Chapter 15

Nursery Cultural Practices: Impacts on Seedling Quality

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Abstract

Better understanding and implementation of nursery cultural practices to improve seedling quality will enable better matching of seedlings to forest sites, reducing the chance of regeneration delay and improving future growth of forest stands. This chapter reviews a number of important cultural practices and the ways in which they affect indicators of seedling quality (morphology and physiology) and, ultimately, field performance (growth and survival). Early spring sowing produces larger seedlings that can complete their growth and be hardened by midsummer. Lowering seedbed density results in more seedlings from a given amount of seed and can improve field survival and growth. A nursery irrigation schedule that imposes moderate stress on seedlings in midsummer Induces earlier budset and seedling dormancy and increases field-survival

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potential. Most often, field survival and growth are improved with growing-season fertilization in the nursery; fail fertilization also may increase field growth of Northwest species. Root wrenching In dry soil and (or) hot, dry weather without immediate Irrigation can greatly stress Douglas-fir seedlings and should be avoided because of increased chance of seedling mortality in nursery beds or reduced growth later in the field. Wrenching to mildly stress seedlings can induce budset and hardening and may benefit field growth and survival. Top pruning, to control shoot height and achieve crop-size uniformity, should be done during the period of active seedling growth in early summer to ensure proper development of terminal buds. Transplant seedlings have more fibrous root systems, larger stem diameters, and lower shoot:root ratios than seedlings of comparable age grown at a standard density; seedlings are most commonly transplanted in spring and are outplanted as 1+1 s or 2+1s. It is important for nursery managers to be aware of interactions among the various nursery practices they employ; if a current practice is altered or discontinued or a new practice added, careful attention should be given to the effect of this change on other cultural practices in the nursery.

15.1 Introduction

A seedling is considered of high quality if it meets the expectations or standards of performance on a particular planting site. The first and most obvious performance standard is survival—without adequate survival a site must be replanted or interplanted. The second performance standard is rapid seedling growth. Levels of survival and growth which are considered adequate must be defined for each individual site. Failure to meet these specified levels means an increase in the time until a particular forest stand reaches merchantable size and may be harvested. This regeneration delay, caused by either a replant of the site or slow initial growth, results in a loss of value and volume yield for that forest site [19]. Better understanding and implementation of cultural practices to improve seedling quality should enable better matching of seedlings to forest sites, reducing the chance of regeneration delay and improving future growth of forest stands.

My objective in this chapter is to review a number of important cultural practices and the ways in which they affect indicators of seedling quality (morphology and physiology) and field performance (growth and survival). Three practices—root culturing, top pruning, and transplanting—are presented in more detail because they are not substantially covered elsewhere in the Manual.

15.2 Seedling Quality Criteria

In attempts to set standards for seedling quality, three types of criteria have been used: (1) stock-type description, (2) morphological characteristics, and (3) physiological condition. The role that each plays in describing seedling quality is discussed in this section.

15.2.1 Stock-type description

Stock is described by seedling age and growing location. A 1+0 is grown for 1 year in a seedbed and 0 years in a transplant bed; a 2 +1 is grown for 2 years in a seedbed and 1 year in a transplant bed. Although studies to determine which stock type survives and grows best on a particular site have been common (see chapter 24, this volume), contradictory results from such comparisons suggest that variability in seedling morphology and physiology must play an important role. Foresters who formerly requested seedlings by stock-type description now realize that more information is needed to describe a seedling and predict its field performance. Some nurseries have already changed the seedling descriptions given to their customers to include average height, stem diameter, and shoot:root ratio in addition to the standard stock-type designation [97].

15.2.2 Morphological characteristics

Morphological characteristics are the physical or visually determinable attributes of a seedling. The major morphological criteria used to describe seedling quality—shoot height, stem diameter, root mass, and shoot:root ratio—are the basis for grading seedlings at the nursery; seedlings thought to have low survival and growth potential (culls) are eliminated. Some studies attempting to show how these morphological criteria are important to successful field performance are discussed in the next sections.

15.2.2.1 Shoot height

Seedling height at the time of outplanting can greatly influence growth rate in the field. Height increment of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] planted as 4-year-old seedlings was strongly correlated with height at the time of planting [75]; at 5 and 10 years of age, height increment of the tallest seedlings was more than twice that of the smallest.

Survival of Monterey pine (*Pinus radiata* D. Don) in Australia was the same regardless of seedling height at the time of field planting, but growth rate during the early years in the field was strongly influenced by initial stock size [72]. Where seedlings were segregated into a large and a small stand, the two stands showed equal growth after 10 years in the field; however, where seedling sizes were mixed, most of the initially small seedlings remained smaller than the larger stock after 8½ years and productivity per acre was correspondingly lower, according to the proportion of small seedlings planted in the stand.

15.2.2.2 Stem diameter

Generally, seedlings with larger root-collar diameters (which tend to be larger stock) have better outplanting success [80]. Anstey [5] found stem diameter alone to be a valuable measurement of 1 +0 Monterey pine seedling quality. Growth after three seasons in the field for seedlings 5 mm or more in diameter was twice that of seedlings with 2-mm diameter. On a harsh site, survival increased from 72% for seedlings with a 2-mm diameter to 89% for 4 mm, to 98% for 6 mm. Chavasse [23] found that root-collar diameter of Monterey pine and Douglas-fir was a -better indicator of seedling quality than shoot height.

15.2.2.3 Root system

Root mass (including dry weight and overall fibrosity) has recently been recognized as one of the most important factors critical to field performance. Survival of Douglas-fir seedlings with poor root systems was significantly lower than that of seedlings with good root systems regardless of shoot-height class [40]; Hermann concluded that a high shoot:root ratio does not necessarily mean low survival if seedlings have a well-developed root system and that root development is a reliable criterion for predicting seedling survival.

In a more recent study, 2+0 ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Douglas-fir seedlings of three different top heights were separated according to root size (large and small) and then planted in north-central Washington [56]. Survival was 22 to 26% greater for Douglas-fir seedlings with large roots and 5 to 15% greater for ponderosa pine seedlings with large roots. Height growth for trees of both species with large roots was 1.2 to 1.7 times that of those with small roots.

15.2.2.4 Morphological grades

In many studies, seedlings have been graded according to morphological characteristics, and then field performance of those ranked morphological grades has been tested. Wakeley [111] established three grades for southern pine nursery stock based on observable and measurable seedling characteristics. Each species had its own specifications for each of the three grades; grades 1 and 2 were considered plantable, and grade 3 was culled. Slash pine *(Pinus elliottii* Engelm.) seedlings from four nurseries and loblolly pine (*Pinus taeda* L.) seedlings from one nursery were separated into three grades similar to Wakeley's [111] and measured after 13 growing seasons in the field [17]. Rust infection and disease were no different among seedling grades. However, grades 1 and 2 generally survived and grew better in the field than grade 3 (Fig. 1), though some exceptions suggested that these grades are not always reliable for ranking subsequent survival and growth [17].

When white spruce *[Picea glauca* (Moench) Voss] seedlings were graded and then measured after 5 years in the field, shoot height, stem diameter, root volume, and shoot:root ratio were all highly significant predictors of subsequent growth, with larger seedlings performing best [69]. Growth and survival of white pine *(Pinus monticola* Dougl. ex D. Don) were predicted by shoot height, stem diameter, and root length [70].

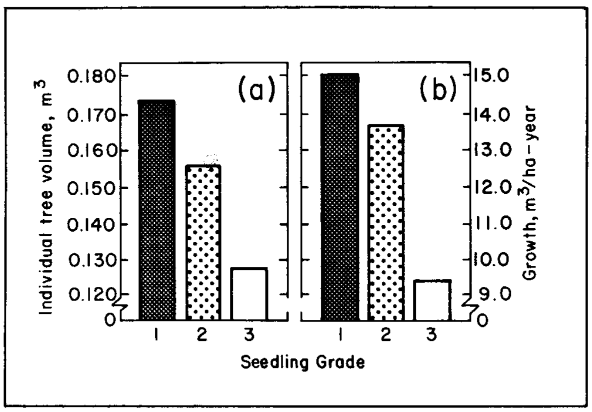

Figure 1. (a) Individual tree volume and (b) volume growth/ha for three seedling grades of slash pine after 13 growing seasons in the field (adapted from[17]).

15.2.3 Physiological condition

The variable results of using only stock-type description and (or) morphological characteristics to predict survival and growth have caused much dissatisfaction. Many authors point out that outplanting performance depends not only on seedling appearance, but on its preconditioning and resultant physiological state [23]. Others have mentioned a need for physiological grades for assessing seedling quality [46, 79, 82]. Chapter 23 (this volume) reviews various techniques for evaluating seedling quality.

Physiological condition of seedlings can influence field performance either independently or in conjunction with morphological characteristics. For example:

- 1+0 Monterey pine seedlings grown at lower density had better root-growth capacity after lifting than those grown at higher density. The seedlings with better root-growth capacity subsequently had better height growth and survival after 2 years in the field [10].
- Earlier dormancy induction due to moderate moisture stress resulted in greater cold hardiness of Douglas-fir seedlings and better growth-room survival [18].
- Root-growth capacity predicted white spruce survival independent of stock type and seedling size [62].
- Fall fertilization of Douglas-fir improved survival after 2 years in the field and growth for 5 years. Presumably, the seedlings that were fertilized had higher concentrations of nitrogen (N) than the unfertilized seedlings [4].
- Root wrenching of Monterey pine seedlings increased the proportion of total carbohydrates translocated to roots, compared to shoots. Roots then grew at the expense of shoots. When outplanted, wrenched seedlings had superior survival and growth, compared to unwrenched seedlings [77, 108].
- Root wrenching of Monterey pine and Douglas-fir many times during the growing season without adequate fertilization decreased seedling nutrient concentrations; seedlings in turn stagnated in the field [14, 77, 108].

How nursery practices influence seedling physiological condition-and, ultimately, field performance—is detailed for each cultural practice in the following sections.

15.3 Sowing

15.3.1 Seed quality

Seed quality is important for growing high-quality seedlings. Seed purity, weight, germination potential, and vigor must be accurately assessed so that the correct sowing rate can be calculated and an evenly spaced seedbed attained (see chapters 4 and 5, this volume). The need for stratification and the treatment time should be carefully determined for seed of different species and geographic origin because it can affect germination rate, vigor, and amount and, therefore, seedbed uniformity.

15.3.2 Sowing depth

Sowing depth can influence germination rate and amount and, thus, the final number of seedlings in the seedbed ([86]; also see chapter 5, this volume). Sowing depth of Douglas-fir seed at nurseries in the Northwest ranges from 1/16 to 1/2 inch (0.16 to 1.27 cm): most nurseries sow seed at 1/4 inch (0.64 cm) (OSU Nursery Survey; see chapter 1, this volume). The recommended sowing depth for optimum germination of Douglas-fir ranges from 1/8 to 1/4 inch (0.32 to 0.64 cm) [86, 103]. Sowing depth of other Northwest species varies from nursery to nursery: ponderosa pine-1/l6 to 1/2 inch (0.16 to 1.27 cm), noble fir *(Abies procera* Rehd.)—1/8 to 1/4 inch (0.32 to 0.64 cm), lodgepole pine *(Pinus contorta* var. *latifolia* Engelm.)-1/8 to 1/2 inch (0.32 to 1.27 cm), and spruce *(Picea* spp.)-3/16 to 1/4 inch (0.48 to 0.64 cm) (OSU Nursery Survey). Recommendations for ponderosa pine vary from 1/4 to 1/2 inch (0.64 to 1.27 cm) [86, 101, 103].

To ensure good growth and crop uniformity, it is important to choose a sowing depth proper for the tree species to be planted, to prepare a level seedbed, and to ensure consistent seed depth throughout the bed. A person continuously walking behind the seeder can check to make sure that proper depth control is maintained. Most nurseries sow on the shallow side, allowing an occasional seed to remain uncovered.

15.3.3 Sowing date

Seeds can be sown in fall or spring. Fall-sown seeds are planted dry, are naturally stratified in the seedbed over winter, and germinate earlier in the spring than spring-sown seed, producing larger 1+0s [86, 90, 103, 106]. In British Columbia, van den Driessche [102, 106] found shoot length and shoot and root dry weights to be larger for fall-sown than spring-sown Douglas-fir and, in another study, seedling dry weights of three of the four species tested to be greater for fall-sown than spring-sown stock (Fig. 2). However, fall sowing has some important disadvantages: (1) seed loss is often extensive during winter due to heavy rains, birds and rodents, or fungi, resulting in poor spacing and stocking of seedlings; (2) when seeds germinate too early in spring, young seedlings can be killed by frost unless protected; (3) natural stratification may be inadequate where nurseries are located in warm climates; and (4) irrigation may be needed to prevent drying of seed in an early spring drought. For these reasons, most sowing in the Northwest occurs in spring. A nursery manager who chooses to sow in fall is taking a great risk that yields will not be adequate.

Spring sowing, if done early enough, can produce 1+0 seedlings as large as those sown in fall. Sorensen [89] found final height of 1+0 Douglas-fir seedlings to be larger by 0.5 mm for each day of earlier sowing in spring; furthermore, these earlier sown seedlings set bud 1 month earlier than those sown later. The height difference was still evident in these seedlings as 2+0s and in the final crop (Fig. 3). In British Columbia, March-sown Douglas-fir seedlings were twice the height of June-sown seedlings and also had greater root length and root and shoot dry weight [102]. Early spring sowing at Webster Nursery (Olympia, Washington) resulted in larger roots and shoots in the fall of the 1+0 year [pers. commun., 3]; these early-sown seedlings were still larger when harvested as 2+0s. At a northern California nursery which had snow until May 16, early sowing (May 16) versus June 15 sowing of ponderosa pine, Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), Douglas-fir, white fir [*Abies concolor* (cord. & Glend.) Lindl. ex Hildebr], and incense-cedar (*Libocedrus decurrens* Torr.) resulted in (1) more rapid and complete germination, (2) more uniform density, (3) a larger number of seedlings, and (4) a greater number of superior 1+0s and, after transplanting, 1+1s and, again after transplanting, 1+1+1s [86].

Ten percent of the Northwest nurseries begin to sow in March, 50% in April, and 40% in May. Almost all nurseries are still sowing on May 15, and 40% are still sowing in June. Although poor weather conditions and wet soils limit access to seedbeds for sowing, there are often short periods of time—even a few days in spring-when nurseries can take advantage of dry weather to sow. If more than one seeder were available at a nursery, seeding could be completed during such favorable sowing "windows."

15.3.4 Conclusions

The importance of early sowing cannot be overemphasized. Early-sown 1+0 seedlings benefit from having the entire growing season and are large enough for hardening by July and August. The final 2+0 crop is larger the next year and again ready for hardening by midsummer. The result of early sowing means better crop control for the nursery manager, reducing the risk of growing seedlings that are too small and that must be "pushed" for additional growth in late summer. Earlier sowing often results in increased yield of high-quality seedlings.

15.4 Seedling Spacing and Seedbed Density

Seedbed density is the number of seedlings growing in an area of seedbed, expressed either on an area basis (seedlings per square meter or foot) or on a lineal basis (seedlings per lineal meter or foot). The spacing between seedlings can vary according to either the distance between drill rows or the distance between each seedling within a drill row. In the Northwest, 2+0 seedbeds have drill rows 6 inches (15.24 cm) apart (OSU Nursery Survey); spacing is usually varied within the drill row. For example, if seedlings are 1 inch (2.54 cm)

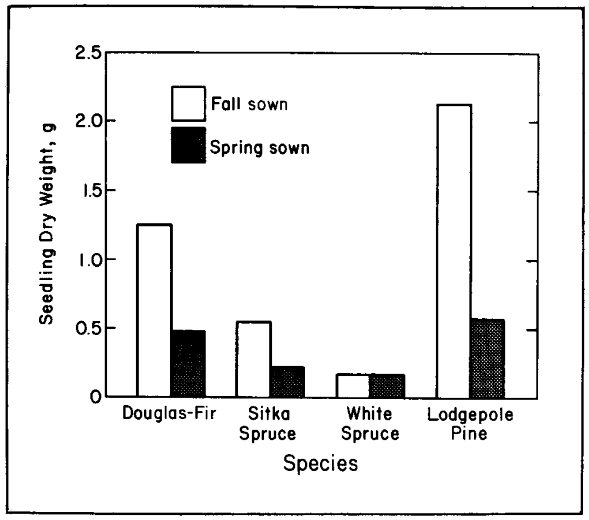

Figure 2. Dry weights of 1+0 seedlings grown from fall- and spring-sown seed for four species (adapted from [106]).

