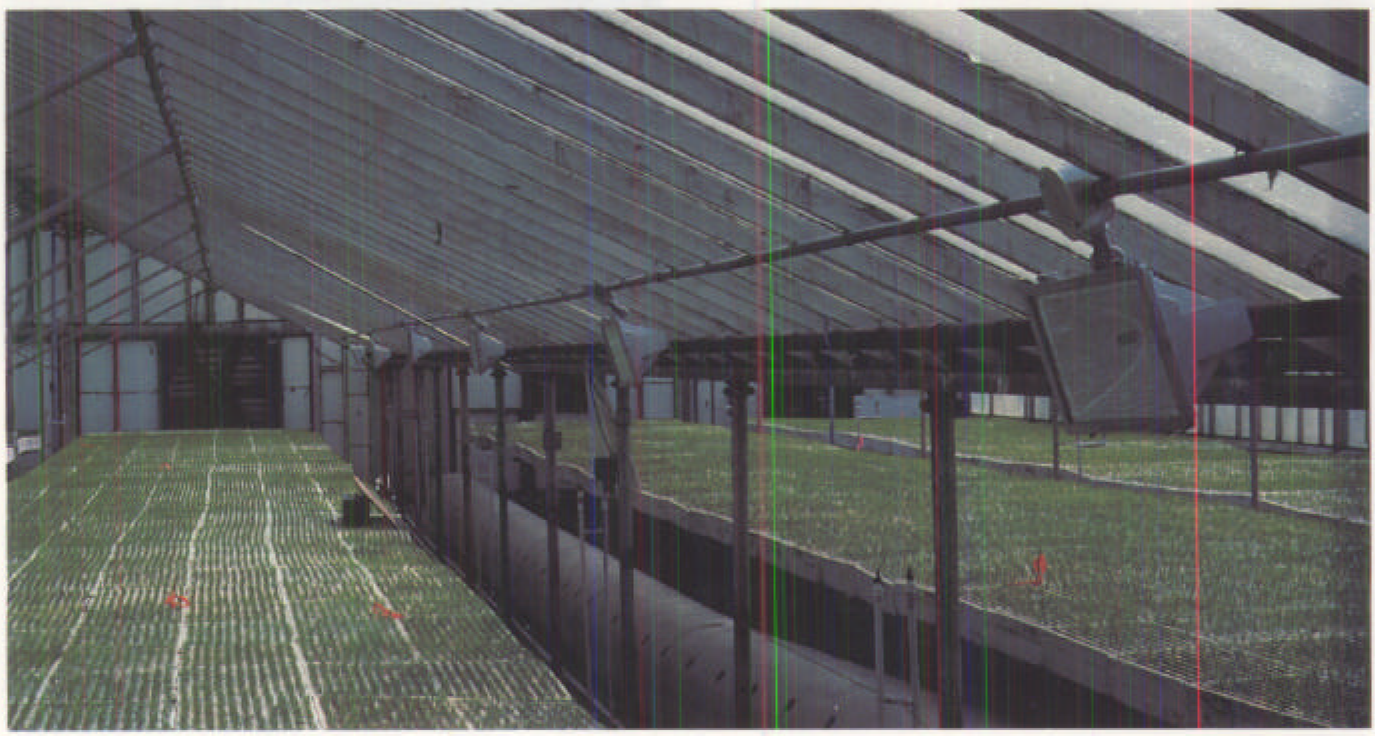


Figure 3.3.29—*Tungsten-halogen ("halogen quartz") lamps are another type of incandescent light that is used for continuous photoperiodic lighting in container tree nurseries. The relatively small, high intensity bulbs are held in special reflectors which are often mounted in a fixed oblique pattern.*

Fluorescent lamps are available with widely different spectral energy distributions, depending on the specific coatings on the bulb; "cool white" bulbs are useful for most horticultural applications (fig. 3.3.26B). The initial installation cost of fluorescent lamps is twice that of incandescent, but they are over three times more efficient in producing visible light. They may last up to 12 times longer than standard incandescent lamps, provided they are not cycled on and off frequently (table 3.3.8). Fluorescent lamps are widely used in growth chambers because they are a linear light source that produces relatively little infrared radiation, which is important in a closed environment (AIdrich and Bartok 1989). Fluorescent lamps have several disadvantages, however. Light intensity per unit area is generally low, although special high-output bulbs are available (table 3.3.8).

The relatively large fixtures (fig. 3.3.30A-B) cast undesirable shadows, but this can be reduced by orienting them north to south so that their shadows move. Waterproof fixtures are recommended for greenhouses. In spite of these restrictions, fluorescent lamps are being used for both photosynthetic and photoperiodic lighting in container tree nurseries in the United States and Canada (table 3.3.7). If they must be used, they are best mounted on an irrigation boom (fig. 3.3.30B).

High-intensity discharge lamps. These compact, high-output lamps are becoming popular for horticultural lighting because they efficiently produce light in the PAR wavelengths and require little maintenance. High-intensity discharge (HID) lamps generate light by passing an electric current through a pressurized gas at high temperature, causing the gas to glow. Several different gases are used, including sodium and mercury-iodide (metal halide), which determine both the intensity and quality of the emitted light (fig. 3.3.26C-D). Because it takes several minutes to generate the necessary gas temperature and pressure, there is a time lag before the lamps are fully operational. Lamp fixtures are relatively large because they require a ballast to regulate the electrical current (fig. 3.3.31); some models are equipped for remote ballasting (Aldrich and Bartok 1989). All HID lamps are significantly more energy efficient than other sources of artificial light (table 3.3.8).

A

B

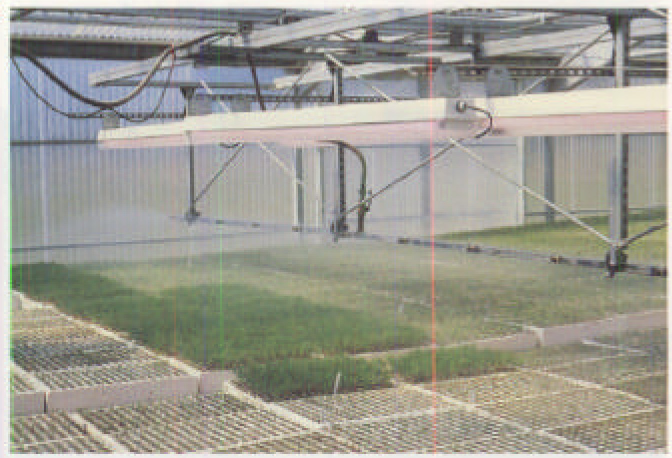


Figure 3.3.30—*Fluorescent lamps have been used for continuous photoperiodic lighting, but the large reflectors cast undesirable shadows* (**A**). *If they are mounted on irrigation booms, they can provide intermittent lighting when the boom moves back and forth* (**B**).

