The Container Tree Nursery Manual

Volume Six
Seedling Propagation

Chapter 4
Seedling Development: The Establishment, Rapid Growth, and Hardening Phases

Contents

6.4.1 Introduction

The objective of this chapter is to present a general description of how a typical crop is grown in a forest and conservation nursery. Of course, the propagation protocol and growing schedules will vary with the crop species as well as the type of nursery environment; however, we feel that going into the details of growing a typical crop will be informative to the novice grower. (Propagation protocols and growing schedules for a variety of other forest and conservation plants are provided on the USDA Forest Service's Home Page at the following uniform resource locator (URL):

» willow.ncfes.umn.edu/snti/snti.htm «

Our example will be seed propagation of a crop of conifer seedlings from the northwestern United States grown in a fully controlled greenhouse. This crop will take 17 months to produce and ship, and a facilities schedule is provided in table 6.4.1 A. The various species will be grouped together on the greenhouse benches according to their cultural requirements. The relatively faster growing species are grown on one table (or bench) and the slower growing ones on another (table 6.4.1 B).

The propagation environment and cultural practices need to be planned for each of the three seedling development phases: **establishment**, **rapid growth**, and **hardening.** For each phase, we will discuss the potentially limiting factors of the propagation environment: the **ambient environment**, which includes temperature, humidity, light, and carbon dioxide, and the **edaphic environment**, which consists of water and mineral nutrients (figure 6.4.1). It should be emphasized that the growing medium and type of container are critically important, not only because they provide a limited reservoir of water and mineral nutrients, but because they are the only factors that cannot be changed after seeds are sown. Nurseries also contain a variety of living organisms that affect seedlings, so both pests and beneficial organisms will also be discussed for each development phase. Lastly, we will talk about typical cultural practices that can be used during each phase.

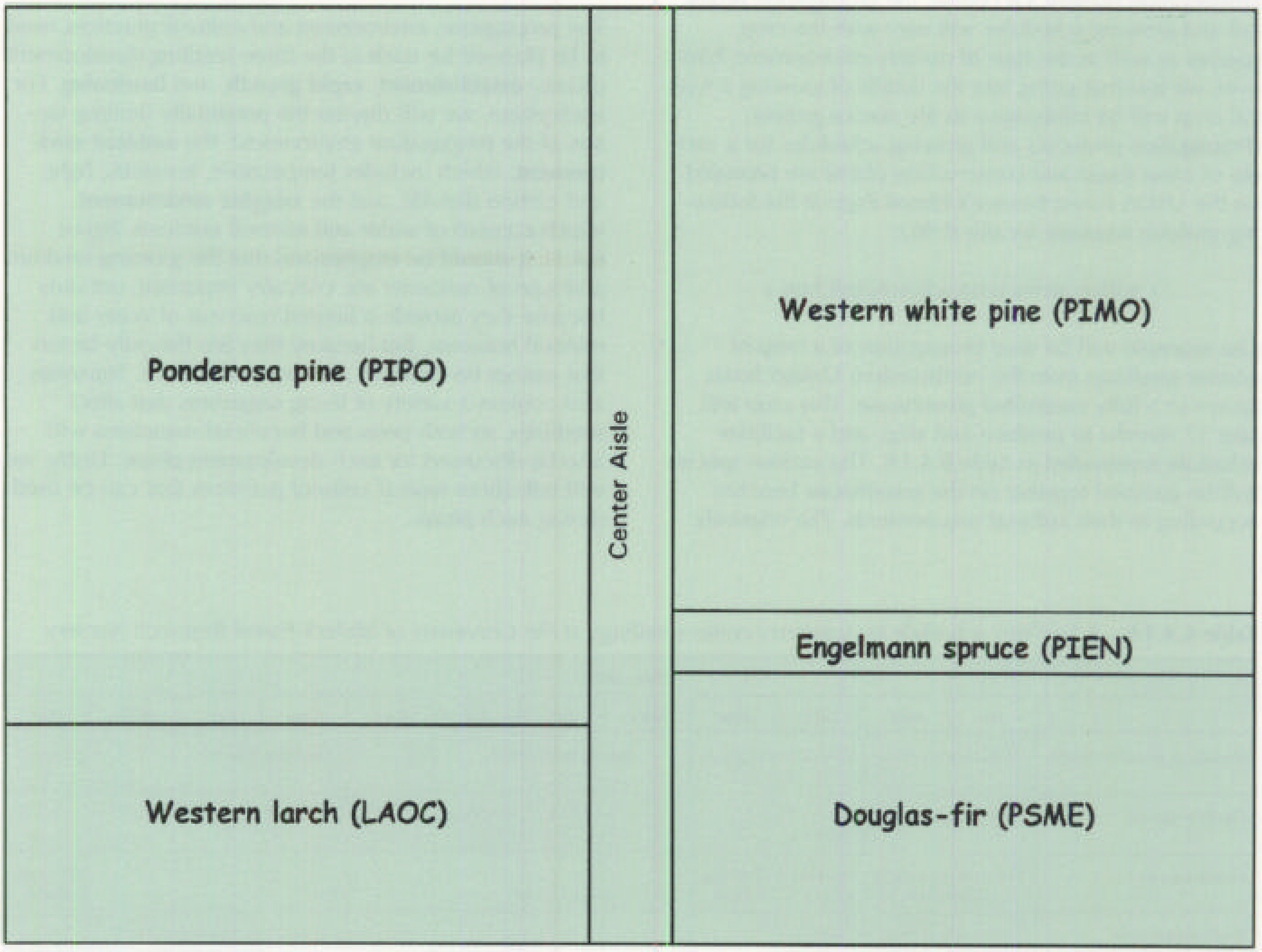
Table 6.4.1A—*A facilities schedule for western conifer seedlings at the University of Idaho's Forest Research Nursery*

Year one												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Seedling growth stage	Seed stratification		Establishment phase		Rapid growth phase			Hardening phase				*Storage*
Facility space	Refrigerator		Greenhouse									Packing shed
Labor needs	Container cleaning & filling crew		Sowing crew	Thinning crew								Packing crew
Equipment and supplies	Containers, growing media & fertilizer		Sowing line							Boxes, bag liners labels		Packing line

Year two												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Seedling growth stage	*Dormant in storage*			Shipping						Seed testing for next crop		
Facility space	Packing shed	Refrigerated storage								Germination chambers		
Labor needs	Packing crew			Shipping crew								
Equipment and supplies	Packing line			Conveyors, delivery trucks					Procure seed for next crop			

Source: Modified from Wenny and Dumroese (1998).

Table 6.4.1B—*Overhead map of the greenhouse layout for a mixed crop of western conifer seedlings at the University of Idaho's Forest Research Nursery*



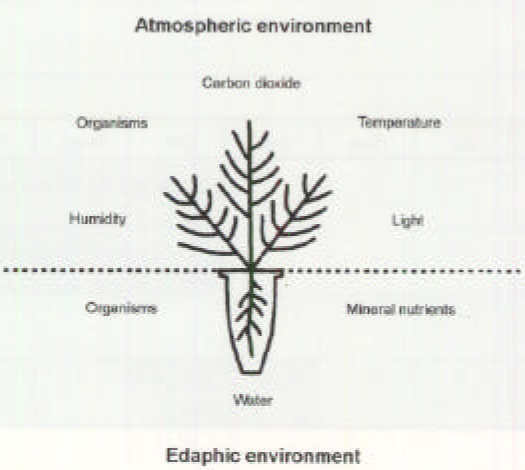


Figure 6.4.1—*The propagation environment can be divided into atmospheric and edaphic factors.*

6.4.2 The Establishment Phase

The establishment phase starts when seeds are sown and continues until seedlings are well established in their containers. With good-quality seeds, germination should be well underway and emerging seedlings visible by the second week (figure 6.4.2A). However, germination often continues into the third or fourth week, especially with seedlots of lower vigor. Young conifer seedlings ("emergents") carry their seedcoats up out of the growing medium until they form the "bird cage" stage (figure 6.4.2B). Following this, seedlings do not grow appreciably in height and most of their energy is diverted to root growth. The radicle grows rapidly downward, typically reaching the bottom of the container by the time the seedcoat is shed (figure 6.4.2C). At the end of establishment phase, a rosette of primary needles forms in the center of the cotyledons.

The cultural objective of the establishment phase is to generate optimum environmental conditions to obtain a well-established healthy stand of seedlings with a minimum number of empty containers. Growers need to be careful because young plants are particularly susceptible to pests and cultural injury. Problems that show up during the establishment phase are difficult, if not impossible, to correct. For example, if poor seed quality results in a significant number of empty containers, the delay caused by resowing will result in a crop of variably sized seedlings. Resown seedlings will always lag behind in growth rate because of competition with their neighbors.

6.4.2.1 The atmospheric environment

Although it is important to keep all potentially limiting factors at optimal levels, seed germination in container nurseries is primarily affected by three environmental factors: temperature, moisture, and light.

Temperature. Warm temperatures are required to stimulate rapid and complete germination, so growers usually keep the greenhouse slightly warmer than normal during the first month of the crop cycle. Although there is some variation between species, an ambient temperature target of 27 °C: (80 °F) during the day has proven to be a good compromise between optimal germination and energy conservation. Greenhouse heating systems can maintain a temperature of ±2 °C (3.5 °F), which converts to a range of 25 to 29 °C (77 to 84 °F). Most growers use different day and night setpoints, and their experience has shown that this practice can save heating costs without a significant loss in growth. For example, the University of Idaho's Forest Research Nursery lowers the temperature a

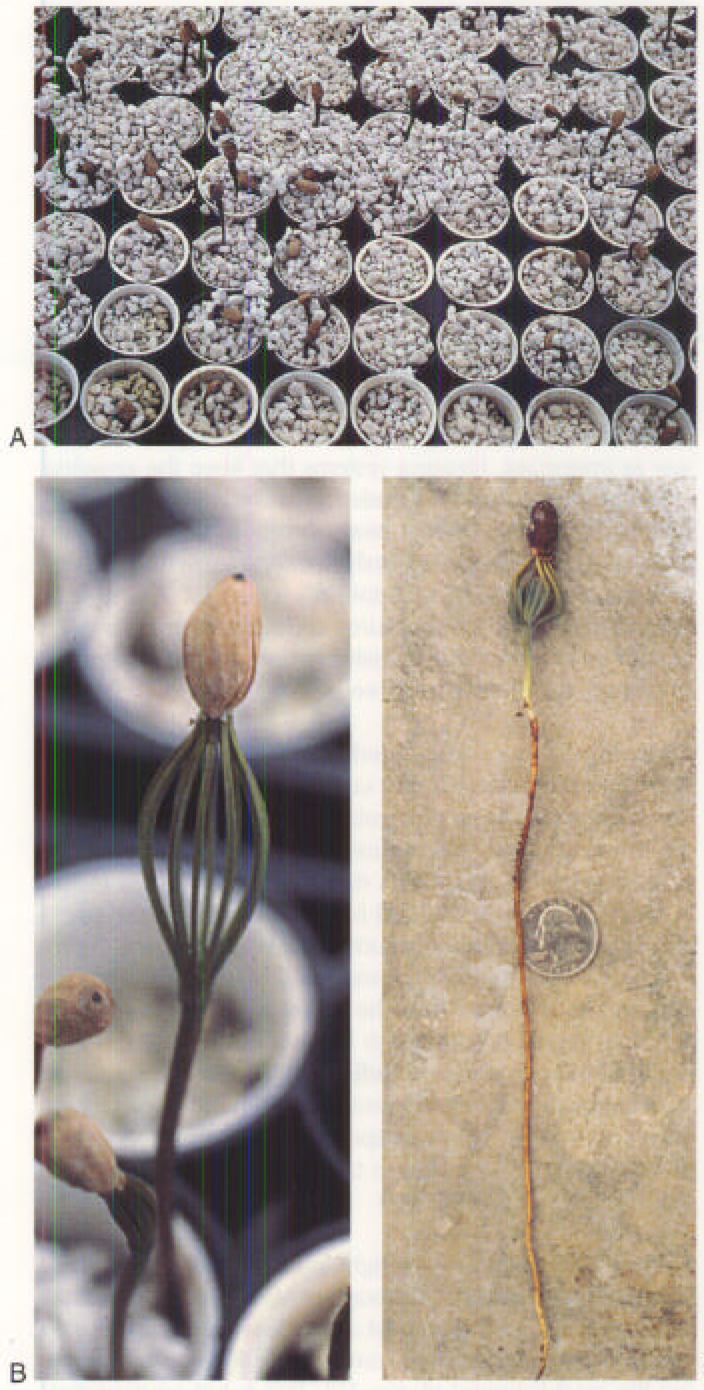


Figure 6.4.2—*Seed germination and emergence is typically variable but should be completed within 3 to 4 weeks* (**A**). *Conifer seedlings exhibit epigeous germination with the cotyledons lifting the seedcoat out of the medium to form what is commonly called the "bird cage"* (**B**). *After this, the shoot stops visible growth while the root rapidly grows to the bottom of the container* (**C**).

full 5°C (10 °F) at night (table 6.4.2). Because seeds begin 1o germinate quickly under warm-moist conditions, variations in seedling size can develop if it takes more than a couple of days to fill the propagation structure. One way to overcome this is to keep the containers dry and cool until all containers are in place in the propagation area, and then turn on the heaters and irrigate the crop.

After germination is complete, the daytime temperature can be lowered to 24 to 27 °C (75 to 80 °F) for the remainder of the establishment phase (table 6.4.2). Note that all' of these targets are air temperatures, but the temperature of the growing medium surrounding the seeds is just as important. Heating systems that keep the growing medium warm-such as underbench heat distribution tubes or overhead radiant heat-promote faster and more uniform germination and early seedling growth. (Heating systems are discussed in detail in section 3.1 .2, and operational target temperatures and ranges for a variety of species during the establishment phase can be found in table 3.1.2 of volume three of this series.)

Humidity. Germinating seeds can dry out rapidly in the high light environment of a container nursery and therefore growers must be particularly vigilant. Evaporation is the primary cause of moisture loss, but a **relative humidity (RH)** range of 70 to 80% (table 6.4.2) will keep evaporation rates low and retard fungal diseases, especially damping-off. Humidity is controlled with frequent, light mistings that keep the growing medium around seeds "moist, but not wet." (See the following irrigation section for more specifics.) Although RH is a useful measurement, the **vapor pressure deficit (VPD)** is a more relevant factor to monitor. (Operational RH and VPD targets and ranges for a variety of species during the establishment phase can be found in tables 3.2.5 and 3.2.6 of volume three of this series.)

Light. Three attributes of light affects plants: **intensity, duration,** and **quality.** Although research has shown that some species germinate best at moderate light intensities, most commercial conifers can tolerate full sunlight during the establishment phase. This fact is not appreciated by many novice growers who assume that shade-tolerant species such as western hemlock would naturally require shady conditions during germination. This belief probably developed from the long-standing practice of using shade frames over seedbeds in bareroot nurseries, which was more for controlling surface soil temperatures than light levels. In container nurseries, the type and color of seed coverings and irrigation can control surface temperatures, so full light is recommended. In fact, it is recommended that some small native plants species be sown without seed coverings to ensure that they receive enough light during germination (Emery 1988).

Light quality has been shown to be important to seed germination. Light with wavelengths in the red spectrum (660 nm) promotes germination of southern pine seeds, whereas far-red light (730 nm) inhibits it. This has little practical importance, however, as there is sufficient red light in sunlight and all types of photoperiodic lighting (Barnett and Brissette 1986).

Although light intensity and quality are not operationally important, duration--the daylength or "photoperiod"--does have a significant affect on seed germination and early seedling growth of many species. For example, both rate and total germination of loblolly pine seeds were much better under photoperiodic lighting whereas the same treatments had no effect on slash pine (Jones 1961). Although not all species or seed sources of a given species may require it, the use of photoperiodic lighting will help overcome growth differences among individual seedlings and result in a more uniform crop. Thus, many growers turn on their crop lights after sowing is complete and leave them on until hardening is initiated. The University of Idaho's Forest Research Nursery supplies 500 lux (50 ft-candles) of incandescent lighting applied intermittently throughout the night (table 6.4.2).(A complete discussion of the types of photoperiodic lighting and other examples of operational lighting systems can be found in section 3.3 of volume three of this series.)

Carbon dioxide. Although carbon dioxide (CO_2) enhancement is not effective until there is enough photo synthetic tissue to absorb it, the cost of operating CO_2 generators is minimal and so most growers turn them on at the beginning of the growing cycle. A CO_2 level of between 750 parts per million (ppm) and 1,000 ppm is a typical target, and generators switch on several hours before sunlight and continue running during the day whenever vents are closed. The University of Idaho nursery does not use CO_2 generators, but encourages good air circulation within the greenhouse (table 6.4.2). (A complete discussion on managing and monitoring CO_2 during the establishment phase can be found in section 3.4.3 of volume three of this series.)