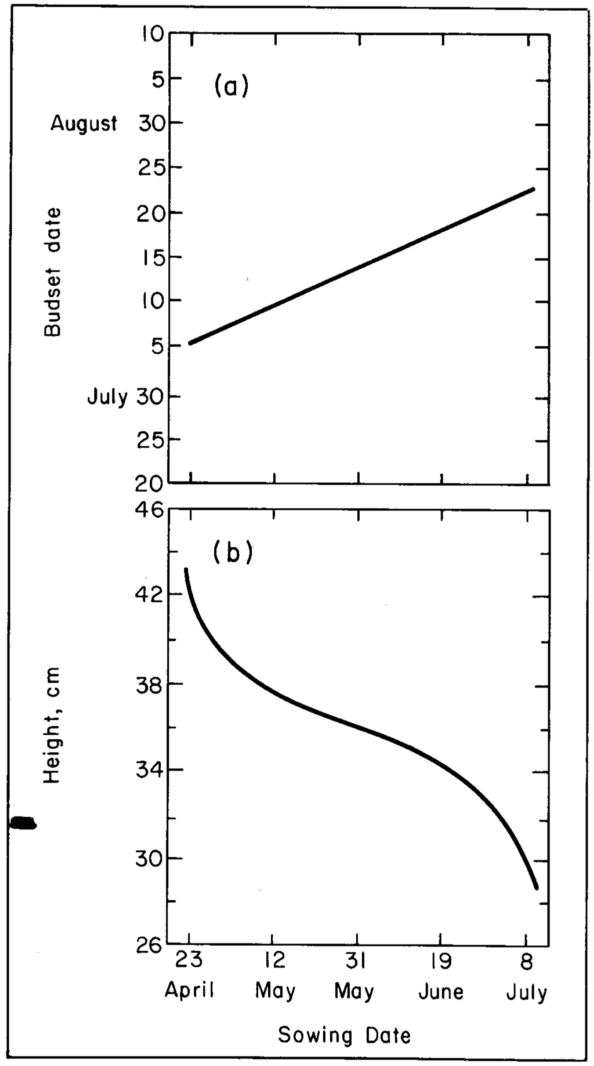

Figure 3. General effect of sowing date on (a) date of 2+0 seedling budset and (b) seedling height (adapted from [89]).

apart, a row would contain approximately 24 seedlings/ft^2 (258 seedlings/m^2); if they are 2 inches (5.08 cm) apart, a row would contain approximately 12 seedlings/ft^2 (129 seedlings/m^2). For a list of seedbed densities used in the Northwest, see chapter 5, this volume.

Uniform spacing between seedlings within a drill row is extremely important to seedbed density. Any local variation caused when seedlings clump in the seedbed results in lack of uniformity in growing conditions and therefore in greater variation in seedling quality. When specific seedbed densities are discussed in the following section, spacings are assumed even, permitting similar growing conditions for all seedlings within that density. However, lack of uniform spacing and inability to control the final growing density are some of the most important problems in Northwest nurseries. Almost all other nursery practices interact with seedbed density—thus density dictates how the crop will respond to practices such as fertilization, root wrenching, or irrigation.

15.4.1 Number of acceptable seedlings

Though lower seedbed densities increase yield percents and reduce the number of culls per lineal foot (meter) of seedbed [31, 84], determining the number of acceptable seedlings-those available for field planting—produced at these lower densities is the "bottom line."

Edgren [33] found that, when using diameter for culling, for a minimum acceptable stem diameter of 4 mm, 40 seedlings were acceptable and none were culls when grown at a seedbed density of 40 seedlings/lineal foot, whereas 48 were acceptable and 232 were culls when grown at a seedbed density of 280 seedlings/lineal foot (Table 1). Several studies have examined the quantity of seedlings produced within each of Wakeley's [111] morphological seedling grades (1, 2, and 3. where 3 = cull) at different seedbed densities [22, 84]. The proportion of large, morphologically high-grade seedlings was usually found to increase as seedbed density decreased [22]. Studies with Monterey pine have used the shoot height:stem diameter ratio as the basis for dividing seedlings into four grades to determine the number of seedlings produced at each seedbed density [10, 64].

These studies all attempt to identify the optimum seedbed density for producing the highest number of plantable seedlings. It should be emphasized, however, that this optimum may change with different nurseries, seed sources, cultural practices, and seedling-quality specifications.

15.4.2 Seedling morphology

in general, lowering seedbed density produces seedlings with larger stem diameters and heavier shoots and roots (dry weight). Seedling heights and shoot:root ratios are only sometimes affected by seedbed density.

Three+0 white spruce grown at 15 seedlings/ft^2 were larger and heavier and had a lower shoot:root ratio than those grown at 30 seedlings/ft^2 (Table 2) [67]. In another study, heights of 2+0 white spruce seedlings were greater when densities were reduced from 80 to 10 seedlings/ft^2 [7].

Lowering Douglas-fir 1+0 seedbed density increased seedling dry weight and stem diameter but did not affect shoot height [103]. More recently, van den Driessche [107] reported that lower seedbed density increased seedling dry weight, root-collar diameter, and, in this case, height of coastal (var. *menziesii)* and interior (var. *glauca)* Douglas-fir, Sitka spruce *[Picea sitchensis* (Bong.) Carr.], and lodgepole pine. Growing 1+0 and 2+0 ponderosa pine at lower densities at two California nurseries increased stem diameter and fresh weight [11]. At the Bend Nursery, stem diameter of 3+0 ponderosa pine grown at 10 seedlings/ft^2 was 7.1 mm, at 30/ft^2 5.2 mm, and at 70/ft^2 4.6 mm; however, height and shoot:root ratio were unaffected by seedbed density [31].

Monterey pine seedlings grown at lower densities were found to have larger root-collar diameters, shoot heights, and root and shoot dry weights [13]; in this study, spacing within the drill row affected seedling size more than distance between rows. Furthermore, variation in seedling size decreased as density decreased-an important point in this and other studies.

In summary, diameter is more affected by seedbed density than height [113], except possibly for white spruce. Decreasing seedbed density (increasing the growing space) for each seedling results in larger stem diameters, increased dry weights, and more uniform crop size for most species.

Table 2. Morphological characteristics of 3+0 white spruce grown at two seedbed densities and two nurseries (adapted from [67]).

Nursery	Seedbed density, seedlings/ft^2	Shoot height, cm	Root length, cm	Stem diameter, mm	Total oven-dry weight, g	Shoot: root ratio
Midhurst	15	26.9	60.9	6.5	14.4	3.08
	30	24.9	52.0	5.3	9.8	3.35
		* *	*	* * *	* * *	* *
Orono	15	28.9	46.8	6.4	13.5	3.43
	30	27.4	44.2	5.7	10.8	3.60
		NS	NS	* *	* *	NS

NS = not significant
* = significant at the 5% level
* * = significant at the 1 % level
* * * = significant at the 0.1 % level

15.4.3 Seedling physiology

Very few studies have investigated differences in physiological condition of seedlings grown at varying seedbed densities. One study in New Zealand measured root-growth capacity of 1+0 Monterey pine grown at various spacings (distances between seedlings within the drill row) [10]. Seedlings were transplanted to pots and grown for 14 and 28 days; both number and total length of white rootlets increased as seedbed density decreased (Table 3). These lower-density-grown seedlings with

Table 1. Number of acceptable and cull 2+0 Douglas-fir seedlings (based on stem diameter as the sole grading criterion) grown at Humboldt Nursery (adapted from [33]).

		Minimum acceptable diameter, mm									
Seedbed density		2		3		4		5		6	
Seedlings/ ft2	Seedlings/ lineal ft	Accept	Cull	Accept	Cull	Accept	Cull	Accept	Cull	Accept	Cull
10	40	40	0	40	0	40	0	36	4	22	18
20	80	80	0	80	0	72	8	44	36	14	66
30	120	120	0	116	4	78	42	28	92	6	114
40	160	160	0	152	8	90	70	22	138	8	152
70	280	280	0	204	76	48	232	11	269	0	280

Table 3. Effect of spacing on root-growth capacity of 1+0 Monterey pine seedlings (adapted from [10]).

Spacing, cm apart within drill row	Number of white rootlets		Total length of white rootlets, mm	
	14 days	28 days	14 days	28 days
2	5	6	24	88
4	10	7	57	141
7	11	9	73	166
10	11	15	76	329

better root-growth capacity also had better growth and survival after 2 years in the field.

We can also speculate that larger seedlings grown at lower seedbed densities have more stored food reserves, which will promote better growth in the field. In addition, their needle surface area is greater, affording them greater photosynthetic capacity when outplanted, which could increase height growth.

15.4.4 Growth and survival

Seedlings grown at lower seedbed densities have altered morphological and, perhaps, physiological characteristics. However, once seedlings are planted in the field, their survival varies regardless of the density at which they originally were grown. But, most often, field growth of seedlings grown at lower density is superior for a number of growing seasons after planting.

In the southern United States, 1+0 slash and loblolly pine grown at 20. 30, 40, 50, and 60 seedlings/ft^2 survived the same in the field in a year with above-average rainfall: but after 2 years, field growth of seedlings grown at lower densities was superior to that of those grown at higher densities [83]. Shoulders [84] found that, in moderately dry years, loblolly and slash pine survived best when grown at lower densities in the nursery but that when rainfall after outplanting was adequate, seedbed density did not affect field survival. When slash and loblolly pine seedlings were graded according to size, the morphologically high-grade seedlings (from all densities) survived and grew better than the low grades after 5 years in the field. The proportion of high- to low-grade seedlings increased as bed density decreased-that is, low seedbed densities produced a greater number of larger seedlings which performed better in the field [22].

Five years after field planting of 1+0 Monterey pine grown at different densities, survival was similarly high for all density classes, but tree height and diameter at breast height were significantly greater for trees grown at lower densities (Table 4) [13]: stem volume was 70% larger on plots planted with seedlings grown at low density than on plots with seedlings grown at high density. This is one of the many examples in which initial seedling height differences became more pronounced with each year after field planting: the slightly larger seedlings grown at lower densities grew faster in the field, over time

Table 4. Effect of density on tree height, diameter at breast height, and stem volume 5 years after planting with 1+0 Monterey pine seedlings (adapted from [13]).

Seedbed density, seedlings/m^2		Height, m	Diameter, cm	volume, m^3/ha
Low:	101	2.52[1]a	3.8a	4.77[2]
Medium:	231	2.34ab	3.3b	3.65
	205	2.44bc	3.4bc	3.45
High:	420	2.28c	3.1c	2.80

[1]Means followed by the same letter within a column are not significantly different at the 5% level.

[2]Not analyzed statistically.

increasing the difference between themselves and the trees grown at higher densities.

Field survival of 2+0 ponderosa pine seedlings from four seed zones was improved if seedlings were grown at lower densities [11]. Survival increased from 62 to 71 to 78 to 83% as growing densities decreased from 50 to 40 to 30 to 20 seedlings/ft^2, respectively. The shorter seedlings grown at higher bed densities remained smaller after the first field-growing season.

Three+0 white spruce seedlings grown at two densities (15 and 30 seedlings/ft2) had equal survival at four field sites [67]: however, tree height after 5 years in the field differed on many of these sites, with the trees grown at lower densities consistently taller (Table 5).

Table 5. Survival and height 5 years after field planting of 3+0 white spruce grown at two seedbed densities and outplanted on four sites (adapted from [67]).

Nursery	Seedbed density, seed-lings/ft^2	Height, cm					Mean sur-vival, %
		Site 1	Site 2	Site 3	Site 4	Mean	
Midhurst	15	69.6	69.0	67.2	67.6	68.4	88.2
	30	64.8	57.7	62.0	59.0	60.9	89.4
		NS	***	*	**		
Orono	15	75.7	67.4	67.7	63.0	68.4	89.3
	30	69.2	58.6	70.6	63.2	65.4	91.1
		*	*	NS	NS		

NS = not significant
* = significant at the 5% level
* * = significant at the 1 % level
* * * = significant at the 0.1 % level

Similarly, 2+0 Douglas-fir seedlings grown at lower densities were larger when outplanted and produced the best height growth during the first field-growing season under four different planting-site conditions [32] (Table 6). In this study, both stem diameter at time of lifting and field height growth were consistently higher as seedbed density decreased. In another study, coastal and interior Douglas-fir and Sitka spruce seedlings grown at wider spacings had 53 to 83% greater new shoot growth after one growing season and had better survival in the field after three growing seasons [107].

Table 6. First-year height growth of 2+0 Douglas-fir seedlings grown at five seedbed densities at the Wind River Nursery and outplanted on sites with different ground cover (adapted from [32]).

Seedbed density, seed-lings/ft^2	Height growth, cm				
	Ground-cover type				
	Vegetation	No vegetation	Debris	No debris	Mean
10	5.7	5.2	5.1	4.7	5.4
20	5.4	4.9	4.4	4.2	4.9
30	4.7	4.2	4.1	4.2	4.4
40	4.1	3.6	3.5	3.5	3.7
70	4.0	3.7	3.4	3.5	3.7

15.4.5 Conclusions

Some advantages of growing seedlings at lower seedbed densities are:

- Because the cull percent decreases with lower seedbed density, a larger number of seedlings may be obtained from a given amount of seed [11, 103]. As use of improved seed becomes more common, nursery managers will not want to waste it on culls.

- The higher cull percent at higher densities means a greater chance of directional selection, which could change the genotypic mix of seedlings produced (see chapter 17, this volume, for genetic implications).
- An increased number of culls means more time is spent grading. This increased time could result in increased stress on seedlings from more handling and exposure and definitely raises seedling production costs. Lowering seedbed densities and reducing the number of culls could perhaps eliminate the need for grading altogether [10].
- Lower seedbed density may shorten the time required to grow an acceptable seedling [31], i.e., a 2+0 seedling grown at low density may meet the same size specifications as a 2 + 1 seedling.
- On some field sites, survival might be improved by planting with seedlings grown at lower densities; on many sites, height growth certainly can be improved, increasing stand volumes and possibly reducing future rotation lengths.
- Size of planting stock may be more uniform. Stock size varies more for seedlings grown at high than at low densities-a difference that is still evident after several years in the field. If young stands are highly variable in size, tree competition, growth, and eventually canopy closure could be delayed or uneven [l 3].

However, all these benefits of growing seedlings at lower densities must in turn be weighed against the costs of using more land to produce the same number of seedlings.

15.5 Irrigation

Irrigation guidelines are established on the basis of [65]:

- Tree species
- Present crop size in relation to seedling specifications
- Stage of crop development
- Weather conditions
- Soil characteristics
- Scheduling of other cultural practices
- Seedbed density

Because these factors vary from nursery to nursery, the best irrigation regime for one nursery may not suit another. However, there are times common to all nurseries when having an irrigation regime ready is critical: (1) to water freshly sown or germinated seed, (2) to maintain proper temperature and moisture control for young seedlings, (3) to promote plant growth, (4) to protect seedlings against frost, (5) to augment other cultural practices such as fertilization, root culturing, lifting, and transplanting, (6) to control moisture stress and harden seedlings, and (7) to help seedlings enter dormancy.

Methods for monitoring plant, soil, and air to determine irrigation needs are discussed. in detail in McDonald and Running [60], Day [2 5], and Morby [65] and in chapters 11 and 12, this volume. This section focuses on one important use of irrigation-controlling moisture stress to promote onset of dormancy-and its possible effects on seedling quality.

15.5.1 Water in the forest environment

Conifers growing under natural conditions in the Northwest complete their height growth in late spring and early summer when adequate soil moisture is available from seasonal precipitation or snow melt. Trees then set bud and height growth ceases during the summer drought, which usually is a time of high evaporative demand, high air temperature, and low soil moisture. Resultant plant moisture stress (PMS) prevents second flushing, and trees enter the dormancy cycle (become hardened) (see chapter 14, this volume, for more information on dormancy). Trees typically have firm winter buds by late summer and will not resume growth or flush again even with early fall rains; in fact, these fall rains help deepen dormancy [115].