High-pressure sodium. High-pressure sodium (HPS) lamps generate light by passing an electric current through sodium vapor in an elongated arc tube (fig. 3.3.31A), which contains a double glass envelope to contain the corrosive sodium vapor (Kaufman and Christensen 1984). The spectral energy distribution extends across the visible spectrum but peaks sharply in the yellow bands, very close to optimum for both photosynthesis and photoperiod lengthening. Very low levels of infrared light are produced (fig. 3.3.26C). HPS lamps emit a very intense light, so the fixtures can be spaced widely enough to avoid blocking much sunlight. Both 400W and 1,000 W lamps are used

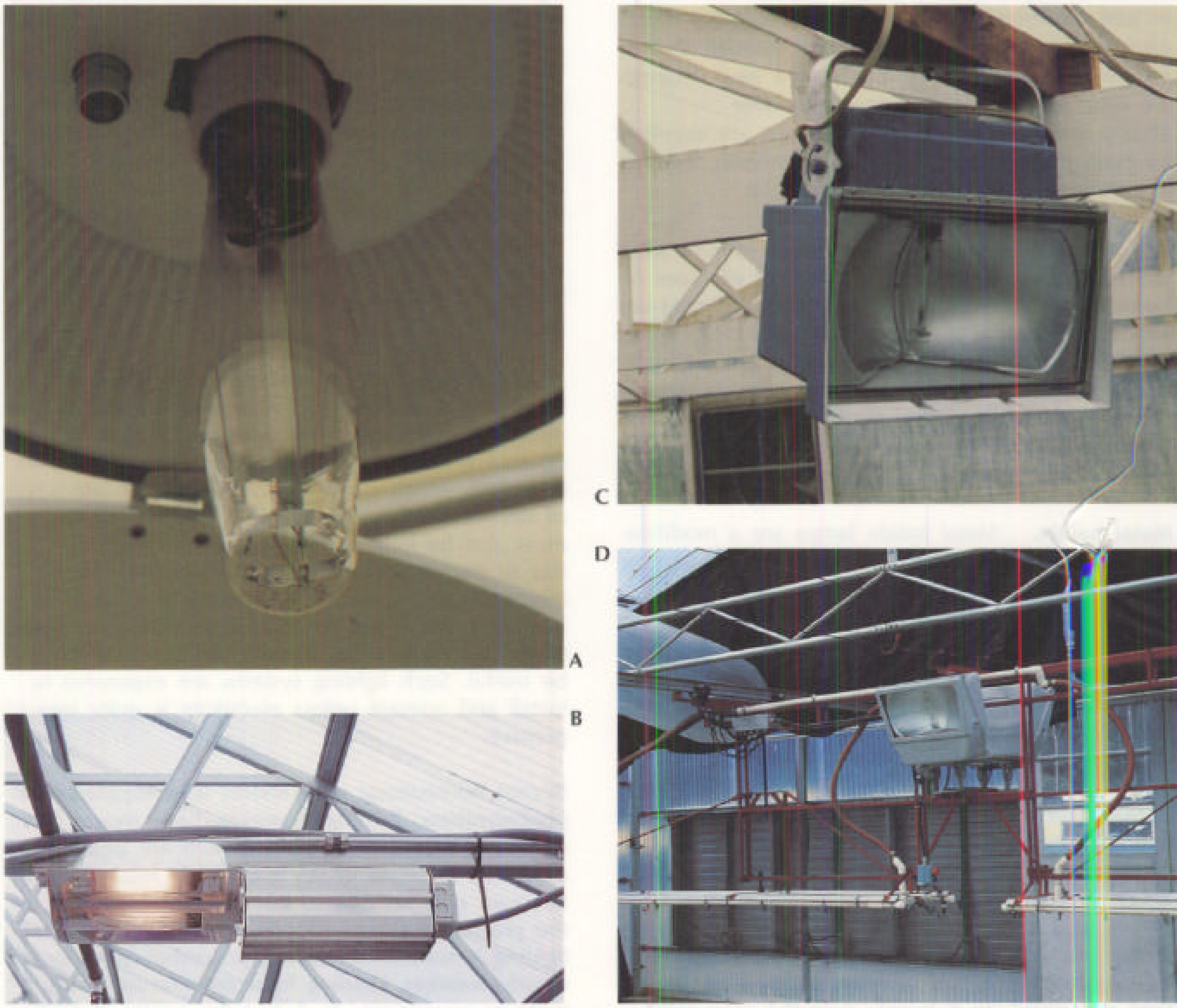


Figure 3.3.31—*High-pressure sodium lamps* (**A**–**D**) *can be used for either continuous photoperiodic lighting or supplemental photosynthetic lighting when mounted in fixed overhead positions* (**B**). *They are also used in fixed oblique mountings* (**C**) *or on irrigation booms to provide intermittent photoperiodic lighting* (**D**).

in tree nurseries. The larger lamps are more efficient if they can be mounted high enough in the growing structure. Development of a new ceramic arc tube has increased lamp life to over 20,000 hours (table 3.3.8). HPS lamps are excellent for both photosynthetic and photoperiodic lighting in container tree nurseries (table 3.3.7).

Low-pressure sodium. Low-pressure sodium (**LPS**) lamps are the most energy efficient of all types of horticultural lighting (table 3.3.8). Their spectral energy distribution is more restricted than HPS lamps (Aldrich and Bartok 1989), but this is not a disadvantage. They are less intense and take up more space, thus creating more shadows, and they have been used for photoperiodic lighting in only a few container tree nurseries (table 3.3.7).

Metal halide. Metal halide lamps are a modification of the older mercury lamps; the arc tube contains various metal halides (for example, dysprosium and thallium iodides) as well as mercury-argon vapor (Kaufman and Christensen 1984). Compared to mercury lamps, metal halide lamps produce 50% more light output, in a well-balanced spectral energy distribution (fig. 3.3.26D). Metal halide lamps are available in wattages of 400W and 1,OOOW and have a life expectancy of 10,000 to 15,000 hours. They are rarely used in container tree nurseries (table 3.3.7), because HPS lamps are more efficient and have a much longer life (table 3.3.8).

Reflectors. All types of lamps used in horticulture require some sort of reflector to focus the light and distribute it evenly over the crop area. External reflectors are often purchased as part of the lighting fixture (fig. 3.3.29 to 3.3.31) but can also be homemade (fig. 3.3.27A). Specialized types of incandescent lamps have built-in reflectors, such as the parabolic aluminized reflector (the established acronym PAR is unfortunately the same as that for photosynthetically active radiation). Of particular interest is the dichroic reflector, which reflects the PAR wavelengths forward and transmits infrared radiation out the rear of the lamp (fig. 3.3.28).