Table 6.4.2—*A 5-week segment of a cultural schedule during the establishment phase for western conifer seedlings at the University of Idaho's Forest Research Nursery (dark vertical line denotes a change in environmental settings)*

Customer: T. Planter **Species:** PIPO, PIMO, PSME, LAOC, PIEN **Seed source:** N. Idaho

Target specifications: **Height:** 12 to 18 cm **Stem caliper:** 3 to 4 mm

Month	Mar	Apr	Apr	Apr	Apr
Weeks from sowing	3	4	5	6	7
Propagation environment	Greenhouse				
Seedling growth stage	Establishment phase				
Cultural processes and operations		Thinning			
Labor: crew size (person-hours)		4–6 people, depending on seedling development			
Temperature: day setpoint (range)	27 °C: (23 to 30) 80 °F (75 to 85)	26 °C (23 to 27) 78 °F (75 to 80)			
Temperature: night setpoint (range)	20 °C (18 to 21) 68 °F (65 to 70)				
Relative humidity: setpoint (range)	Ambient				
Light: ambient	Full sunlight				
Light: photoperiod intensity & duration	24-hour daylength using intermittent incandescent lights that produce an intensity of 500 lux (50 ft-candles) at plant level				
Carbon dioxide: rate & timing	Ambient				
Irrigation: amount & frequency	Keep growing medium moist, but not wet Maintain container weights at 85-90% of wet weight				
Fertilization: nitrogen (N) rate & frequency	Fertigate twice per week with starter solution (50 ppm N)				
Pest management: monitoring pesticide and rate	**Check daily for damping-off:** apply fungicides only if damage exceeds economic threshold				

Source: Modified from Wenny and Dumroese (1998).

6.4.2.2 The edaphic environment

Irrigation. The sown containers should be thoroughly irrigated until they reach full saturation as soon as they are placed in the propagation area. Some types of peat moss are difficult to wet, however, so a surfactant may need to be applied with the initial irrigation if it was not already included as an amendment to the growing medium. If no surfactant is used, it may take several days of irrigation to completely hydrate the growing medium (Wood 1994).

Following this initial soaking, subsequent irrigations should be frequent but short in duration until germination and emergence are complete. Overwatering floods the macropores that provide oxygen to the germinating seeds, so these light mistings should keep the growing medium "moist but not wet" (table 6.4.2). Proper watering allows the seed covering to dry out between irrigations, which helps control damping-off and prevents moss and algae from developing. As mentioned in the humidity section above, irrigation is used to maintain humidity as well as supply water to germinating seeds and young emergents.

After most seedlings are past the bird cage stage, a regular irrigation schedule can begin. Some growers rely on a calendar method based on previous experience such as two irrigations per week. The University of Idaho nursery uses container weight to help determine the amount of water to apply per irrigation (table 6.4.2). The fully saturated **wet weight** is determined at the time of initial saturation, and the **target weight** (when irrigation is required) is expressed as a percentage of wet weight. For example, white spruce seedlings should be irrigated when the weight of the containers has dropped to 80% of wet weight (Wood 1994). (The procedure for developing container weights is described in detail in section 4.2.6 of volume four of this series.)

Mineral nutrition. Some growers prefer to incorporate a small amount of slow-release fertilizer into their growing medium to supply some nutrition to young germinants. Overhead irrigation containing injected mineral nutrients (known as **fertigation**) often is not applied during the germination stage because seedlings receive adequate mineral nutrients from seed reserves and because of increased risk of damping-off or salt injury. Once germinants are fully established, however, fertigation is initiated. Some growers use a constant-feed program in which fertilizer is injected with each irrigation; others fertigate once or twice per week with regular irrigation supplied as needed. In addition to the full range of 13 mineral nutrients, fertigation solutions typically contain a weak acid such as phosphoric acid to help maintain the pH of the growing medium in the range of 5.0 to 6.0.

Each of these fertigations should last long enough to leach unused fertilizer salts from the container; it should then be followed by a clear water rinse to remove salts from the succulent foliage and prevent salt burn. Most growers, including the University of Idaho nursery, use a low-nitrogen (for example, 50 to 100 ppm) fertilizer solution during the establishment phase because seedlings are so small (table 6.4.2). Recently, growers are beginning to try an exponential fertilization program in which the concentration of nutrients is gradually increased during the growing season as seedlings grow in size (Timmer and others 1991). For example, exponential fertilizer applications produced acceptable Douglas-fir seedlings with 60% less N early in the growing season (Dumroese and others 1995). (Complete instructions on how to formulate and monitor fertigation can be found in section 4.1.6 of volume four of this series.)

6.4.2.3 Cultural operations

The establishment phase is an anxious time in the nursery because this is when young seedlings are most susceptible to cultural injury and pests. Therefore, growers should be particularly vigilant and inspect their crops daily (table 6.4.2).

Monitoring germination. After about 2 weeks, newly sown containers should be inspected to determine if germination is occurring normally. The seed covering can be carefully brushed aside and seeds inspected with a 5 to 10 power hand lens. Complete absence of seeds in a high number of containers indicates a sowing problem, or predation by birds. If seeds appear swollen and cracked, then they are probably healthy and should be returned to the container and remulched. If they do not appear ready to germinate, then a small sample should be removed from the container and cut in half with a single-edge razor blade. Inspect the bisected seeds with a hand lens. Healthy seed will be white to cream in color and firm in texture-similar to coconut meat in appearance. Diseased seed will be brown or black or with a soft texture. (An illustrated diagnostic key to seed problems is provided in section 5.1 .3 in volume five of this series.)

Thinning. Typically, 2 or more seeds are sown per cavity to minimize the chances of empty cells. Extra germinants should be thinned as soon as possible, and two techniques are used: pulling and clipping.

- ***Pulling***--This technique consists of carefully extracting ,extra germinants from each cavity by hand. Pulling must be done before seedlings develop lateral roots or it becomes difficult to remove the seedling without injuring the remaining crop seedling. Workers must be trained to remove smaller or less vigorous seedlings and be careful not to injure the remaining ones during the process. Thinned seedlings are collected in trays and removed from the growing area.
- ***Clipping***--This involves using small pointed scissors to snip extra seedlings out of each cell (figure 6.4.3A). Seedlings can be clipped at a much more advanced age than they can be successfully pulled. Clipped seedlings must be collected in trays and removed to avoid the possibility of disease. Leaving severed stems and root systems in the container has not proved to be detrimental, however.

Thinning must be accomplished as soon as possible to minimize effects on seedling development-competition for water, nutrients, and eventually light will quickly decrease growth. The effects of leaving multiple seedlings in container cells have been evaluated with longleaf, loblolly, and slash pine (Barnett and Brissette 1986). The most marked effect was on size: seedlings grown 2 or 3 to the cavity had 50% or less biomass than those grown with only 1 per cavity at the end of 14 weeks in the greenhouse (figure 6.4.313). Interestingly enough, this effect of intracavity competition even persisted after outplanting for one of the species: longleaf pine seedlings that were not thinned to 1 seedling per cavity had much poorer survival after 3'h years in the field (figure 6.4.3C).

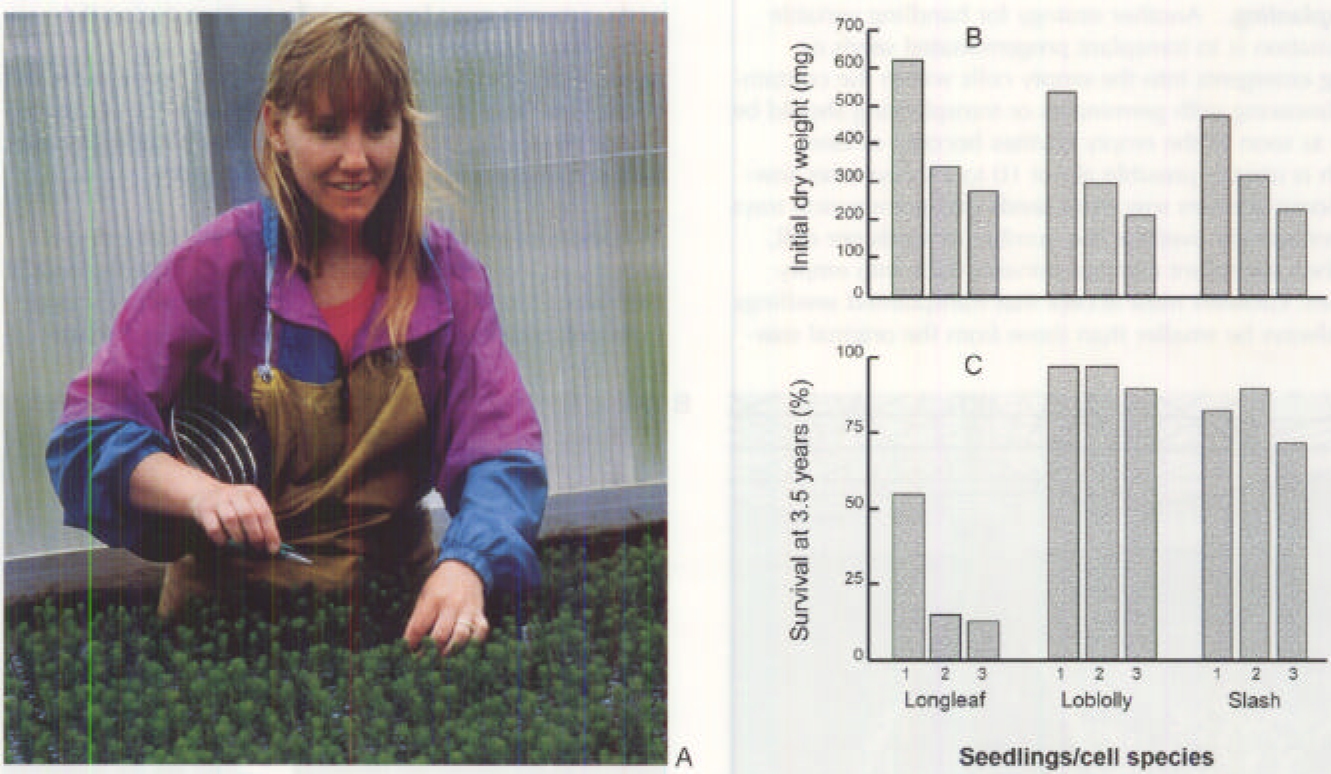


Figure 6.4.3—*Multiple seedlings should be thinned to 1 per cavity by either pulling or clipping (**A**). Thinning should be done as soon as possible because thinned southern pine seedlings were significant larger than unthinned ones (**B**). For longleaf pine, the adverse effects of multiple sowing even carried over to the outplanting site, where single-sown seedlings (**C**) survived much better than those sown 2 or 3 to the cavity (B and C, modified from Barnett and Brissette 1986).*

Resowing. If germination is erratic, then the decision must be made quickly whether to resow new containers to alleviate the shortfall, sow germinants, or transplant emergents into the empty cavities. As a general rule of thumb, if the percentage of empty cavities is between 5 and 15%, resowing with germinating seeds or transplanting emergents from seed trays is a feasible alternative (Barnett and Brissette 1986). If more than 15% of the cells are empty, the shortfall should be made up by sowing additional containers. If growers anticipate a germi nation problem, then they may sow extra containers initially to compensate for the expected empty cells--the **oversow factor.** This is one advantage to single-cell containers, such as RL Single Cells®, because they can be **consolidated**--empty cells can be removed and replaced with cells containing emerging seedlings. With block containers, however, oversowing wastes valuable production space. Resown containers will always lag behind the first sowing and often have to kept growing longer into the growing season to reach the same size (figure 6.4.4A).

Transplanting. Another strategy for handling variable germination is to transplant pregerminated seeds or young emergents into the empty cells within the containers. Resowing with germinants or transplanting should be done as soon as the empty cavities become evident, which is usually possible about 10 to 14 days after sowing. Some growers sow extra seeds into germination trays or intentionally oversow the number of seeds per cell, and then transplant extra germinants back into empty cavities. Growers must accept that transplanted seedlings will always be smaller than those from the original sowing (figure 6.4.413). In a study with southern pines, seedlings from transplanted germinants were always smaller than direct-sown seedlings, especially for]longleaf pine (table 6.4.3). Using germinants with longer radicles helped make up the size to some degree but, unfortunately, these germinants are more difficult to transplant correctly. In fact, nurseries that routinely transplant emergents from germination trays ("pricking out") find that clipping the tap root to about 50% of the original length increased survival and growth after transplanting (Singh and others 1984). However, with jack pine and black spruce seedlings, transplanting is not recommended as a routine practice because of the high incidence of root deformity and the high labor costs (Scarratt 1991). (The correct procedure for handling and positioning germinants and transplanting emergents can be found in section 6.2.8 of this volume.)

6.4.2.4 Pests and abiotic problems

Because germinating seeds and newly emerged seedlings are so susceptible to environmental stress and nursery pests, growers must be especially vigilant during the establishment phase. A description of the common diseases, insect pests, and abiotic stresses of germinants and young seedlings can be found in section 5.1 .3 of volume five of this series, but growers should be particularly alert for the following abiotic problems and pests.

Temperature extremes. Because of their limited root system, young germinants are very susceptible to drought and direct heat-injury to the succulent hypocotyl tissues. Light-colored seed coverings and frequent light irriga-

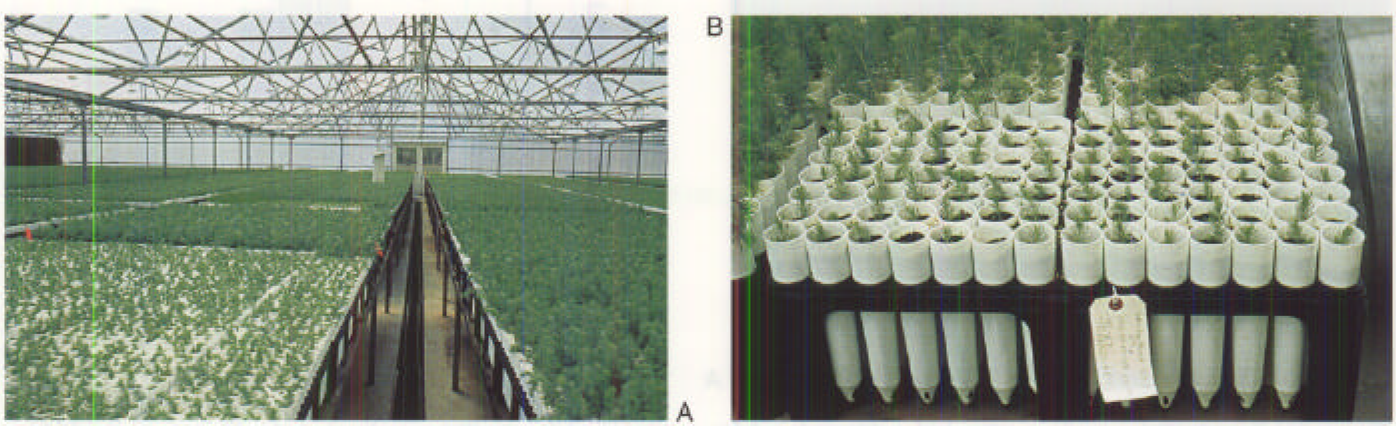


Figure 6.4.4—*Resowing to make up for poor germination will result in a group of seedlings that will always be smaller than the original sowing* (left foreground in **A**). *Transplanting emergents into empty cells induces a temporary transplant shock and causes these seedlings to lag behind the rest of the seedlings in the container* (**B**).

tions or "mistings" are commonly used to keep temperatures low around the stem. Emerging germinants are most susceptible to heat injury but become more tolerant as they grow older and develop bark tissue. The temperature at the soil surface can be monitored by placing the tip of a thermometer just under the seed covering and monitoring it frequently during sunny weather. Some nurseries establish guidelines to help nursery workers determine at what surface temperature they should begin cooling with irrigation, and the critical temperature becomes higher as seedlings grow older (table 6.4.4).

For nurseries that raise seedlings in open growing compounds, late-spring frosts can also cause damage. Newly emerged seedlings are not very cold hardy and must be protected from temperatures below freezing. Scots pine seedlings at 20 to 30 days after sowing can be physically injured by a short 2-hour exposure to temperatures below -4.5 °C (24 °F). After such an exposure, even visually healthy cotyledons and primary needles were found to have cellular injury that was reflected in reduced growth rates (Holopainen 1988; Holopainen and Holopainen 1988). Therefore, growers must be prepared to physically cover their stock or irrigate to prevent cold injury. (Frost protection of nursery stock with irrigation is discussed in volume seven of this series.)