15.5.2 Water in the nursery environment

Irrigation in spring and early summer promotes growth of both new germinants and recently flushed second- and third-year seedlings. It is important to pay attention to unusually hot or dry periods in late spring, which could stress seedlings and hamper their growth. While seedlings are actively growing, frequent irrigation generally increases their height and dry weight [20, 39, 59]. However, it is crucial to closely monitor PMS throughout the growing season because too much or too little water can harm seedling quality and subsequent field performance.

15.5.2.1 Too much water

Unrestricted watering throughout the summer promotes growth. Seedlings will continue to grow, and if they do set bud, a second flush in the late summer or early fall is very likely. Although the increased plant size may seem favorable, delayed budset or second flushing is most often harmful to plant vigor because (I) the new, recently grown plant tissue is not hardy and is therefore susceptible to frost damage, and (2) delayed budset inhibits completion of the subsequent phases of dormancy, which may be necessary for seedlings to successfully tolerate nursery processing after lifting [65] and to ensure vigorous field growth the next spring [52, 115]. For example, at two hypothetical nurseries with different irrigation regimes (Fig. 4). seedlings grown with a restricted watering regime (R) completed their second-year height growth by mid- but those watered throughout the summer (U) continued to grow taller [52]. The potential field survival of seedlings grown with no imposed moisture stress (U) is low because they did not set bud until fall and were unable to adequately complete their dormancy cycle.

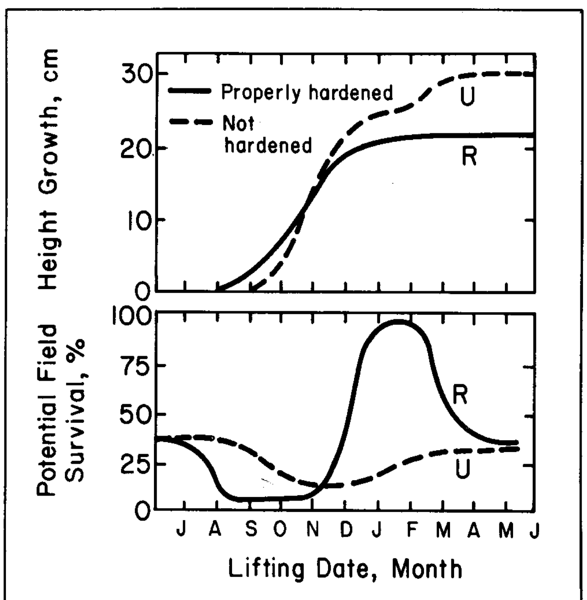

Figure 4. Cumulative nursery height growth and potential field survival of 2+0 Douglas-fir seedlings grown under restricted (R) and unrestricted (U) watering regimes throughout the summer (adapted from [52]).

15.5.2.2 Too little water

High moisture-stress regimes in the nursery can also negatively affect seedling morphology and physiology. Seedlings grown under a dry regime—watered beginning in spring only when predawn PMS reached 15 bars—set bud early but were too small to meet minimum size standards for plantable seedlings [115]. High PMS was found to inhibit budset of Douglas-fir grown under three different moisture-stress regimes [39]. In another study, although moderate stresses improved cold hardiness, higher stresses (10 to 15 bars) reduced cold hardiness of Douglas-fir seedlings [18]. Root growth as well as shoot growth may also be inhibited at these high stress levels [25]. High moisture stress results in smaller seedlings with decreased height and shoot and root dry weights, or low seedling vigor, or mortality [20, 39, 65, 115].

15.5.2.3 Moderate moisture stress

A nursery irrigation schedule that imposes moderate stress on seedlings in mid summer may result in:

- Earlier budset [39]
- Earlier induction of seedling dormancy [51, 115]
- Increased cold hardiness [18]
- Greater tolerance to exposure during lifting, storage, and handling [115]
- Smaller seedlings [81]
- No delay of budburst the following spring [52]
- Increased field-survival potential [18, 52, 115]

The date of moisture-stress induction also is important; seedlings undergoing earlier initiation of moisture stress were shorter and had higher root dry weights, resulting in lower shoot:root ratios (Table 7). In addition, cold hardiness of Douglas-fir seedlings decreased as initiation date of moisture stress was delayed [18].

In summary, most reports agree that moderate stress is favorable and that extremely low or high stress can be harmful to seedlings. The difficult point for nursery managers is defining what a moderate stress level should be.

Table 7. Effects of moisture-stress induction date on morphological characteristics of 2+0 Douglas-fir seedlings. Seedlings were subjected to moisture stress for 30 days, then well watered and lifted in mid-October (adapted from [18]).

Seedling characteristic	Moisture-stress induction date			
	July 15	Aug 1	Aug 15	Sept 1
Seedling height,[1] cm	21.15[2]a	23.20b	25.35c	25.15c
Root dry weight,[1] g	1.19a	0.94b	0.97b	0.81c
Seedling caliper, mm	4.02a	3.80a	4.07a	3.89a
Shoot:root ratio [1]	2.00a	2.60b	2.90c	3.12d

[1]Significantly affected by induction date at the 1 % level.
[2]Means followed by the same letter within a row do not differ significantly at the 5 % level.

15.5.3 Irrigation schedules in the Northwest

Many nurseries have developed irrigation schedules for inducing dormancy (e.g., [65, 115]). Of the 21 Northwest nurseries surveyed, 95% reduce watering in midsummer to harden seedlings (OSU Nursery Survey), though the date of initiation, the growth year (first growing season, second growing season, or both) in which stressing occurs, and the levels of stress employed vary widely. In the first year of producing a 2+0 crop., 1/3 of the nurseries do not reduce watering to stress seedlings; others water only to cool seedlings; some reduce water only if the crop has reached a particular size; and a few let seedlings reach predetermined stress levels (e.g., 10 bars predawn PMS after mid-August, 20 bars midday PMS by September 1, 15 bars predawn PMS by August 1). In the second year, most nurseries stop watering regularly in July to let seedlings reach predetermined PMS levels, then rewater when seedlings attain them; levels range from 8 to 15 bars predawn PMS, with most around 12. A few nurseries do not reduce irrigation until September. Not all nurseries use a PMS measurement to indicate when to water (see chapter 12, this volume, for other monitoring methods).

15.5.4 Irrigation regime and growth and survival

Most studies to determine irrigation levels for restricted watering have measured how restricted watering affects budset date (as an indication of onset of dormancy) and morphology—but not how it affects growth and survival in the field. In one study [18], groups of 2+0 seedlings which had received three different stress treatments in the nursery (0 to 4, 4 to 6, and 6 to 8 bars predawn PMS) were lifted and stored for 30 days, then potted and placed in a growth room for 6 weeks. Survival was 78, 85, and 94%, respectively. The authors concluded that imposing *moderate* moisture stress (4 to 8 bars) on seedlings enhanced onset of dormancy.

Others noted that seedlings that had second-flushed in the nursery and were therefore not conditioned properly for winter chilling had less vigorous root growth, delayed budburst, and reduced survival potential in the field [52]. However, no published data are available on the effects of different nursery irrigation regimes on *field* survival and height growth, and some negative effects are possible if these watering levels are too high or too low. Seedlings overstressed in the nursery may lay down fewer needle primordia (in buds that set at the end of the second growing season), which can result in less field growth [37, 74], or they may have decreased food reserves available for growth the next spring [541. Douglas-fir seedlings stressed by root wrenching in the nursery had impaired field growth up to 3 years after planting [29].

15.5.5 Conclusions

At this point we know that either a wet irrigation regime or a high stress regime may adversely affect seedling survival and growth, but we have not defined the optimum level of irrigation which will promote survival and growth. A general recommendation is to begin moderate stress (8 to 12 bars predawn PMS) as soon as the crop has reached its proper height and caliper. But because the optimum moderate stress level probably varies according to soil type, climatic conditions, seedling species, and so forth, exact levels will have to be defined for each nursery. Tailoring irrigation schedules and determining their effect on seedling quality at each nursery site are essential before proper prescriptions can be made.

15.6 Fertilization

One important goal of nurseries today is maintaining an adequate level of soil fertility to produce high-quality seedlings (see chapter 7, this volume). Long-term nursery productivity can only be assured by careful management of those factors affecting soil fertility-such as cation exchange capacity, pH, and organic matter content-and by proper fertilization (see chapters 6 through 10).

The signs of poor seedling nutrition are (1) a decrease in or cessation of growth and (2) under extreme conditions, visually recognizable deficiency symptoms. In contrast, seedlings with adequate nutrition grow to a specified size early in the summer, allowing ample time for hardening. Whereas it may be possible to improve seedling quality by altering the timing and level of fertilization in the nursery or by monitoring the nutritional status of seedlings during or after active growth, little is known yet about the optimum nutritional status or needs of outplanted seedlings, especially when comparing good and poor sites [16]. For example, should trees destined for a poor site be grown under nutrient-deficient conditions in the nursery, or should they be well supplied with nutrients when planted? Do trees grown under optimum nutrient conditions at the nursery grow best in the field? Is there danger in overfertilizing seedlings? Many of these questions remain unanswered, and some have different answers according to the species being grown, nursery soil, timing of application, or cultural practices used. Changing irrigation regime or seedbed density, for example, can also alter seedling response to fertilization [8]. This complex relationship among fertilization, site conditions, and other cultural practices,. makes fertilization decisions some of the most difficult in nursery management.

15.6.1 Seedling morphology

15.6.1.1 Growing-season fertilization

In general, fertilization—and especially N fertilization—during the first and second growing seasons produces 2+0 seedlings that are taller and heavier and have larger shoot diameters [4, 68, 88, 95]. Most often, seedlings have greater shoot:root ratios with fertilization [8, 68, 104] and may have greater root mass [4].

van den Driessche [104] found that shoot height, root and shoot dry weights, and shoot:root ratio increased in both 1+0 and 2+0 Douglas-fir seedlings in the nursery as more N was applied (Table 8). The rise in seedling dry weight also was correlated with increased foliar N levels, and maximum dry weights of both roots and shoots were obtained at 2.0 to 2.1 % N concentration. Often, as in this study, when fertilizing during the growing season, an application level exists above which adding more fertilizer will not further increase seedling size; for example, increasing second-year N rates above 100 kg/ha did not further increase shoot height or caliper (Table 8) [104]. If the optimum level could be determined for each nursery site and species, unnecessary applications of costly fertilizers could be eliminated. In the same study, adding phosphorus (P) in the form of superphosphate fertilizer did not increase seedling P concentration or affect shoot height or weight, although available P in the nursery soil was raised by the addition.

The overall result of increasing seedling size with N fertilization has been to increase the number of plantable seedlings produced from a nursery bed [8, 95].

Table 8. Effects of fertilization at various rates of N on morphology of first- and second-year Douglas-fir seedlings (adapted from [104]).

Morphological measurement, by seedling age	~ ~ ~ ~ ~ ~ N rates, kg/ha ~ ~ ~ ~ ~ ~				
	First year				
	0	25	50	75	100
Shoot height, cm	4.5[1]a	5.8b	6.4b	6.2b	6.3b
Shoot dry weight, g	0.l 1a	0.16b	0.l8c	0.18c	0.18c
Root dry weight, g	0.08a	0.11 b	0.12 b	0.12 b	0.12b
Shoot:root ratio (dry wt.)	1.30a	1.39ab	1.47bc	1.49bc	1.54c
	Second year				
	0	50	100	150	200
Shoot height, cm	8.8a	13.9b	16.5c	16.1c	16.8c
Shoot dry weight, g	0.35a	0.99b	1.42c	1.34c	1.45c
Root dry weight, g	0.3la	0.87b	1.01b	0.91b	0.92b
Shoot:root ratio (dry wt.)	1.14a	1.14a	1.39b	1.45bc	1.54c

[1]Means followed by the same letter within a row are not significantly different at the 5% level.

15.6.1.2 Fertilization and hardening

Seedling growth patterns can be altered by withholding—as well as adding—nutrients (see chapter 7). Armson [6] found that fertilized trees grow longer during the growing season than unfertilized trees. Most nurseries in the Northwest stop fertilizing in July or early August in both the first and second growing seasons because they believe that this arrested fertilization, along with restricted watering, helps seedlings harden properly (OSU Nursery Survey).

15.6.1.3 Fall fertilization

Fertilizing seedlings in fall after growth ceases has been shown to have no effect on seedling height and stem diameter at the time of harvesting the following winter [16, 98]. However, bud height, a possible indicator of next year's growth, varied significantly with fall application of N and P [98]: P decreased bud height, whereas N in the absence of P increased it.

15.6.2 Seedling physiology

15.6.2.1 Frost hardiness

The most commonly known effect of fertilization on seedling quality is the reduction of frost hardiness when N is applied during the growing season. N fertilization can prolong seedling growth in the nursery, delaying hardening or the onset of dormancy and later resulting in frost damage in the nursery or damage to inadequately hardened stock during lifting or cold storage [105]; it can also cause earlier budbreak the following spring, resulting in possible frost damage [16]. High levels of P applied to Sitka spruce seedlings extended their active growth period and caused frost damage [58].

Potassium (K) nutrition also may play an important role in the development of frost hardiness [105], although findings have been mixed. Adequate K levels in Douglas-fir slightly increased-frost hardiness in winter [48, 49], though K levels in Sitka spruce had no influence on frost damage at two heavily damaged field sites [16]. Timmis' [99] work with Douglas-fir container seedlings showed frost hardiness to be more closely related to the K:N balance than to the level of any single nutrient; a lower K:N ratio (0.6) resulted in hardier seedlings.

Low boron (B) levels have been reported to increase frost damage to tree species (see chapter 7).

Late-season or fall fertilization, which does not usually affect seedling growth and diameter (see 15.6.1.3), has been found to affect frost hardiness. K and N applied as a top dressing decreased December frost damage of Sitka spruce and western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] seedlings [15]. By contrast, in another more recent report [16], N application increased frost damage of Sitka spruce on one of two severely damaged field sites. However, on these same sites, four other species—Norway spruce [*Picea abies* (L.) Karst], western hemlock, grand fir [*Abies grandis* (Dougl. ex D. Don) Lindl.], and lodgepole pine—sustained less severe frost damage, with no increase in injury due to late-season N application. Fall application of K also did not affect frost damage. Applying N in late fall increased frost hardiness of Douglas-fir seedlings, whereas fertilizing with P had no effect [98].

15.6.2.2 Drought resistance

Optimal N levels in seedlings generally can improve their ability to endure and grow during drought in the field. However, N levels that are too low or too high for optimum growth can cause damage during drought and inhibit recovery and growth afterward [73].

Two+0 jack pine (*Pinus banksiana* Lamb.) tested under a drought regime typical of field conditions was significantly more drought resistant when fertilized with intermediate levels of N [91]. Loblolly pine seedlings, when grown at varying N levels in sand culture, were most drought resistant when provided an optimum supply for growth [73]. Longleaf pine (*Pinus palustris* Mill.) had improved drought resistance when grown under a balanced supply of N, P, and K [2].

15.6.3 Growth and survival

15.6.3.1 Growing-season fertilization

Though little is known about the effects of nursery fertilization on seedling performance in the field, where studies have been done, positive effects of fertilization on either height growth or survival have often been reported. van den Driessche's [104] previously mentioned study, in which N fertilization increased Douglas-fir seedling size in the nursery (see 15.6.1.1), also revealed substantially improved Douglas-fir seedling performance in the field. Two years after outplanting, all seedlings fertilized with N in the nursery survived significantly better than unfertilized controls (Fig. 5). The percentage of N in the 2+0 foliage was positively correlated with increased N fertilization levels of 0, 75, 150, 225, and 300 kg/ha. Interestingly, survival dropped off when the percentage of N was greater than 2; often, overfertilization with N results in taller seedlings with high shoot:root ratios which may have poorer survival, especially on dry sites. In van den Driessche's [104] study, surviving seedlings from all treatments had similar growth rates in the field; thus, the fertilized seedlings were still significantly taller at the end of 2 years.