3.3.4.4 Photosynthetic lighting

Because of high energy costs, it is rarely practical to provide enough artificial light to increase photosynthesis in container tree nurseries. The exception is at higher latitudes, where it is sometimes economical to use photosynthetic lighting to supplement natural daylight during the fall, winter, and spring (Bickford and Dunn 1972). At present, only about 5% of the forest nurseries in the United States and Canada supply photosynthetic lighting (table 3.3.7).

Light intensity. If artificial lights are the only source of illumination, as in a growth chamber, the minimum requirement for commercial plant production is considered to be about 250 µmol/s/m2 (--20 klx), which is about one-eighth the intensity of normal sunshine (ASHRAE 1989). The lights must also be kept on for at least 12 hours per day to permit reasonable rates of growth. Highintensity lights generate a tremendous amount of heat, but this is less of a problem when photosynthetic lighting is used at night, for the heat may be useful. Such lighting systems are expensive to install and operate unless electricity is quite inexpensive.

Recent horticultural experiments with supplemental photosynthetic lighting, however, have shown that significant increases in plant growth are possible, especially in terms of dry weight. At least some of this gain may be due to the incidental warming of the growing medium (Downs 1985). Supplemental lighting is sometimes needed to compensate for cloudy weather, shading from greenhouse structures or equipment, or during the winter at higher latitudes. When 122 µmol/s/m2 (-10 klx) of PAR light is added for 8 to 16 hours per day, growth rates can approach those obtained in growth chambers (ASHRAE 1989). In Alberta, where normal December sunlight is only 70 µmol/s/m^2 (~3.8 klx), 12 conifer species responded strikingly to supplemental winter lighting. Two different lighting systems were effective-60 to 100 µmol/s/m^2 (~4.7 to 7.9 klx) of fluorescent lighting or 210 to 220 µmol/s/m^2 (~17.6 to 18.4 klx) of high-pressure sodium lighting, supplied for 18 or 24 hours per day (Dymock and Wilson 1986). In Wisconsin, the addition of between 18 and 63 µmol/s/m² (~1.4 to 5.0 klx) of PAR during the winter significantly increased the growth of white spruce, jack pine, and hybrid poplars (Roberts and Zavitkovski 1981).

Light quality. Because not all wavelengths are equally effective for photosynthesis, artificial lighting should be high in the PAR bands (fig. 3.3.1). The most efficient wavelengths of light are 600 to 700 nm, in the red part of the visible spectrum; blue, green, and yellow light (400 to 600 nm) have only one-half to two-thirds the efficiency of red light. Infrared light (> 700 nm) is not effective for photosynthesis but is merely absorbed and increases leaf temperature. Ultraviolet light (< 400 nm) is also ineffective and can be damaging.

High-pressure sodium lights are recommended for photosynthetic lighting because they are the most efficient and cost effective. Metal halide and fluorescent lamps can also be used but are less desirable in terms of PAR output per watt and life expectancy (table 3.3.8).

Lamp fixtures and positioning. Because of the high light intensity that is required, lamps for photosynthetic lighting must be positioned close to the crop. Mounting photosynthetic lights on the irrigation boom would not produce continuous lighting, and so fixtures must be mounted in a regular, fixed pattern over the crop.

3.3.4.5 Photoperiodic lighting

The greatest use of artificial lighting in horticulture is for extending the photoperiod (Bickford and Dunn 1972). The majority of the plants grown for forestry and conservation purposes require extended photoperiods to produce rapid growth rates, and so most growing areas are equipped with some type of lighting for extending daylength (table 3.3.7). Nurseries in southern climates and coastal areas with mild maritime climates that grow ecotypes native to those areas may not need photoperiodic lighting. (See section 3.3.2.2 for more information on when photoperiodic lighting is needed.)

Most of the major lamps have the desired red wavelengths (fig. 3.3.26) for photoperiod control, and incandescent, fluorescent, and high-intensity discharge types have been used successfully. The choice of the best lighting system, therefore, is one of economics and the layout of the nursery. If the growing area is already equipped with photosynthetic lighting, the same equipment can be generally used to extend the daylength.

For photoperiodic lighting to be fully effective, other environmental factors, such as temperature, humidity, water, and mineral nutrition, should be optimal. Stressed seedlings do not respond normally to light stimuli.

Types of photoperiodic lighting. A variety of terms have been used to describe photoperiodic lighting systems, and confusion has resulted because a useful term must denote both duration (how long the lights are left on), and timing (when the lights are activated).

The duration of photoperiodic lighting has traditionally been described as either continuous or intermittent, and both types have been used successfully. In **continuous lighting,** lights are turned on for prolonged periods. Although many types of lamps can be used for continuous lighting, the HID types are the only cost-effective option and HPS lamps are recommended.

In **intermittent lighting,** the night is interrupted with short bursts of light at regular time intervals during the prescribed period. The lights can be left on for as little as 3% of the time, provided no dark period is longer than 30 min (Tinus and McDonald 1979). Arnott and Mitchell (1982) reported that supplying light for 2 out of every 30 min was effective. Intermittent lighting can be achieved in two ways, depending on the type of lamps used. Lights that will tolerate repeated switching, such as standard incandescent lamps, are mounted in fixed arrays, while those that require ballasting must be mounted on a moving irrigation boom because of their slow start-up time. In this application, the lamps must remain on continuously and intermittent lighting is achieved by moving the boom back and forth. Obviously, this lighting option is only practical in nurseries with boom irrigation systems.

All types of lamps have been used on irrigation booms: incandescent (fig. 3.3.27A), fluorescent (fig. 3.3.30B), and high-pressure sodium (fig.3.3.31 D).

Continuous and intermittent lighting can be applied in three different time sequences (fig. 3.3.32)

- **Night-break lighting** is a technique in which the lights are turned on for a few hours in the middle of the night, breaking it into two shorter dark periods (Vince-Prue 1975). The night-break can be either continuous or intermittent, although the former is more common.
- **Daylength extension lighting** involves supplying 2 to 4 hours of artificial light after dusk or before dawn (Nitsch 1957). Continuous lighting is normally used for daylength extension.
- **All-night lighting** is a technique in which the lighting system is activated all night long. Intermittent lighting is the most economical option.

Therefore, to be completely accurate, **photoperiodic lighting systems should be described with a term that denotes both duration and timing,** for example, "continuous night-break lighting" or "intermittent all-night lighting" (fig. 3.3.32).

