Hardening

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To promote survival and growth following outplanting, nursery stock must undergo proper hardening. Without proper hardening, plants do not store well over winter and are likely to grow poorly or die on the outplanting site. It is important to understand that native plant nurseries are different from traditional horticultural systems in that native plants must endure an outplanting environment in which little or no aftercare is provided.

Hardening refers to a series of horticultural practices during the nursery cycle that increase plant durability and resistance to stresses. Plant hardiness primarily develops internally, although certain external characteristics such as thickening stems, a tougher feel to the foliage, and leaf abscission of deciduous species are indicators of the hardening process. Promoting hardiness is critical to prepare plants for the stresses they will endure after leaving the nursery. This process takes time and a common mistake of nursery growers, particularly with novice or inexperienced growers, is not to schedule adequate time to harden their crops.

To properly harden plants to withstand stresses of outplanting, it is important to consider the Target Plant Concept presented in chapter 2. Using knowledge of the expected conditions of a given outplanting site, nursery cultivation may be adjusted to acclimatize plants for site conditions by promoting specific traits. For instance, on sites where drought is anticipated, a larger proportion of roots relative to shoots may be desirable to improve plant resistance to moisture stress.

Cascade mountain-ash showing fall colors by R. Kasten Dumroese.

Figure 12.1—*Succulent shoot tissue can be damaged by freezing temperatures during early spring, late fall, or during overwinter storage. Note that the dormant buds on the plant in the middle are not injured.* Photo by Thomas D. Landis.

Figure 12.2—*(A) Nursery plants always undergo some degree of "transplant shock" as soon as they are outplanted. (B) This shock is primarily due to moisture stress and lasts until the roots are able to grow out into the surrounding soil.* Photo by Thomas D. Landis, illustration by Jim Marin.

In this chapter, we illustrate the importance of proper hardiness in promoting plant performance following outplanting, discuss how hardiness naturally changes through the course of the nursery growing cycle, describe how plants may be conditioned to prepare them for the characteristics of a particular outplanting site, and suggest horticultural treatments that may be used in small native plant nurseries to help promote hardiness.

EXPOSURE TO STRESSES FOLLOWING NURSERY CULTURE

During the nursery growing cycle, the objective is to promote ideal plant growth and development. This is largely accomplished by providing optimal levels of all potentially limiting factors and minimizing environmental stresses. Following nursery culture, however, plants must be hardened prior to outplanting.

Nursery plants are exposed to a series of stresses starting with harvesting. The harvesting process requires the moving and handling of plants, which creates potential for physical and internal damage. Following harvesting, nursery stock is usually overwintered outdoors or sometimes stored under refrigeration for several months while awaiting transport to the outplanting site. To withstand cold temperatures, plants must be sufficiently dormant and hardy or else injury may occur (figure 12.1). After nursery plants are transported to the outplanting site, they are often exposed to unfavorable environmental conditions until actually outplanted. For instance, sunny and windy conditions on the outplanting site can result in overheating or desiccation damage.

After nursery stock is outplanted, the plants must tolerate a period of "transplant shock" (figure 12.2A). This *shock* occurs as a result of moving plants that have grown under a favorable nursery environment, in which they receive plenty of water and fertilizer, to the outplanting site, where these factors are always limiting. Recently outplanted nursery stock must rapidly develop new roots that can grow out into the surrounding soil to access water and nutrients (figure 12.2B), compete with other plants, resist animal browse damage, and endure extreme high or low temperatures. All these stresses create the potential for physical or physiological injury that may limit outplanting success. Thus, it is important to understand how the capacity of plants to resist these stresses changes over the growing cycle and how nursery horticultural practices can increase hardiness.

PLANT GROWTH STAGES, DORMANCY, AND STRESS RESISTANCE

It is very important for growers to understand the relationship between plant growth stages and their ability to tolerate stresses. When plant shoots are actively growing, their ability to resist stress is relatively low. This condition is particularly true during the rapid growth phase of nursery production. See Chapter 3, *Crop Planning and Developing Propagation Protocols*, for descriptions of the phases. Toward the end of the rapid growth period, growth slows as plants begin to physiologically prepare to endure the stresses of winter by entering a state of dormancy (figure 12.3).