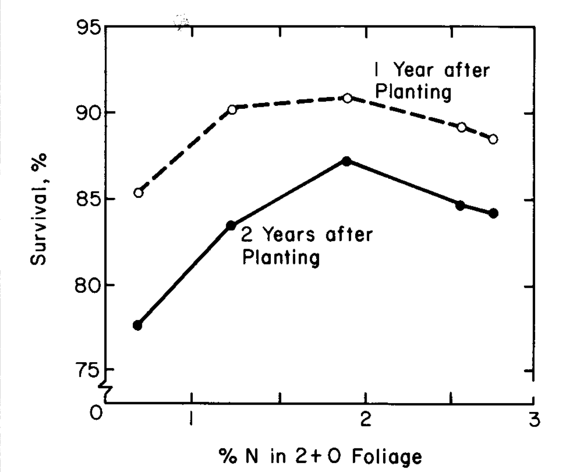

Figure 5. Survival of 2+0 Douglas-fir seedlings 1 and 2 years after outplanting at different foliar N concentrations (adapted from [104]).

In a more recent study, nursery fertilization at 235 kg N/ha increased new shoot growth in the first field season by 51 % for coastal Douglas-fir, 36% for interior Douglas-fir, and 58% for Sitka spruce, compared to that at 60 kg N/ha. After three growing seasons in the field, the effect of N on new shoot growth diminished, ranging from 0 to 42% [107]; high N level increased survival of coastal Douglas-fir and Sitka spruce slightly but decreased that of interior Douglas-fir. In another study with Douglas-fir, inorganic fertilizers applied at the nursery increased seedling size, then increased field survival from 70 to 95% and field height after 4 years from 74 to 94 cm [88]; the authors noted in 1966 that improved use of nursery fertilization could increase field growth by 26%.

A series of experiments in the Lake States involving seedlings from four nurseries showed a slight but consistent gain in field survival of jack, red (*Pinus resinosa* Ait.), and white (*Pinus strobus* L.) pine when fertilized with N, P, and K, but no differences in growth were found after 5 to 8 years in the field [91]. In another study, jack, red, and Scotch (*Pinus sylvestris* L.) pine survived the same in the field but had 20 to 30% greater field height growth after fertilization in the nursery [112].

Nursery fertilization improved field height growth of white spruce but did not affect survival [67]; red and white pine also were unaffected [68]. Height of loblolly pine after 3 years in the field was positively correlated with foliar N content increased by nursery fertilization (Fig. 6) [95].

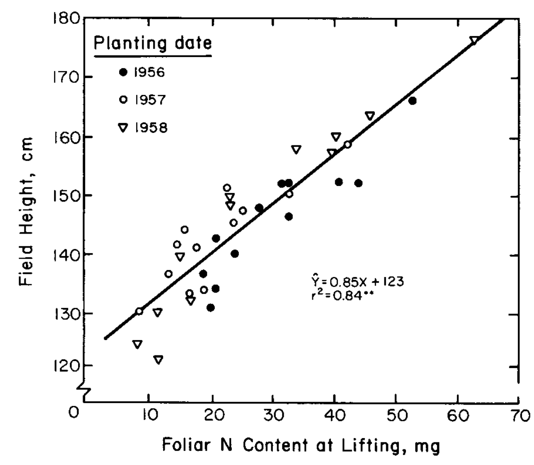

Figure 6. Regression line indicating the relationship between field height at 3 years and foliar N content at lifting of loblolly pine (adapted from [95]).

15.6.3.2 Fall fertilization

The few studies investigating fall fertilization have shown varied effects on field performance. Loblolly and slash pine outplanted after receiving up to 400 lb N/acre in late October survived the same as unfertilized seedlings [38]. Fall fertilization increased N concentration in five tree species [16]; N advanced budbreak of all species except grand fir during the first summer in the field and had no negative effect on survival. Although seedling size in the nursery was unaffected by this fall fertilization, height growth after field planting of Sitka spruce was improved up to 18%, with similar improvement in diameter. In another study, seedlings from five Douglas-fir seed sources, fall fertilized in the nursery with 50 lb N/acre, had improved field survival after 2 years (Fig. 7a) and grew 0.03 to 0.05 m (0.1 1 to 0.16 ft) taller than unfertilized trees in each of the 5 years after outplanting (Fig. 7b) [4].

15.6.4 Conclusions

The status of nursery soil and crop nutrition should be constantly examined and modified as necessary (for more detail on soil and foliar analysis, see chapter 8, this volume). Recommended fertilizer applications for a 2+0 seedling crop range from 112 to 285 kg of N, 67 to 200 kg of P, and 75 to 150 kg of K per ha (see chapter 7) but should be calibrated for each crop species and nursery site. However, increased fertilization during the growing season generally results in taller and heavier seedlings with larger diameters. Because seedlings grow longer in the growing season when fertilized, most nurseries stop fertilizing in July or early August to harden seedlings. Fall fertilization, usually around October, does not affect seedling height or diameter but can affect terminal bud size and frost hardiness (either positively or negatively). Nurseries fertilizing in fall should apply 30 to 50 kg of N/ha.

Most studies show improved field growth and survival as a result of growing-season fertilization; in addition, fall fertilization may increase field growth of Northwest species. However, effects of seedling nutritional status on field performance require further investigation.

15.7 Root Culturing

Root culturing is the broad term for describing the various nursery practices implemented in the seedbed to alter seedling root growth. Two practices, undercutting and wrenching, involve the mechanical cutting of the root system with a blade drawn horizontally under the seedbed. Two other practices, lateral pruning and box pruning, involve the cutting of the root system with vertical blades. Due to lack of information about undercutting, lateral pruning, and box pruning, most of this section will emphasize results obtained from root-wrenching studies.

15.7.1 Undercutting and wrenching

Undercutting is the drawing of a thin, sharp blade under the seedbed parallel to the surface. The blade severs the taproot and all other roots extending beyond the regulated depth of the undercut. Ninety-five percent of the nurseries in the Northwest undercut, mainly to stimulate root growth in the upper zone of soil so that seedlings gain a more fibrous root system (OSU Nursery Survey).

Nurseries undercut their 2+0 seedlings in fall (of the first growing season), or spring (of the second growing season), or sometimes summer (of the second growing season). Most undercut only once, although some undercut once in spring and then again in early summer. The depth for undercutting ranges from 4 to 12 inches (10 to 30 cm), with most at 5 to 6 inches (13 to 15 cm) (OSU Nursery Survey).

Wrenching, which usually follows undercutting, is done with a thicker, broader blade tilted at an angle (20 to 30°) when drawn under the seedbed. Wrenching cuts off any newly penetrating roots and lifts seedlings, loosening and aerating the soil. Eighty percent of nurseries in the Northwest root-wrench their seedlings to (1) stimulate root growth and enhance fibrous root development, (2) stress and harden seedlings in summer, (3) control shoot height, and (4) aerate and loosen the soil (OSU Nursery Survey). A few nurseries wrench in fall to prevent late flushing and promote root growth.

Wrenching at Northwest nurseries is done in the 2+0 year, usually after undercutting, with the angled blade drawn at a depth of 8 to 10 inches (20 to 25 cm). About 1/3 of the surveyed nurseries wrench only once, usually in June or July; the rest wrench from 2 to 10 times during the summer of the second growing season, usually beginning in June or July and ending in August or September (OSU Nursery Survey). Seedlings may be wrenched once a month, once every 2 or 3 weeks, or even once a week. Multiple wrenching varies considerably in its timing and frequency; the pattern of this variation seems unrelated to species or nursery location. Some nurseries also wrench their transplants (1+1s and 2+1s) approximately 6 weeks after spring transplanting, again a second time for hardening, and perhaps a third time in fall.

One of the most critical factors affecting wrenching is soil moisture. If seedlings are wrenched when the soil is dry and (or) the weather is hot and dry, high plant-moisture stress (PMS) can result. However, seedlings wrenched when the soil is moist or watered immediately after wrenching experience only moderate to low PMS.

Seedlings are undercut and wrenched with a fixed or reciprocating blade attached to a tractor (Fig. 8; see also chapter 3, this volume). Most nurseries in the Northwest use a fixed blade. A specialized root-culturing implement that both undercuts and wrenches with a reciprocating blade reportedly cuts roots without pulling or dragging tree seedlings [57, 110]; its drawbacks have been related to its slow speed, blade breakage, and inability to control the depth of the cut.

15.7.2 Lateral and box pruning

Lateral pruning, also called side pruning or side cutting, is the passing of cutting blades or colters between the drill rows on both sides of the seedlings to sever excessively long lateral

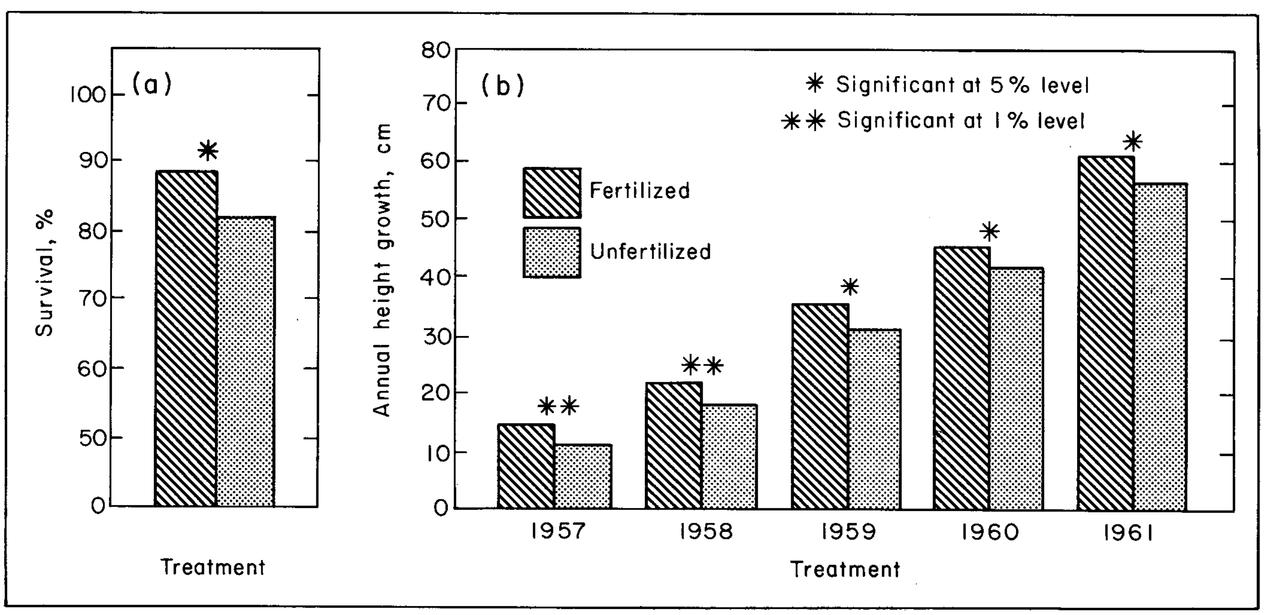

Figure 7. (a) Second-year field survival and (b) 5-year height growth of fall-fertilized and unfertilized Douglas-fir seedlings from five seed sources (adapted from [4]).

Figure 8. Root wrenching 2+0 Douglas-fir seedlings with a fixed blade tilted at a 20 to 30° angle.

roots (Fig. 9). Ninety-five percent of Northwest nurseries lateral-prune their 2+0 seedlings to (1) decrease root tangling among seedlings and facilitate lifting, (2) encourage root growth and fibrosity, and (3) retard shoot height growth (OSU Nursery Survey). Most nurseries (75%) lateral-prune only once, but the others prune 2 or 3 times during the second year. When lateral pruning once, 40% of the nurseries prune in April to May, 40% in June to July, and 20% in September to October. Nurseries that prune more than once usually do so in late spring and then again in late summer or fall. The depth of lateral pruning varies from 4 to 10 inches (10 to 25 cm), with no single depth most common.

Box pruning, a new practice in New Zealand, is the vertical cutting of lateral roots in a four-sided box shape around a seedling. Seedlings to be box-pruned must be in drill rows and must be equally spaced within each row [21]. This alternative root-culturing technique is being investigated because of the concern over root distortion to Monterey pine caused by undercutting, wrenching, and lateral pruning. Although their effects are not yet quantified, undercutting and wrenching may cause poor taproot development after planting [108]. Seedlings need a well-balanced root system: laterals must be evenly distributed and the taproot sturdy if seedlings are to remain stable and not topple in the field [21].

Lateral root pruning is done with tractor-mounted stationary blades or rolling colters drawn between each drill row. The same machine is used to box-prune between drill rows, but the beds are crosscut by hand with a spade [21].

15.7.3 Seedling morphology

15.7.3.1 Shoots

Any of these root-culturing practices, which cuts roots before or during the growing season, arrests or retards seedling height growth. Wrenched Monterey pine seedlings stopped or continued growing at a very slow rate for 3 months after cutting (Fig. 10) [77]. In New Zealand, Monterey pine do not set bud during their first year in the nursery; root wrenching therefore is used to stop growth and to condition or harden nursery stock [108].

Northwest nurseries also wrench to limit shoot growth and harden seedlings. Earlier budset-and shorter seedlings—result in most cases (Fig. 11) [29, 45]. Other studies have shown that root wrenching can control height of southern pines [85, 96] and reduces height of white pine and white spruce [66]. Though very little information is available on how undercutting and lateral root pruning affect shoot morphology, Tanaka et al. [96] note that in their studies undercutting in spring reduced height growth and, therefore, final seedling height. Lateral root pruning at different times from May to September did not reduce height growth of western hemlock, Sitka spruce, or Douglas-fir seedlings in the nursery [34, 35].

Both the timing and frequency of root wrenching can greatly affect final shoot height of seedlings. Generally, shoot height decreases with increased severity or frequency of wrenching [14, 29, 110]. Duryea and Lavender [29] found that single-wrenched trees had slightly reduced shoot height, compared to unwrenched controls, and that multiple-wrenched trees were even shorter (Fig. 12). Benson and Shepherd [14] reported that multiple-wrenched Monterey pine seedlings were 1/2 the height of unwrenched controls and that the number of culls increased due to wrenching.

Another factor that is important in influencing final seedling height is the timing of the root wrenching. If roots are cut too early in the growing season and height growth is arrested, seedlings may not reach plantable size [110]. Rook [77] found

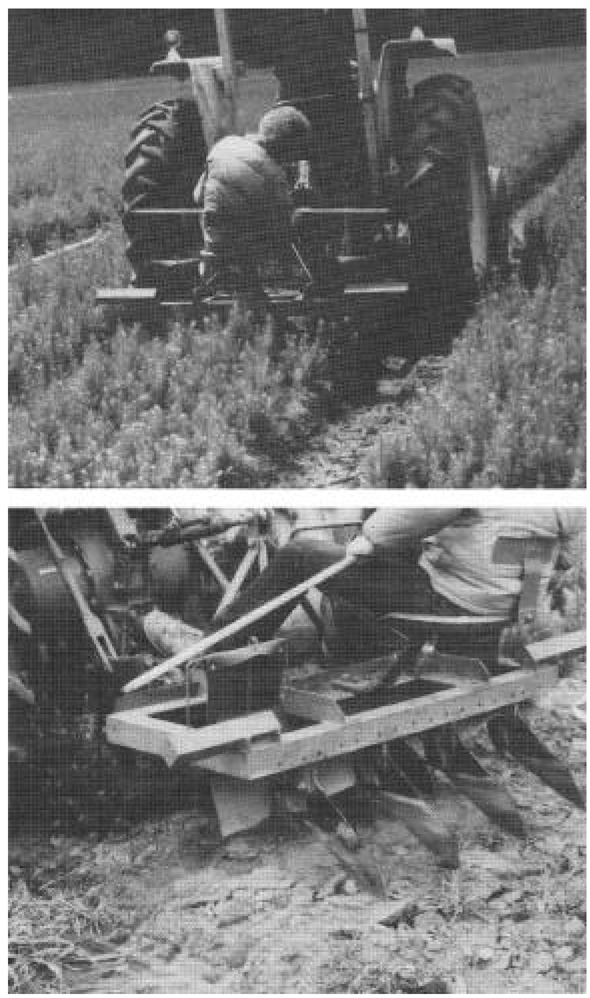

Figure 9. Lateral root pruning between the drill rows to sever excessively long lateral roots.

that seedlings should be near their desired height and diameter before wrenching because any further growth will mainly be root growth. On the other hand, wrenching late in the growing season may have little effect on height growth in Northwest species because most of their growth is completed by then [96]: this late wrenching may, however, stop lammas growth [1].

