Chapter 6
Bareroot Seedling Culture

John G. Mexal and David B. South

Abstract

The attributes of the ideal seedling (ideotype) depend on whether the regeneration forester is concerned with short-term or long-term reforestation goals. Once the regeneration forester specifies the ideotype, the nursery manager can proceed to convert seeds into as many seedlings of the desired ideotype as feasible. This Chapter reviews some of the practices nursery managers use to modify roots and shoots so the seedlings produced will match the desired ideotype. Major considerations necessary to produce quality seedlings include seed stratification, sowing density, sowing date, fertilization, and pruning. Emphasis is placed on the time of seedling emergence, which greatly affects mortality, development, and uniformity of the seedling crop.

6.1 Introduction

Artificial reforestation in the South depends primarily on bareroot seedlings. During the 1986-87 planting season, more than 994,400 ha (98.4%) of southern pines were planted with bareroot seedlings [213]. During this time, direct seeding accounted for about 13,800 ha (1.4%), container-grown seedlings for 1,600 ha (< 0.2%). Bareroot seedlings are grown at about 70 nurseries by managers who produce more than 1.8 billion seedlings/year, most from genetically improved seed. Obviously, cultural practices used to produce bareroot seedlings have a major influence on reforestation success in the South.

Both the nursery manager and the regeneration forester are important to successful reforestation. Indeed, the degree of success depends on cooperation among all team members (silviculturist, geneticist, seed-orchard manager, seed-extraction manager, nursery manager, regeneration forester, field forester, and tree planter). However, cooperation is especially critical between the nursery manager and regeneration forester if the regeneration effort is to be consistently successful.

One duty of a regeneration forester is to determine suitable seed sources for specific sites. This is an important decision because both the seed source (see Chapter 11, this volume) and the seed condition (see Chapter 4, this volume) affect reforestation success. If the seedlot is poor, the nursery manager can expect a poor seedling yield. On the other hand, a regeneration forester who spends $180/kg to produce second-generation seed expects management practices that will maximize seed efficiency.

Another duty of the regeneration forester is to choose the seedling ideotype — or ideal seedling (see 6.2). Silviculturists, the nursery manager, and field foresters together should ascertain the best seedling characteristics for the particular soils (Mountain, Piedmont, or Coastal Plain), sites (upland or flood plain), method of planting (machine or hand), and time of planting (fall, winter, or spring). Discussions should include decisions on genotype, major management practices, and lifting schedules, all of which can affect seed efficiency, ideotype, and field performance. After evaluating the economic trade offs, the regeneration forester chooses the ideotype best for each situation.

Various nursery-management practices affect the production of the desired ideotype. This chapter reviews some of the more important practices that affect seedling production and performance.

6.2 Ideotypes

An ideotype is described in terms of an ideal seedling. However, the definition of the ideal seedling can vary depending on the point of view of the individual [192]. For example, a tree planter (paid by the number of trees planted in a day) may want a seedling with a small root system, which may be faster to plant correctly by hand. Conversely, a regeneration forester (in charge of reforesting marginal lands where survival has traditionally been poor) may want a seedling with a more fibrous root system.

The concept of an ideal seedling has changed over time, partly as the result of research as well as changes in reforestation, nursery, and planting practices, genetics, and even the planting site. To avoid mistakes of the past, it is important to understand how we arrived at determining the ideotype of today.

M.L. Duryea & P.M. Dougherty (eds), Forest Regeneration Manual, pp. 89–115.

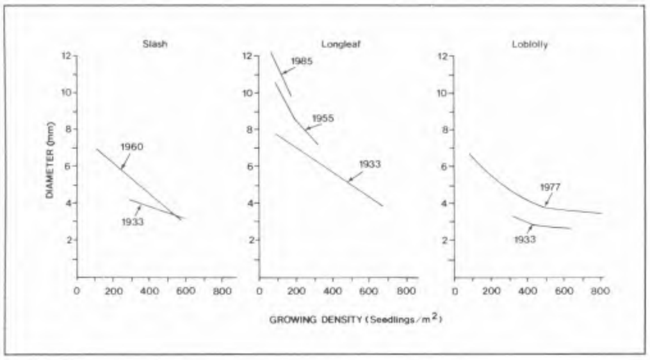

Figure 6.1. Effect of growing density on root-collar diameter of slash, longleaf, and loblolly pine seedlings. The larger diameter seedlings in recent times (note years associated with curves) indicate a trend toward better cultural practices (adapted from [53, 87, 90, 129, 178]).