Damping-off. The most common disease during the establishment phase is known by the traditional name of "damping-off," and there are two different types: pre-

Table 6.4.3—*When resowing into empty cavities, larger germinants are better able to compete with the older seedlings from the original sowing*

Radicle length of germinant at transplanting (cm)	Seedlings at 15 weeks of development			
	Shortleaf pine		Longleaf pine	
	cm	mg	mm	mg
1.5–2.0	8.61 a	137 a	1.12 a	168 a
3.0–3.5	9.36 a	173 b	1.20 a	210 b
4.5–5.0	9.48 b	188 b	1.28 a	237 c
Control (direct seeded)	9.93 b	280 c	1.48 b	342 d

Source: Modified from Pawuk (1982).

Table 6.4.4—*The temperature of the seed covering is cooled with irrigation to prevent heat damage to the stem, and the allowable temperatures are gradually raised as the seedlings get older (0 to 100 days from sowing)*

Species/ ecotype		Surface temp.					
		0 days	20 days	40 days	60 days	80 days	100 days
Douglas-fir (coastal)	°C	32	32	32	35	40	45
	°F	90	90	90	95	104	113
Douglas-fir (interior)	°C	32	32	32	35	40	48
	°F	90	90	90	95	104	118
Interior spruce	°C	32	32	32	35	38	43
	°F	90	90	90	95	100	110
Western redcedar	°C	32	32	32	35	38	43
	°F	90	90	90	95	100	110
Lodgepole pine	°C	32	32	32	45	50	50
	°F	90	90	90	113	122	122

Source: Green Timbers Nursery (1993).

emergence and post-emergence. **Pre-emergence damping-off** is caused by several fungal pathogens and occurs before the germinant emerges from the medium. Unfortunately, pre-emergence damping-off is often mistaken for poor-quality seed, so growers should carefully excavate a sample of sown seeds after a couple of weeks and inspect them with a hand lens. The presence of cottony-appearing mycelia confirms fungal damping-off (figure 6.4.5), but a few slow-to-germinate seeds should also be cut in half with a razor blade to see if their contents appear healthy. The inside of healthy seeds should appear white to cream-colored, whereas that of decayed seeds is dark and watery in texture.

Figure 6.4.5—*Seeds covered with cottony mycelia (see arrow) confirm that fungal infection prevented germination, a condition known as "pre-emergence damping off."*

Symptoms of **post-emergence damping-off** are more obvious: the young emergent falls over due to a constriction at the surface of the growing medium. If the cause is a fungus, the hypocotyl and root appear discolored or decayed. Damping-off also can be caused by heat or chemical injury; in this case, the hypocotyl is damaged right at the surface of the growing medium but the root will not be decayed. (A damage key and color photographs to help diagnose the differences can be found in section 5.1 .3 of volume five of this series.)

***fungus gnats*.** One of the most serious insect pests during the establishment phase are the larvae of dark-winged fungus gnats. Adult gnats *(Bradysia spp.)* are commonly found in greenhouses and, although they do not directly feed on seedlings, they have been shown to vector spores of other fungal pathogens, including *Fusarium* spp. and *Botrytis* spp. (James and others 1994). The larvae feed on many types of organic matter, including seeds and young seedlings and can become a serious problem especially where over-irrigation and poor water management occur. The larvae remain hidden in the „rowing medium and so the appearance of adults flying ,round the crop is the first sign of a fungus gnat infesta tion. Some growers monitor the relative populations with yellow-sticky cards and use this information to decide When control is warranted. (Damage keys, color photographs, and more specific identification and control information can be found in section 5.1.4 of volume five of this series.)

***Cryptogams and weeds*.** Once cryptogams-algae, moss, and lichens-and weeds are introduced into the containers, there is no easy or cheap way to remove them. They seriously compete with young seedlings for water, mineral nutrients, and eventually light. This problem should not occur during the establishment phase unless the containers were not clean or the growing medium was not sterile. In one case, weeds became a serious problem from seeds that mice carried into bags of stored growing medium. Spores of algae, mosses, and lichens and small weed seeds can also be introduced in unfiltered irrigation water. This can be a particularly serious problem when water from ponds or other surface sources is used. Although these plant pests will eventually invade the nursery through airborne spores, they should not become a problem before seedlings grow large enough to reach crown closure and completely shade the surface of the growing medium. Because they are also plants, it is difficult to find pesticides that kill cryptogams and weeds without harming the crop seedlings (that is, they are not phytotoxic). Ferrous sulfate and sterilants such as Agribrom© have been used, but prevention is the best solution. (Damage keys, color photographs, and more specific identification and control information can be found in section 5.1 .5.4 of volume five of this series.)

Birds and rodents. Sown seeds, especially the larger pine seeds, are very attractive to both mice and birds. Both will disturb the seed covering while searching for the seeds, but birds usually carry seeds off before eating them, whereas rodents leave empty seed coats behind in containers to taunt you. Bird entry can usually be prevented by screening greenhouse vents and making sure that doors are promptly closed. In open growing areas, covering sown containers with large-mesh screening until germination is complete is effective. It is almost impossible to completely prevent small rodents from entering propagation structures. However, establishing small bait stations with extra seed around the perimeter of the growing area will show when there is a problem. Chemical seed repellents have been used but are not recommended because they may reduce germination. After a rodent problem has been diagnosed, poison baits and snap traps can be effective if they are used safely and properly. (Damage keys, color photographs, and more specific identification and control information can be found in section 5.1.3 of volume five of this series.)

6.4.3 Rapid Growth Phase

The rapid growth phase begins when the terminal shoot in the middle of the cotyledons begins to grow quickly and continues until most of the crop approaches target height. With our example crop of western conifers at the University of Idaho's Forest Research Nursery, this phase starts at about 8 weeks after sowing and continues for about another 3 months (table 6.4.1). Although terminal shoot growth is the predominant characteristic of the rapid growth phase, lower lateral branches also expand without forming buds (figure 6.4.6A). It is during the rapid growth phase that the real benefit of container nursery culture is dramatically illustrated as shoot growth can be two to three times as much as that of a normal seedling in the wild (figure 6.4.613). Depending on species and propagation environment, height growth may not be continuous but instead consist of a series of spurts or flushes. Because most of the energy resources are going to the shoot, the lateral cambium also becomes more active and stem diameter growth slowly increases. Roots continue to expand and grow and should occupy the entire cavity by the end of the rapid growth phase.

The cultural objective during the rapid growth phase is to keep all environmental factors in the propagation environment at optimal levels. Because seedlings are still very succulent, growers must minimize any type of unnecessary environmental or cultural stress. As seedlings grow older and stronger, the potential for outright mortality decreases but the crop is still susceptible to abiotic injury or pests. So, growers should still schedule regular scouting trips throughout the propagation area and look for areas of low vigor, stunting, and other injury.

6.4.3.1 The atmospheric environment

Temperature. Both the target temperature and the allowable temperature range during the rapid growth phase will depend on the type of propagation environment and the species. Fully controlled greenhouses can maintain both day and night temperatures to within a couple of degrees, whereas open compounds are at the mercy of the local climate. Serious growth delays have occurred in open compounds during cool and cloudy

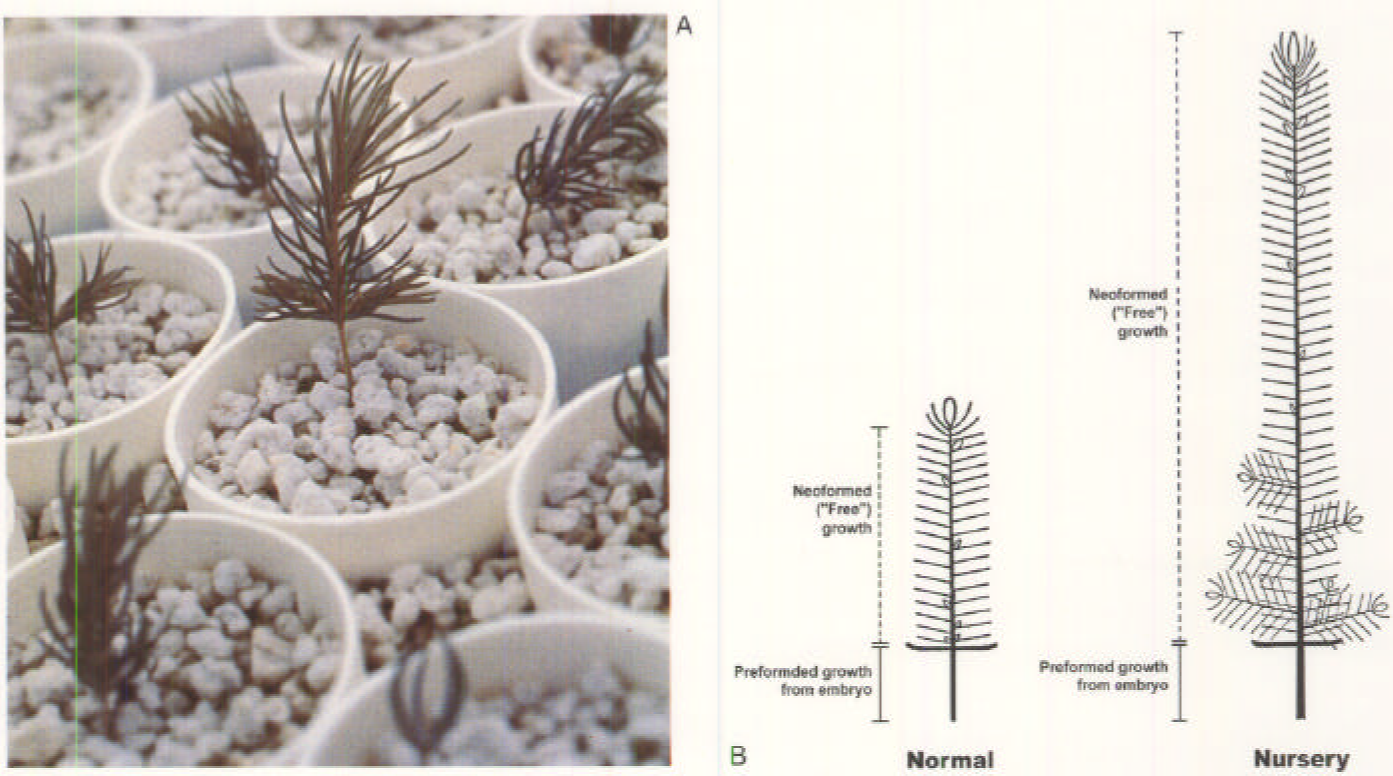


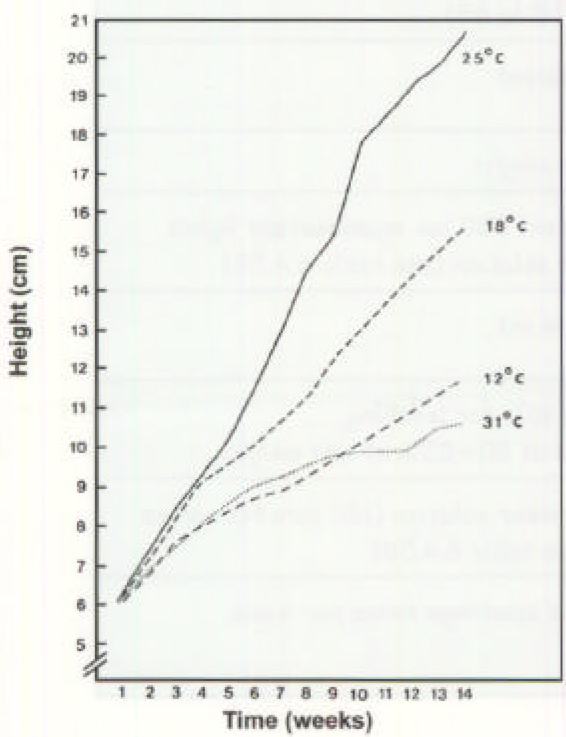
Figure 6.4.6—*Expansion of the terminal shoot is the primary characteristic of the rapid growth phase* (**A**). *Because of the ideal growing conditions, nursery seedlings can grow many times larger than a normal wild seedling* (**B**) *(modified from Powell 1982).*

late spring or summer weather, and it is difficult, if not impossible, to force the crop to make up for lost growth later in the season. On the other hand, controlling height growth can be a real problem with different species in the same structure, especially with fast-growing species like western larch or quaking aspen. Even with relatively slower growing species like Colorado blue spruce, shoot growth is directly proportional to temperature (figure 6.4.7A) and so seedlings can rapidly surpass target heights under warm conditions.

Optimum day and night temperatures are one of the primary reasons for accelerated growth in modern greenhouses. However, warmer is not necessarily better. For example, a "warm" growing regime-20 to 27 °C (68 to 80 °F)-produced more seedlings of 3 commercial conifers and these seedlings were of higher quality than a "hot" regime with temperatures reaching the 30 to 35 °C (86 to 94 °F) range. These differences were attributed to inhibitory effects of the higher temperatures on seedling metabolism and less resistance to cold injury in the fall (Owston and Kozlowski 1981).

Operational results have proven that many species can be grown in the same propagation structure and most will grow acceptably under a relatively wide temperature range. In our example crop at the University of Idaho nursery, target temperatures are kept in the 21 to 24 °C (70 to 75 °F) range during the day, with about a 5 °C (10 °F) setback at night (table 6.4.5A). Early in the season, heating is still required at night and in the early morning until sunlight warms the greenhouse. By early summer, however, cooling will become more of a problem in fully enclosed greenhouses because of intense sunlight and longer days. Convective cooling with vents is sufficient in moderate climates, but evaporative cooling, shadecloth, or misting is necessary in semi-arid environments. Horizontal airflow fans promote lateral air movement and help eliminate hot or cold spots with a greenhouse (figure 6.4.713). (Heating and cooling systems are discussed in detail in section 3.1.2 and operational target temperatures and ranges for a variety of species during the rapid growth phase can be found in table 3.1 .2 of volume three of this series.)

Humidity. Because the roots have expanded throughout the growing medium, seedlings are less susceptible to sudden moisture or heat stress and so relative humidities can be reduced to a target range of 60 to 80%. This moderate humidity level is sufficient to keep evapotranspirational losses low enough to encourage cell expansion and division but is not so high as to promote fungal diseases. A vapor pressure deficit of approximately 1.00 kPa is a reasonable target during the rapid growth phase.