The shorter shoot may have an accompanying decrease in diameter caused by wrenching early in the growing season [29, 45], although in another study wrenching caused no decrease in diameter of Douglas-fir [96]. Diameter growth of Monterey pine continued for 1 month and then stopped, resulting in smaller shoot diameters for wrenched seedlings (Fig. 10) [77].

Due to their smaller shoot heights and diameters, wrenched seedlings most often have lighter shoot dry weights [14, 29, 45].

15.7.3.2 Roots

Monterey pine has a carrotlike taproot. When this taproot is severed by undercutting and wrenching, root growth rates on an oven-dry basis are similar for wrenched and unwrenched seedlings, but the final root system is quite different in form. Cutting the taproot causes a loss in apical dominance in the entire root system: lateral root growth increases and many new tertiary roots grow, resulting in a more compact, fibrous root system [14, 77, 108, 110].

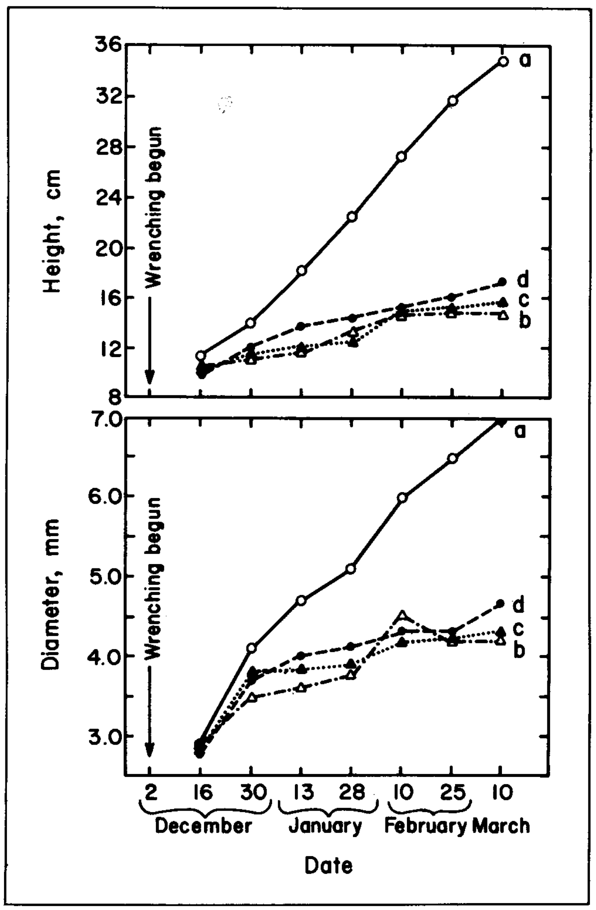

Figure 10. Height and diameter growth of Monterey pine seedlings that were (a) neither undercut nor wrenched; (b) undercut, then wrenched weekly; (c) undercut, then wrenched every 2 weeks; and (d) undercut, then wrenched monthly. Treatment differences were significant at the 1% level (adapted from [77]).

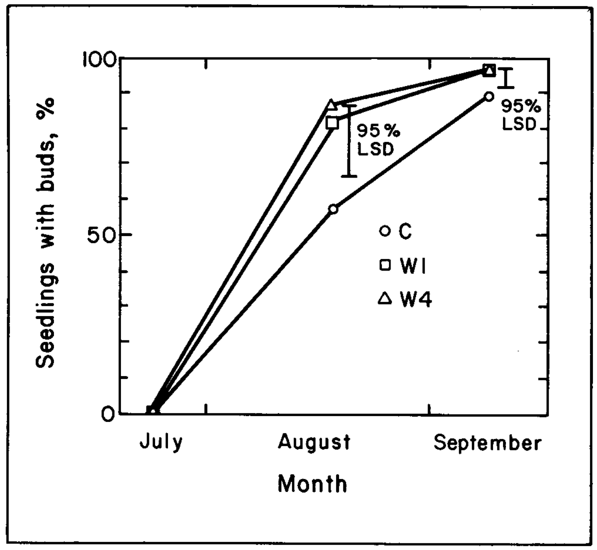

Figure 11. Budset in Douglas-fir nursery beds of unwrenched controls (C), single-wrenched seedlings (W1), and multiple-wrenched seedlings (W4) in the Northwest [unpubl. data, 28].

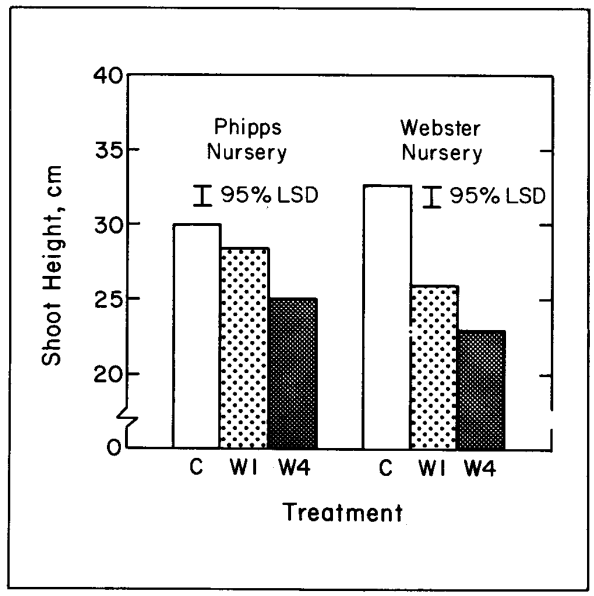

Figure 12. Shoot height at lifting of unwrenched controls (C) and single-wrenched (W1) and multiple-wrenched (W4) Douglas-fir seed lings at two nurseries (adapted from [29]).

Slower growing evergreen species such as firs, spruces, Douglas-fir, and hemlocks tend to have a more fibrous root system than Monterey pine [29, 108]. Results from root cutting of these species have been much more variable. In root-wrenching experiments with different seed sources of Douglas-fir grown at two nurseries in Oregon and Washington, wrenching did not change the total length or dry weight of lateral roots, the total number of root tips, or the total dry weight of the root system [29]. Another study in California also showed that the weights of Douglas-fir root systems did not change with wrenching [45]. Yet these results contradict those of an earlier study [96] in which root dry weights of wrenched seedlings were greater than those of unwrenched seedlings: though root tips were not counted, the authors reported that previous studies (unpublished data) showed repeated wrenchings in late summer to stimulate root growth.

Lateral root pruning has reportedly increased fibrosity in Douglas-fir, Sitka spruce, and western hemlock [34-36], the differences in fibrosity being largely due to the timing of the lateral pruning. Pruning early in the second growing season did not affect lateral root development unless blades were drawn within 6 cm of seedlings. However, Davis and Long [36] found that lateral pruning of Douglas-fir after early August caused formation of callus tissues around wounds where roots had been cut. When these seedlings were lifted in October, new roots had not regenerated nor had secondary roots grown but by the next spring, an abundance of new roots had originated from the callus. This study and Tanaka et al.'s [96] may show that root wrenching or lateral pruning in late summer or early fall can promote root growth.

Recently, there has been some concern about the effect of root form on early tree growth and windthrow in the field [21, 55]. Differences in nursery culturing can impact seedling root systems up to 7 years after field planting [55]. Wrenched and unwrenched seedlings from Tanaka et al.'s [96] study were excavated after 5 years in the field: root-system constriction (Table 9) and L-rooting were significantly greater in the wrenched trees [55]. Long [55] noted that the increase in L-shaped bending may have resulted from the difficulty in planting the larger, more fibrous root system resulting from wrenching.

In New Zealand, there has also been concern over malformities in wrenched root systems—specifically, the absence of a taproot to securely anchor the Monterey pine root system in the field [21]. Studies have shown that box pruning can produce an unbranched taproot with evenly distributed laterals. Root excavations after field planting have shown that box pruning results in less root distortion and better root form than wrenching [21].

Toppling and taproot malformation of lodgepole pine also have been observed in plantations in British Columbia. Lodgepole pine may not regenerate a taproot when undercut deeply, which makes it more prone to toppling after outplanting [30].

15.7.3.3 Shoot:root ratio

Root-culturing practices most often result in reduced shoot:root ratios of seedlings. The lower shoot:root ratio of wrenched Monterey pine is usually due to its lighter shoot [14, 108]. Duryea and Lavender [29] and Koon and O'Dell [45] found that wrenching of Douglas-fir did not change the root dry weight but did reduce the shoot:root ratio due to the lighter shoot. Tanaka et al. [96] found a decrease in the shoot:root ratio of Douglas-fir, attributable to a heavier root system.

15.7.4 Seedling physiology

15.7.4.1 Carbohydrate distribution

Undercutting and wrenching of Monterey pine caused an increase in the proportion of total carbohydrates (^{14}C-photosynthate) translocated to seedling root systems [77]. After roots were cut, carbohydrates were diverted from the foliage to form new root tissue; thus, roots were grown at the expense of shoots [108]. Once again, timing of the wrenching is important: a smaller proportion of current photosynthate went to roots of Monterey pine undercut and wrenched after late summer than earlier in the summer, when height growth was more vigorous [77].

15.7.4.2 Hardening

In New Zealand, Monterey pine seedlings do not normally form a bud and become dormant during their first year [110]. When seedlings are wrenched, growth is arrested, buds are formed, and shoots become more lignified [14]. Field survival of hardened, more dormant, wrenched stock has been shown superior to that of unwrenched stock that is actively growing [110].

Although, in the nursery, wrenched Douglas-fir seedlings set bud earlier than unwrenched seedlings, dormancy of wrenched and unwrenched seedlings has not been measured. However, wrenched and unwrenched Douglas-fir seedlings lifted and stored in fall (November 1) survived and grew equally under moist and dry planting conditions as did those lifted in winter (January), perhaps indicating that wrenching does not affect stage of dormancy [29].

15.7.4.3 Nutrition

Wrenching reduces the foliar concentrations of N, P, and sometimes K. Concentration of N and P in Monterey pine shoot tissue decreased as wrenching severity increased (Table 10) [14]; however, fertilizing seedlings that had been root-wrenched 5 times increased their N and P levels. Menzies [63] also found wrenched Douglas-fir seedlings to have lower foliar concentrations of N, P, and K. Accompanying these lower concentrations can be a yellowing of the needles due to a significant reduction in chlorophylls a and b and in carotenoids [77]. Fertilizer should therefore be applied when wrenching because such nutrient-deficient seedlings have been known to stagnate when outplanted [108].

15.7.4.4 Drought resistance

Wrenching stresses seedlings while in the seedbed, causing them to close their stomata [29]. When planted in the field, however, wrenched Monterey pine have been found to have higher rates of transpiration than unwrenched seedlings, though wrenched and unwrenched Douglas-fir did not differ [29, 76]. During drought, wrenched Monterey pine seedlings maintained higher relative turgidities and more active root growth than unwrenched seedlings [76, 108]. Under an imposed drought in pots simulating drought in the field, wrenching did not affect Douglas-fir seedlings' ability to withstand drought, even though this ability varied among seed sources: however, wrenched seedlings did not set bud as promptly during drought and had fewer active roots than unwrenched seedlings [29]. This lessened ability to regenerate roots and to set bud during drought could lower field survival and growth potential for wrenched Douglas-fir seedlings.

Table 9. Root and shoot characteristics of wrenched and unwrenched 2+0 Douglas-fir 5 years after outplanting (adapted from [55]).

Seedling type	Root			Diameter, mm	Height, cm	Current height growth, cm	Dry weight, g		Shoot:root ratio
	Constriction	Symmetry	Balance				Root	Shoot	
Wrenched	1.28	2.84	1.74	36.9	176.7	48.8	121.3	794.7	0.20
Unwrenched	0.94	2.89	1.62	30.0	159.3	44.0	76.6	510.0	0.16
	*	NS	NS	*	*	*	*	*	NS

NS = not significant
* = significant at the 5% level

Table 10. Foliar nutrient concentrations of wrenched and unwrenched Monterey pine seedlings at harvest (adapted from [14]).

Treatment	N. %	P ~ ~ ~ ~ ~ ppm	K ~ ~ ~ ~ ~
Unwrenched control	1.92[1]a	1,750a	10.290a
Root-wrenched twice	1.39b	1,320b	8,240a
Root-wrenched 5 times	1.21c	890c	7.540a
Root-wrenched 5 times; fertilizer added twice	1.31bc	1,120bc	7,270a

[1]Means followed by the same letter within a column are not significantly different at the 5% level.

15.7.4.5 Growth regulators

The roots of wrenched Monterey pine had lower levels of inhibitory abscisic acid (ABA) and higher levels of root-growth-promoting indole-3 acetic acid (IAA) than unwrenched controls [94].

15.7.5 Growth and survival

15.7.5.1 Monterey pine

Rook [76] demonstrated that wrenched seedlings survive planting, especially into dry field conditions in New Zealand, better than unwrenched seedlings. van Dorsser and Rook [110] later concluded that Monterey pine must be undercut and wrenched if consistently high survival rates are to be obtained from planting bareroot seedlings.

Wrenched Monterey pine also grow better in the field. In one study, height increment of unwrenched and wrenched seedlings after the first two field seasons was 41.5 and 63.25 cm [109]. Unwrenched seedlings may suffer from severe leader damage (due to their nonlignified shoot) after planting in the field, which retards their growth [14]. In Australia, seedlings wrenched twice during summer had increased stem volume after 5 years, compared to unwrenched controls and to seedlings wrenched 5 times [14]. Box-pruning Monterey pine seedlings to decrease root distortion resulted in superior field growth compared to that for undercut and wrenched stock [21].

15.7.5.2 Other pines

Undercutting increased field survival of longleaf pine, but survival of loblolly and slash pine has varied [85]. In one study, first-year survival of wrenched loblolly pine improved from 70 to 93%, the increase greater at droughty than moist sites [96]; however, height did not differ after one growing season in the field.

In Australia, most planting of Caribbean pine (*Pinus caribaea* Mor.) has been with container seedlings, due to the poor survival of bareroot stock [9]; however, wrenching has been found to increase field survival of bareroot seedlings to an acceptable level [9, 14].

A single wrenching of white pine either did not affect survival or, if done during the growing season of the 3+0 year, decreased it [66]; wrenching during the growing season also decreased white pine growth for 5 years in the field. Tanaka et al. [96] noted that at several locations in southern Oregon, field survival of ponderosa pine was not improved when wrenched biweekly. Preliminary results of another study also indicate no differences in survival for undercut ponderosa pine seedlings and controls planted on a south-facing slope in southern Oregon [unpubl. data, 41].

15.7.5.3 White spruce

When 3+0 white spruce were single-wrenched at four different times in the growing regime, one wrenching during June's flush of growth improved field survival and growth, but fall wrenching in the 2+0 year decreased survival [66].

15.7.5.4 Douglas-fir

In studies at two nurseries with five different seed sources, Duryea and Lavender [29] found that wrenching did not improve survival of Douglas-fir seedlings under either favorable (moist) or unfavorable (dry) planting conditions. Tanaka et al. [96] reported that wrenched Douglas-fir seedlings from a Cascade Mountains source, when planted on a droughty south-facing slope, survived better than unwrenched seedlings (88 vs. 65%), though on the nearby north slope, survival did not differ (58 vs. 57%). Similarly, Koon and O'Dell [45] reported that wrenching Douglas-fir seedlings at 20-cm depth improved their survival from 31 to 56% on a droughty site in California, but wrenching at 15 cm did not. Preliminary results of a recent study indicate that undercutting Douglas-fir seedlings at different times in spring and during the growing season did not improve survival on a south-facing slope in southern Oregon [unpubl. data, 41].