6.2.1 Past Ideotype

During the first half of the 20th century, the ideotype for longleaf pine *(Pinus palustris* Mill.) seedlings was smaller than it is today. In the past, a U.S.D.A. Forest Service bale would contain 1,200 to 1,800 longleaf pine seedlings weighing about 18 g each [223]; today the Forest Service's Ashe Nursery packs 500 seedlings (weighing about 50 g each) per bale. Seedlings with root-collar diameters as small as 4.8 mm were once considered plantable [221]. But seedlings of this size would take several years to overcome the grass stage and begin gaining height. In one study, only 11% of the Grade 1 seedlings were taller than 15 cm after 4 years in the field [220]. For this reason, many foresters began to plant slash and loblolly pines *(Pinus elliottii* Engelm. and *Pinus taeda* L.) instead of longleaf pine. It would be several decades before researchers began to recommend planting longleaf seedlings with larger root-collar diameters [53, 172].

During the same period, the minimum root-collar diameter of a plantable loblolly, slash, or shortleaf *(Pinus echinata* Mill.) seedling was about 3.2 mm (1,500 to 3,000 seedlings/bale). Today, because seedling size has increased (Fig. 6.1), most nurseries pack no more than 1,000 seedlings/bale.

Regardless of species, the presence of secondary needles was a requirement for the southern pine seedling ideotype. In fact, the exact height of the seedling was considered less important than the presence of secondary needles [221]. However, the presence of a winter bud was not a requirement. Tests conducted in 1937-38 indicated that any effects of winter buds on survival were overshadowed by seedling size [223]. Therefore, seedlings were seldom culled for lack of a winter bud.

Although loss of lateral roots by breakage was a frequent and important cause of low survival, Wakeley [223] did not include lateral root characteristics in his morphological grades, possibly because he found that half to three-fourths of the laterals could be removed without skilled graders being aware of the damage.

Although loss of lateral roots would decrease the root:shoot (R:S) ratio (dry-weight basis), the R:S ratio *per se* was not considered important in describing the ideotype of the past. Wakeley [223] said that such ratios had never proven useful in grading southern pine seedlings.

6.2.2 Present Ideotype

For longleaf pine, the current ideotype has a larger diameter than proposed by Wakeley [221]. Because the time required for seedlings to emerge from the grass stage depends on the root-collar diameter [115], the minimum root-collar diameter for plantable longleaf pine seedlings is now 12.7 mm [130]. Longleaf pine seedlings with larger diameters also tend to survive better than seedlings with smaller diameters [232].

For loblolly pine, Barnett et al. [18] identified 4.8 mm as the average diameter for a target seedling for well-drained soils in Oklahoma and Arkansas. For slash pine, the average is also 4.8 mm [7, 23, 42], and for shortleaf pine the average is at least 4.5 mm [37, 48]. However, except for longleaf pine, there has been no increase in the minimum root-collar diameter for a plantable southern pine seedling for the past 50 years [221]. In fact, in some cases the minimum acceptable diameter has been lowered to 2.5 mm [16, 123].

Because of the importance of lateral roots, some authors have tried to quantify the number of first-order lateral roots for the loblolly pine ideotype. Barnett et al. [18] have suggested that target seedlings should have at least seven primary laterals, whereas May [130] proposed 20 or more. Apparently, May was counting both small and large lateral roots, whereas Barnett was counting only the large first-order laterals. The total number of first-order laterals might be twice as great as the number of large first-order laterals that are at least 0.5 mm in diameter at the taproot [91, 107, 228]. In addition, not all large first-order laterals contribute equally to successful regeneration [91].

Some authors now consider the presence of a winter resting bud (as opposed to an immature bud or a bud that has set, broken, and then stopped elongating) as a requirement for the target seedling [16, 18, 36, 38, 130]. Some even suggest that seedlings without such buds should be culled [49]. However, for southern pines, there is little evidence to support this concept. Independent of seedling size and needle morphology, little data indicate that a seedling with a winter resting bud will survive better than seedlings with buds in other stages of development (see 6.5.5).

Regardless of species, the presence of secondary needles is still a requirement for the southern pine seedling ideotype. Reducing the number of secondary needles reduces root-growth potential [79, 223]. Top pruning only 20% of the shoot length can diminish the proportion of secondary needles by 45% [146]. As a direct result, severe top pruning of loblolly pine can reduce field survival and height growth [197].