A

B

Figure 6.4.7—*The importance of proper temperature is well illustrated by the shoot growth of these Colorado blue spruce seedlings—both too warm and too cool temperatures depress growth* (**A**). *Horizontal airflow fans* (**B**) *promote lateral air movement and help eliminate hot or cold spots with a greenhouse as well as supply carbon dioxide to the seedlings. (A, modified from Young and Hanover 1978).*

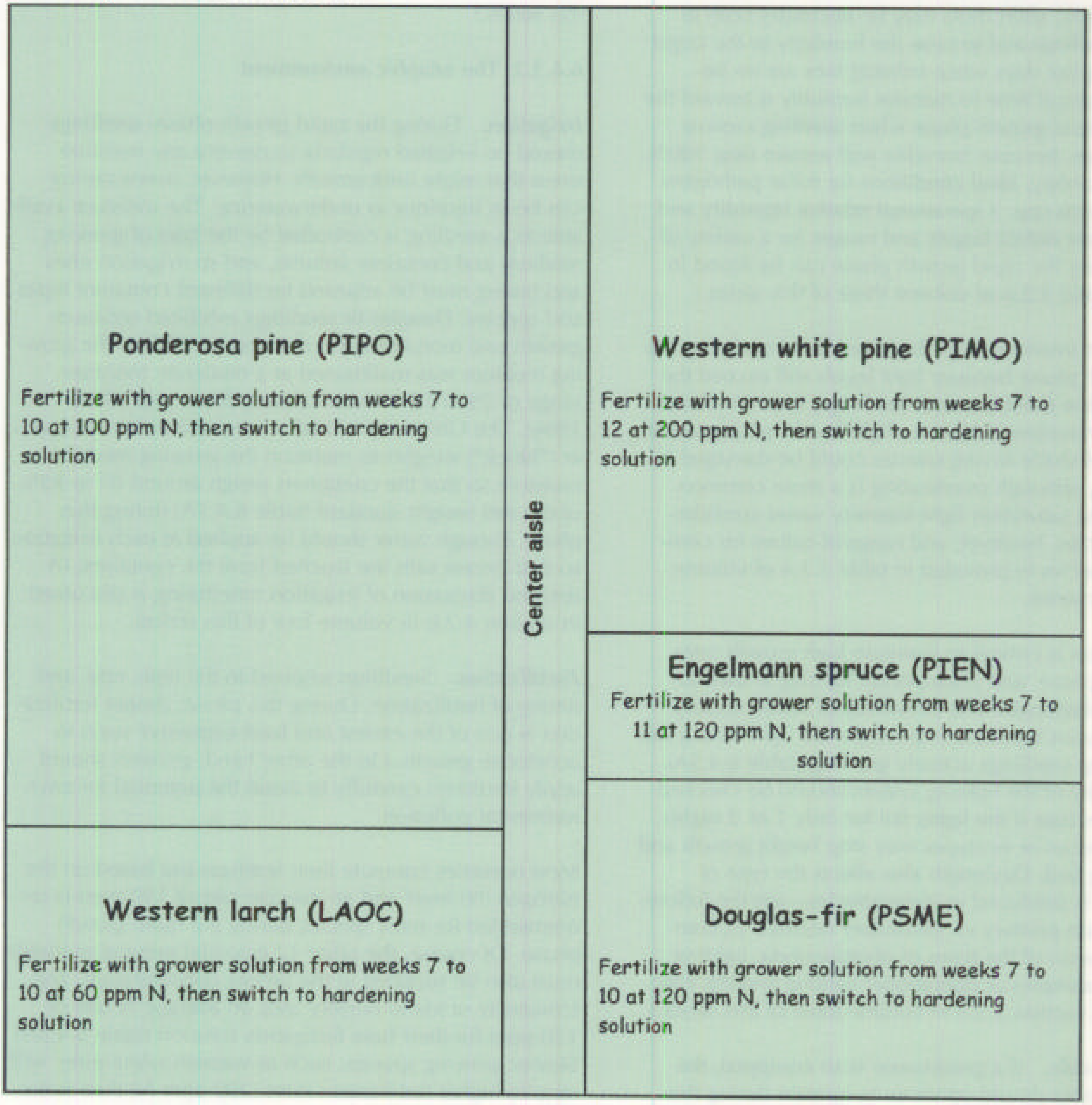
Table 6.4.5A—*A 5-week segment of a cultural schedule during the rapid growth phase for western conifer seedlings at the University of Idaho's Forest Research Nursery*

Customer: T. Planter	**Species:** PIPO, PIMO, PSME, LAOC, PIEN	**Seed source:** N. Idaho
Target specifications:	**Height:** 12 to 18 cm	**Stem caliper:** 3 to 4 mm

Month	May	May	May	May	June
Weeks from sowing	8	9	10	11	12
Propagation environment	Greenhouse				
Seedling growth stage	Rapid growth phase				
Cultural processes and operations	Inventory				
	Take seedling heights and calipers every 2 weeks				
Labor: crew size (person-hours)	1 or 2 people, as needed				
Temperature: day setpoint (range)	22 °C (21 to 24) 72 °F (70 to 75)				
Temperature: night setpoint (range)	18 °C (16 to 19) 63 °F (60 to 65)				
Relative humidity: (Range)	Ambient				
Light: ambient	Full sunlight				
Light: photoperiod intensity & duration	24-hour daylength using intermittent 500 lux incandescent lights, as long as species receives grower solution (see table 6.4.5B)				
Carbon dioxide: rate & timing	Ambient				
Irrigation: amount & frequency	Fully saturate + 10% for leaching Maintain container weights at 80–85% of wet weight				
Fertilization: nitrogen (N) rate & frequency	Fertigate twice per week with grower solution (120 ppm N); varies by species (see table 6.4.5B)				
Pest management: monitoring pesticide and rate	Walk–through and inspect seedlings twice per week.				

Source: Modified from Wenny and Dumroese (1998).

Table 6.4.5B—*Overhead map of greenhouse layout for a crop of western conifer seedlings at the University of Idaho's Forest Research Nursery showing changes in fertigation rates, based on nitrogen (N) level, and scheduling for the different species*



Source: Modified from Wenny and Dumroese (1998).

The University of Idaho Nursery does not monitor relative humidity regularly but maintains ambient conditions (table 6.4.5A). Because relative humidity is so dependent on temperature, short mists may be necessary both to cool the seedlings and to raise the humidity to the target range during hot days when exhaust fans are on frequently. A critical time to monitor humidity is toward the end of the rapid growth phase when seedling crowns begin to close, because humidity will remain near 100% within the canopy, ideal conditions for foliar pathogens such as Botrytis spp. (Operational relative humidity and vapor pressure deficit targets and ranges for a variety of species during the rapid growth phase can be found in table 3.2.5 and 3.2.6 of volume three of this series.)

Light. Light intensity rarely becomes limiting during the rapid growth phase because light levels still exceed the light saturation point for most seedlings, even on cloudy days. Under extremely high sunlight levels, young succulent tissue of shade-loving species could be damaged by solarization, although overheating is a more common problem. The saturation light intensity varies considerably by species, however, and range of values for common tree species in provided in table 3.3.4 of volume three of this series.

Light duration is critical to maintain high growth rates during this phase, and photoperiod lighting is used to extend the daylength. The University of Idaho nursery uses continuous intermittent photoperiod light during the night to keep seedlings actively growing (table 6.4.5A). The reliability of the lighting system should be checked regularly because if the lights fail for only 1 or 2 nights, sensitive species or ecotypes may stop height growth and set a resting bud. Daylength also affects the type of foliage that is produced in some species-see the following section on primary vs. secondary needles. (A complete discussion of the types of photoperiodic lighting and other examples of operational lighting systems can be found in section 3.3.4 of volume three of this series.)

Carbon dioxide. If a greenhouse is so equipped, the CO_2 generators should continue to operate during the early mornings of rapid growth phase. Although the actual time that they are running will be less because solar heating will cause vents to open earlier, the high photosynthesis rates require a steady supply of CO_2. In addition to generators, horizontal air flow fans help encourage good CO_2 exchange in the growing area in addition to cooling (figure 6.4.713). The University of Idaho nursery relies on frequent ventilation to keep ambient CO_2 levels adequate (table *6.4.5A). (A* complete discussion on managing and monitoring COZ during the rapid growth phase can be found in section *3.4.3* of volume three of this series.)

6.4.3.2 The edaphic environment

Irrigation. During the rapid growth phase, seedlings should be irrigated regularly to prevent any moisture stress that might limit growth. However, overwatering can be as injurious as underwatering. The moisture available to a seedling is controlled by the type of growing medium and container volume, and so irrigation rates and timing must be adjusted for different container types and species. Douglas-fir seedlings exhibited optimum growth and morphological development when the growing medium was maintained at a moderate moisture range of 29 to 53% water content (Khan and others 1996). The University of Idaho nursery monitors container ("block") weights to maintain the growing medium moisture so that the containers weigh around 80 to 85% of the wet weight standard (table 6.4.5A) during this phase. Enough water should be applied at each irrigation so that excess salts are leached from the container. (A detailed discussion of irrigation monitoring is discussed in section 4.2.6 in volume four of this series).

Fertilization. Seedlings respond to the type, rate, and timing of fertilization. During this phase, proper fertilization is one of the easiest and least expensive ways to accelerate growth. On the other hand, growers should apply fertilizers carefully to avoid the potential for environmental pollution.

Most nurseries compute their fertilizer use based on the nitrogen (N) level and an average rate of 150 ppm is recommended for most species during the rapid growth phase. Of course, the other 12 essential mineral nutrients must also be supplied at the proper concentration. The University of Idaho nursery uses an average N rate of 120 ppm for their base fertigation solution (table 6.4.5A). Slower growing species, such as western white pine, will require higher fertilization rates (200 ppm N) than faster growing ones, such as western larch, which can get by with only 60 ppm N (table 6.4.513). Even different ecotypes of a species can respond quite differently to fertilization. For example, when six ecotypes of Douglas-fir seedlings were grown in the same greenhouse, those from coastal regions in Washington required lower N rates than those from Montana (figure 6.4.8A).

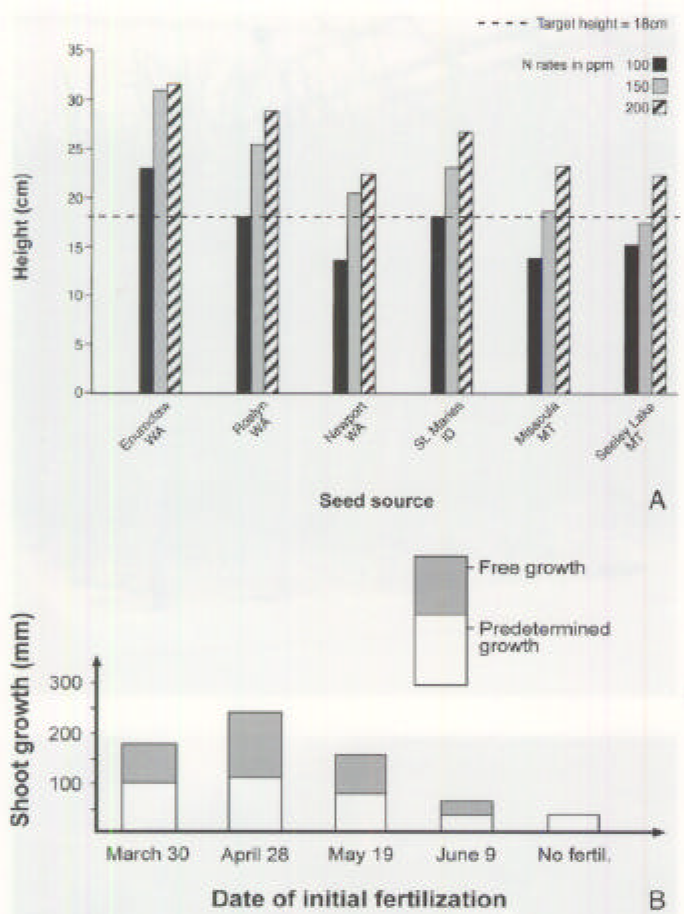


Figure 6.4.8—*Nitrogen (N) fertilization is one of the primary ways to control height growth; in this example* (**A**), *the Douglas-fir ecotypes from coastal western Washington should receive a lower N rate than those from the eastern part of the state or the mountains of Montana. Fertilization must start early in the growing season as evidenced by the increase in both the predetermined and free shoot growth of these Norway spruce seedlings* (**B**). *(A, modified from Thompson 1995; B, modified from von Wuehlisch and Muhs 1991).*

The University of Idaho's Forest Research Nursery has grown five species of northwestern conifers in one greenhouse by manipulating N rate and the length of the fertilization period. Western white pine is the slowest growing species; Engelmann spruce, Douglas-fir, and ponderosa pine have intermediate growth rates; and western larch is the fastest growing. The slower the species grows, the more N the seedlings receive and for a longer time period (table 6.4.513).

The timing of fertilization is critical. Nutrient uptake begins in a matter of minute s, but its effects on seedling growth are not apparent for days. This effect is especially critical for species, such as spruce, that exhibit free growth after a period of predetermined growth. For example, Norway spruce seedlings produced both more predetermined and free shoot growth when fertilization began earlier in the growing season (figure 6.4.813).

Monitoring shoot growth rates provides a good indication of how well seedlings are responding, and foliar tissue samples can also help to determine if fertilization levels are appropriate. If one species is lagging behind the target growth curves, increasing the N level of the fertilizer can accelerate shoot growth and help to make the target by the end of the growing season-for an example, see Figure 6.1 .10 in chapter 1 of this volume. (A complete discussion of nutritional targets and fertilization procedures is provided in volume four of this series.)

6.4.3.3 Cultural operations

Although the primary cultural objective of the rapid growth phase is to promote shoot growth, it also is important to produce a well-balanced seedling with a sturdy stem diameter (caliper) and roots that are well distributed throughout the plug. However, these are secondary concerns because root and stem diameter growth will be encouraged during the hardening phase.

Culturally controlling shoot height. One of the most common mistakes during the rapid growth phase is to allow shoot growth to continue for too long, which results in seedlings that are too tall for their corresponding caliper (figure 6.4.9A). These top-heavy seedlings are undesirable because they dry out quickly in the nursery and, in addition, are physically difficult to handle and expensive to plant. Finally, because of their excessive shoot to root ratio, they are subject to high moisture stress after transplanting or outplanting.

The key cultural controls to produce a sturdy shoot are (1) seedling growing density, (2) light, and (3) N fertilization rate. As far as growing density goes, the basic rule of thumb is the greater the distance between seedlings, the greater their caliper because they are less likely to grow too tall (figure 6.4.913). The low light intensity in overly-dense seedlings will cause them to grow disproportionately in height ("stretch"). Of course, once the seeds are sown there is no way to control density unless you are using single-cell containers that could be spaced further

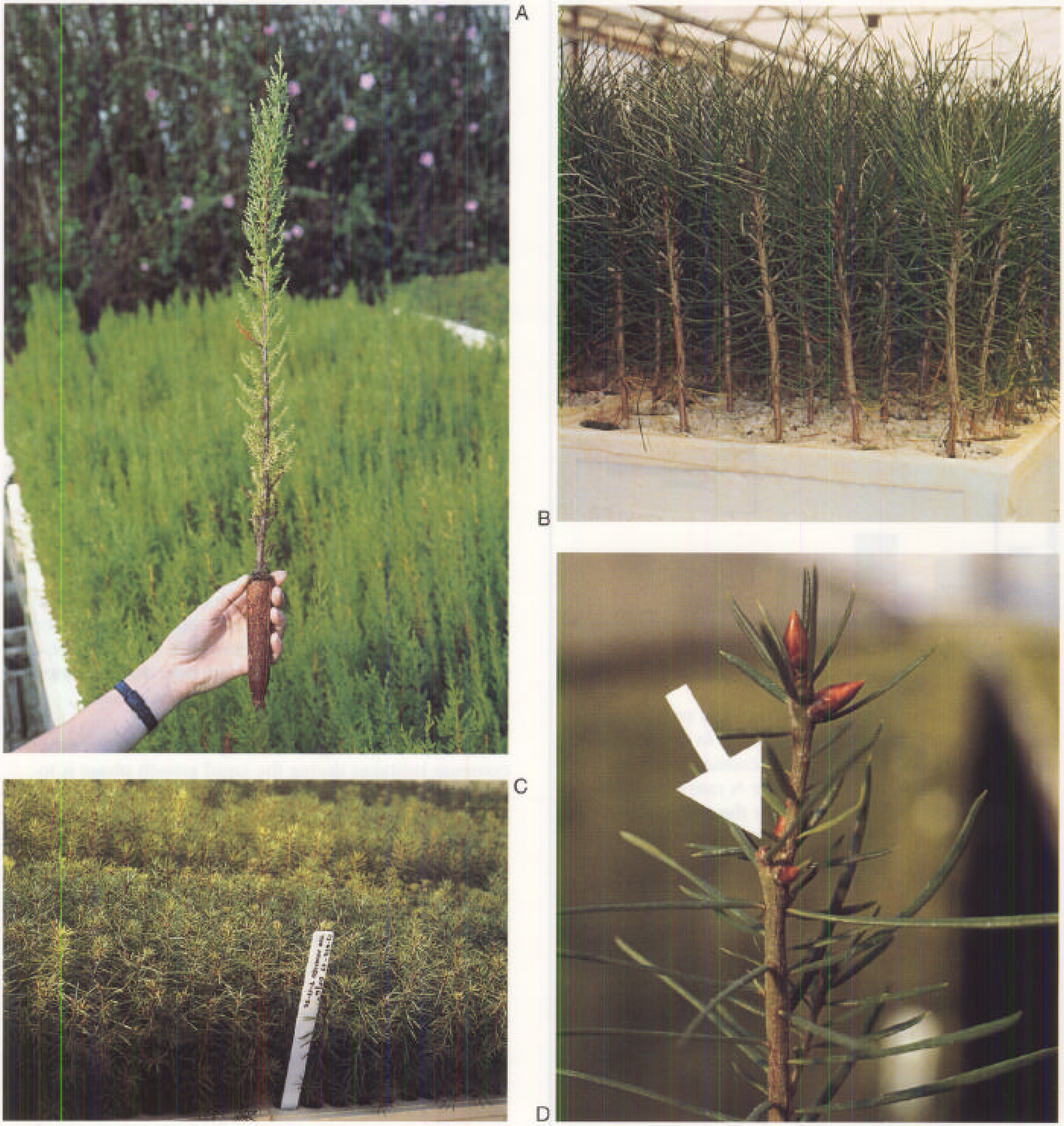
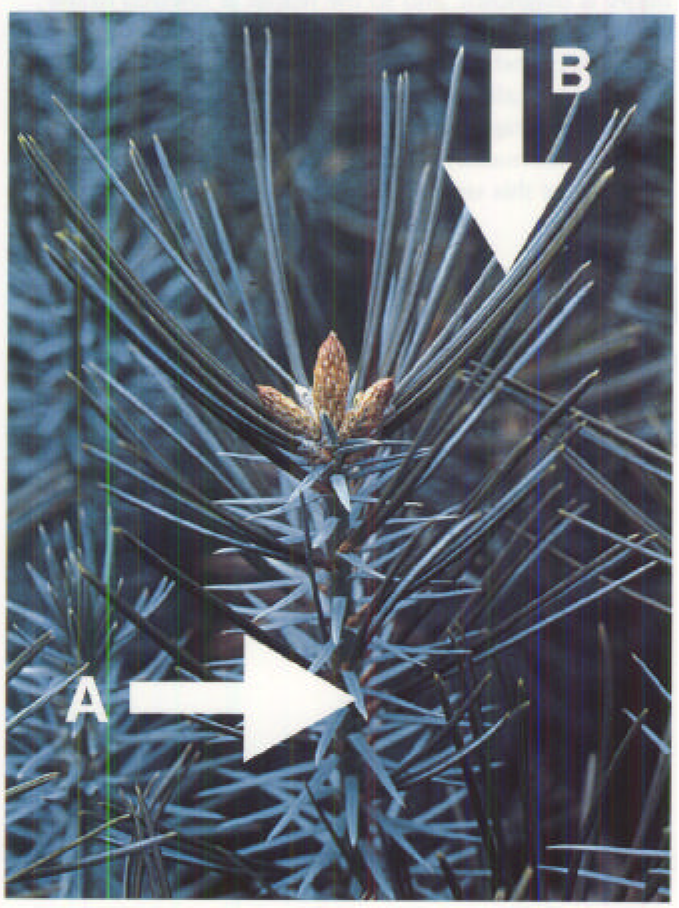