Duryea and Lavender [29] found no case in which root wrenching improved field growth of Douglas-fir seedlings, and in one year's planting of trees from four seed sources, first-year growth was consistently greater for unwrenched than for wrenched seedlings under a number of planting-site conditions. After 3 years in the field, height difference between wrenched and unwrenched seedlings increased (Fig. 13a), indicating that wrenching continued to negatively affect growth in the field. Here it should be pointed out, however, that this wrenching was a multiple one (4 times at 2-week intervals) stressing the seedlings during the growing season. In another study, wrenched trees were superior to unwrenched trees in height [96] (Fig. 13 b) and diameter [55] (Table 9) after 5 years in the field; but this wrenching was done later in the growing season to seedlings which had not been stressed but were well watered throughout the summer. It may be that wrenching overstressed the seedlings in Duryea and Lavenders [29] study, whereas those of Tanaka et al.'s [96] were in need of the moderate stress imposed by wrenching to aid hardening.

15.7.6 Conclusions

All species mentioned above, excluding Monterey pine, have an extremely mixed response to root-culturing practices. This response can probably be attributed to variation in: (1) wrenching regime-timing, frequency, and depth; (2) other nursery cultural practices-irrigation, seedbed density, and fertilization; (3) initial size of seedlings to be wrenched; (4) nursery soil and climate; and (5) seed-zone differences. Therefore, calibrating root culturing to the specific nursery site and conditions is extremely important.

However, some general results and recommendations are the following:

- Root wrenching during the growing season results in earlier budset and smaller seedlings.
- Wrenching too soon-that is, before the crop has met its size parameters-may result in a final crop that is too small and therefore has a lower yield.
- Wrenching in dry soil and (or) hot, dry weather without immediate irrigation can greatly stress Douglas-fir seedlings and should be avoided because there may be seedling mortality in the beds or reduced growth later in the field.
- Wrenching to mildly stress seedlings can help induce budset and hardening and may aid field growth and survival.
- Late-summer or fall root wrenching may promote seedling root fibrosity and should be further investigated.

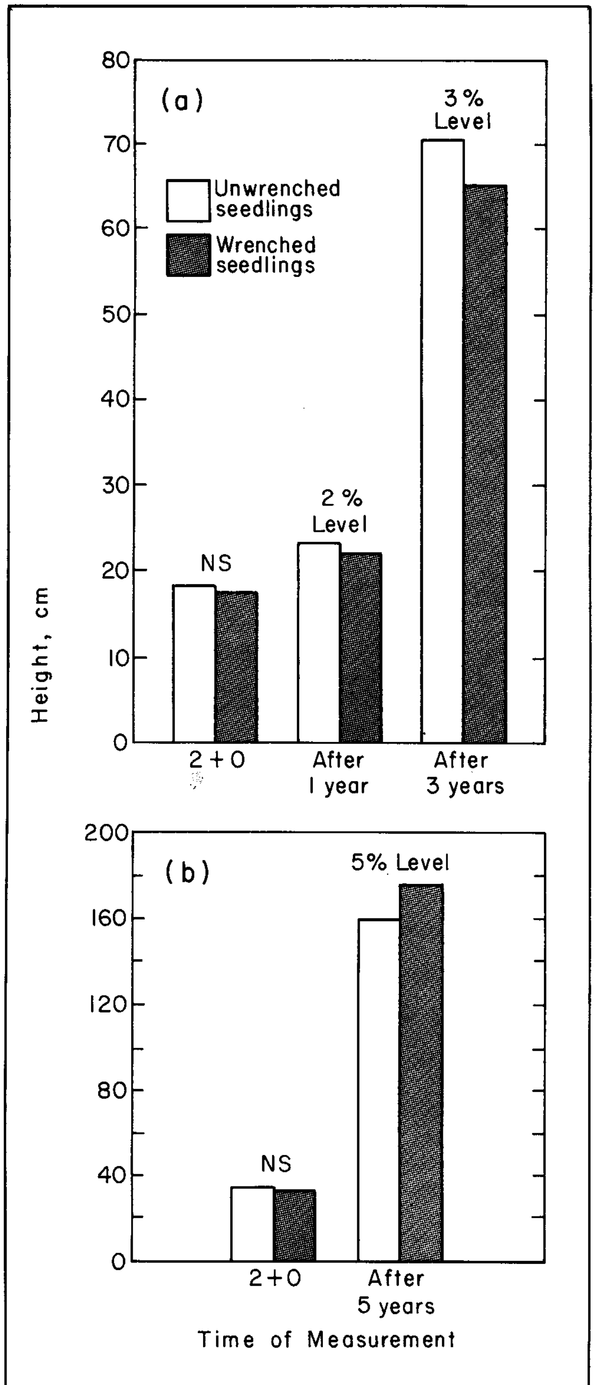

Figure 13. Two contrasting studies showing height of wrenched and unwrenched 2+0 Douglas-fir seedlings at planting and (a) 1 and 3 years (adapted from [29]) and (b) 5 years (adapted from [55, 96]) after planting in the field. In (a), heights were pooled because wrenching affected all seed sources equally. Significance levels are given above paired bars; NS = not significant.

15.8 Top Pruning

Top pruning, also called top mowing or clipping, is the passing of a cutting blade over the seedbed to sever seedling terminal leaders (Fig. 14). Although this nursery practice is common for altering the shoot:root ratio of hardwood species, it has rarely been used for conifers in temperate regions until recently [53].

Today, 92% of the U.S. Douglas-fir nurseries top-prune, though none of the Canadian nurseries surveyed or the U.S. nurseries producing predominantly pine seedlings do so (OSU Nursery Survey). Douglas-fir is the major Northwest species being top-pruned. Most top pruning occurs on 2+0 seedlings to be outplanted or to be transplanted and grown as 2+1s; 3+0 seedlings are pruned in the second year and sometimes again in the third. One nursery top-prunes fall-transplanted plug+1 seedlings, and two nurseries are testing top pruning of 1-year-old seedlings. Occasionally, bareroot transplants (1+1s and 2+1s) also are pruned after transplanting and during the growing season (OSU Nursery Survey).

The main reasons for top pruning in the Northwest are: (1) to control shoot height, (2) to facilitate nursery transplanting of seedlings (1+1s and 2+1s), (3) to achieve crop-size uniformity, and (4) to decrease the shoot:root ratio, especially of seedlings to be planted on harsh sites (OSU Nursery Survey). Nurseries that top-prune mainly for crop-size uniformity do so as many as 3 times in a growing season; usually, 10 to 20% of the tallest seedlings are cut to the desired crop size. Other nurseries prune once or twice during the season. Cutting height ranges from 9 to 16 inches (23 to 41 cm) for 2+0s and 6 to 14 inches (15 to 36 cm) for 3+0s (pruned in their second year); 2+0s for 2+1s are usually cut shorter, 6 to 12 inches (15 to 30 cm).

Figure 14. Top pruning 2+0 Douglas-fir seedlings with a rotary mower.

15.8.1 Timing

Seedlings in the Northwest should be pruned during the flush of growth in early summer. Such timing ensures the proper development of wound calluses and terminal buds. Pruning wounds made during the early-summer flush heal better than those made at other times of the year [42]. Furthermore, stems pruned in late summer after budset may flush again, producing new, succulent, unhardened shoots that are susceptible to winter injury [42]. Even though hardwoods not pruned in the nursery may not be adversely affected when cut at the time of field planting, Douglas-fir seedlings pruned after lifting may suffer [78]. Survival of seedlings pruned to 15 to 20 inches (38 to 51 cm) after lifting was 0%, whereas that of unpruned trees ranged from 41 to 78%, according to rootsystem size [40]. The most appropriate time to top-prune will differ at each individual nursery location and should be determined by time of budbreak, crop growth rate, and crop-size specifications.

15.8.2 Disease

Because open wounds, in general, are potential sites for disease infection, it is advisable to take certain precautions when top pruning. Clean tools and equipment decrease the chances of carrying spores throughout the nursery. Actively growing seedlings that are top-pruned, adequately watered, and adequately fertilized close wounds promptly, reducing the chance of infection. In a Mississippi nursery, 3,000,000 longleaf pine seedlings became infected with brown-spot needle blight, caused by *Scirrhia acicola* (Yearn) Siggers, after top pruning [44]. Spores from infected seedlings were transported throughout the nursery on the cutting blades: in addition, infected seedling tops left in seedbeds and paths contaminated water, which caused other parts of the nursery to become diseased. Infection and tissue mortality on each seedling occurred near the location where needles had been pruned.

Although top pruning has not been connected with any disease infection in the Northwest, it is important to be aware of this possibility. The most likely problem with disease could be increased risk of gray mold [*Botrytis cinerea* (Fries) Persoon] due to dead, pruned plant material lying in the beds, which creates a favorable microclimate and site for gray mold sporulation. To avoid development of this disease, pruned plant material should be raked and removed from nursery beds immediately after pruning.

15.8.3 Seedling morphology and physiology

Most top pruning work has been done with loblolly pine in the southern U.S. Because the longer growing season there can result in tall, spindly loblolly pine seedlings, top pruning was first investigated as a way to control this kind of top growth and produce a better-balanced seedling with higher survival potential [26]. Because little is known about the effect of top pruning on Northwest species, most of the information reported here is from southern pruning studies.

As in the Northwest, seedlings in the South are pruned to an average crop height. Clipping arrests height growth for 3 weeks, several fascicle buds develop just below the cut, and height growth then resumes. In the meantime, seedlings not pruned because they are shorter than the pruning height selected are said to be "released": they continue to grow during the 3 weeks when the top growth of the other larger, pruned seedlings is suspended. Diameter growth of the pruned seedlings also is reduced [26, 27]. The overall result is a crop that varies less in both height and diameter.

In the field, top-pruned seedlings may conserve moisture better because their transpiring surface area has been reduced in relation to their root area [42]. This altered shoot:root ratio may aid in reducing transplant shock and in promoting successful plant establishment [42]. Top pruning does not seem to affect the morphology of loblolly pine root systems; seedlings with the same size root collar have similar root systems [26]. Due to the smaller shoot, however, top pruning produces seedlings with decreased shoot:root ratios.

15.8.4 Growth and survival

Top pruning most often improves survival of loblolly pine. Dieurauf [26] found that top pruning of taller seedlings significantly improved field survival (Table 11) but did not influence field height growth of surviving seedlings. Furthermore, forking of top-pruned loblolly pine is not a problem. When seedlings are planted in the field, many leaders are present: but one leader soon dominates, and after two or three seasons, no forks originate from the point of pruning [26, 61].

Table 11. Third-year field survival of top-pruned loblolly pine seedlings planted at two field sites (adapted from [26]).

Treatment	Date	Field survival, % Pocahontas State Forest	Field survival, % Cumberland State Forest
Taller seedlings			
Control		51.7[1]a	43.3a
Pruning height, in.			
6	8/12	78.3ab	95.0b
6 and 7	8/12 and 9/9	78.3ab	91.7b
7	9/9	93.3b	93.3b
Shorter seedlings			
Control		91.7b	96.7b
Pruning height, in.			
4.5	8/12	98.3b	93.3b
4.5 and 5.5	8/12 and 9/9	88.3ab	96.7b
5.5	9/9	96.7b	96.7b

[1]Means followed by the same letter within a column are not significantly different at the l % level.

For longleaf pine, a difficult species to regenerate, needle clipping (cutting needles to a length of 13 cm just before planting) increased field survival of seedlings from four separate nurseries. This increase was attributed to reduced moisture loss from a decreased needle-surface area [71].

Four hardwood species, top-pruned immediately before planting, differed in their field survival on a droughty site: severe top pruning did not lower survival of sycamore (*Platanus occidentalis* L.) and ash (*Fraxinus* spp.), decreased survival of water oak (*Quercus nigra* L.) only slightly, but substantially lowered survival of cherrybark oak (*Quercus falcata* var. *pagodifolia* Ell.) [114]. Northern red oak (*Quercus rubra* L.) pruned at the time of planting did not differ in survival from unpruned stock: pruned seedlings had faster initial growth in the field, but height of pruned and unpruned stock was equal after two growing seasons [78].

Ponderosa pine top-pruned during active growth in the 3+0 year at a North Dakota nursery had lower survival (34%) than unpruned trees (49%) [93]. In another study, 3+0 ponderosa pine seedlings pruned to 6 inches in the third year and then outplanted showed little effect of top pruning on multiple leaders, disease, or insect damage [47]. As previously mentioned, Hermann's [40] study showed that pruning ponderosa pine seedlings after lifting caused 100% mortality after outplanting.

There are very few studies on effects of top pruning Northwest species. Therefore, we can only speculate about possible pruning effects. Trees intended for droughty sites might be better balanced and survive better if top-pruned. The number of culls in a crop might drop because top pruning releases the smaller trees. But many questions about Northwest species remain unanswered: How are shoot diameter and height, needle surface area, and shoot and root dry weights of individual trees and the entire crop affected when seedlings are top-pruned? How does top pruning affect field growth? Does it affect the number of needle primordia laid down in the new bud and, therefore, growth the next year? How does top pruning affect field survival on moist and dry sites?

The Nursery Technology Cooperative at OSU is currently investigating the effects of top pruning on Douglas-fir seedlings. Studies installed at six nurseries using nine seed sources are designed to answer some of these questions about top pruning.

15.8.5 Conclusions

Top pruning helps the nursery manager control shoot height and achieve crop-size uniformity. Seedlings should be pruned when actively growing in early summer to ensure the proper development of terminal buds. Dead, pruned plant material should be removed from beds immediately after pruning to reduce chances of disease.

So far, little information is available on the effects of top pruning on individual seedling or crop characteristics for Northwest species. Although pruning is an effective alternative when a crop has excessively tall trees, the nursery manager should examine the overall coordination of cultural practices and should be alert to those, such as moderate moisture stress or root wrenching, which might help prevent overly tall crops in future years.

15.9 Transplanting

Transplanting is lifting seedlings from their original seedbed to plant in another location in the nursery (the transplant bed). Seedling density in the transplant bed is lower than that in the original seedbed, allowing more growing space for each seedling. Compared to a seedling of the same age grown at higher densities in a seedbed and not transplanted, transplanted seedlings have larger stem diameters, shoot heights, and root and shoot dry weights. Increased size may give them an advantage on difficult outplanting sites, such as those with heavy brush or severe animal browsing (see chapter 24, this volume). Because of the increased success with these larger seedlings, nurseries report an increasing trend in transplant orders (OSU Nursery Survey); in 1980, 19% of all seedlings produced in the Northwest nurseries surveyed were transplants. Although, in the past, only cull seedlings or those that were too small for field planting were transplanted [33], today seedlings are most often grown specifically for that purpose.

Although very little data are available, transplant seedlings are reported to have (1) more fibrous root systems, (2) larger stem diameters, and (3) lower shoot:root ratios than seedlings of comparable age grown at a standard density (25 to 35 seedlings/ft^2) [8, 43, 93. 103]; their height is usually equivalent or slightly greater than that of comparable, nontransplanted seedlings [8, 43].

15.9.1 General procedure

Transplant steps vary slightly with the time of the year seedlings are transplanted and with nursery location and conditions. Generally, seedlings are (1) watered well, (2) lifted (usually with the same lifting method as for field planting), (3) graded, (4) root-pruned, (5) packed (if storage is necessary), and (6) (sometimes) stored. The transplant bed is prepared (sometimes including fumigation and bed forming); transplant seedlings are planted in prewatered ground and then irrigated.

15.9.1.1 Irrigation and lifting

Care should be taken to minimize stress when transplanting, using guidelines and practices similar to those for lifting for field planting. If moisture stress is high, as it is likely to be in fall or summer transplanting, seedlings should be well irrigated before lifting; because hot, dry weather conditions are likely at the time of lifting, it is important to protect seedlings from overheating and drying. When fall or summer transplanting, many nurseries either lift only as many seedlings as can be processed in the same day or plan to store seedlings only up to 4 days to avoid transplant shock (OSU Nursery Survey).

15.9.1.2 Grading, root pruning, packing, and storing

After grading out culls and trees too large for the transplanter, roots of seedlings to be transplanted are pruned to facilitate the transplanting process and to avoid L-rooting in the transplant bed. Most roots are pruned to 5 to 6 inches (13 to 15 cm); two Canadian nurseries prune all roots to 4 inches (10 cm) (OSU Nursery Survey).