Many different photoperiodic lighting systems have been used in container tree nurseries, and the best system will depend on the type of greenhouse and type of lamps that are available. Either continuous or intermittent night-break lighting can be just as effective as a longer light period (Arnott 1989). Continuous daylength extension is sometimes used but is less economical than other systems. Electrical consumption was reduced by 75% and lamp life increased considerably when HPS lamps were used to provide continuous night-break lighting in a British Columbia container nursery (Forestry Canada 1991). Standard incandescent lamps are commonly used to produce intermittent all-night lighting, and energy savings of 60 to 80% over continuous lighting are possible (Bickford and Dunn 1972). Regardless of the economics, providing continuous light for the entire night (that is, a 24-hour photoperiod) is not desirable and can even be detrimental. Continuous all-night lighting may reduce height growth of container tree seedlings by as much as 30% (Tinus and McDonald 1979).

Light intensity and quality. Research trials have determined photoperiodic lighting intensities for many species and ecotypes (table 3.3.5), and these recommendations have been validated in operational container nurseries (table 3.3.7). To ensure that photoperiodic lighting will be effective, the light intensity should be at least 8 µmol/s/m^2 (~430 lx), and should be increased to 16 µmol/s/m^2 (~860 lx) when the crop has a higher light requirement. Some species can be grown with even less light intensity (Arnott and Macey 1985). If the exact light intensity is unknown for a species or ecotype, it is always better to supply more light than to risk providing too little. Some species that set bud and become dormant require chilling before they will initiate new shoot growth. This can be economically disastrous because the crop will not meet height specifications within the allotted crop schedule.

Because phytochrome is triggered by the relative amounts of red: far-red light, the light output should be high in the red (600 to 700 nm) band and low in the far-red (700 to 800 nm) band (see section 3.3.2.2 for more details).

Nurseries should have a backup source of electrical power for their photoperiodic lighting systems because loss of extended daylength, even for a short time, can be damaging. Research studies have shown that light failure for a period of one night (Arnott 1984), or three nights (Arnott and Simmons 1985), caused significant height reduction of white spruce and mountain hemlock seedlings, respectively. The authors have observed a similar response with Engelmann spruce (fig. 3.3.12D), blue spruce, and green ash.

Lamp fixtures and positioning. In container tree nurseries, photoperiodic lighting is typically installed in either fixed or mobile systems. Although some lamps can be installed in either manner, others are best suited for one specific type.

Fixed systems. Photoperiodic lighting, installed either overhead in a regular grid pattern or mounted at an oblique angle on side walls or posts, can be used for either intermittent or continuous lighting. With either type of mounting, the placement of the individual lamps is critical because the light intensity can vary in three dimensions.

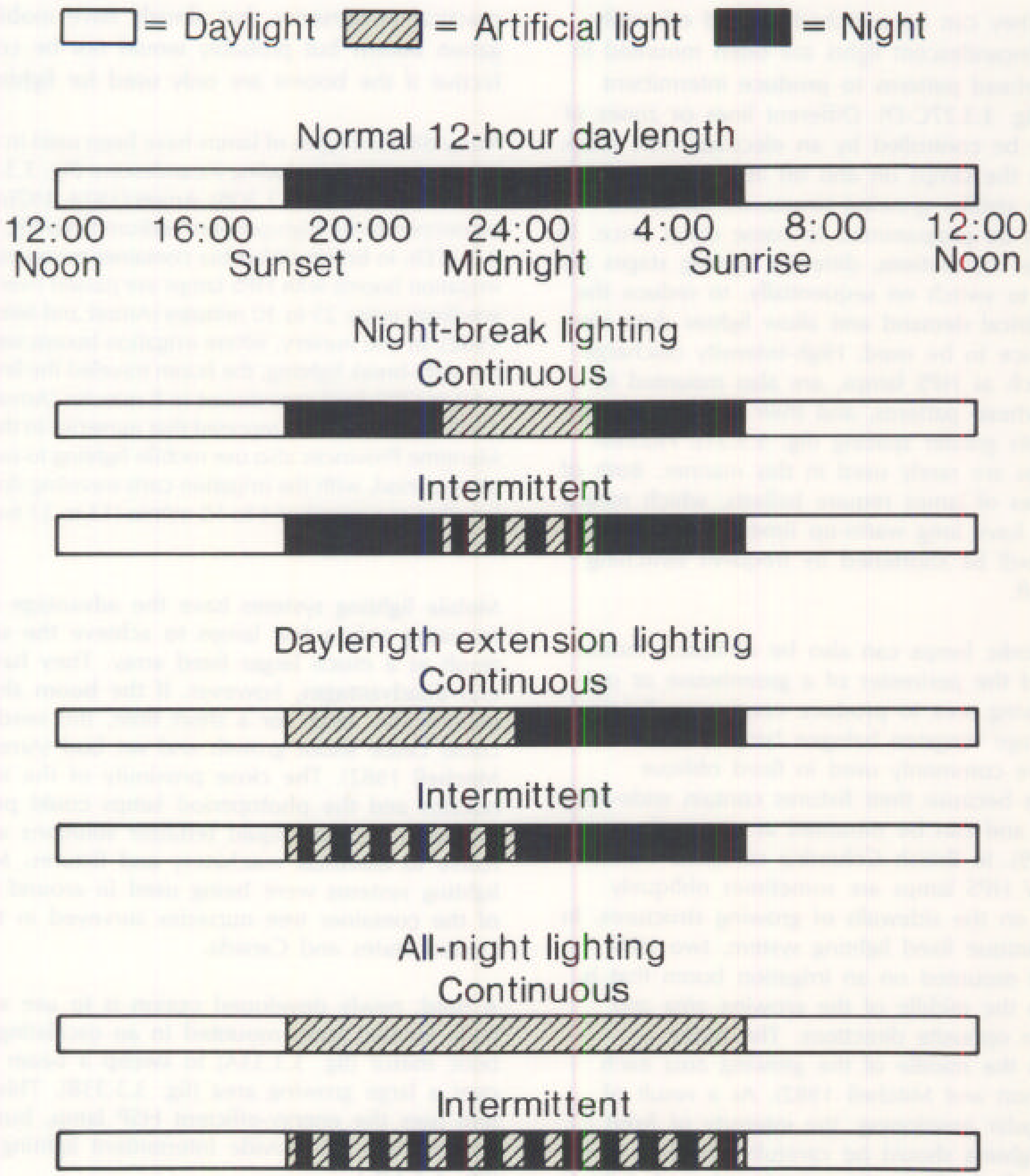


Figure 3.3.32—*Photoperiodic lighting systems should be described with terms that denote both duration (how long the lights are left on) and timing (when the lights are activated). The duration can be either continuous or intermittent, and the timing alternatives include night-break, daylength extension, or all-night. Combining these two concepts produces an accurate and descriptive nomenclature.*