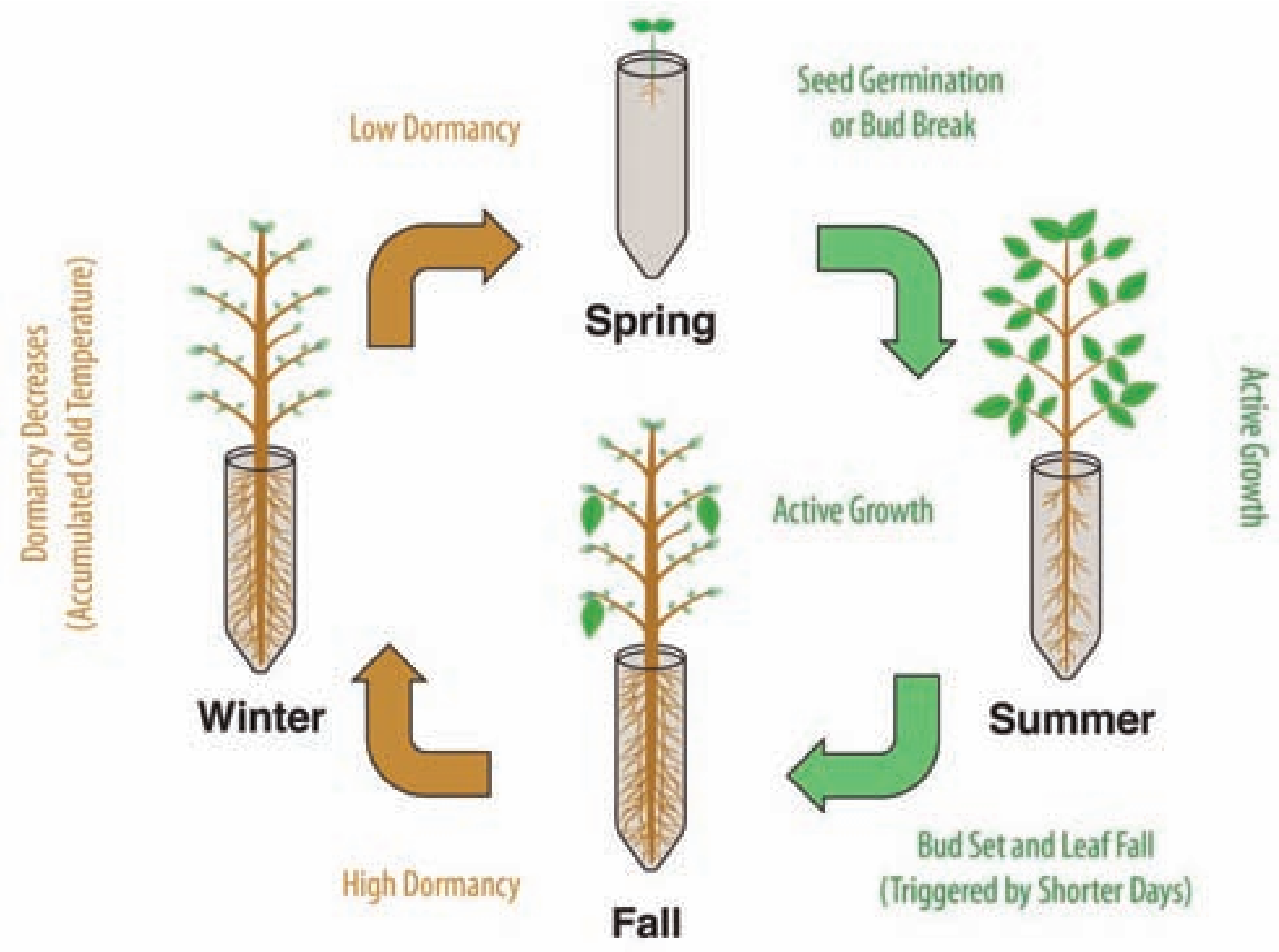

Figure 12.3—*Plants go through an annual cycle of active gowth and dormancy. As they become more dormant in autumn, their resistance to stress increases and is greatest during midwinter.* Illustration by Jim Marin.