If seedlings are to be transplanted immediately, as in summer and fall, they are returned to field containers and covered with wet burlap (see chapter 22, this volume). Seedlings to be transplanted in spring, which must be stored up to 6 months, are packaged in containers (bags or boxes) similar to those for field planting. Storage, mainly of spring transplants, is most often under the same conditions as for seedlings to be outplanted—that is, in refrigerators at 1 to 2°C with 90% relative humidity or in freezers at –1 to -2 °C (OSU Nursery Survey).

15.9.2 Equipment and bed density

Almost all transplanting is done by machine, either with a tractor-drawn mechanical transplanter or a self-propelled transplanter (OSU Nursery Survey); one custom-made machine plants four trenches to a bed instead of the normal six.

Common complaints about transplanters are (1) they are slow, (2) the trench or furrow is not deep enough, resulting in L-rooting of seedlings, and (3) seedling density cannot easily be altered. Transplant-bed densities range from 4 to 12 seedlings/ft^2 (43 to 129 seedlings/m^2), with most transplants grown at 5 to 6 seedlings/ft^2 (53 to 64 seedlings/m^2) (OSU Nursery Survey).

15.9.3 Timing

Seedlings are transplanted at three times of the year—fall, spring, and early summer; in the Northwest, spring is the most common time. A few nurseries transplant part of their 2+1 Douglas-fir crop in fall and the rest in spring. Canadian nurseries transplant their 2+1, 1+1, and 1+2 stock in spring and their 1½+½ and 1½+1½ stock in early summer (for information on plug+ I transplanting, see chapter 16, this volume).

15.9.3.1 Summer transplanting

Summer transplanting, also called hot transplanting, is common in many Canadian nurseries ([8, 103]; OSU Nursery Survey). In British Columbia, 1½+½ and 1½+1½ interior spruce *(Picea glauca* and *engelmannii),* lodgepole pine, and to a lesser extent Douglas-fir are transplanted in June or July, approximately half way through the growing season of their 2+0 year—hence the 1½ (OSU Nursery Survey). The main consideration in deciding when to summer-transplant is that leaders, though stiff and partly lignified, are still flexible enough to avoid breakage when handled [8]. Summer-transplanted seedlings have larger stem diameters and bushier root systems than 2+1, 1+1, or 1+2 transplants [8, pers. commun., 87]. However, it is advisable to thoroughly irrigate seedlings before lifting and after summer transplanting to avoid the consequences of high plant-moisture stress [103].

15.9.3.2 Fall and spring transplanting

Fall-transplanted Douglas-fir 2+1 seedlings are lifted in September and October at the end of the second growing season, stored only if necessary for a maximum of 4 days, and replanted into transplant beds immediately. Seedlings transplanted in spring are lifted sometime beween December and March, stored from 2 weeks to 6 months, and planted between March and late May (OSU Nursery Survey). No data are available on effects of storage followed by late-spring transplanting on transplant-bed growth and survival. To be safe, however, nurseries should lift during their established "lifting windows" and transplant as early as possible to assure early budburst and adequate growth in the transplant bed. Any seedlings lifted in spring should be stored as little as possible before transplanting.

Data from several Weyerhaeuser Company annual nursery reviews show that there is a critical period for fall transplanting.

Transplanting in late October, compared to late September, improved transplant-bed survival from 70 to 91% for trees from six seed sources [pers. commun., 100]; the differences in seedling condition (the later-transplanted seedlings were more hardened) or in weather conditions immediately after transplanting and during winter interacting with seedlings in different physiological states could be responsible for these results.

Only one published report comparing fall and spring transplants was found. In the plains region of Canada, survival of fall-transplanted Scotch pine, white spruce, and Colorado blue spruce *(Picea pungens* Engelm.) varied tremendously in transplant beds according to transplanting date; spring transplanting resulted in less variable survival and was most often better than transplanting in fall [24]. Inconsistent survival of fall transplants could again be due to different weather conditions or different nursery handling procedures of stock that was not completely dormant. On the other hand, two unpublished Northwest reports showed fall transplanting of Douglas-fir to be as favorable as spring [pers. commun., 50, 100]. Seedlings transplanted on October 25, 1976, had the same transplant-bed survival as those transplanted on April 2 5, 1977, but had earlier budburst (April 22 vs. May l5), greater height, larger stem diameter, and higher shoot:root ratio at lifting (Table 12) [50]. In the other study, spring and fall transplants from two seed sources survived equally well (99%) in the transplant bed and were equal in height, but fall transplants had slightly larger stem diameters and shoot and root dry weights [pers. commun., 100].

In summary, fall transplanting has several major advantages: (1) fall is a time when nursery activities are at a low; fall transplanting therefore lightens the workload in spring, (2) fall-transplanted seedlings may have larger diameters and root masses, and (3) earlier budburst in spring means that fall transplants reach their desired size sooner, leaving more time for hardening in summer. These advantages warrant further investigation.

However, most Northwest nurseries do not transplant in the fall because (1) success is too variable—transplant-bed mortality is greater in fall than spring, (2) frost heaving occurs more frequently on fall transplants because the root system has not yet adequately anchored the seedling, (3) ground is not available in fall, (4) height control is sometimes difficult, and (5) nurseries generally do not see an advantage of fall over spring and summer transplanting (OSU Nursery Survey).

15.9.4 Conclusions

Transplant seedlings have more fibrous root systems, larger stem diameters, and lower shoot:root ratios than seedlings of the same age grown at a standard density (25 to 35 seedlings/ft^2). Important steps to ensure successful transplanting are (1) watering thoroughly before lifting, (2) lifting, grading, and root pruning, (3) packing and storing if necessary, (4) preparing the transplant bed, and (5) transplanting into prewatered ground and irrigating after planting.

Summer transplanting is common in Canadian nurseries; spruce and lodgepoie pine are transplanted in June and July, resulting in 1½+½ and 1½+1½ seedlings. Spring transplanting is most common in U.S. nurseries, mainly because success of fall transplanting is too variable. Typical transplant stock types are 1+1s and 2+1s.

15.10 Interactions Among Nursery Practices

When two nursery practices interact, the effect of one practice will depend on the particular level of the other. For example, irrigation levels and different seedbed densities interact; that is, trees grown at lower densities will respond to watering levels differently than those grown at higher densities. In general, if no interaction exists, practices are said to be independent of one another (see chapter 28, this volume, for more information on interactions).

Some examples of interactions are:

- Fertilizer applications increased seedling height if seed was sown early, but not if it was sown late [89].
- Changes in water supply affected fertilized and unfertilized seedlings differently [12].
- Fall fertilization increased the chance of frost damage to Sitka spruce but not to Norway spruce, western hemlock, grand fir, and lodgepole pine [16].

It is important for nursery managers to be aware of interaction among practices in their nurseries. If a decision is made to alter or discontinue a current practice or to add a new one, careful attention should be paid to other practices affected by this change. Thinking ahead about the implications of such changes will avert problems that could lower crop quality and yield.

15.11 Conclusions and Recommendations

- In addition to stock-type description, morphological characteristics and physiological condition of seedlings can have a tremendous impact on seedling quality and ultimate field performance.
- Sowing depth can influence both the rate and the total amount of germination and therefore the final number of seedlings in the seedbed. To ensure good growth and crop uniformity, it is important to choose a proper sowing depth, specific to the tree species and soil conditions; then to prepare a level seedbed; and, finally, to make sure that seed depth is consistent throughout the bed.
- The importance of early sowing cannot be overemphasized. Early-sown first-year seedlings benefit from the entire growing season and are large enough for hardening by July and August. The final 2+0 crop is larger the next year and is again ready for hardening by midsummer.
- Lowering seedbed density produces seedlings with larger stem diameters and heavier shoots and roots. Furthermore, seedlings grown at lower densities may have an improved ability to regenerate new roots. Field survival of seedlings varies regardless of seedbed density, but height growth of seedlings grown at lower densities most often is superior for several growing seasons after planting.
- Irrigation schedules that induce a moderate plant moisture-stress level during hardening result in earlier budset, increased cold hardiness, smaller seedlings, and increased field-survival potential. Extremely low or high plant

Table 12. Morphology (at time of lifting), phenology (in the nursery), and survival of fall- and spring-transplanted 2+1 Douglas-fir seedlings [pers. commun., 50].

Transplanting date	Height, cm	Diameter, mm	Fresh weight, g	Shoot:root ratio, g dry wt.	Budburst date	Survival in transplant bed, %
10/25/76	33.9	7.5	49.9	1.52	4/22/77	95
4/25/77	29.0	6.9	36.9	1.30	5/15/77	91

moisture-strqss levels can be harmful to seedlings. However, so far, no published investigations define moderate levels or their effect on field performance.

- Fertilization, especially with N, produces taller, heavier seedlings with larger shoot diameters. The timing of N application seems important to seedling frost hardiness. Though little is known about the effects of nursery fertilization on seedling performance in the field, where studies have been done, effects of fertilization on either growth or survival often have been positive.
- Root-culturing practices that cut roots before or during the growing season arrest or retard seedling height growth. The effects of this on Douglas-fir root systems have varied, with no reported measurements of increased root fibrosity, although root wrenching or lateral pruning in late summer or early fall may promote root growth. Both field survival and height growth of root-wrenched seedlings compare inconsistently with the survival and growth of unwrenched seedlings.
- Seedlings are most often top-pruned to control shoot height when shoots elongate in early summer. However, there are no published reports on the effect of this growing-season top pruning on Douglas-fir morphology, physiology, or field performance.
- Transplanted seedlings have larger stem diameters, shoot heights, and root and shoot dry weights than seedlings of the same age grown at higher seedbed densities and not transplanted. This increased size is reported to give transplants an advantage on difficult outplanting sites, such as those with heavy brush or severe animal browsing.
- When two nursery practices interact, the effect of one practice will vary with the particular level of the other. If a nursery manager decides to alter or discontinue a current practice or to add a new one, careful attention should be given-to the effect of this change on other cultural practices in the nursery.

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References

1. Aldhous, J. R. 1972. Nursery practice. Her Majesty's Stationary Office, London. Forestry Commun. Bull. 43. 184 p.
2. Allen, R. M., and T. E. Maki. 1955. Response of longleaf pine seedlings to soil and fertilizers. Soil Sci. 79:3 59-362.
3. Anderson, H. W. 1976. Personal communication, State of Washington, Dep. of Resources, Div. of Forest Land Management, Olympia.
4. Anderson, H. W., and S. P. Gessel. 1966. Effects of nursery fertilization on outplanted Douglas-fir. J. Forestry 64:109-112.
5. Anstey, C. 1971. Survival and growth of 1/0 radiata pine seedlings. New Zealand J. Forestry 16(1):77-81.
6. Armson, K. A. 1966. The growth and absorption of nutrients by fertilized and unfertilized white spruce seedlings. Forestry Chronicle 42(2):127-136.
7. Armson, K. A. 1968. The effects of fertilization and seedbed density on the growth and nutrient content of white spruce and red pine seedlings. Univ. of Toronto, Faculty of Forestry, Ontario. Tech. Rep. 10. 16 p.
8. Armson, K. A., and V. Sadreika. 1979. Forest tree nursery soil management and related practices. Ontario Ministry of Natural Resources, Toronto. 179 p.
9. Bacon, C. J., and P. J. Hawkins. 1979. Intensive root wrenching: a prerequisite for the successful establishment of 1-0 *Pinus caribaea* Mor. seedlings. Tree Planters' Notes 30(1):5-7.
10. Balneaves, J. M., and A. R. McCord. 1976. Precision sowing improves quality and performance of 1/0 radiata pine seedlings. New Zealand Forest Serv., Forest Res. Institute. Rangiora. Production Forestry Rep. 90 (unpubl.). 11 p.
11. Baron, F. J., and G. H. Schubert. 1963. Seedbed density and pine seedling grades in California nurseries. U.S.D.A. Forest Serv., Pacific SW Forest and Range Exp. Sta., Berkeley, California. Res. Note PSW-31. 14 p.
12. Bengtson, G. W., and G. K. Voight. 1962. A greenhouse study of relations between nutrient movement and conversion in a sandy soil and the nutrition of slash pine seedlings. Soil Sci. Society of America Proc. 26:609-612.
13. Benson, A. D., and K. R. Shepherd. 1976. Effect of nursery practice on Pinus radiata seedling characteristics and field performance: I. Nursery seedbed density. New Zealand J. Forestry Sci. 6(l):19-26.
14. Benson, A. D., and K. R. Shepherd. 1977. Effects of nursery practice on Pinus radiata seedling characteristics and field performance: 11. Nursery root wrenching. New Zealand J. Forestry Sci. 7:68-76.
15. Benzian, B. 1966. Effects of nitrogen and potassium concentrations in conifer seedlings on frost damage. Pages 101-102 *in* Rep. of Forest Research 1966. Forestry Commission, London. As cited in van den Driessche [105, this list], p. 111.
16. Benzian, B., R. M. Brown, and S. C. R. Freeman. 1974. Effect of late-season top-dressings of N (and K) applied to conifer transplants in the nursery on their survival and growth on British forest sites. Forestry 47:153-184.
17. Blair, R., and F. Cech. 1974. Morphological seedling grades compared after thirteen growing seasons. Tree Planters' Notes 25(1):5-7.
18. Blake, J., J. Zaerr, and S. Hee. 1979. Controlled moisture stress to improve cold hardiness and morphology of Douglas-fir seedlings. Forest Sci. 25:576-582.
19. Brodie, J. D., and P. L. Tedder. 1982. Regeneration delay: economic cost and harvest loss. J. Forestry 80(1):26-28.
20. Brown, J. H. 1970. Seedling growth of three Scotch pine provenances with varying moisture and fertility treatments. Forest Sci. 16:43-4 5.
21. Brunsden, G. J. 1981. Box pruning and field results. Pages 142-153 in Forest nursery and establishment practice in New Zealand. New Zealand Forest Serv., Forest Res. Institute, Rotorua. FRI Symp. 22.
22. Burns, R. M., and R. H. Brendemuehl. 1971. Nursery bed density affects slash pine seedling grade and grade indicates field performance. U.S.D.A. Forest Serv., Southeastern Forest Exp. Sta., Asheville, North Carolina. Res. Pap. SE-77.7 p.
23. Chavasse, C. G. R. 1977. The significance of planting height as an indication of subsequent seedling growth. New Zealand J. Forestry 22(2):283-296.
24. Cram, W. H., and A. C. Thompson. 1981. Fall and spring transplanting of conifers in the Plains region. Tree Planters' Notes 32(1):16-19.
25. Day, R. J. 1980. Effective nursery irrigation depends on regulation of soil moisture and aeration. Pages 52-71 *in* Proc., North American forest tree nursery soils workshop (L. P. Abrahamson and D. H. Bickelhaupt, eds.). State Univ. New York, Coll. Environ. Sci. and Forestry, Syracuse.
26. Dieurauf, T. A. 1976. Top clipping in the nursery bed. Pages 37-43 in Proc., Southeast Area Nurserymen's conf. (C. Lantz, ed.). Eastern Session, Charleston, South Carolina, Aug. 3-5; and Western Session, Mobile, Alabama, Aug. 17-19.
27. Dieurauf, T. A., and J. W. Garner. 1980. Simulated root wrenching. Virginia Div. of Forestry Occasional Rep. 55. 3 p.
28. Duryea, M. L. 1977. Unpublished data, Dep. of Forest Sci., Oregon State Univ., Corvallis.
29. Duryea, M. L., and D. P. Lavender. 1982. Water relations, growth, and survival of root-wrenched Douglas-fir seedlings. Can. J. Forest Res. 12:545-555.
30. Dykstra, G. F. 1974. Undercutting depth may affect root-regeneration of lodgepole pine seedlings. Tree Planters' Notes 25:21-22.
31. Edgren, J. W. 1966. Bed density and size of ponderosa pine seedlings at the Bend Nursery. Pages 21-29 *in* Proc., 10th Biennial Western Forestry Nursery Council meeting.