Because they can be switched on and off easily, standard incandescent lights are often mounted in fixed overhead patterns to produce intermittent lighting (fig. 3.3.27C-D). Different lines or zones of lights can be controlled by an electrical time clock that turns the lamps on and off at prescribed intervals. In smaller growing structures, all of the lamps can be programmed to come on at once. In most larger installations, different lighting stages are designed to switch on sequentially, to reduce the total electrical demand and allow lighter duty electrical service to be used. High-intensity discharge lamps, such as HPS lamps, are also mounted in fixed overhead patterns, and their higher light output permits greater spacing (fig. 3.3.31). Fluorescent lamps are rarely used in this manner. Both of these types of lamps require ballasts, which means that they have long warm-up times, and their usable life will be shortened by frequent switching on and off.

Photoperiodic lamps can also be obliquely mounted around the perimeter of a greenhouse or outdoor growing area to produce continuous lighting. High-wattage tungsten halogen lamps ("flood lights") are commonly used in fixed oblique mountings because their fixtures contain wide-angle reflectors and can be mounted at any angle (fig. 3.3.29). In British Columbia container nurseries, 400W HPS lamps are sometimes obliquely mounted on the sidewalls of growing structures. In another unique fixed lighting system, two HPS lamps are mounted on an irrigation boom that is moved to the middle of the growing area and pointed in opposite directions. The boom is moved to the middle of the growing area each night (Arnott and Mitchell 1982). As a result of their irregular positioning, the intensity of fixed oblique lighting should be carefully checked to insure that all seedlings are receiving enough light. Shadows from vertical structural supports can also be a problem.

Mobile systems. The second type of photoperiodic lighting systems uses lamps mounted on a mobile irrigation boom, which produces intermittent lighting by moving back and forth. Fewer lamps are required and their pattern of overlap is only critical in one dimension. Mobile lighting is practical in nurseries that already have mobile irrigation booms but probably would not be cost effective if the booms are only used for lighting.

Many different types of lamps have been used in mobile lighting systems, including incandescent (fig. 3.3.27A) and fluorescent (fig.3.3.30B). Arnott (1974, 1976) recommends the high-pressure sodium lamp (fig. 3.3.31 D). In British Columbia container nurseries, irrigation booms with HPS lamps are passed over the seedlings every 25 to 30 minutes (Arnott and Mitchell 1982). In one nursery, where irrigation booms were used for night-break lighting, the boom traveled the length of a 60-m (200-foot) greenhouse in 8 minutes (Arnott 1989). Hallett (1982) reported that nurseries in the Maritime Provinces also use mobile lighting to extend photoperiod, with the irrigation carts traveling down the benches at a speed of 4 to 10 m/min (13 to 33 feet per minute).

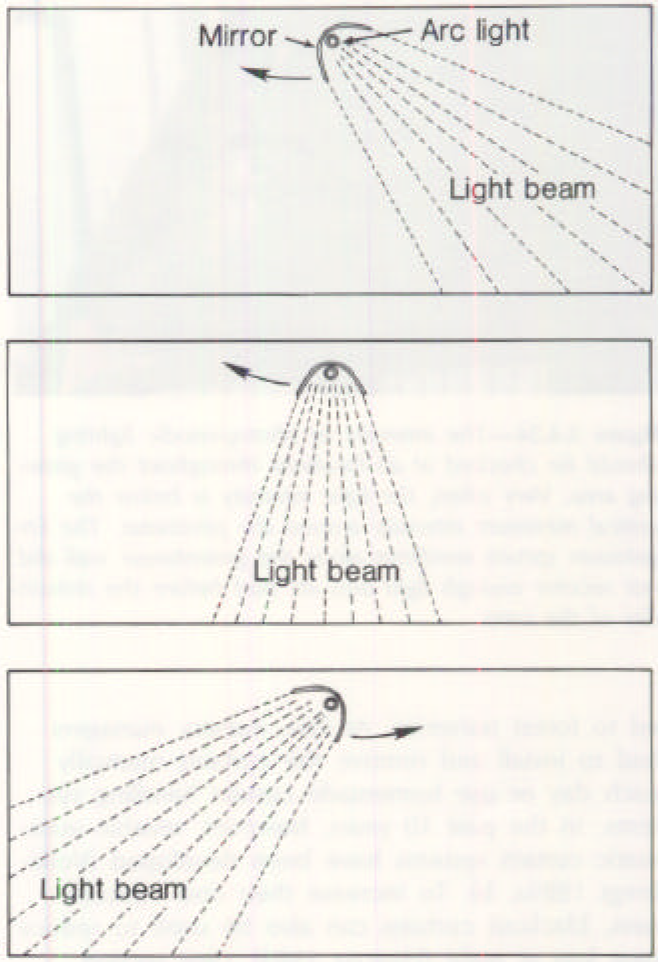
Mobile lighting systems have the advantage of requiring only a few lamps to achieve the same result as a much larger fixed array. They have several disadvantages, however. If the boom should malfunction, even for a short time, the seedlings could cease shoot growth and set bud (Arnott and Mitchell 1982). The close proximity of the irrigation nozzles and the photoperiod lamps could produce problems because liquid fertilizer solutions are corrosive to electrical machinery and fixtures. Mobile lighting systems were being used in around 20% of the container tree nurseries surveyed in the United States and Canada.

A third, newly developed option is to use a centrally located lamp mounted in an oscillating parabolic mirror (fig. 3.3.33A) to sweep a beam of light over a large growing area (fig. 3.3.33B). This system uses the energy-efficient HSP lamp, burning continuously, to provide intermittent lighting (fig. 3.3.33C).

When designing a photoperiodic lighting system, container nursery managers should consult with a horticultural lighting expert. Applying the lighting information from manufacturers' specifications or another local nursery can cause problems, and it is strongly recommended that growers test any potential arrangement under operational conditions.

A

B



C

Figure 3.3.33—*A newly developed type of photoperiodic light features a centrally mounted high-pressure sodium lamp in an oscillating mirror* (**A, B**). *This system produces intermittent lighting by oscillating the mirror back and forth across the growing area* (**C**).