A seed or plant is dormant when it will not grow even when all environmental conditions are ideal. It is important to realize that dormancy refers only to the growing points of a plant, which are known as "meristems." Plants have three meristems: foliar buds, a lateral meristem just inside the bark of the stem, and the root tips (figure 12.4A). Dormancy refers only to foliar buds because the lateral meristem and the roots never undergo true dormancy and will grow whenever conditions are favorable (figure 12.4B). Plants rely on environmental cues, especially shortening daylength, to trigger the onset of dormancy (figure 12.4C). Dormancy deepens through late autumn to early winter, when it is at its greatest (see figure 12.3). Exposure to temperatures just above freezing is an environmental cue to increase dormancy. After reaching full dormancy, the accumulated exposure to cold temperatures ("chilling hours") gradually releases dormancy (figure 12.3). This release continues until late winter to early spring, when all dormancy has been lost and buds are ready to grow again. Buds "break" under a combination of warm temperatures, moisture, and longer days, which initiates the growth cycle again.

Dormancy is related to stress resistance because plants that have stopped growing are more hardy than those that are still growing. Although the stress resist-

TWO STEPS IN THE HARDENING PHASE

Plants must first be cultured into reducing shoot growth and setting buds, and then conditioned to withstand stress

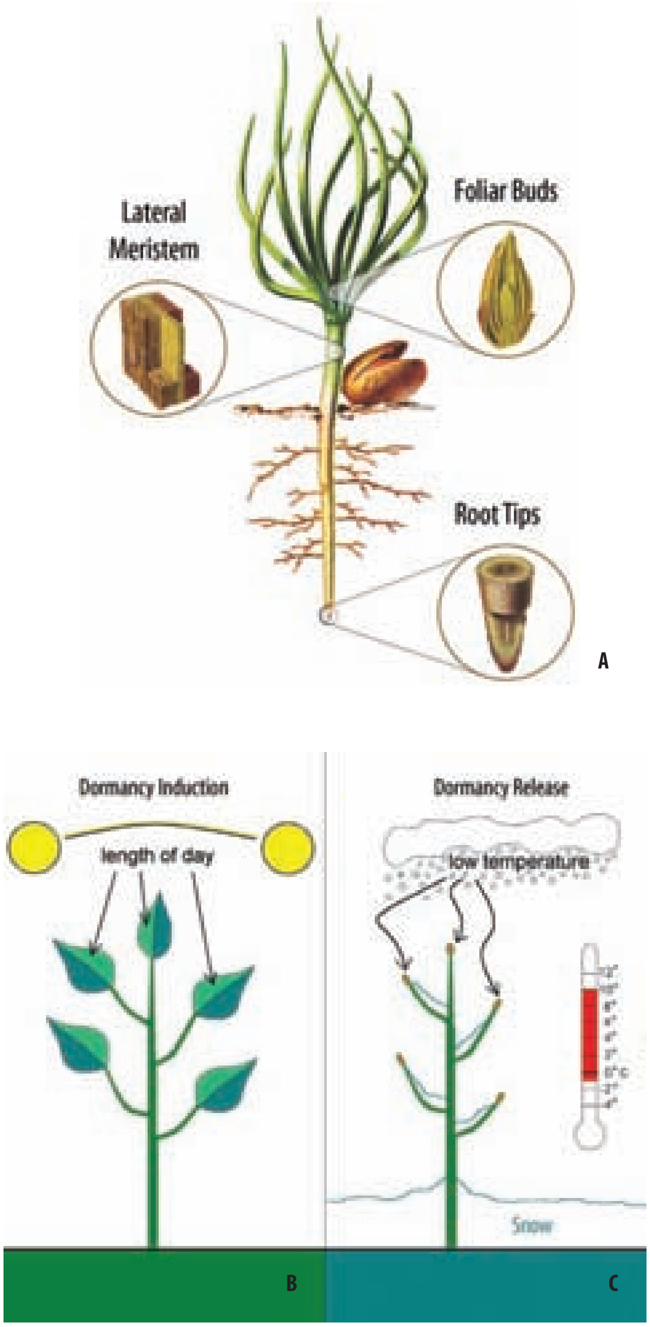

Figure 12.4—*(A) Of the three growing points in plants, only foliar buds undergo true dormancy. The lateral meristem in the stem and especially the root meristem will grow whenever temperatures permit. (B) In late summer, plant leaves receive the cue of shortening days to begin the dormancy process. (C) As dormant buds accumulate more "chilling hours" through the winter, they gradually lose dormancy.* Illustration by Jim Marin.