Figure 6.4.9—*Excessive shoot height is a common problem during the rapid growth phase, especially under high temperatures and high-nitrogen fertilization* (**A**). *The volume of cavities and the spacing between them strongly affect stem caliper and shoot-to-root ratio* (**B**). *Top pruning can be used but the treatment window is only a few weeks* (**C**). *Pruning into woody tissue may cause shoot deformities* (**D**).

apart in their racks. This is generally uneconomical (and impossible with block containers), so the best solution is to choose a container with the proper volume and spacing to produce the desired target seedling specifications. The traditional use of shadecloth to lower temperatures is not recommended because it lowers available light; if high temperatures are a problem, light irrigation or mistings should be used. Nitrogen fertilization is the one cultural factor that can be easily controlled in any nursery. Nitrogen acts like the "accelerator" in an automobile--the more you apply, the faster the shoot grows. The N proper concentration for the species being grown and the type of N fertilizer are also important. For example, fertilizers high in ammonium or urea will produce taller seedlings of many species than will those with a higher proportion of nitrate.

Top-pruning. Unfortunately, excessive shoot height is a difficult problem to control. Some conifer species, such as western redcedar, can be top-pruned easily as long as it is done before the tissue becomes too woody. Top-pruning is more difficult with others such as Douglas-fir because the timing is so critical (figure 6.4.9C). The cultural window when shoot tissue is still soft enough to tolerate pruning is only a few weeks in most cases. Shoots that are pruned into woody tissue are permanently damaged and often exhibit growth abnormalities (figure 6.4.9D). Other conifers, such as longleaf pine, can be top-pruned several times during the rapid growth phase (Barnett and McGilvray 1997). Most broadleaved species are much more tolerant to top pruning and can be pruned without damage. Still, growers should strive to control the rate of shoot height growth and use top-pruning only when absolutely necessary.

Primary versus secondary needles. Besides the increased growth rate, one of the most visible differences between the establishment and rapid growth phases is the nature of seedling foliage. Several species of conifers and some hardwoods produce primary leaves or needles from the apical meristem in the middle of the cotyledons that are very different from mature foliage. For example, the primary needles of pine seedlings are flat and needlelike (figure 6.4.10A/B), whereas primary needles of junipers are short spikes. Some customers prefer their seedlings to have secondary needles (Rose and others 1990); for instance, lodgepole pine seedlings with secondary needles have better outplanting performance (van Steenis 1993). Some species of pine seedlings normally produce primary needles during the first flush of shoot growth and, under natural daylength, will continue to do so throughout the first growing season.



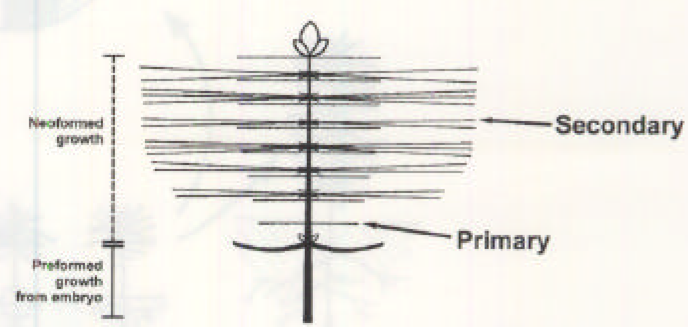


Figure 6.4.10—*Species like this pinyon pine first produce sharp pointed primary needles* (**A**)*, followed by fascicled secondary needles that form in the axils of the primaries* (**B**) *(drawing modified from Powell 1982).*

Photoperiod treatments, such as short days ("blackout') that are applied for as short as 2 weeks during the summer will cause secondary needles to form on some species of pines such as Scots pine (Rosvall-Ahnebrink 1982). In an operational nursery trial, two morphologically different types of lodgepole pine seedlings were created by manipulating photoperiod. Seedlings with mostly primary needles were produced in greenhouses with natural daylength whereas seedlings with mostly secondary needles were the result in greenhouses with supplemental lighting (Omi and others 1993; Omi and Eggleston 1993). The primary-needled seedlings were significantly shorter and had more roots than those with secondary needles (figure 6.4.1013). This effect is species specific, however, because other pines such as western white pine were unaffected by the light treatments.

6.4.3.4 Pests and abiotic problems

***Fusarium root rot*.** One of the most common diseases of northwestern conifer seedlings during the rapid growth phase is a root rot caused by *Fusarium spp.* These ubiquitous fungi typically are introduced into the nursery in growing media, on contaminated containers, or on seeds (figure 6.4.5). *Fusarium* spp. sometimes attack germinating seedlings causing damping-off, but more often produce minor root infections without obvious symptoms. Warm temperatures favor the *Fusarium* fungus, however, and so advanced root rot often develops during the warm moist conditions of the rapid growth phase. Then, during the early stages of hardening, foliar symptoms often develop after a few days of high temperature and moisture stress (Sutherland 1990). Fusarium root rot is difficult to diagnose because most nursery managers are unaware that they have a problem until the typical curled, necrotic needles develop (James and others 1991). When root systems of symptomatic seedlings are examined, the cortex easily strips away to reveal brown, decayed tissue. Fusarium root rot can spread from seedling to seedling through windborne or waterborne spores (figure 6.4.11), resulting in disease pockets. (Damage keys, color photographs, and more specific identification and control information can be found in section 5.1.4 of volume five of this series.)

***Insects*.** Although insects are not a serious problem in nurseries that practice good pest prevention practices, some can cause small localized problems. The larvae of webworms (that is, grubs), crane flies, root weevils, and fungus gnats feed on the root systems; only the adults of the fungus gnats are readily visible. The type of chewing injury is diagnostic and so the reader is referred to the damage key in section 5.1.4 of volume five of this series. Lygus bugs and thrips can also cause distorted shoot growth in localized pockets of seedlings. (Damage keys, color photographs, and more specific identification and control information can be found in section 5.1.4 of volume five of this series.)

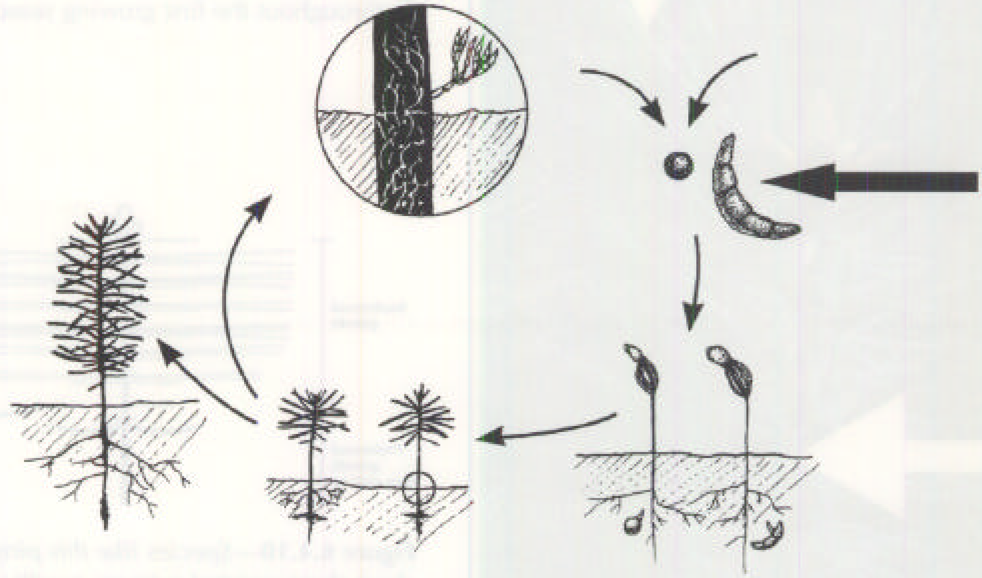


Figure 6.4.11—*Fungi of the genus* Fusarium *cause root rot of conifer seedlings; spores (see arrow) are spread by water or wind (modified from Sutherland 1990).*

6.4.4 The Hardening Phase

6.4.4.1 Introduction

Hardening is one of the most important periods in the culture of forest and conservation seedlings because they must be prepared to endure a considerable amount of stress after they leave the nursery. For example, conifer seedlings in the western United States must be lifted when dormant, stored long periods under refrigeration, shipped long distances, and then outplanted in relatively harsh environments with no postplanting care. In Ontario, the success or failure of spruce crops can almost always be traced to poor hardening practices (Odium 1992). In the southern United States, properly hardened container seedlings have been shown to survive and grow better than those which are not (table 6.4.6).

Problems with non-hardy seedlings. Hardiness problems may not be apparent during nursery culture and often do not appear until seedlings are stored or after they are outplanted. It is relatively easy to grow a crop of seedlings to target height and caliper specifications, but it is much more difficult to harden them to endure the stresses of handling, storage, and outplanting. This is evidenced by several catastrophic losses caused by non-hardy stock in recent years. Container tree seedling nurseries in British Columbia lost over 20 million seedlings during an early cold snap in October 1985, valued in Canadian dollars at $4.5 million. A couple of years later, Ontario Ministry of Natural Resources reported a loss of 7 million black spruce seedlings, worth approximately $1 million, that was attributable to poor seedling quality (Lewis 1988). In February 1996, a crop of 400,000 container longleaf pine seedlings being overwintered in an open compound in southern Mississippi were exposed to unexpected low temperatures. After the freeze, the seedlings still looked fine, so the nursery shipped them, not realizing that the roots had been killed. The problem became obvious several weeks after outplanting when seedlings began dying, In such cases, the economic impact also includes the cost of shipping and planting, which far exceeds the face value of the seedlings.

Although seedling mortality is the most dramatic result of non-hardy stock, other types of sublethal injury may not be immediately apparent. Roots will grow whenever temperatures are favorable (figure 6.4.12A) and, because they are exposed, can be easily damaged by heat or cold temperatures (figure 6.4.1213). Plants with sublethal root injury do not exhibit symptoms immediately but may gradually decline over time or may fall prey to some opportunistic pathogen. Conifer seedlings often reflect hardiness problems as "transplant shock," with characteristic chlorosis and bottlebrush foliar symptoms and consequent poor performance during the first growing season.

Hardiness terminology. The terminology used to describe the hardening process can be quite intimidating For example, one recent system for categorizing dormancy uses complicated terms such as "photoperiodic endodormancy" and "hydrational ecodormancy" (Lang 1987). We prefer simpler definitions. In forest and conservation nurseries, the terms "dormancy" and "hardiness" are often used interchangeably, but there are important differences. **Hardiness** can be defined as a condition of durability, or resistance to stress (Landis 1988). Although hardiness can refer to one specific stress, it stands to reason that seedlings that are cold hardy also are resistant to all the stresses that will be encountered during handling, storage, and outplanting. Cold hardiness is operationally useful because it is relatively easy to monitor. **Hardening** or **acclimation** can be defined as the process of inducing hardiness and occurs in concert with the dormancy process.

Table 6.4.6—*Loblolly pine seedlings that received sufficient hardening exhibited better resistance to cold injury and performed significantly better after outplanting*

Length of hardening period (weeks)	Cold hardiness (LT_{50})		Outplanting performance	
	°C	°F	Survival (%)	Shoot growth (cm)
0	− 4.3	24.3	28	3.9
2	− 6.4	20.5	52	10.1
6	213.6	7.5	76	18.2

Source: *Modified from Mexal and others (1979).*
LT_{50} = the lethal temperature at which 50% of the seedlings were killed.

Dormancy can be defined as the inability of a plant tissue to grow, even under environmentally favorable conditions (Lavender 1985). **Note that dormancy refers to specific meristematic tissue (buds, lateral meristems, or root tips), whereas hardiness refers to shoots or roots and, what is more significant operationally, often the entire seedling.** Be aware that much of the published literature only deals with bud dormancy and, although that is important, nursery managers must deal with the entire seedling. There is some overlap between dormancy and hardiness; in fact, dormancy is a prerequisite to high levels of hardiness. Although non-dormant tissue can harden to some degree, seedlings cannot achieve full hardiness if they are still growing (Weiser 1970). The highest levels of hardiness are reached after the plant has already passed through dormancy (figure 6.4.13).

Objectives of the hardening phase. A well-designed hardening phase can have several different objectives:

1. **Manipulate seedling morphology**--The first objective of the hardening phase is to stop shoot growth and promote bud set while encouraging caliper and root growth. In fact, the crop will grow very little in height during the hardening phase, which allows photosynthates to be shifted to the stem and root meristems (see figure 6.1.8 in this volume). At the end of the rapid growth phase, the seedlings are dis-

A

B

Figure 6.4.12—*Roots do not undergo a true dormancy period and therefore will grow anytime that temperatures are favorable (**A**). Because many of these roots are on the outside of the container plug, they can easily be damaged by moisture or temperature stress (**B**).*

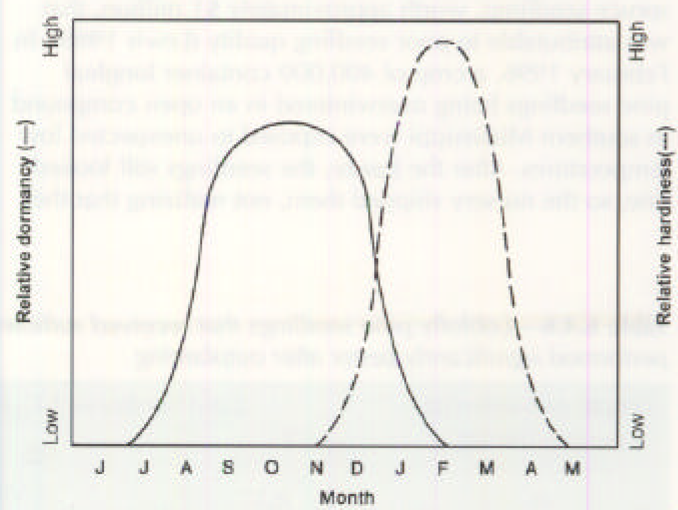


Figure 6.4.13—*Dormancy and hardiness are related in time because seedlings must have stopped active growth before they can achieve full hardiness (modified from Lavender 1985).*

proportionately tall fro their caliper and root system and the hardening phase should be used to develop a study stem and subsequently a better shoot-to-root ratio. Because some customers prefer mature needles on their conifer crops, developing secondary needles may be another cultural objective (see section 6.4.3.3). Most western conifers develop dormant buds that contain preformed shoot primordia for the next season's growth (figure 6.4.14A). Although a terminal bud does not develop on all species, many customers prefer their seedlings to have them. Likewise, the presence of numerous lateral buds is considered desirable because they will help develop a full crown the following season (figure 6.4.14 B).

2. **Acclimate seedlings to the natural environment**--Container seedlings have been growing at an accelerated rate during the rapid growth phase and therefore are very succulent and susceptible to a variety of stresses. For crops that will be outplanted during summer or fall, this is the primary objective of the hardening phase, as the seedlings must rapidly acclimatize to the outplanting site when they leave the nursery.
3. **Develop stress resistance for handling, storage, and shipping**--When the hardening phase is completed, the crop will either be moved to sheltered storage or harvested and packed for shipment. For our example crop of western conifers, the seedlings will be pulled from the growing container, wrapped or bagged in

Figure 6.4.14—*A firm terminal bud on a ponderosa pine seedling is a good indication of shoot dormancy and hardiness* (**A**). *Numerous lateral buds, like on these Douglas-fir seedlings* (**B**) *will develop into lateral branches the following season.*

plastic, and then stored under refrigeration for 2 to 4 months (table 6.4.1 A). Therefore, seedlings must be resistant to heat, cold, and moisture stress and be able to tolerate mechanical shocks.