All photoperiodic lighting systems should be checked immediately after installation for uniformity and adequate light intensity. In particular, light intensity is never completely uniform from fixed overhead installations. Lamps laid out in grids produce circular intensity patterns similar to the watering patterns from fixed overhead irrigation systems. The magnitude may not always be evident to the human eye, but the variation in light intensity that is measured directly under a lamp and between lamps can be significant (fig. 3.3.34). Oblique installations produce a fan-shaped light pattern, the intensity of which decreases with distance. The overall intensity pattern should be carefully mapped, therefore, to ensure that there are no areas with below-minimum light levels. If the installed lighting is found to be inadequate in intensity, the problem can sometimes be solved by leaving the lights on for a longer time; there is evidence for a reciprocal relation between light duration and light intensity, at least for blue spruce (Young and Hanover 1977).

3.3.4.6 Short-day treatments

Whereas shortening the dark period with photoperiodic lighting promotes shoot growth and inhibits dormancy, lengthening the dark period triggers cessation of height growth and budset. And just as intermittent photoperiodic lighting is as effective as longer light periods, a relatively short period of darkness has worked well. These short-day or "blackout" treatments have been used for years in the floriculture industry to promote flowering of short-day plants but have only recently been adapt-

Figure 3.3.34—*The intensity of photoperiodic lighting should be checked at all locations throughout the growing area. Very often, the light intensity is below the critical minimum intensity around the perimeter. The Engelmann spruce seedlings along the greenhouse wall did not receive enough light and set bud before the remainder of the crop.*

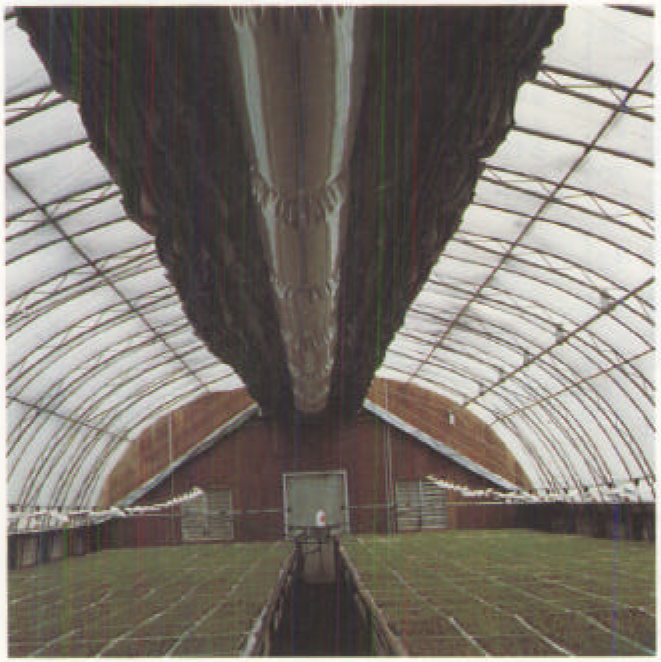
ed to forest nurseries. At first, nursery managers had to install and remove the curtains manually each day or use homemade curtain handling systems. In the past 10 years, however, reliable automatic curtain systems have been developed (Vollebregt 1989a, b). To increase their cost effectiveness, blackout curtains can also be used to reduce heat loss at night (Heacox 1989). (See section 3.1.4.4 for more discussion on heat curtains.)

Blackout curtains can be constructed of several different materials. Originally black shadecloth or polyethylene tarp was used. Initial trials revealed some problems: dark shadecloth absorbs solar radiation and impermeable sheeting retards ventilation, which may result in damaging heat buildup in enclosed structures. The following criteria should be considered when purchasing a blackout curtain (Vollebregt 1990):

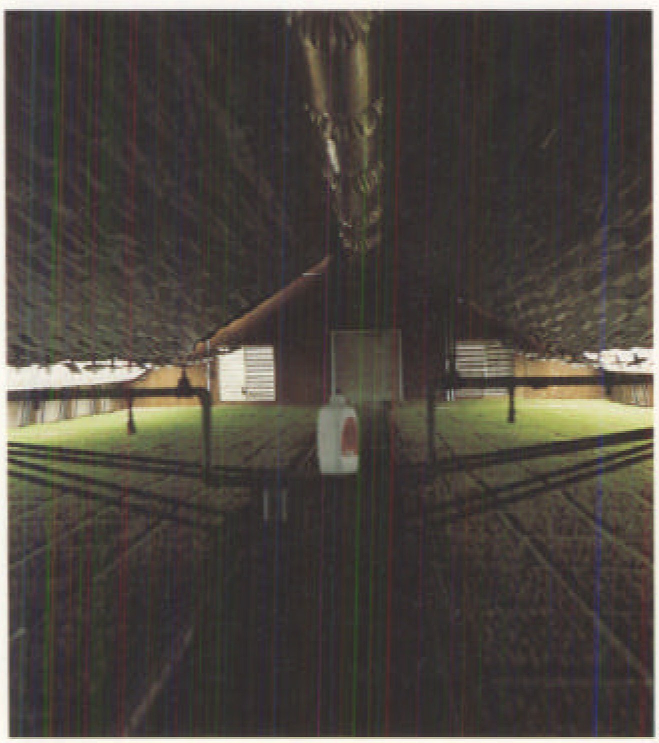
- Reflective upper surface-Curtains with a white or aluminized covering (fig. 3.3.35A) that reflects both visible and infrared radiation will remain cooler than other materials.
- Porosity -A permeable curtain will not allow water from condensation or leaks to accumulate on the fabric. Prolonged exposure to water could damage the fabric or the mechanical deployment system. A porous material will also encourage air exchange and lower the humidity of the air below the cover. 9 Pliability -Blackout curtains should furl or bundle easily and compactly so that they will not interfere with normal sunlight transmission during the day (fig.3.3.35B).

Automatic blackout curtains (fig. 3.3.35D) are available to fit most types of growing structures, and it is much easier and more economical to incorporate a blackout curtain into the original greenhouse design than to retrofit an existing structure. Gabled structures can be fitted with curtains that roll up and down along the side walls. For the overhead portion there are two basic installations: gutter-to-gutter systems, which unfold like an accordion horizontally across the house, and truss-to-truss systems, which unfold from one truss to the next, often following the roof line. For