ance of plants cannot be measured, it is closely related to their cold hardiness. Thus, during winter, when plants must endure exposure to cold temperatures, they are also most able to resist other stresses. This midwinter dormant period is the best time to harvest, ship, and outplant nursery stock. Because many native plant nurseries are located in milder climates than their clients, plants must be harvested and stored until conditions on the outplanting sites are optimal. For more information on the "lifting window" and "outplanting window," see Chapter 13, *Harvesting, Storing, and Shipping*.

CREATING HARDY PLANTS IN NURSERIES

In nature, plants harden gradually as summer changes into autumn, but it is possible to achieve a greater level of stress resistance in a shorter amount of time through horticultural treatments in the nursery. These treatments must not be too severe, however, because overly stressed plants will actually be less hardy. In particular, plants with low levels of photosynthetic reserves cannot acclimate properly. In the following sections we describe how specific nursery horticultural treatments may be adjusted to induce hardiness and properly condition plants to resist stresses.

Scheduling the Hardening Phase

Scheduling enough time for the hardening phase is one of the most critical concepts in growing native plants, but it is not appreciated by inexperienced nursery managers growing their first crops. Proper hardening takes time, and it is a common mistake to try to rush the process. This mistake often happens when growing more than one crop 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 realize that root-collar diameter 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.

Environmental Factors Affecting Hardening

To better understand how horticultural practices affect hardening, growers need to know the role that environmental conditions play on dormancy induction. The four main factors that affect plant dormancy and hardiness are intensity and duration of light, temperature, soil moisture, and fertility (figure 12.5). When nursery plants have reached their optimum ("target") height, nurseries horticulturally manipulate these four factors to stop shoot growth and induce hardiness.

Light

In temperate regions, daylength begins to slowly decrease following the summer solstice. Plants have adapted to recognize this change in daylength and use this environmental cue to start their preparation to resist the stresses of winter. Horticultural lighting should be discontinued at the beginning of the hardening period to ensure that the shortening daylength is recognized by plants. This practice is very effective for plants from high elevations and northern environments, in which they are particularly attuned to daylength.

Temperature

Air temperature also has a large effect on dormancy induction in temperate regions. Exposure to gradually lower temperatures during autumn provides another important cue that winter is approaching and increasing cold hardiness is needed to resist freezing temperatures. For nursery plants in greenhouses, the temperature settings are lowered in stages. Attempting to induce hardening in an enclosed greenhouse is difficult, however, because the intense sunlight keeps temperatures warm and humidity levels high. It is more effective to expose crops to a moderate level of temperature shock to help facilitate the hardening process. Therefore, moving nursery plants from the greenhouse to ambient conditions in a shadehouse or open compound is a good strategy (figure 12.6). See Chapter 4, *Propagation Environments,* for a description of these structures.

Water Stress

A reduction in water availability to create a mild moisture stress also slows shoot growth and helps induce hardiness. For plants from mild climates, such as along ocean coastlines, moisture stress is more effective than other treatments. Typically, watering frequency should be gradually reduced but it is important that plants do not permanently wilt or come under severe water stress (figure 12.7). As you can imagine, inducing water stress is one of the trickiest parts of growing native plants and requires close observation and experience. The best way to quickly and accurately evaluate the water status of container plants is to weigh the growth container. With experience in monitoring container weights, a grower can gain a feel for when watering is necessary. See Chapter 10, *Water Quality and Irrigation,* for a discussion of irrigation monitoring with container weight.

After nursery plants reach their target size (usually expressed in terms of target height) at the end of the rapid growth phase, they need about 2 months to continue growing stem tissue and roots and then to harden enough to tolerate the stresses of harvesting, storage, shipping, and outplanting.