The desired height of the loblolly pine ideotype can vary depending on climate and site conditions. For many sites, the target height is 15 to 30 cm. Target height can range from 15 to 25 cm on droughty sites [18, 211, 212] and from 15 to 20 cm on sites subject to severe cold weather following planting. The height range is still 15 to 35 cm for slash pine [40] and 15 to 25 cm for shortleaf pine [36].

Although it cannot be used to grade individual seedlings before outplanting, the R:S ratio (dry-weight basis) is now considered important when planting on sites where survival may be low [130]. The optimum ratio is reported to be 0.40 to 0.45 for loblolly pine [18, 111, 130, 228] and > 0.4 for shortleaf pine [36]. However, the value of the R:S ratio can vary depending on when and how it is calculated (see 6.9).

6.2.3 Future Ideotype

When selecting seedlings for outplanting, the regeneration forester can choose either unimproved or genetically improved seedlings. In the future, nursery managers could also provide foresters with a choice of either regular (Ideotype B) seedlings or morphologically improved (Ideotype A) seedlings (proposed ideotypes for loblolly, slash, and shortleaf pine are described in Table 6.1; the ideotypes for longleaf pine are essentially the same as those described by May [130]). Ideotype A seedlings are morphologically improved because the minimum root-collar diameter for a plantable seedling is increased to 4 mm, the seedling weight is increased, and the R:S ratio is greater.

Table 6.1. Ideotypes proposed for bareroot loblolly, slash, and shortleaf pine seedlings.

Characteristic	Ideotype A	Ideotype B
Root-collar diameter of cull seedling, mm	< 4	< 3
Median root-collar diameter (of plantable seedlings), mm	> 5	> 4
Median number of "strong" primary lateral roots	> 7	> 5
Height (varies with site conditions), cm	15–25	15–30
Secondary and tertiary roots	Fibrous	Fibrous
Mycorrhizae	Many	Many
Length of secondary needles subtending the first budset,[1] cm	> 5	> 5
Median foliar nitrogen content/seedling, mg	> 25	> 20
Median root volume (by December 15), cm^3	> 3	> 2
Median root dry weight (by December 15), g	> 0.8	> 0.5
Median root:shoot ratio (by December 15)	> 0.4	> 0.33
Production cost,[2] cents	< 4	< 3
Bud dormancy status	(see below)[3]	

1 Presence of a well-formed winter bud is not an absolute requirement.

[2] Includes cost of seed and genetic improvement as well as fixed and variable costs.

[3] Bareroot southern pine seedlings may be planted from October through March if they are planted in moist soil (wetter than —40 kPa) and within 48 hours of lifting. During this time, the buds of loblolly pine may change from paradormancy (October-November), to endo-dormancy (November-December), to eco-dormancy (January-February) [33, 109]. See chapter 16 (this volume) regarding when seedlings will withstand prolonged cool storage.

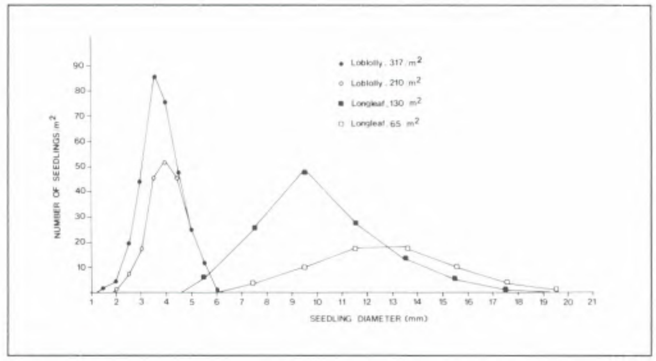

Figure 6.2. Effect of growing density on diameter distribution of loblolly and longleaf pine seedlings (adapted from [91; unpubl. data, 196]). For loblolly, the percentage of seedlings with diameters > 4 mm is 54% for the low seedbed density, 37% for the high seedbed density. For longleaf, the percentage of seedlings with diameters > 12 mm is 50% for the low seedbed density, 16% for the high seedbed density.