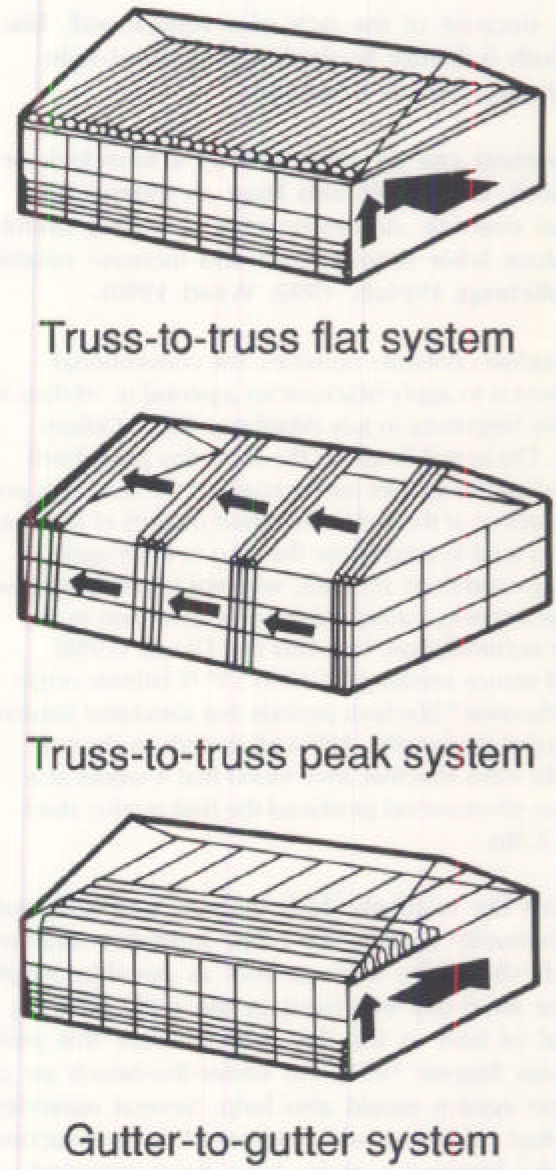
A



B



C



D

Figure 3.3.35—*Container nurseries at high latitudes use blackout curtains to exclude light and create short-day conditions during the naturally long days of midsummer. Some curtains have a reflective outer surface to effectively exclude light and heat* (**A**). *Automated curtain systems are available for most types of growing structures* (**B–D**). (**D**, *courtesy of Cravo Equipment, Ltd.)*

either of these systems to be installed it is important that no machinery be suspended from the purlins or go vertically through the roof (like a flue pipe). In gutter-to-gutter systems the cloth lies flat on wire along the bottom of the trusses. In truss-to-truss systems this may also be the case, but the cloth can also be suspended against part or all of the roof in a peaked configuration. Peaked truss-to-truss curtains are more expensive to install, but have the advantage that climate control equipment mounted above the purlins, such as a carbon dioxide generator, can be used when the curtain is in place. Because of the lack of a vertical wall, blackout cloth is harder to deploy in quonset-style greenhouses, but it is possible.

Deployment can be controlled by a timeclock or photocell, but should also have an independent manual override. Automatic control is very useful to reduce labor requirements and increase reliability (Vollebregt 1989ab, 1990; Weed 1990).

In Canadian container nurseries, the conventional treatment is to apply blackout for a period of 10 days to 6 weeks beginning in July (Matthews 1983, Odlum 1991). The actual length of the short-day period will depend on the species and ecotype of the seedlings and the objective of the treatment. Short periods of less than 2 weeks tend to predispose the crop to flush again if growing conditions are ideal, whereas longer treatments, such as 6 weeks, cause a significant reduction in dry matter accumulation. Hawkins and Draper (1988) treated spruce seedlings of 49 to 55° N latitude origin with "dynamic" blackout periods that simulated naturally decreasing daylengths. Although periods as short as 2 weeks were effective, they found that 4 weeks at a 13-hour photoperiod produced the best quality stock (fig. 3.3.36).

Because the relatively thick curtains trap heat and high humidity around the crop, short-day treatment periods should be kept as brief as possible. Applying the short-day treatment in the early morning instead of later in the day can minimize this problem (van Steenis 1991). An under-the-bench air circulation system would also help. Several nurseries have had problems with lammas shoot production after the blackout curtains have been removed (fig. 3.3.16A). It is important to make sure that no light from adjacent sources, such as security lights, reaches the crop or the seedlings may break bud (Colombo and Smith 1984).

Recent research has shown that the phenological effects of short-day treatments can persist for at least 1 year after outplanting. (See section 3.3.2.2 for more discussion.)

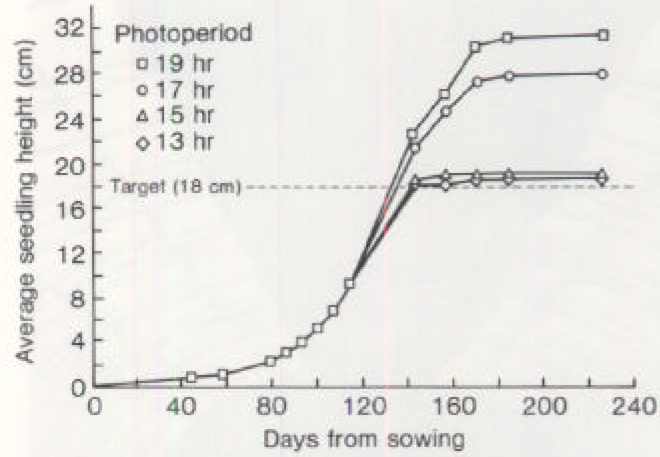


Figure 3.3.36—*Short-day treatments for only a few weeks can be effective with sensitive species. These spruce seedlings stopped height growth and set bud at the target height when treated with "dynamic" short-day treatments of 13 hours of darkness for 4 weeks. (Adapted from Hawkins and Draper 1988.)*

3.3.5 Light Monitoring and Control Systems

3.3.5.1 Measuring light levels

The proper light measuring equipment will depend on the objectives of the individual and the particular application.

Photometers. Photometers measure radiant energy in the visible spectrum; they include the common "light meters" that are sold through camera shops or laboratory supply companies (fig. 3.3.37A). They are portable, inexpensive ($50 to 100), and give readings in lux or foot-candles (Aldrich and Bartok 1989). Photometers will provide a relative measure of solar intensity and can also be used to check the intensity patterns of photoperiodic or photosynthetic lights. Because the quality of light varies with the type of lamp, conversion tables must be used to compensate for the difference between the sensitivity spectrum of the meter and the light spectrum of the lamp (table 3.3.3). Even the light meters built into cameras are usable, because values in lux or foot candles can be calculated from film speed, shutter speed, and lens opening (table 3.3.9).