4. **Fortify the seedling for survival and growth after outplanting**--Once seedlings are harvested, they will not be able to manufacture food through photosynthesis until they are established on the outplanting site. This means that they must have accumulated enough stored food reserves to maintain them for a period of days in the case of summer "hot" outplanting, or months in the case of frozen storage for spring outplanting at high-elevation sites.

***Factors affecting seedling hardiness**. There* are a number of different factors that can affect seedling hardiness in container nurseries and three are particularly noteworthy:

1. **Genetic factors**--Different species go through the hardening process at different rates under the same environmental conditions. Even within a species, there are genetic differences in hardiness between ecotypes. For example, seedlings of four northwestern conifers that grow together in nature were shown to harden at different rates under nursery conditions. Interior spruce not only hardened more rapidly but also reached a greater level of cold hardiness than the other species (figure 6.4.15).
2. **Type of tissue**--Stems, buds and foliage of a seedling harden at different rates (figure 6.4.16). Part of the reason for this variable response is due to the physical nature of different types of cells. Thin-walled meristematic cells are more vulnerable to cold injury than are older cells with thicker walls. Thus, in shoots, the terminal meristem is most often damaged by cold temperatures because it is the last to quit growing and become hardy. One of the most sensitive areas on container tree seedlings is the root collar. The exact reason for this is uncertain. Either this tissue is the last to harden or the tissue may be more similar to root tissue and therefore less cold tolerant. Another consideration is that this root collar area is physically protected by the container and the lower

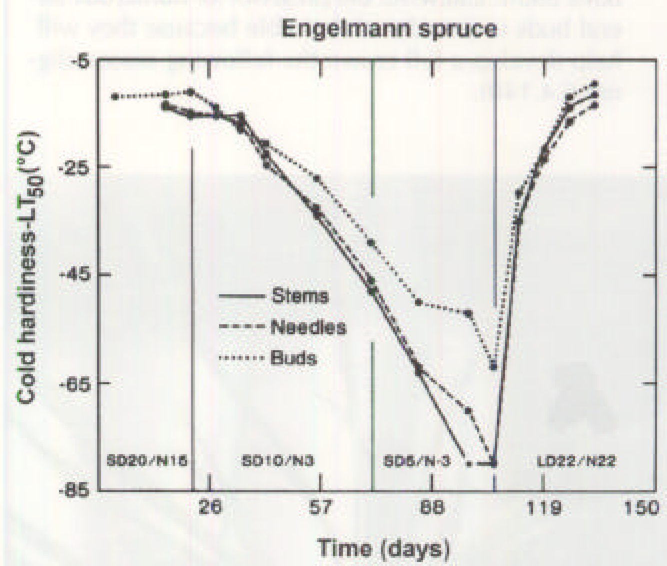


Figure 6.4.16—*Tissue from the stem, bud, and needles of Engelmann spruce seedlings hardened at different rates in response to short photoperiod (SD) and decreasing day/night temperatures.*

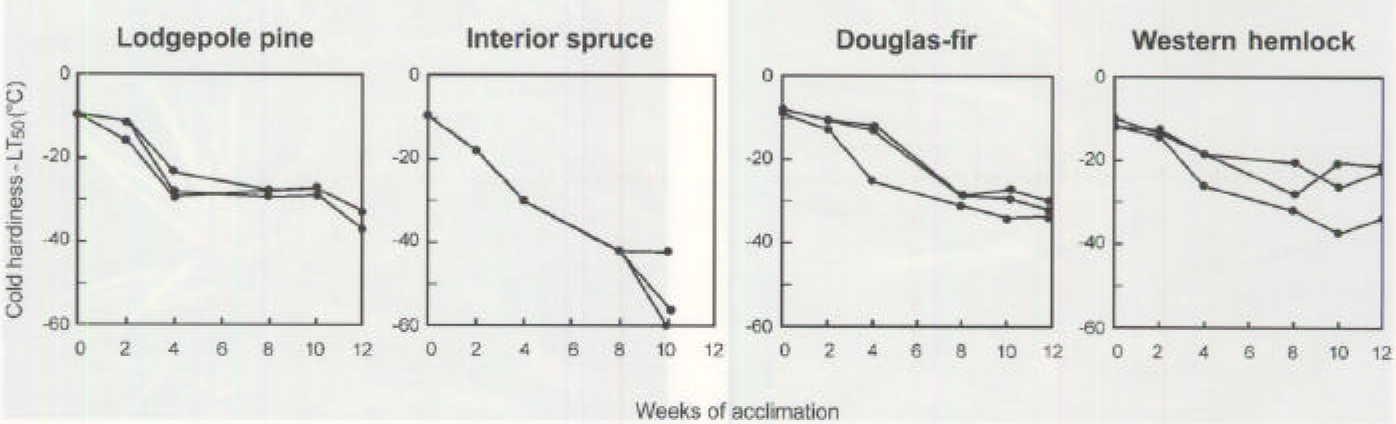


Figure 6.4.15—*Cold hardiness tests of four ecotypes of four northwestern conifers showed that hardening rates varied both between species and ecotype (modified from Simpson 1990).*

seedling foliage and therefore may never become as hardy as other parts of the stem.

Seedling root systems never become as hardy as the shoots and some species, such as longleaf pine, do not harden at all. Older, mature roots of commercial conifer seedlings from climates with cold winters are able to achieve moderate cold hardiness of -10 to -15 °C (5 to 14 °F) during late fall and winter. Newer roots are much less hardy than older ones, and young white roots harden little if at all (figure 6.4.12B). Because roots will grow whenever soil temperatures allow, they can be damaged during sudden frosts. Root injury is not always apparent in container stock under nursery conditions due to frequent irrigation but can be devastating after out-planting. For example, cold injury to Norway spruce seedlings resulted in a 50% reduction in root growth capacity and a 40% reduction in shoot growth (Lindstrom and Nystrom 1987).

3. **Growth stage**--Cold hardiness develops in a typical seasonal pattern in natural environments. Seedlings harden gradually through a series of stages in fall but deharden rapidly in spring (figure 6.4.16). Several models have been developed to describe growth and hardening cycles in plants. One of the most popular is the degree growth stage model, which shows the yearly cycle of plant growth as a series of different stages (Fuchigami and Nee 1987) that can be described in terms of shoot dormancy, hardiness, and stress resistance (Burr 1990). The model represents the annual seedling growth cycle as a sine wave, starting with bud break at 0% and ending with bud break the following season (360%) (figure 6.4.17). Active shoot growth occurs in the first (upper) half of the cycle with bud set occurring at 180%. The second (lower) half goes through shoot dormancy, which actually is initiated during the 90 to 180% stage, and ends with the post dormant phase from 315 to 360%. Again, note that this model deals only with buds and does not address dormancy or cold hardiness of lateral meristems or roots. Roots, in particular, have been shown to grow whenever temperatures are favorable and therefore do not have a true dormancy, as such. Therefore, nursery managers should use the degree growth stage model as a good conceptual framework guide but realize that they must view seedling dormancy and hardiness in a true holistic sense.

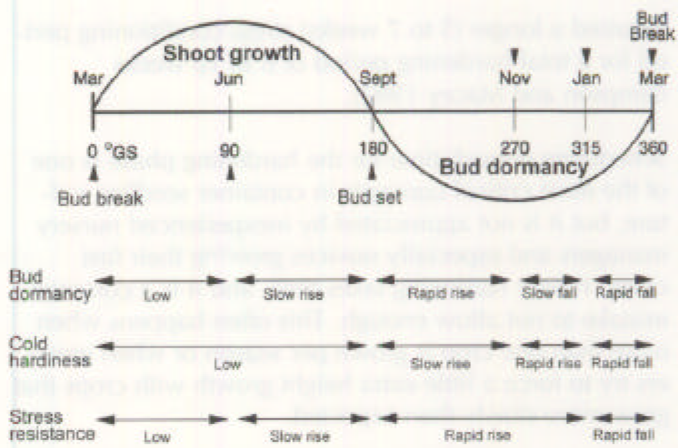


Figure 6.4.17—*One of the best ways to illustrate the hardening and dormancy process is the degree growth stage model, which breaks the annual cycle into 360 degrees (modified from Fuchigami and Nee 1987).*

Scheduling the hardening phase. For practical purposes, the hardening phase can be divided into two consecutive time periods: **dormancy induction** and **stress conditioning.** In a typical growing schedule, container seedlings must become dormant before they can develop full hardiness (Weiser 1970). Because objectives are different for these two stages, the cultural regimes will be different. The dormancy induction stage "shocks" the terminal shoot into dormancy while still encouraging stem diameter and root growth. For most of the western conifers in our example crop, lateral and terminal buds form, enlarge in size, and become covered with tight bud scales.

Once shoot dormancy has been achieved, the crop can be stress-conditioned. Seedlings are naturally hardened by exposing them to ambient conditions, but it is possible to achieve a greater level of stress resistance in a shorter time by imposing special cultural treatments in the nursery. These treatments must not be too severe, however, because overly stressed seedlings will actually be less hardy. Plants that have low levels of photosynthetic reserves cannot acclimate properly (Weiser 1970). The relative amount of time in dormancy induction and stress conditioning varies with crop species and type of hardening regime. A combination of 3 weeks of warm temperatures/short photoperiod to induce dormancy followed by 3 weeks of cold temperatures/short photoperiod to develop stress resistance was found to be best for interior spruce. Lodgepole pine, on the other hand, required a longer (5 to 7 weeks) stress conditioning period for a total hardening period of 8 to 10 weeks (Simpson and Macey 1992).

Scheduling enough time for the hardening phase is one of the most critical concepts in container seedling culture, but it is not appreciated by inexperienced nursery managers and especially novices growing their first crops. Proper hardening takes time, and it is a common mistake to not allow enough. This often happens when more than one crop is grown per season or when growers try to force a little extra height growth with crops that grow more slowly than expected.

Many growers do not appreciate the fact that stem and root growth require a steady supply of photosynthate, so the hardening phase must be scheduled when there is still enough solar energy to fuel this growth. While it is possible to achieve stress conditioning during the late fall and early winter, there is just not enough sunlight at this time of year to support caliper and root growth. After seedlings reach their target height at the end of the rapid growth phase, they need about 2 months to continue growing stem tissue and roots and then harden enough to tolerate the stresses of harvesting, storage, shipping and outplanting. Mexal and others (1979) found that loblolly pine container seedlings required at least 6 weeks of hardening, whereas Douglas-fir seedlings exposed to a sequence of hardening treatments required 18 weeks for full hardening (figure 6.4.18). For our example of western conifers at the University of Idaho nursery, the hardening phase typically takes from 2 to 4 months (table 6.4.1 A).

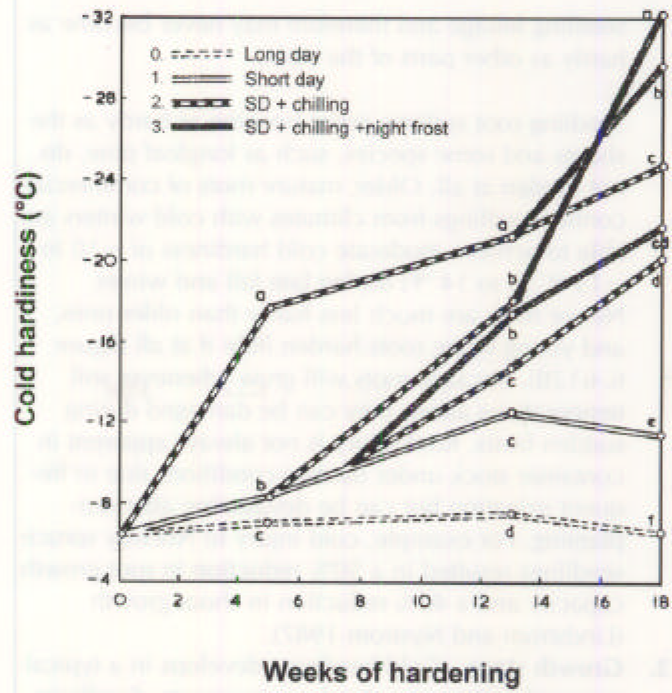


Figure 6.4.18—*Douglas-fir seedlings reached maximum cold hardiness when exposed to a sequence of short photoperiod (SD) and chilling temperatures, followed by a frost. Full hardening required 18 weeks (modified from Timmis and Worrall 1975).*

6.4.4.2 The atmospheric environment

In this section, we will discuss the same potentially growth-limiting environmental factors as in the establishment and rapid growth phases but, in addition, nurseries often change the propagation structure to initiate the hardening phase.

Propagation structures. Whereas the establishment and rapid growth phases are often easiest in fully controlled propagation structures such as greenhouses, this is not always the case for hardening. It is difficult to induce full hardening in a greenhouse. For example, Scots pine seedlings that were hardened in a greenhouse, even with short photoperiod treatments, suffered more post-outplanting injury than those receiving ambient treatments (figure 6.4.19). Traditionally, growers who produce their crops in greenhouses move seedlings to a shadehouse or open-growing compound at the end of the rapid growth phase so that the stock will be exposed to the ambient environment. Growers with poly-covered structures sometimes remove the greenhouse roof to achieve the same effect. Semi-controlled environments, such as shelterhouses, are ideal structures for hardening because it is easy to roll up the sides and expose the crops to ambient conditions. The latest models of semicontrolled structures feature retractable roofs that are controlled by computers. The roof can be opened at the beginning of the hardening phase and closed in the case of frost. The University of Idaho's Forest Research Nursery currently hardens its seedlings in the propagation greenhouse (table 6.4.7). Some fast-growing species, such as western larch, are moved to an outdoor growing compound to begin the hardening phase. (See section 1.3.2 in volume one of this series for a complete discussion on the attributes of various propagation environments.)

Regardless of the type of propagation environment, four factors are especially critical to inducing and maintaining

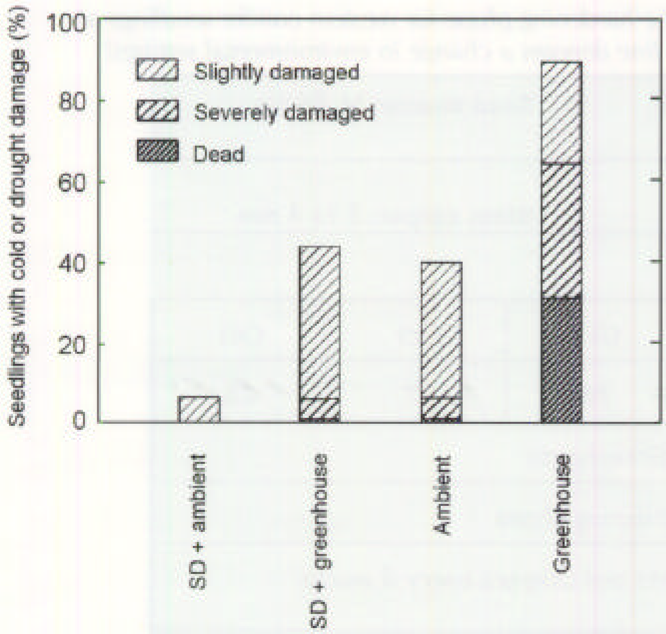


Figure 6.4.19—*Scots pine seedlings that were hardened for 6 weeks in a greenhouse suffered the greatest cold or drought damage after fall outplanting, compared to those treated with short photoperiods (SD) and ambient conditions (modified from Rosvall-Ahnebrink 1982).*

hardiness in forest and conservation seedlings: temperature, moisture, mineral nutrients, and photoperiod (figure 6.4.20). Hardening treatments are applied simultaneously or in sequence. Douglas-fir seedlings reached maximum hardiness when exposed to chilling temperatures, short photoperiods, and finally an exposure to below-freezing temperatures (figure 6.4.18). By contrast, only one of these factors is important to the dehardening process--temperature (van den Driessche 1969)--which is of critical importance during the storage period (see volume seven in this series.)

Temperature. Because temperature has such a pervasive effect on physiological processes, the control of day and night temperature in the propagation area is crucial to the hardening process. Exposure to cold temperatures that simulate normal fall conditions affects many aspects of seedling dormancy and cold hardiness, and a combination of cold temperatures and shortened photoperiod is often effective. For example, a sudden switch to short photoperiod under warm temperatures followed by a change to cool temperatures induces dormancy and develops the maximum stress resistance of northern conifers (Simpson and Macey 1992).