Mineral Nutrition

Reducing fertilizer also acts to slow growth and harden plants to help prepare them to withstand outplanting stresses. Among the mineral nutrients, nitrogen, particularly in the ammonium form, is the primary driver of shoot growth. During hardening, it can be helpful to reduce or stop nitrogen fertilization for several weeks to induce a mild nutrient stress. The use of controlled-release fertilizers with more than a 6- to 8-month release period can prevent hardiness from developing and potentially make plants susceptible to frost injury in autumn.

Some fertilizers have been specifically developed to aid in plant hardening, often containing a low nitrogen– high potassium formulation. Calcium nitrate is also a useful hardening fertilizer because it contains the nitrate form of nitrogen, which does not promote shoot growth. Calcium also helps develop strong cell walls and leaf waxes to protect plants during overwinter storage. Be sure not to use a similar product known as calcium ammonium nitrate because this fertilizer can stimulate shoot growth.

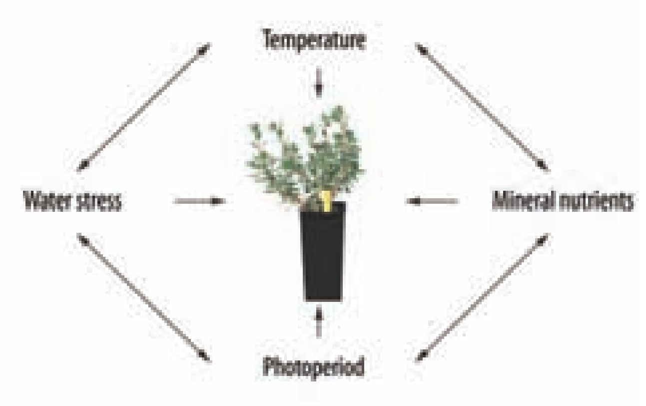

Figure 12.5—*Nurseries manipulate four environmental factors to stop shoot growth and induce hardiness.* Illustration by Jim Marin.

Figure 12.6—*Proper hardening requires that plants be exposed to the natural (ambient) environment, in which they receive environmental cues such as decreased daylength and temperatures. Moving plants from an enclosed greenhouse to a shadehouse or open compound is an effective method to begin hardening.* Photo by Thomas D. Landis.

Figure 12.7—*Reducing irrigation to induce a mild moisture stress helps induce dormancy and begin hardening but severe stress, such as in these quaking aspen plants, can be harmful.* Photo by Thomas D. Landis.

CONDITIONING PLANTS FOR OUTPLANTING

Other horticultural techniques can be used to properly condition nursery plants for outplanting. In determining how to properly condition plants for the intended outplanting site, it is important to consider several factors. First, we must understand the ecological characteristics of the species being grown. For instance, is this a light-demanding species or a shade-loving species? Next, we must be aware of the potential stresses on the outplanting site. Is this site an open field or a riparian zone or will the stock be outplanted underneath an existing canopy of trees? Will the site be prone to extended dry periods? Understanding the character of the site is best accomplished by interacting closely with the client ordering the plants.

These factors all reflect the main principles of Chapter 2, *The Target Plant Concept,* which suggests that the characteristics of nursery stock must be matched to those of the intended outplanting site. The goal of these treatments is to acclimatize plants to conditions on the outplanting site. Some of the major considerations regarding plant conditioning are shoot-to-root balance, shade, water stress conditioning, and root or shoot pruning.

Shoot-to-Root Balance

Shoot-to-shoot balance is the relative ratio of shoot biomass to root biomass, not shoot length to root length. It is one important way to describe plant size. Growing nursery plants to the appropriate size for a specific container is critical, and container volume and plant spacing are important. Plants in small containers and those grown close to one another grow tall and spindly and do not have enough stem strength to resist physical stresses after outplanting (figure 12.8A). These "topheavy" plants do not have enough roots to provide moisture to the foliage, so water stress can develop after outplanting. Roots in containers that are too small often begin to spiral and become compacted (figure 12.8B). In these "rootbound" plants, most roots become woody and less effective in water uptake and, after outplanting, do not grow out from the compacted root mass to promote structural stability.