A

B

C

Figure 3.3.37—*Container nursery managers should check the intensity of sunlight in their growing stuctures and the intensity patterns of their lighting systems with light meters. Portable, inexpensive photometers are available which give readings in illumination units* (**A**). *More accurate light meters feature digital readouts* (**B**) *and have different sensors that will measure all aspects of light intensity: energy units, radiation units, or illumination units* (**C**). (**B**, **C**, *courtesy of Li-Cor, Inc.*)

Table 3.3.9—*Procedure and conversions for using a camera's light meter to measure light intensity*

1. Set the camera for film speed ASA400 and a shutter speed of 1/30 second.
2. Point the camera at the light source and read the lens aperture (f-stop).
3. Use the table below to determine brightness.

f-stop	lux	foot-candles
1.0	16	1.5
1.4	32	3
2.0	63	6
2.8	125	12
4.0	250	23
5.6	500	47
8.0	1,000	93
11.0	2,000	190
16.0	4,000	375
22.0	6,000	750
32.0	16,000	1,500
45.0	32,150	3,000
65.0	64,300	6,000

Source: Eastman Kodak Co., Rochester, NY.

Radiometers. Radiometers measure radiant energy over a wide range of wavelengths. Portable, moderately expensive ($450) meters have separate sensors ($300) that can measure all three aspects of electromagnetic radiation: energy (µmol/s/m²), radiation (W/m²), and illumination (lx) (fig. 3.3.37B and C). Data recorders ($1,100) are also available to provide continuous readings of light as well as temperature and relative humidity.

A light sensor must be properly used; it should be held at crop level, facing the light source. Readings should be taken on a regular grid pattern throughout the growing area, especially in locations that appear to be shaded. When checking the intensity pattern of photoperiodic lights, take readings both directly under and between the lamps to determine the minimum intensity.

3.3.5.2 Control systems

Horticultural lighting systems must be precisely regulated to achieve the desired cultural objective. Reliability is crucial with photoperiodic lighting because the system must operate unattended during the night. For certain sensitive species, if the lights fail for even a single night, the seedlings can terminate height growth. Such a failure can be economically disastrous because some species and ecotypes will not resume growth until a chilling requirement has been met, or will exhibit bud break in irregular patterns (fig. 3.3.12). For this reason it is advantageous to have photoperiodic lights wired into the greenhouse alarm system.

There are two basic control devices: timers and photocells. **Timers**-electromechanical timeclocks or solid-state microprocessors-switch the lights on and off at preselected times. In the simplest system, a 24-hour timer turns lights on at dusk and off at dawn or for a shorter period during the middle of the night. This would provide a long day and could also augment photosynthesis, depending on the light intensity. For intermittent photoperiodic lighting a 60-division timer with a 6to 30-minute cycle would operate in series with the 24-hour timer to provide short bursts of light throughout the night. **Photocells** (fig. 3.3.38) respond to changes in light intensity and can be used in conjunction with timers, eliminating the need to reset the clock after power outages or as the natural daylength changes throughout the year. For photosynthetic lighting, photocells can turn on lights when sunlight intensity drops below a critical level (Aldrich and Bartok 1989).

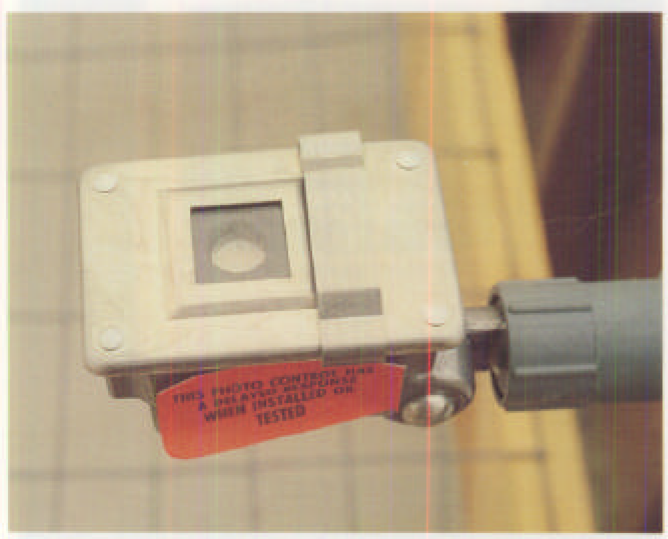


Figure 3.3.38—*Photocells can sense changes in light intensity and therefore can be used to control greenhouse lighting systems.*

3.3.6 Conclusions and Recommendations

Light is the most complex and variable of the limiting factors that affect the growth of container tree seedlings. Light affects all the different phases of seedling growth and development, from seed germination to bud set and hardening. The amount and timing of solar radiation affects both crop scheduling and the number of crops that can be grown per year. The location of the nursery and the type of growing structure affect the amount of light that will be available for seedling growth.

Container nursery managers manage light for two reasons: to increase photosynthesis and to control seedling dormancy by modifying the photoperiod, or daylength. Growers can stimulate high photosynthetic rates by supplementing sunlight in areas of low natural light intensity. But, because of the high light intensities that are required, it is usually not considered economical to provide enough artificial lighting for photosynthesis, although some nurseries supplement natural sunlight during the fall or winter. If photosynthetic lighting is required, high-pressure sodium lamps should be arranged to produce about 85 $\mu mol/s/m^2$ (~7.0 klx) at plant level. They must operate continuously for several hours to produce a measurable effect on seedling growth.

Many forest species are very sensitive to photoperiod, and so growers can extend the growing season by providing photoperiodic lighting. Because it is neither intense nor continuous, photoperiodic lighting is a relatively inexpensive cultural tool for growing uniform crops of container tree seedlings. Although some species and ecotypes from lower latitudes and mild climates do not respond to photoperiod extension, ecotypes from high latitude, high elevation, or continental climates require it. Photoperiodic lighting systems should be described with a term that denotes both duration and timing. Many different photoperiodic lighting systems have been used in container tree nurseries, and the best system will depend on many factors, including the type of greenhouse structure and the types of lamps that are available. Intermittent light is often cheaper, although continuous lighting has also been used effectively. Photoperiodic light intensities should be at least 8 $\mu mol/s/m^2$ (~430 Ix), and should be increased to 16 $\mu mol/s/m^2$ (~860 Ix) where the species or ecotype has a higher light requirement.

The photoperiod can also be shortened by excluding light and creating short-day conditions. Short-day treatments are used to stop height growth, set full buds, and induce cold hardiness in sensitive species; this technique is primarily used in nurseries at higher latitudes. In most other nurseries, simply turning off the photoperiodic lighting is effective. Because blackout curtains affect other environmental conditions, especially temperature and humidity, they must be used properly. Growers should use light meters to check the amount of sunlight transmitted through their growing structures. Coverings with poor light transmission should be cleaned or replaced. Photoperiodic lighting systems should be checked regularly to make sure that the critical minimum intensity is exceeded throughout the growing area. Sensitive species will stop height growth and set a terminal bud after only a brief interruption of photoperiodic lighting, which can have disastrous economic consequences.

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