Dormancy induction. Because the objective of this stage is to stop height growth but encourage stem and caliper growth, the temperatures in the growing area are gradually reduced. This has the effect of maintaining sufficient rates of photosynthesis and respiration to promote caliper and root growth. Changing to cool temperatures affects the timing of growth cessation and bud set and dormancy initiation (Fuchigami and Nee 1987) as well as the number of primordia that form in the developing bud (Templeton and others 1993). Moderately warm temperatures are required to allow the number and size of the primordia to increase; for example, night temperatures of 15 to 20 °C (59 to 68 °F) were found to promote bud initiation and development in white spruce seedlings (Odium 1992).

The final effect of temperature during the hardening phase is dormancy release. The bud dormancy of most woody plants is released by long-term exposure to temperatures slightly above freezing-5 to 7 °C (40 to 45 °F). This time/temperature treatment is commonly known as the **chilling requirement** (Burr and others 1989). Other species require exposure to freezing. For example, two species of birch seedlings broke bud more quickly and completely when exposed to below-freezing temperatures after reaching full dormancy (Rinne and others 1997).

During the hardening phase, the University of Idaho nursery gradually lowers the day and night temperatures in the greenhouse at 5 to 10 °F increments until they reach their target temperatures (table 6.4.7). This begins the acclimatization process but keeps the temperatures warm enough to develop stem diameter and root growth (Wenny and Dumroese 1998).

Stress conditioning. Most temperate zone seedlings must be able to tolerate temperatures well-below freezing during outside overwinter storage or after outplanting. When about 90% of the crop has reached the target height and bud set is complete, temperatures can be lowered to begin conditioning the seedlings. Night temperatures have been shown to be more important than day temperatures for developing cold hardiness in Douglas-fir (van den Driessche 1969), Norway spruce, and Scots pine (Aronsson 1975). One interesting but not widely appreciated fact is that some species can be hardened to below-freezing temperatures without ever subjecting them to these temperatures. For example, Tinus (1974) was able to fully harden several western conifers to tolerate -30 °C (22 °F) with a maximum day tempera-

Table 6.4.7—*A 5-week segment of a cultural schedule during the hardening phase for western conifer seedlin the University of Idaho's Forest Research Nursery (dark vertical line denotes a change in environmental settin*

Customer: T. Planter	**Species:** PIPO, PIMO, PSME, LAOC, PIEN	**Seed source:** N. Idaho
Target specifications:	**Height:** 12 to 18 cm	**Stem caliper:** 3 to 4 mm

Month	Sept	Sept	Oct	Oct	Oct
Weeks from sowing	24	25	26	27	28
Propagation environment	Greenhouse				
Seedling growth stage	Hardening phase				
Cultural processes and operations	Take seedling heights and calipers every 2 weeks				
Labor: crew size (person-hours)	1 or 2 people, as needed				
Temperature: day setpoint (range)	13 °C (10 to 16) 55 °F (50 to 60)		7 °C (4 to 10) 45 °F (40 to 50)		
Temperature: night setpoint (range)	10 °C (8 to 12) 50 °F (45 to 55)		4 °C (1 to 7) 40 °F (35 to 45)		
Relative humidity: setpoint (range)	Ambient, vent after irrigation to prevent condensation				
Light: ambient	Full sunlight				
Light: photoperiod intensity & duration	None—ambient daylength only				
Carbon dioxide: rate & timing	Ambient, but stimulate air exchange and vent whenever possible				
Irrigation: amount & frequency	Fully saturate media +10% for leaching Irrigate when container weights reach 70-80% of wet weight				
Fertilization: Nitrogen (N) rate & frequency	Fertigate twice per week with hardening solution (50 ppm N)				
Pest management: monitoring pesticide and rate	**Be alert for *Botrytis* development.** Rogue-out any diseased seedlings and spot treat with fungicides when damaged exceeds threshold				

Source: Modified from Wenny and Dumroese (1998).

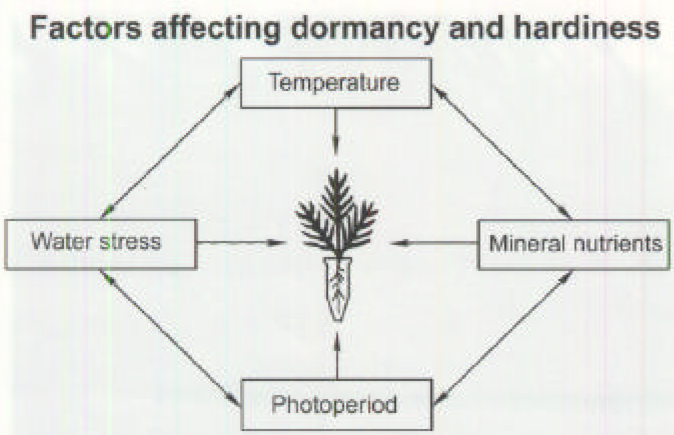


Figure 6.4.20—*Four environmental factors are modified during the hardening phase to induce seedling dormancy and hardiness.*

ture of 10 °C (50 °F) and a night temperature just above freezing.

Around the first week in November, the University of Idaho nursery continues the hardening process by exposing seedlings to ambient temperatures. This prepares them for the freezing temperatures they will experience in late fall and during storage. To keep root plugs from freezing solid and to protect the irrigation system, temperatures in the greenhouses are not allowed to go lower than 28 °F (-2 °C) (Wenny and Dumroese 1998). (Operational target temperatures and ranges for a variety of species during the hardening phase can be found in table 3.1 .2 of volume three of this series.)

Humidity. During the hardening phase, relative humidity is maintained at ambient levels, which helps prepare seedlings for the conditions they will experience on outplanting sites. Irrigations are done early in the morning and the greenhouse is ventilated immediately afterwards to exhaust humid air and help dry seedling foliage (table 6.4.7). This is a critical procedure to prevent condensation, which favors fungal development. Backpack leaf blowers work well to dry foliage and stimulate caliper development. (Operational relative humidity and vapor pressure deficit targets and ranges for a variety of species during the hardening phase can be found in tables 3.2.5 and 3.2.6 of volume three of this series.)

Light. Both light intensity and duration are important to the hardening process and daylength (photoperiod) is a critical factor for species and ecotypes from northern latitudes and high elevations. Species may even have photoperiodic ecotypes-Scots pine seedlings from northern latitudes stopped shoot growth up to 50 days earlier than those from more southerly locations (Oleksyn and others 1992). Those species from coastal climates and lower latitudes are less affected by shortened photoperiod treatments.

Dormancy induction. A short photoperiod treatment is one of the most important environmental factors triggering the termination of shoot growth and formation of buds in western conifers. Photoperiod lights extend the natural daylength during the rapid growth phase, and sometimes just shutting-off these lights will induce a rapid bud set. Growers should be aware that it is the relative rather than the absolute photoperiod that is effective. For example, seedlings that were grown under a 24hour intermittent photoperiod initiate hardening under a 18-hour treatment even though the latter is their normal summer daylength. For seedlings from northern latitudes that will be outplanted during summer, blackout curtains have been used to shorten the daylength to 8 or 10 hours to induce dormancy. With Scots pine, it has been demonstrated that short days are the most important cultural treatment for inducing dormancy and cold hardiness (figure 6.4.19). The effect of shortened photoperiod can happen quickly. Birch seedlings responded to shortened photoperiod treatments after only 5 days by slowing shoot growth, which ceased completely after 10 days (Rinne and others 1997). As mentioned earlier, sunlight intensity must remain high enough during this stage of the hardening phase to promote growth of buds, stems, and roots.

Stress conditioning. Short photoperiods also help induce cold hardiness in many species, especially when combined with cold temperatures. A short (8-hour) photoperiod was found to induce cold hardiness levels in loblolly pine comparable to seedlings that had been acclimated naturally outdoors (Mexal and others 1979).

The University of Idaho nursery shuts off the photoperiod lights at the beginning of the hardening phase. This, combined with mild nutrient and moisture stress, slows height growth, promotes terminal buds, and begins the stress acclimatization process (table 6.4.7). (Wenny and Dumroese 1998). (The cultural management of light during the hardening phase is discussed in section 3.3.3.4 of volume three of this series.)

Carbon dioxide. Carbon dioxide does not have a significant effect on the hardening process and so nurseries that USE! generators leave them running through the dormancy induction stage. High carbon dioxide levels retard normal leaf abscission of some broadleaved species, however, and so generators should be shut off at the beginning of stress conditioning. The University of Idaho's Forest Research Nursery does not use carbon dioxide generators but ventilates to encourage good air exchange (table 6.4.7) (Wenny and Dumroese 1998). (A complete discussion on managing and monitoring CO_2 during the hardening phase can be found in section 3.4.3 of volume three of this series.)

6.4.4.2 The edaphic environment

Irrigation. A mild moisture stress has been shown to reduce shoot growth and promote dormancy and hardiness in some species of container seedlings such as Colorado blue spruce and Douglas-fir. With other species, however, even moderate moisture stress can be detrimental to the hardening process. For example, moisture stress had no effect on induction of shoot dormancy in western hemlock and actually inhibited the beneficial effects of the other dormancy treatments (O'Reilly and others 1989). Mild moisture stress should be considered a hardening technique only for species that have demonstrated a positive response and for those species where other treatments are ineffective.

Dormancy induction. Inducing *moderate* levels of plant moisture stress can be achieved by withholding irrigation and lowering humidity. The trick is to allow the seedlings to dry clown until they have just begun to wilt Then, they should be irrigated and maintained under a mild moisture stress for several weeks. This procedure is more of an art than a science however, and requires constant vigilance to make sure that stresses do not reach injurious levels. When this happens, the apical meristem tissues where cells are actively dividing and elongating are injured. In the case of a mild stress, the meristems will recover but when stresses reach severe levels the damage can be long-term ("blown tops") (figure 6.4.21 A). For example, a moderate plant moisture stress (PMS) treatment of -1.5 MPa induced bud set and shoot dormancy in blue spruce seedlings but, if the stress reached higher PMS levels of -1 .8 to -2.0 MPa, foliar injury occurred (Young and Hanover 1978). Periodic moisture stress treatments of -1.7 MPa was effective in inducing termi nal bud formation in white spruce although the number of needle primordia was significantly lower (figure

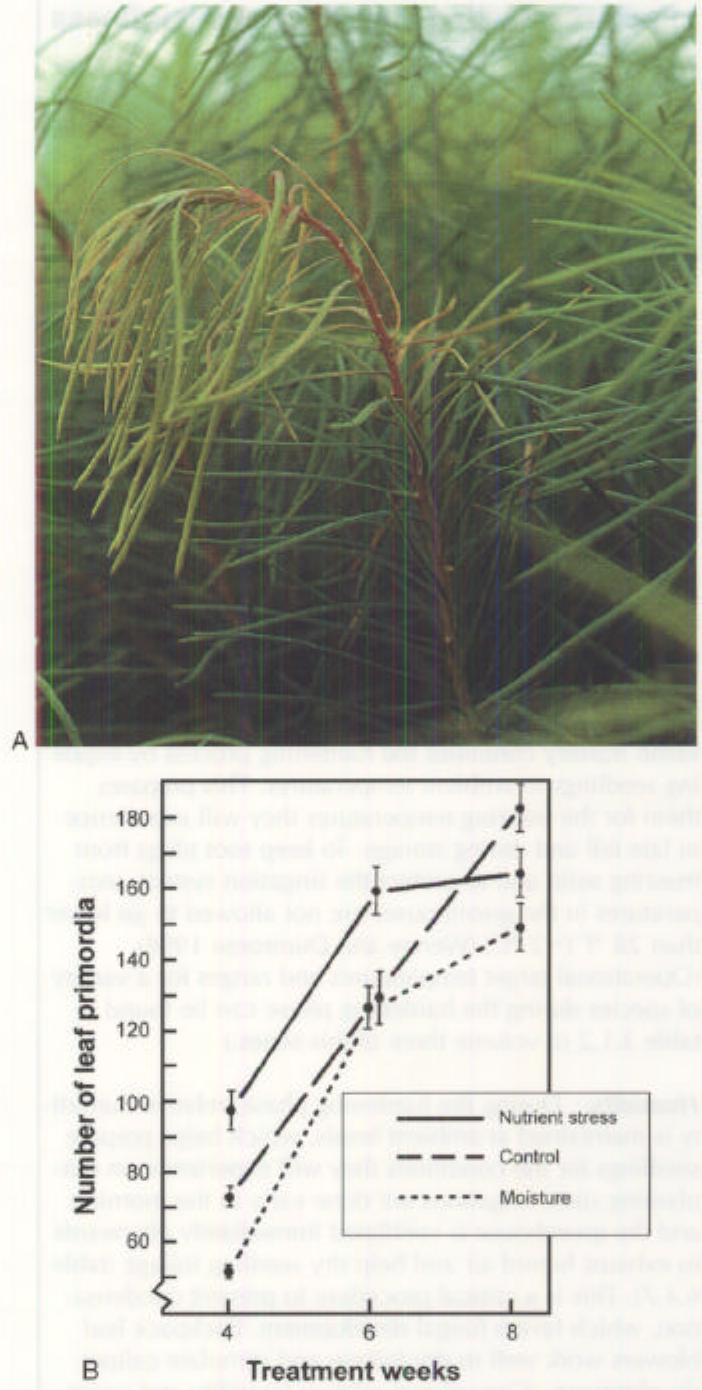


Figure 6.4.21—*Mild moisture stress is effective in slowing shoot growth with some species although meristematic tissue in buds or developing needles can be injured by severe stress* (**A**). *A 2-week hardening treatment of moderate moisture stress or no fertilizer reduced the number of bud primordia of white spruce seedlings* (**B**) *(B, modified from Macey and Arnott (1986).*

6.4.21 B). Tinus (1974) concluded that moisture stress should be considered a temporary shock treatment and not maintained any longer than necessary (a complete discussion of moisture stress terminology and treatments can be found in section 4.2.2 of volume four of this series).

Stress conditioning. Moisture stress in combination with other cultural practices is sometimes used for hardening some species of seedlings. A sequence of moderate moisture stress (-1 .0 MPa at mid-day) followed by a shortened photoperiod and a low-nitrogen fertilizer regime was recommended for coastal ecotypes of Douglas-fir and ponderosa pine (Lavender and Cleary 1974). In another study, however, water stress alone was shown to be ineffective in the hardening of coastal Douglas-fir seedlings unless followed by a period of cold temperatures (Tanaka and Timmis 1974).

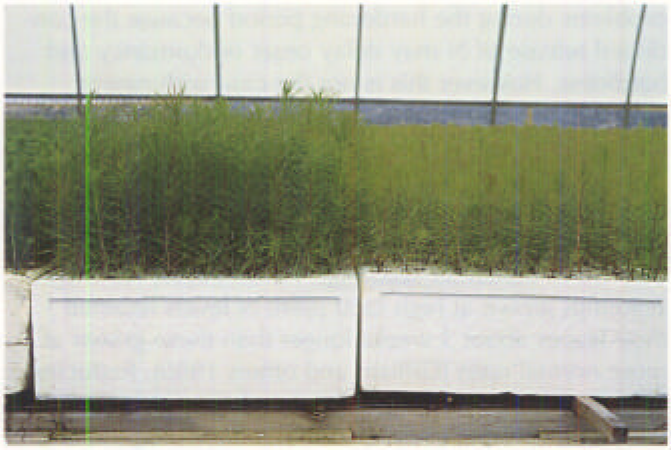
Monitoring block weights is a popular way of regulating irrigation in many western container nurseries and so this technique is particularly useful during the hardening process. As seedlings transpire, the weight of the block decreases until some predetermined level when the seedlings are irrigated. Container weight scales can be developed from experience and observation or from soil moisture retention curves and provide a visual and repeatable method of determining when moisture stress has reached a mild levels. For example, the University of Idaho nursery allows the weight of the containers to drop to 70 to 80% of the wet weight before irrigating (table 6.4.7) (Wenny and Dumroese 1998). Of course, this will vary considerably between species and with weather conditions (see section 4.2.7 in volume four of this series for details).

Fertilization. Lowering mineral nutrient levels in the growing medium will logically slow shoot growth, and so reducing or even temporarily eliminating fertilizer is used to shock seedlings into dormancy and hardiness. just as high nitrogen (N) is one of the primary cultural factors used to stimulate shoot growth during the rapid growth phase, lowering the N level is a logical and effective way to control height and induce hardiness (Young and Hanover 1978). Specialized fertilizers have been developed for the hardening period in container nurseries, but recent operational trials have shown that they are really not necessary. Nitrate, rather than ammonium, and increased calcium levels have also proven beneficial in hardening fertilizer solutions. Some slow-release fertilizers incorporated into the growing medium can cause problems during the hardening period because the continued release of N may delay onset of dormancy and hardiness. However this is not the case with newer controlled-release fertilizers, which give growth benefits after outplanting.