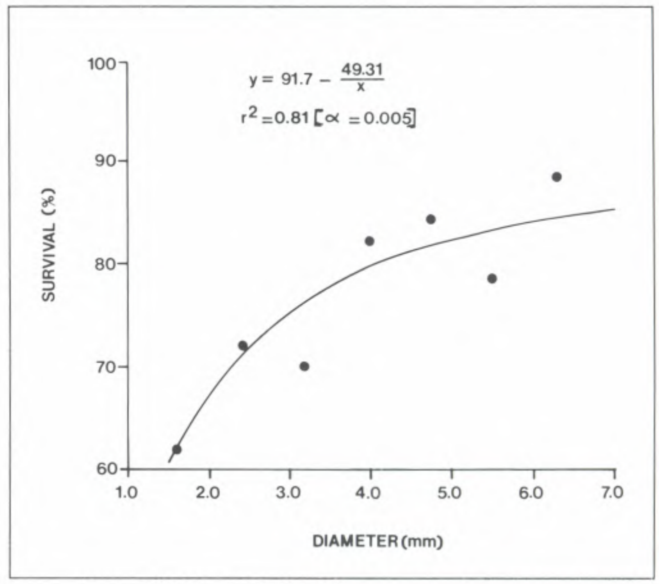

Figure 6.3. Relationship between seedling diameter at time of lifting and field survival; data for seven diameter classes compiled from 11 studies on loblolly and slash pine [192].

If Ideotype A seedlings are selected for outplanting, only seedlings with root-collar diameters of 4 mm or greater will be considered plantable. Although many nurseries on the West Coast use this diameter limit, only a few nurseries use this limit in the South [123]. However, it is not intended that all attributes listed in Table 6.1 be used when culling seedlings. In fact, some attributes like foliar nitrogen content and R:S ratio cannot be used to separate individual seedlings before planting. Instead, these attributes define goals the nursery manager should seek to achieve when growing a seedling crop. The future goal of nursery managers will be to produce < 8% culls and a high percentage of either Ideotype A or Ideotype B seedlings. Lowering the seedbed density is one way the nursery manager can increase the percentage of Ideotype A seedlings. Although lowering the seedbed density produces fewer seedlings with small diameters, it does not necessarily produce more large seedlings per square meter (Fig. 6.2).

Because a number of studies found survival to be correlated with root-collar diameter (Fig. 6.3; [188]), the survival of properly planted Ideotype A seedlings will, on the average, be higher than that of Ideotype B seedlings. However, the incremental increase in survival depends on both the severity of the planting site and the environmental conditions during and after planting (see 6.10). Because the growth of Ideotype A seedlings can be greater than that of Ideotype B, the present value of the larger Ideotype A will also be greater [23, 188]. However, there are trade offs when planting ideotype A seedlings. For example, when planting by hand with dibbles, Ideotype B may be easier to plant on certain Piedmont soils; however, when planting with machines or shovels on sandy soils, the differences in planting rates between the two ideotypes should be marginal. Storage, packing, and shipping costs will be greater for Ideotype A seedlings because fewer seedlings can be placed in a bag or box.

6.3 Improving Nursery Seed Efficiency

Seed efficiency is determined by dividing the number of plantable seedlings produced by the number of pure live seed sown. High seed efficiency is important because seed represents a considerable portion of the cost of seedling production [183, 223]. For example, some lots of unimproved longleaf seed may cost 0.5 cent/pure live seed. At this price, a low seed efficiency of 30% would result in a seed cost of $16.66/thousand plantable seedlings.

Good seed efficiency is even more important when using genetically improved seed with a high present net value [183, 187]. Efficient use of second-generation orchard seed increases the number of hectares that can be outplanted with second-generation seedlings. Therefore, when seeds from second-generation orchards are limited, poor seed efficiency will lower the overall potential productivity of newly established plantations. When seeds have a present net value of 5 cents/pure live seed, wasting 5 million pure live seed could lower the present value of a seedling crop by $250,000. A loss of 5 million seed is not uncommon for a nursery that produces 20 million plantable seedlings.

Seed efficiency at bareroot nurseries is the South can range from 40 to 90% [190]. An estimate of the average seed efficiency for all bareroot nurseries in 1985 would be about 66%. However, with good seed and good management practices, an experienced bareroot-nursery manager can consistently achieve a seed efficiency of > 80%.

To improve seed efficiency effectively, the nursery manager must first identify the stages of seedling development where loss of seed and seedlings occurs [141]. Once the problem areas are identified, action can be taken to prevent future losses.

6.3.1 Seedbed Erosion

Heavy rains, from time of sowing until the radicle has anchored the seedling, can cause seed loss by disturbing seed placement and eroding seedbed shoulders. Heavy rains are among the leading causes of seedling loss [28]. For example, a single storm can result in mortality of 4% or more [46]. Seedling yield at one nursery was increased 15% by the use of a soil-stabilizing chemical. Other factors that affect the potential for loss from rain include (1) seed treatments that promote rapid emergence, (2) depth of sowing, (3) type of mulch used, and (4) soil texture.