The key to developing a plant with a sturdy shoot and well-balanced root system (a good shoot-to-root balance) is to select a container that is appropriate for the species and conditions on the outplanting site. Plants should be moved from the greenhouse as soon as they

Table 12.1—Examples of native plant species commonly grown under full sun versus shaded conditions, along with some species which often grow under either condition

Species	Common Name	Sun Requiring	Shade Requiring	Sun or Shade
Artemisia tridentata	Big sagebrush	■		
Carex aquatilis	Water sedge	■		
Juniperus virginiana	Eastern redcedar	■		
Pinus edulis	Pinyon	■		
Prunus virginiana	Chokecherry	■		
Dryopteris filis-mas	Male fern		■	
Chimaphila umbellata	Pipsissewa		■	
Gymnocarpium dryopteris	Oakfern		■	
Rubus pedatus	Strawberry leaf raspberry		■	
Abies bifolia	Subalpine fir			■
Ceanothus sanguineus	Redstem ceanothus			■
Rubus parviflorus	Thimbleberry			■
Streptopus amplexifolius	Twisted stalk			■
Pteridium aquilinum	Bracken fern			■

have reached their target height. Experienced growers know that moving plants from the greenhouse to a shadehouse or open compound is an easy and effective way to keep them in proper shoot-to-root balance.

Shade

The use of shading as a conditioning treatment depends on the shade tolerance of the species (table 12.1) and the conditions on the outplanting site. The amount of light a plant receives can be reduced by installing shadecloth or moving the crop to a shadehouse (figure 12.9). Shading is probably an overused treatment in nurseries, however, because most species (even those classified as shade tolerant) tend to grow best in full sunlight. In addition, many native plants tend to grow excessively in height ("stretch") under excessive shade, which may create a shoot-to-root imbalance. Nonetheless, if the species is shade loving and will be planted onto a site underneath an existing canopy, then shading may be a useful treatment. Plants that will be planted into full sun conditions should receive minimal or no shading at any point during nursery cultivation including during the hardening phase.

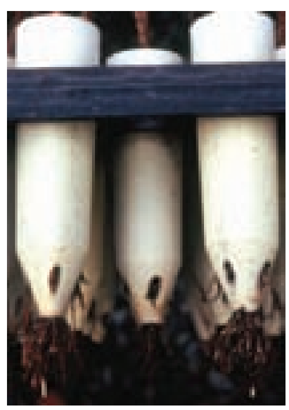

Figure 12.8—*(A) Maintaining a proper shoot-to-root balance can be difficult with fast growing species in small containers. (B) Often, these plants become "rootbound" when they are held too long*. Photos by Thomas D Landis.

Proper conditioning requires that we think like a plant!

Figure 12.9—*A shadehouse is sometimes used to help condition shade-loving plants or those for outplanting sites with shady conditions, such as underplantings in existing forests.* Photo by Thomas D. Landis.

Figure 12.10—*(A) Containers and benches must be designed to promote "air pruning" of roots at the drainage hole. (B) Plants in an open-growing area should be placed on benches designed to facilitate air pruning and prevent roots from growing into the ground.* Photos by Thomas D. Landis.

Irrigation

Reducing irrigation duration or frequency can help condition nursery stock to withstand droughty conditions on dry outplanting sites. How would this characteristic occur? Giving plants less water slows shoot growth, reducing the possibility of producing top-heavy plants, but nursery stock can also physiologically adjust to mild water stress. Less irrigation also encourages the formation of smaller leaves with thicker cuticles that transpire less after outplanting. Because moisture stress is the primary cause of transplant shock, it makes sense to precondition plants only before shipping them.

Root Culturing

Native plants that are grown in containers with root-controlling features encourage the formation of a healthy, fibrous root system that is not damaged during harvesting, is easily planted, and is able to rapidly proliferate after outplanting to access water and nutrients. Containers should always have vertical ribs to limit root spiraling and should be designed to promote good air pruning at the drainage hole (figure 12.10A). Other root culturing features such as sideslit air pruning and copper pruning are effective, especially with very vigorous rooted species. See Chapter 6, *Containers,* for more information on these features. Whether root culturing features are cost worthy for all species of native plants needs to be determined by nursery trials, as explained in Chapter 17, *Discovering Ways to Improve Crop Production and Plant Quality.*

After plants are moved to a shadehouse or an outdoor compound, it is important not to place the containers directly on the ground. Instead, plants should be placed on benches or pallets to facilitate air pruning of roots (figure 12.10B). Otherwise, roots may grow directly into the ground, which will require the added expense of root pruning during harvest. This severe pruning immediately before storage or outplanting makes the plants more vulnerable to pathogenic fungi and may delay quick root outgrowth after outplanting.