Dormancy induction. In general, the continued application of high-N fertilizers promotes shoot growth and succulence in container seedlings. For example, red maple seedlings grown at high (300 ppm) N levels retained their leaves about 3 weeks longer than those grown at more normal rates (Gilliam and others 1980). Reducing N concentration in the fertigation solution is a standard cultural technique at the start of the hardening phase and some nurseries withhold nitrogen completely for a few weeks to induce a stress. Nitrogen stressing is commonly used for species, such as western larch, that growth rapidly in height and do not respond to other hardening techniques (figure 6.4.22A). Eliminating fertilization for 2 weeks reduced the number of bud primodia in white spruce seedlings (figure 6.4.21 B), but Bigras and others (1996) found no evidence that N fertilization had any effect on the number of bud primordia of black spruce. Inducing N stress in Colorado blue spruce seedlings caused bud set but the buds were small and light-colored (Young and Hanover 1978).

Stress conditioning. It is widely known that high fertilization levels, especially of N, cause plants to grow later into the fall when they are more susceptible to cold injury. Pellett and Carter (1981) did an exhaustive literature review and concluded that seedlings grown at normal fertilization rates will be more cold hardy, and therefore stress resistant, than those grown under either very low or excessively high fertilization levels. This has been confirmed with research on commercial conifer seedlings. Although it varies with plant species, fertigation solutions with a N concentration of from 50 to 100 ppm during the hardening phase should produce seedlings with a foliar N concentration in the range of 2.0 to 2.5%.

Nutrient-deficient seedlings have problems with dormancy and are just as susceptible to cold and other stresses as those that have been over fertilized. Black spruce seedlings grown under suboptimal fertilization were less hardy than those with higher foliar nitrogen levels (Bigras and others 1996). The same conclusion was reached in a study with Scots pine as well-fertilized seedlings had less cold injury than those which were nutrient deficient (Rikala and Repo 1997). Over fertilizing is a more com-



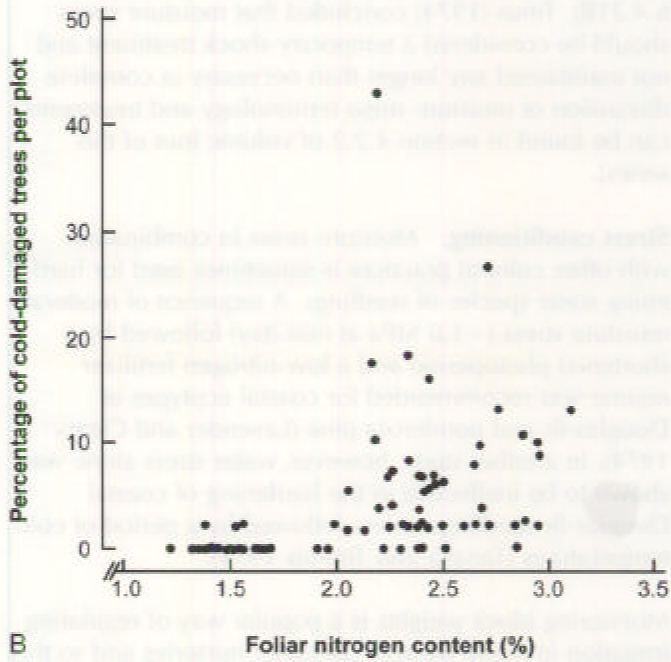


Figure 6.4.22—*Nitrogen stress is used to control height growth with fast-growing species such as western larch; the seedlings on the right have been stressed* (**A**). *High-nitrogen fertilization (foliar content > 2.0%) reduces seedling cold hardiness at the nursery and after outplanting* (**B**) *(B, modified from Aronsson 1980).*

mon problem in container nurseries, however, as numerous studies have shown that seedlings with high nitrogen contents suffer more cold injury than those grown under more moderate fertilization (figure 6.4.22B). (See section 4.1 .10 in volume four of this series for more information on the effects of heavy fertilizer use.)

The University of Idaho nursery uses mild moisture and nutrient stress at the beginning of the hardening phase to initiate bud set and begin the cold acclimatization process, and continues the moisture stress until harvest (table 6.4.7) (Wenny and Dumroese 1998). Foliar fertilizers can be used to recharge seedling reserves after nutrient stress and as a way to fertilize when irrigations are undesired in order to maintain mild moisture stress (Montville and others 1996).

6.4.4.3 Cultural operations

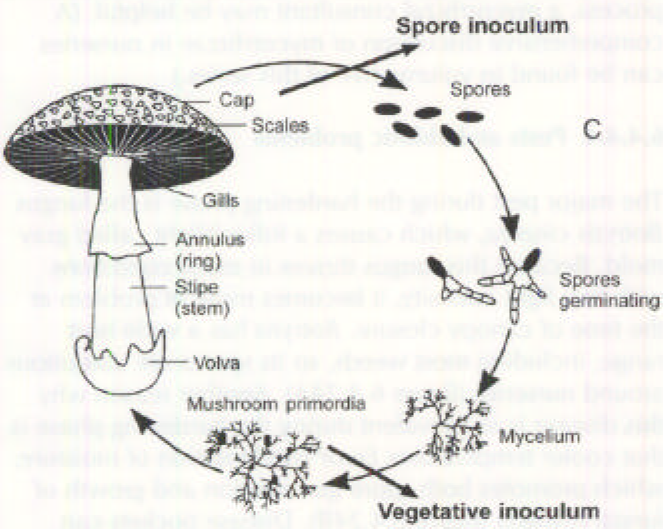
There are few special cultural operations during the hardening phase beyond the normal procedures discussed earlier. However, many customers are requesting that their seedlings be inoculated with beneficial microorganisms such as mycorrhizal fungi. Although there are three possible times to inoculate (at the time of sowing, during the crop cycle, or during outplanting), the use of low-N fertilizer and the presence of many new root tips make the hardening phase an ideal time.

Inoculating with mycorrhizal fungi. Probably more research has been done on mycorrhizae than on any other single aspect of nursery culture. Yet, most nursery managers are either unsure about whether their seedlings have mycorrhizae or have no idea of which organisms are involved. A mycorrhiza is the anatomical structure resulting from the symbiotic association between a plant root and a fungus. There are two main types that are distinguished by their morphology: ectomycorrhizae (ECM) and endomycorrhizae--which are more correctly known as vesicular-arbuscular mycorrhizae (VAM). What type is present at a nursery will depend on what species of seedlings are being grown. ECM are the mycorrhizae that are most often noticed in forest and conservation nurseries because of their mushroom fruiting bodies (figure 6.4.23A) or the colored sheath of fungal hyphae with surrounding mycelia can be seen with a hand lens on the short feeder roots (figure 6.4.23B).

When considering inoculation with mycorrhizal fungi, growers should think about what they hope to gain. The benefits of mycorrhizae can be separated into nursery effects and outplanting effects. The experience at many nurseries has been that high-quality crops can be grown without mycorrhizal inoculation because the nursery environment supplies all the growth requirements of a seedling. The other major nursery benefit of mycorrhizae is protection against root pathogens but, with a sterile

A

B



C

Figure 6.4.23—*Ectomycorrhizal fungi can be seen fruiting in containers* (**A**) *or their mycelia are often obvious on the outside of the root plug* (**B**). *Two types of ectomycorrhizal inocula (spores or vegetative) can be applied to seedlings in container nurseries* (**C**) *(C, modified from Molina and others 1993).*

growing medium and containers, these pests should not be much of a problem. One of the most widely advertised benefits of mycorrhizae is increased survival and growth on afforestation sites. And, of course, one of the most important benefits is from a marketing standpoint because seedlings with well-developed mycorrhizae are widely considered to be high-quality nursery stock.

When considering a nursery inoculation program, several things need to be considered:

1. The proper species of fungi for each crop
2. The most appropriate type of inoculum for your nursery system
3. The proper timing and technique
4. Cost effectiveness

Species selection. There are two possible routes to take when selecting a mycorrhizal fungus for inoculation: (1) selection of a species adapted to a broad range of hosts or site conditions, and (2) selection of a species adapted to a specific host or particular type of outplanting site. Obviously, the first step is to select a species that can colonize the plant species that is desired. Most VAM fungi and ECM species such as Cenococcum geophilum, Pisolithus tinctorius, and *Thelephora terrestris* have broad host ranges. Broadly adapted mycorrhizal fungi are advantageous because many nursery crops can be inoculated at the same time, and inoculated seedlings would be adapted to a wide variety of outplanting site conditions. On the other hand, host-specific or site-specific mycorrhizal fungi will produce maximum seedling performance in a given application.

Types of mycorrhizal inocula. There are two basic categories of inocula currently being used in forest and conservation nurseries: spores and vegetative inocula (Figure 6.4.23C). Fungal spores of ECM fungi are obtained from fruiting bodies collected from wild stands, or vegetative inoculum is produced from fungal mycelia grown in pure culture on an artificial medium. Both spore inoculum and vegetative inoculum are available commercially. Several firms have developed sophisticated techniques for culturing ECM fungi on artificial media. Other companies collect fruiting bodies of ECM fungi, harvest the spores, and sell them to nurseries.

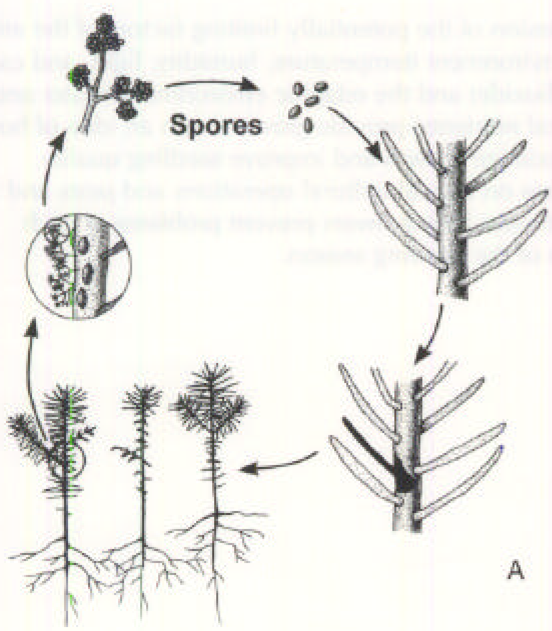
How and when to inoculate. In container nurseries, ECM fungal spores can be applied to seeds before sowing. Vegetative inoculum of ECM or VAM fungi can be incorporated into the growing medium before the containers are filled. ECM fungal spores can also be applied in a water suspension either by hand, or through the existing irrigation system starting as soon as seedlings have enough roots for successful colonization. Many nursery cultural practices, especially high fertilization rates, inhibit development of mycorrhizae and so inoculating during the hardening phase with its lower N fertilization has some merit. The drawback is that roots may already be infected with other mycorrhizal fungi, especially the ubiquitous T. terrestris, which thrives in the nursery environment.

Cost effectiveness. Mycorrhizal inoculation must make sense from an economic as well as biological point of view. If inoculation is believed to improve seedling quality, a cost-benefit analysis should be performed. The total cost of inoculation (including inoculum price and application costs) should be compared to the benefits either in the nursery or on the outplanting site. The savings associated with less fertilizer, disease reduction, higher seedling survival, and increased growth need to be documented. The marketability of seedlings that have been inoculated with a specific mycorrhizal fungus may be a significant benefit. A nursery could advertise that its seedlings were mycorrhizal and stress the associated benefits, just like they do for seedling size, seed origin, and vigor.

The decision whether to inoculate seedlings is complicated. So, unless there is a good understanding of the various fungi/host combinations and the inoculation process, a mycorrhizal consultant may be helpful. (A comprehensive discussion of mycorrhizae in nurseries can be found in volume five of this series.)

6.4.4.4 Pests and abiotic problems

The major pest during the hardening phase is the fungus *Botrytis cinerea*, which causes a foliar blight called gray mold. Because this fungus thrives in moist conditions with low light intensity, it becomes more of problem at the time of canopy closure. Botrytis has a wide host range, including most weeds, so its spores are ubiquitous around nurseries (figure 6.4.24A). Another reason why this disease is so prevalent during the hardening phase is that cooler temperatures favor condensation of moisture, which promotes both spore germination and growth of fungal mycelia (figure 6.4.24B). Disease pockets can quickly develop and therefore frequent scouting is necessary (figure 6.4.24C; table 6.4.7).



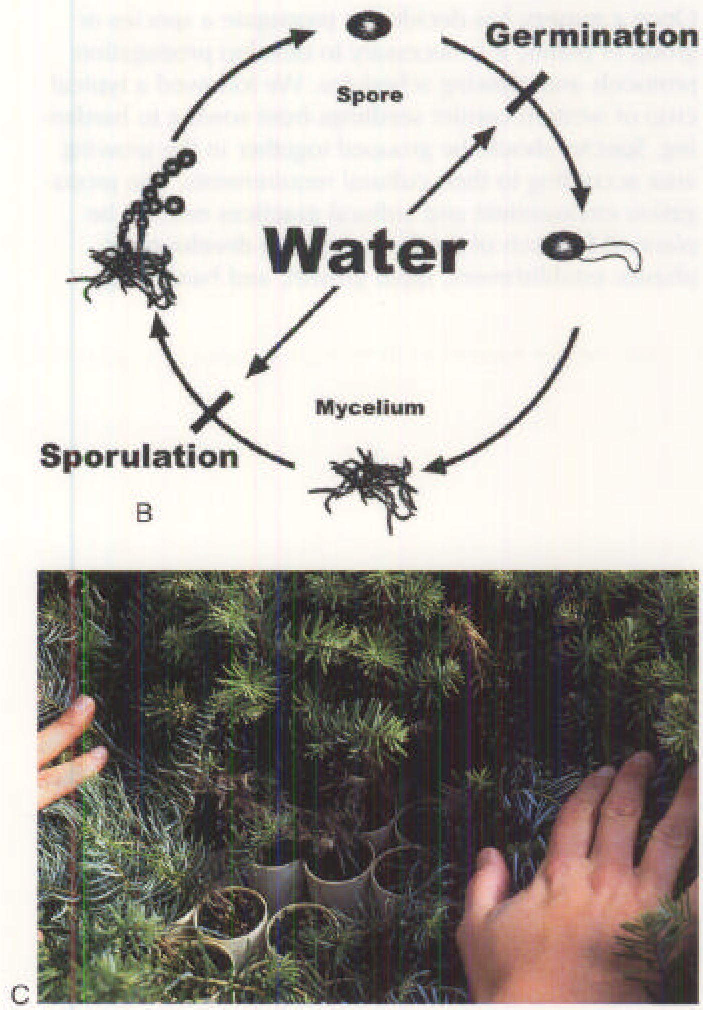


Figure 6.4.24—*Gray mold is a disease caused by the fungus* Botrytis cinerea, *which is very common during the hardening phase. It can spread rapidly by spores* (**A**), *which are encouraged by poor irrigation practices* (**B**). *Careful scouting of senescent foliage in overcrowded seedlings should be done frequently* (**C**). *(A, modified from Russell 1990).*

Fungicides can be effective in preventing development of the disease but do little to eradicate existing infections. Also, there are strains of *Botrytis* that have become resistant to many common fungicides, making it necessary to use several chemicals in rotation for effective control. Integrated pest management (IPM) is a better option, as cultural controls have proven quite effective. Using containers with more space between cells, managing the timing of irrigation, providing good ventilation, and roguing diseased individuals can greatly reduce the chances of developing a serious problem (Russell 1990). Some growers inject a surfactant during irrigation that helps foliage dry more quickly. The University of Idaho nursery has greatly reduced its use of fungicides through an aggressive IPM program (Dumroese and others 1990) and uses cultural controls such as vacuuming dead needles from western larch to reduce *Botrytis* infections (Dumroese and Wenny 1992).

6.4.5 Summary

Once a nursery has decided to propagate a species or group of plants, it is necessary to develop propagation protocols and growing schedules. We followed a typical crop of western conifer seedlings from sowing to hardening. Species should be grouped together in the growing area according to their cultural requirements. The propagation environment and cultural practices need to be planned for each of the three seedling development phases: establishment, rapid growth, and hardening.

Discussion of the potentially limiting factors of the ambient environment (temperature, humidity, light, and carbon dioxide) and the edaphic environment (water and mineral nutrients) provide growers with an idea of how to maximize growth and improve seedling quality. Sections on typical cultural operations and pests and abiotic stresses help growers prevent problems at each phase of the growing season.

6.4.6 Literature Cited

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