Rapid seedling emergence induced by increasing the length of seed stratification can result in more established seedlings 3 weeks after sowing (Fig. 6.4). The nursery crop is most vulnerable during the period from sowing to emergence. Generally, the shorter this period, the less chance of damage from heavy rains. Long stratification shortens this time period (see Chapter 4).If a heavy rain falls 3 to 4 weeks after sowing, rapid emergence will result in fewer seed being dislodged from the seedbed.

Depending on the type of mulch used, the sowing depth will also affect seed loss. With hydromulch or no mulch, seed sown on the soil surface are more susceptible to displacement than seed covered with 6 mm of soil [57, 164]. However, simply pressing seed into the seedbed will suffice if mulches like pine bark or pine straw are used. Not only do mulches effectively prevent seed from being dislodged by the impact of rain droplets, but they also protect seed from drying out.

Fine-textured soils with poor percolation can suffer more loss of seed from heavy rains than coarse-textured soils with good percolation. As long as the percolation rate exceeds the rainfall rate, the amount of puddling and surface movement of water will be minimal.

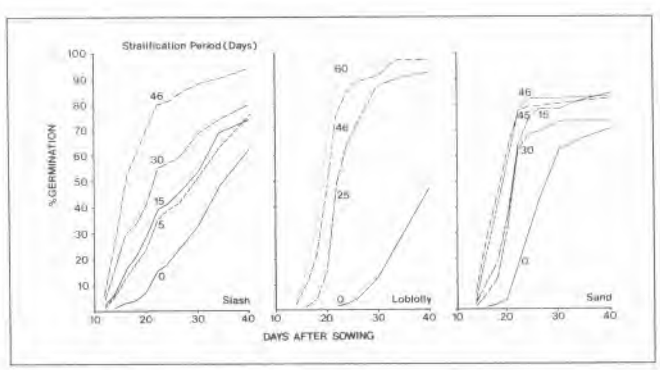

Figure 6.4. Effect of stratification length on seedling emergence of slash, loblolly, and sand pine [*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.] at the Superior Tree Nursery in Lee, Florida [unpubl. data, 227].

6.3.2 Prompt Emergence

Seedlings that emerge late are often wasted because they have a greater chance of dying and less chance of becoming plantable [27, 147]. Management practices that reduce the number of late germinants include seed treatments that promote rapid emergence and seedbed treatments that reduce moisture loss.

For most southern pine seedlots, increasing stratification time achieves more rapid, uniform germination in the field [15]. For loblolly pine, the often recommended 30 days of stratification is not based on nursery performance, but on the minimum period required for complete germination under controlled laboratory conditions. However, many studies have demonstrated that to obtain rapid emergence, loblolly pine requires at least 60 days of stratification [15, 19, 67, 117, 133]. Several nursery managers have found that stratifying loblolly pine for at least 60 days can speed emergence and increase yield.

Slash pine, longleaf pine, and sand *[Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg.] pine seeds are often sown in the U.S. without stratification. Total germination of some seedlots can be reduced with as little as 15 days of stratification [133]. Nevertheless, stratification of slash pine [63] and sand pine is recommended to speed emergence (Fig. 6.4) and improve seedling uniformity [27]. For longleaf pine, speed of emergence can also be increased by stratification [103]. Ideally, to increase germination speed, the optimal stratification length should be determined for each large seedlot.

Following sowing, mulching and irrigation maintain seedbed moisture needed for rapid emergence. However, some irrigation systems provide poor water distribution under windy conditions, and some mulches do not prevent soil drying as well as others. When using hydromulch or no mulch, more irrigation will be needed during emergence than with pine straw or pine bark mulch. Because high soil temperatures dry out seedbeds faster, the nursery manager should avoid sowing in May or June [33].

Seed emergence is also affected by soil crusts. Sowing on fine-textured soils prone to crusting can reduce seed efficiency [156]. Soil crusting can be reduced with various mulches or soil stabilizers.

6.3.3 Seedling Protection

Seed efficiency can be reduced by many damaging factors, including damping-off, insects, birds, weeds, herbicide injury, heat, moisture stress, and hypoxia. The incidence of damping-off, whether before or after emergence, can be reduced by soil fumigation, certain fungicides, proper time of sowing, seed quality, soil moisture, and sowing density (see Chapter 20, this volume). If seed has a present net value of 3 cents or more, methyl bromide fumigation is cost effective with only a 4% increase in seed efficiency. For postemergence damping-off, fungicide sprays should be applied prophylactically, or as soon as symptoms are detected. In general, fungicides are usually less effective than proper methyl bromide fumigation. Damping-off depends, to some extent, on the average distance between seed [26, 77]. So spacing seed farther apart may reduce the chance of spreading certain damping-off fungi.