Shoot Pruning

Pruning shoots (“top pruning”) is sometimes required if the top is growing too large for the root system. Shoot pruning can maintain a proper shoot-to-root balance and reduce water stress resulting from an excessively high transpirational demand. In addition, the shock of pruning stimulates more stem and root growth and allows all plants to receive more irrigation and fertigation. One of the most important reasons to prune shoots is to make the height of the entire crop more uniform. When done properly, pruning occurs at the level just above the height of the smaller plants that have been overtopped (figure 12.11A). This practice releases smaller plants and the additional light helps them re-establish a growth rate that is consistent with the rest of the crop (figure 12.11B).

It is critical that shoot pruning treatments not be too severe; a rule of thumb is never to remove more than one-third of the total shoot. Plants to be pruned should also be in general good health and have enough stored energy to rapidly grow new tissue. It is best to prune succulent tissue because woody stem tissue tends to split and has less regenerative ability (figure 12.11C). Some native plants respond better than others, however, so a small trial is always recommended. Generally, grasses, forbs, and shrubs respond well to pruning and their shoots may be pruned several times during the growing season.

Other Conditioning Practices

The horticultural techniques described previously prepare plants to endure the stresses that occur during the processes of lifting, handling, transport, and outplanting. Experience is the best teacher—experiment on a few plants and discover which treatment or combination of practices work best in your circumstances.

One such treatment is known as “brushing.” This practice developed from the observation that plants that are repeatedly handled during crop monitoring tend to develop greater root-collar diameter. Growers tried to replicate this effect by moving a pole through the crowns of the plants in both directions (figure 12.12A). Of course, this practice must be done gently, especially