32. Edgren, J. W. 1975. Douglas-fir 2+0 nursery stock size and first-year field height growth in relation to seed bed density. Pages 72-79 *in* Proc., Servicewide conf. on planting stock production, Coeur d'Alene, Idaho, Sept. 16-18.
33. Edgren, J. W. 1976. Seedbed density, diameter limit culling, and 2+0 Douglas-fir seedling production. In Proc., Western Forest Nursery Council and Intermountain Nurserymen's Assoc., Richmond, B.C., Aug. 10-12.
34. Eis, S. 1968. Lateral root pruning—a promising forest nursery practice. Forestry Chronicle 44(5):12-13.
35. Eis. S., and J. R. Long. 1972. Lateral root pruning of Sitka spruce and western hemlock seedlings. Can. J. Forest Res. 2(3):223-227.
36. Eis, S., and J. R. Long. 1973. Root pruning in the nursery. Tree Planters' Notes 24(1):20-22.
37. Garrett, P. W., and R. Zahner. 1973. Fascicle density and needle growth responses of red pine to water supply over two seasons. Ecology 54:1328-1334.
38. Gilmore, A. R., E. S. Lyle, Jr., and J. T. May. 1959. The effects on field survival of late nitrogen fertilization of loblolly pine and slash pine in the nursery seedbed. Tree Planters' Notes 36:22-23.
39. Griffin, A. R. 1974. Geographic variation in juvenile growth characteristics of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) from coastal ranges of California. Ph.D. thesis, School of Forestry, Oregon State Univ., Corvallis. 153 p.
40. Hermann, R. K. 1964. Importance of top-root ratios for survival of Douglas-fir seedlings. Tree Planters' Notes 64:7-11.
41. Hobbs, S. D. 1982. Unpublished data, FIR Program, Medford, Oregon.
42. Janick, J. 1979. Directing plant growth. *In* Horticultural Science. 3rd ed. W. H. Freeman and Co., San Francisco, California. 608 p.
43. Jones, E. W. 1968. A note on the dimensions of shoots and roots of planting stock. Forestry 4l (2):199-206.
44. Kais, A. G. 1978. Pruning of longleaf pine seedlings in nurseries promotes brown-spot needle blight. Tree Planters' Notes 29(1):3-4.
45. Koon, K. B., and T. O'Dell. 1977. Effects of wrenching on drought avoidance of Douglas-fir seedlings. Tree Planters' Notes 28(2):15-16.
46. Kozlowski, T. T. 1971. The challenges of research in forest biology. Forestry Chronicle 47:192-195.
47. Lanquist, K. B. 1966. Top pruning of ponderosa pine. Tree Planters' Notes 79:3-8.
48. Larsen, J. B. 1976. Untersuchungen uber die Frostempfindlichkeit von Douglasienherkünften ünd uber den Einfluss der Nahrstoffversorgung auf die Frostresistenz der Douglasie. Forst- and Holzwirt 31(15):299-300. 302. As cited in van den Driessche [105, this list], p. 1 12.
49. Larsen, J. B. 1978. Untersuchungen uber die Bedeutung der Kalium and Stickstoffversorgung fur die Austrocknungsresistenz der Douglasie (*Pseudotsuga menziesii*) in Winter. Flora 167:197-207. As cited in van den Driessche [105, this list], p. 112.
50. Lavender, D. P. 1977. Personal communication, Dep. of Forest Sci., Oregon State Univ., Corvallis.
51. Lavender, D. P.. K. K. Ching, and R. K. Hermann. 1968. Effect of environment on the development of dormancy and growth of Douglas-fir seedlings. Botanical Gazette 129(1):70-83.
52. Lavender, D. P., and B. D. Cleary. 1974. Coniferous seedling production techniques to improve seedling establishment. Pages 177-180 in Proc., North American containerized forest tree seedling symp. (R. W. Tinus, W. I. Stein. and W. E. Balmer, eds.). Great Plains Agric. Res. Publ. 68.
53. Lavender, D. P., and R. K. Hermann. 1976. Role of forest tree physiology in producing planting stock and establishing plantations. Unpubl. paper presented at XVI IUFRO World Congress, Division 11. Oslo, Norway. 12 p.
54. Levitt, J. 1972. Responses of plants to environmental stresses. Academic Press. New York. 697 p.
55. Long, J. N. 1978. Root system form and its relationship to growth in young planted conifers. Pages 222-234 *in* Symp. on root form of planted trees, Victoria, B.C., May 16-19.
56. Lopushinsky, W. 1976. Relationship of shoot-root ratio to survival and growth of outplanted Douglas-fir and ponderosa pine seedlings. U.S.D.A. Forest Serv., Pacific NW Forest and Range Exp. Sta., Portland, Oregon. Res. Note PNW-274.7 p.
57. Lott, J. R., and G. Hallman. 1973. New Zealand root pruner evaluation for U.S. use. Tree Planters' Notes 24(4):18-20.
58. Malcolm, D. C., and B. C. Y. Freezaillah. 1975. Early frost damage on Sitka spruce seedlings and the influence of phosphorus nutrition. Forestry 48:139-145.
59. McClain, K. M., and K. A. Armson. 1975. Growth responses of pine and spruce seedlings to regimes of soil moisture and fertility. Soil Sci. Society of America Proc. 39(1):140-144.
60. McDonald, S. E., and S. W. Running. 1979. Monitoring irrigation in western forest tree nurseries. U.S.D.A. Forest Serv., Rocky Mt. Forest and Range Exp. Sta., Fort Collins, Colorado. Gen. Tech. Rep. RM-61. 8 p.
61. McLemore, B. F. 1982. Comparison of 1-0 and 2-0 loblolly pine seedlings. Tree Planters' Notes 33(2):22-23.
62. McMinn, R. G. 1980. Root development of white spruce and lodgepole pine seedlings following outplanting. Pages 186-190 *in* Can. Forestry Serv., Pacific Forest Res. Centre, Victoria. B.C. As cited in Schmidt-Vogt [80, this list].
63. Menzies, M. I. 1980. Effect of nursery conditioning on the water relations of two-year-old Douglas-fir seedlings after lifting and outplanting. Ph.D. thesis, Univ. of Washington, Seattle. 208 p.
64. Menzies, M. I., J. C. van Dorsser, and B. W. A. Moberly. 1974. Effect of seedling spacing on grade return in the nursery and growth in the field. New Zealand Forest Serv., Forest Res. Institute, Rotorua. Forest Establishment Rep. 55 (unpubl.). 12 p.
65. Morby. F. E. 1982. Irrigation regimes in a bare-root nursery. Pages 55-59 *in* Proc., 1981 Intermountain Nurserymen's Assoc. meeting, Edmonton, Alberta. Aug. 11-13. Can. Forestry Serv., Edmonton. Inf. Rep. NOR-X-241.
66. Mullin, R. E. 1966. Root pruning of nursery stock. Forestry Chronicle 42:256-264.
67. Mullin, R. E., and L. Bowdery. 1977. Effects of seedbed density and nursery fertilization on survival and growth of white spruce. Forestry Chronicle 53(2):83-86.
68. Mullin, R. E., and L. Bowdery. 1978. Effects of nursery seedbed density and top dressing fertilization on survival and growth of 3+0 red pine. Can. J. Forest Res. 8:30-35.
69. Mullin, R. E., and C. Christl. 1981. Morphological grading of white spruce nursery stock. Forestry Chronicle 57(3):126-130.
70. Mullin, R. E., and C. Christl. 1982. Morphological grading of white pine nursery stock. Forestry Chronicle 58(1):40-43.
71. Parker, J. A., and L. W. Haines. 1981. Longleaf pine seedling survival studies. U.S.D.A. Forest Serv., Southern Forest Exp. Sta., New Orleans. Lousiana. Gen. Tech. Rep. SO-34. 4 p.
72. Pawsey. C. K. 1972. Survival and early development of *Pinus radiata* as influenced by size of planting stock. Australian Forest Res. 5(4):13-24.
73. Pharis, R. P., and P. 1. Kramer. 1964. The effect of nitrogen and drought on loblolly pine seedlings. Forest Sci. 10:143-150.
74. Pollard, D. F. W., and K. T. Logan. 1977. The effects of light intensity, photoperiod, soil moisture potential, and temperature on bud morphogenesis in Picea species. Can. J. Forest Res. 7:415-421.
75. Richter, J. 1971. Das Umsetzen von Douglasien im Kulturstadium. Allgemeine Forst- and lagdzeitung 142:65-69. As cited in Schmidt-Vogt [79, this list], p. 75.
76. Rook, D. A. 1969. Water relations of wrenched and unwrenched *Pinus* radiata seedlings on being transplanted into conditions of water stress. New Zealand J. Forestry 14:50-58.
77. Rook, D. A. 1971. Effect of undercutting and wrenching on growth of *Pinus* radiata D. Don seedlings. J. Applied Ecology 8:477-490.
78. Russell, T. E. 1973. Survival and growth of bar-slit planted northern red oak studied in Tennessee. Tree Planters' Notes 24(3):6-9.
79. Schmidt-Vogt, H. 1974. Planting material. Pages 70-86 *in* Symp. on stand establishment. IUFRO Joint Meeting, Div. 1 and 3, Wageningen, The Netherlands, Oct. 15-19.
80. Schmidt-Vogt, H. 1981. Morphological and physiological characteristics of planting stock: present state of research and research tasks for the future. Pages 433-446 *in* Proc., IUFRO XVII World Congress. Freiburg i. Br., Federal Republic of Germany.
81. Schomaker, C. E. 1969. Growth and foliar nutrition of white pine seedlings as influenced by simultaneous changes in moisture and nutrient supply. Soil Sci. Society of America Proc. 33:614-618.
82. Schubert, G. H., and R. S. Adams. 1971. Reforestation practices for conifers in California. State of California, Dep. of Conservation, Div. of Forestry, Sacramento. California. 359 p.

83. Shipman, R. D. 1964. Low seedbed densities can improve early height growth 'of planted slash and loblolly pine seedlings. J. Forestry 62(11):814-817.
84. Shoulders. E. 1961. Effect of nursery bed density on loblolly and slash pine seedlings. J. Forestry 59(8):576-579.
85. Shoulders, E. 1963. Root-pruning southern pines in the nursery. U.S.D.A. Forest Serv., Southern Forest Exp. Sta., New Orleans. Louisiana. Res. Pap. SO-5.
86. Show, S. B. 1930. Forest nursery and planting practice in the California pine region. U.S. Dep. Agric., Washington, D.C. Circular 92.
87. Simpson, D. G. 1982. Personal communication, B.C. Ministry of Forests. Victoria.
88. Smith, J.H.G., A. Kozak, O. Sziklai, and J. Walters. 1966. Relative importance of seedbed fertilization, morphological grade, site, provenance, and parentage to juvenile growth and survival of Douglas-fir. Forestry Chronicle 42:83-86.
89. Sorensen, F. C. 1978. Date of sowing and nursery growth of provenance of Pseudotsuga menziesii given two fertilizer regimes. J. Appied Ecology 15:273-279.
90. Stiell, W. M. 1976. White spruce: artificial regeneration in Canada. Can. Forestry Serv., Forest Management Institute, Ottawa. Inf. Rep. FMR-X-85. 275 p.
91. Stoeckeler, J. H., and H. F. Ameman. 1960. Fertilizers in forestry. Advances in Agronomy 12:127-195.
92. Stoeckeler, J. H., and G. W. Jones. 1957. Forest nursery practice in the Lake States. U.S.D.A. Forest Serv., Washington, D.C. Agric. Handb. 110. 124 p.
93. Stoeckeler, J. H., and P. E. Slabaugh. 1965. Conifer nursery practice in the Prairie-Plains. U.S.D.A. Forest Serv., Washington, D.C. Agric Handb. 279. 93 p.
94. Sweet, G. B., and D. A. Rook. 1972. Inhibitor levels associated with growth in seedlings of *Pinus radiata*. New Phytologist 72:1107-1111.
95. Switzer, G. L., and L. E. Nelson. 1963. Effects of nursery fertility and density on seedling characteristics, yield, and field performance of loblolly pine (*Pinus taeda* L.). Soil Sci. Society of America Proc. 27:461-464.
96. Tanaka, Y., J. D. Walstad, and J. E. Borrecco. 1976. The effect of wrenching on morphology and field performance of Douglas-fir and loblolly pine seedlings. Can. J. Forest Res. 6:453-458.
97. TerBush, F. A. 1977. Tree seedling description code. Tree Planters' Notes 28(3. 4):6.
98. Thompson, B. 1983. Why fall fertilize? Pages 85-91 *in* Proc.. Western Nurserymen's conf. Western Forestry Nursery Council, Medford, Oregon, Aug. 10-12, 1982. Southern Oregon State Coll., Ashland.
99. Timmis, R. 1974. Effect of nutrient stress on growth, bud set, and hardiness in Douglas-fir seedlings. Pages 187-193 *in* Proc., North American containerized forest tree seedling symp. (R. W. Tinus. W. I. Stein, and W. E. Balmer, eds.). Great Plains Agric. Res. Publ. 68.
100. Triebwasser, M. 1981. Personal communication, Weyerhaeuser Co., Mima Tree Nursery, Olympia, Washington.
101. U.S.D.A. Forest Service. 1974. Seeds of woody plants in the United States. U.S. Dep. Agric., Washington, D.C. Agric. Handb. 450. 883 p.
102. van den Driessche, R. 1963. Nursery experiments with Douglas-fir. Commonwealth Forestry Review 42(3):242-2 54.
103. van den Driessche, R. 1969. Forest nursery handbook. B.C. Forest Serv., Victoria. Res. Notes 48. 44 p.
104. van den Driessche, R. 1980. Effects of nitrogen and phosphorus fertilization on Douglas-fir nursery growth and survival after outplanting. Can. J. Forest Res. 10:65-70.
105. van den Driessche. R. 1980. Health, vigour and quality of conifer seedlings in relation to nursery soil fertility. Pages 100-120 *in* Proc., North American forest tree nursery soils workshop (L. P. Abrahamson and D. H. Bickelhaupt, eds.). State Univ. New York, Coll. Environ. Sci. and Forestry, Syracuse.
106. van den Driessche, R. 1982. Overwinter sowing of seed pelleted by Hilleshog. B.C. Ministry of Forests, Victoria. Progress Rep., Project 786. 13 p.
107. van den Driessche, R. 1982. Relationship between spacing and nitrogen fertilization of seedlings in the nursery, seedling size, and outplanting performance. Can. J. Forest Res. 12:865-875.
108. van Dorsser, J. C. 1981. Seedling conditioning. Pages 128-142 *in* Forest nursery and establishment practice in New Zealand. New Zealand Forest Serv., Forest Res. Institute, Rotorua. FRI Symp. 22.
109. van Dorsser, J. C., and B. W. A. Moberly. 1969. Conditioning of autumn sown Pinus radiata planting stock. New Zealand Forest Serv., Forest Res. Institute, Rotorua. Establishment Rep. 6 (unpubl.). 20 p. As cited in van Dorsser and Rook [110, this list], p.71.
110. van Dorsser, J. C., and D. A. Rook. 1972. Conditioning of radiata pine seedlings by undercutting and wrenching: description of methods, equipment, and seedling response. New Zealand J. Forestry 17:61-73.
111. Wakeley, P. C. 1954. Physiological grades of southern pine nursery stock. Pages 31 1-322 in Proc., Society of American Foresters. Washington, D.C.
112. Wilde, S. A., R. Wittenkamp, E. L. Stone, and H. M. Galloway. 1940. Effect of high rate fertilizer treatments of nursery stock upon its survival and growth in the field. J. Forestry 38:806-809.
113. Wilson, B. C., and R. K. Campbell. 1972. Seedbed density influences height, diameter, and dry weight of 3-0 Douglas-fir. Tree Planters' Notes 23(2):1-4.
114. Woessner, R. A. 1972. Four hardwood species differ in tolerance to pruning. Tree Planters' Notes 23(1):28-29.
115. Zaerr. J. B., B. D. Cleary, and J. Jenkinson. 1981. Scheduling irrigation to induce seedling dormancy. Pages 74-78 *in* Proc., Intermountain Nurserymen's Assoc. and Western Forest Nursery Council combined meeting, Boise, Idaho. Aug. 12-14, 1980. U.S.D.A. Forest Serv., Intermountain Forest and Range Exp. Sta., Ogden, Utah. Gen. Tech. Rep. INT-109.