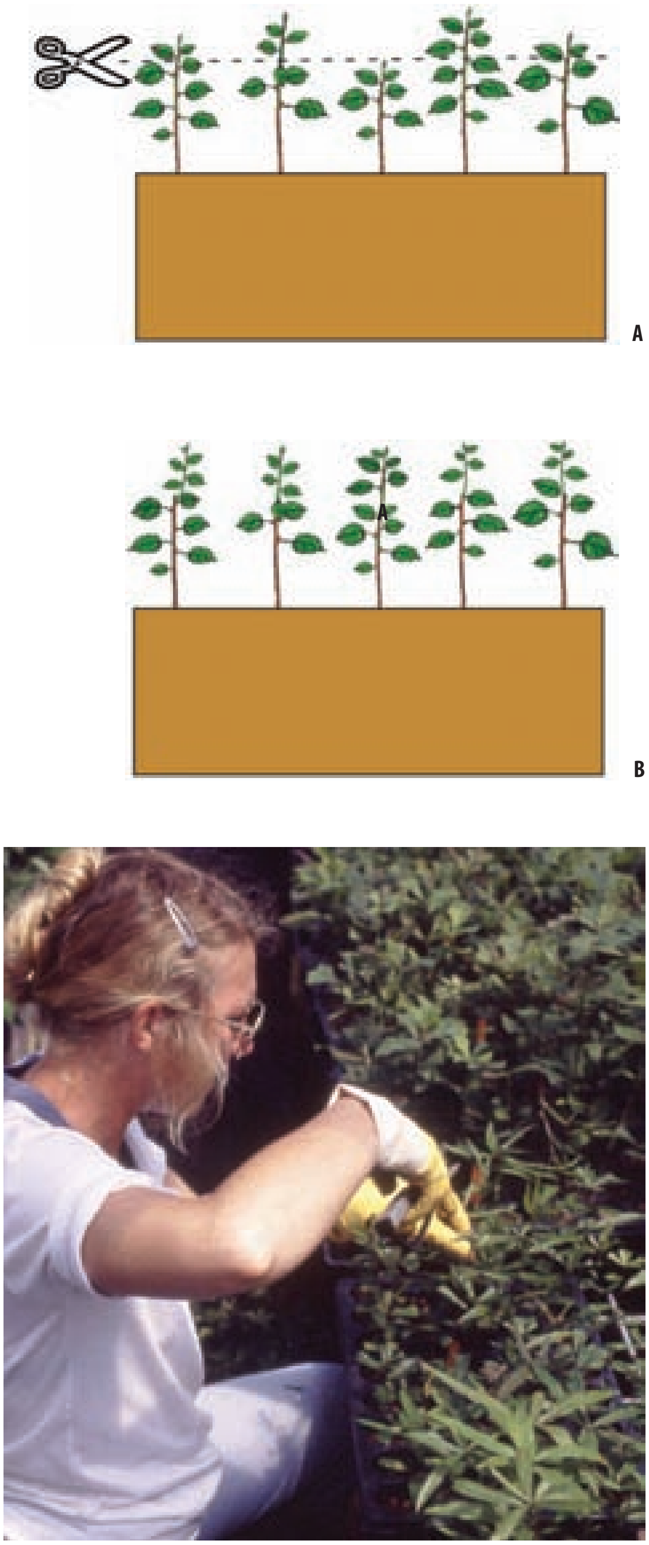

Figure 12.11—*(A) The objective of pruning shoots is to reduce height of taller plants and (B) “release” smaller ones. It is best to prune non-woody stem tissue so new buds and shoots can form. (C) It is best to prune shoots while they are still succulent.* Photo by Thomas D. Landis, illustration by Jim Marin.

Figure 12.12—*(A) "Brushing" plants promotes greater stem diameter and (B) increasing the distance between plants promotes air circulation and the development of a sturdier plant.* Photos by Thomas D. Landis.

when the foliage is still very succulent. Nurseries with traveling irrigation booms have mechanized the process by attaching a polyvinyl chloride pipe to the boom. A good time to brush plants is right after overhead irrigation because the rod also shakes excess water from the foliage and reduces the potential for foliar diseases such as *Botrytis* later in the season.

Increased distance between individual cells or containers allows more sunlight to reach lower leaves, improves air circulation, and promotes hardening. Increased spacing encourages the development of shorter plants with more root-collar diameter and also promotes thickening of the leaf cuticle. One real advantage of containers comprising individual, removable cells is that individual containers can be moved to every other slot to increase spacing within the trays during the hardening period (figure 12.12B).

SUMMARY

Remember two key aspects of hardening: (1) the goal of these treatments is to acclimatize plants to the harsher conditions of the outplanting site and (2) nursery managers must plan sufficient time in the crop schedule to allow for sufficient hardening. Plants can be hardened by adjusting the type and amount of nitrogen fertilizer, reducing irrigation frequency, moving plants from inside greenhouses to outdoor areas, increasing exposure to colder temperatures, and manipulating the intensity and duration of light. The hardening principle is connected directly to the target plant concept, which emphasizes the need for good communication between nursery managers and their clients. Because the "all-purpose" plant does not exist, hardening regimes will need to be developed for specific species and seed sources.

ADDITIONAL READINGS

Landis, T.D.; Tinus, R.W.; Barnett, J.P. 1999. The container tree nursery manual: volume 6, seedling propagation. Agriculture Handbook 674. Washington, DC: U.S. Department of Agriculture, Forest Service. 167 p.

APPENDIX 12.A. PLANTS MENTIONED IN THIS CHAPTER

big sagebrush, *Artemisia tridentata*
bracken fern, *Pteridium aquilinum*
Cascade mountain-ash, *Sorbus scopulina*
chokecherry, *Prunus virginiana*
eastern redcedar, *Juniperus virginiana*
male fern, *Dryopteris filix-mas*
oakfern, *Gymnocarpium dryopteris*
oaks, *Quercus* species
pinyon pine, *Pinus edulis*
pipsissewa, *Chimaphila umbellata*
quaking aspen, *Populus tremuloides*
redstem ceanothus, *Ceanothus sanguineus*
strawberry leaf raspberry, *Rubus pedatus*
subalpine fir, *Abies lasiocarpa*
thimbleberry, *Rubus parviflorus*
twisted stalk, *Streptopus amplexifolius*
water sedge, *Carex aquatilis*