Insects were usually not much of a problem when chlordane was used prior to sowing. Since the banning of chlordane, the incidence of insect problems in southern forest nurseries has increased. However, once a potential problem is identified, several insecticides and management practices can reduce the insect population [6, 61] (see Chapter 20, this volume). Although birds caused large reductions in seed efficiency in the past, they are rarely a major problem because seed are usually treated with a bird repellent (e.g., thiram).

Weeds still reduce seed efficiency if they are not managed with sanitation practices [182] and herbicides [184]. However, with certain herbicides, there is a trade off between providing effective weed control and decreasing seed efficiency. Depending upon the weather during emergence, certain diphenylether herbicides can cause a 5 to 10% reduction in yield when used at sowing [191]. The injury results, in part, when herbicide-treated soil is splashed onto the hypocotyl. However, this type of injury can be somewhat mediated with a soil stabilizer or a mulch that reduces sand splash.

In the South, high soil temperatures and lack of surface soil moisture during late May and June can cause mortality and stunting of newly emerged seedlings. Heat lesions can develop on the hypocotyls of new germinants [88]. Although frequent, light irrigations during the day can lower soil and air temperatures, sowing early to avoid exposing the succulent seedlings to excessive heat is preferred. Sowing in May rather than April reduced seed efficiency at one nursery below 45% [190].

Seedlings can suffer from hypoxia (inadequate oxygen) because of excess water in the upper soil horizon. If corrective measures are not taken, growth may be reduced. This can occur at nurseries located on fine-textured soils (< 75% sand) where both surface drainage and percolation are poor. Percolation can also be reduced by machine lifting during wet weather, which tends to destroy the structure of fine-textured soils. When percolation rates are low, hypoxia may result from either excessive irrigation or periods of rainy weather. Some nursery managers tend to keep their soil wetter than field capacity [13I, 161] because they do not monitor soil moisture. In some situations, excessive irrigation will reduce shoot height and shoot weight [161, 202].

6.3.4 Reducing the Number of Culls

Seedlings that do not meet the minimum specifications of an ideotype are "culls". Culls include seedlings with (1) disease, (2) mechanical injury, (3) small root-collar diameter (see 6.4), or (4) excessive height (see 6.5.2). Diseased seedlings could include trees with fusiform rust or black root rot (see Chapter 20, this volume). Infection from fusiform rust can be reduced by treating the seed with the fungicide triadimefon [104, 105] along with proper timing of fungicidal sprays [141]. Soil contaminated with black root rot should be fumigated with methyl bromide containing 33% chloropicrin [175]. Mechanical injury can be caused by improper root pruning or improper lifting [167]. When lifting under less than ideal conditions, half the lateral roots can be stripped from the seedlings [224].

6.4 Improving Diameter Growth

Generally, there are four reasons why seedlings do not grow large enough in diameter: (1) seed sown too close together, (2) seed germinating late, (3) insufficient nitrogen, and (4) excessive stress. However, the nursery manager can use several cultural practices to increase diameter growth.

6.4.1 Growing Density and Seed Spacing

Growing density (number of surviving seedlings per square meter) has the same effect on the diameter growth of all southern pine species. High densities produce more seedlings with smaller diameters than do low densities (Fig. 6.2; [30]). Although the relationship varies depending on other management practices (e.g., fertilization), in general there appears to be a curvilinear relationship between growing density and diameter (Fig. 6.5). The overall outplanting performance generally improves when seedlings are grown at lower densities [4, 10, 37, 42, 53, 90, 152, 166, 172, 177, 178, 206, 214, 215]. As an example, when field performance of longleaf pine was consistently poor, nursery managers decided to lower the growing density to < 120/m² to improve seedling quality. To improve field performance of loblolly and slash pine, managers of the Ashe Nursery lowered the density to about 200/m².

Although we often talk about the average growing density, it is the median distance between seed within the seed row that is the critical factor. For any given density, the median spacing between live seeds depends on the number of drills per bed, the type of sower, and the amount of empty and dead seed sown. For example, when seed are sown precisely at 300/m², they might be 2.2 cm apart (for 8 single drills/bed), 4.4 cm apart (for 8 "offset-double" drills/bed), or 5.5 cm apart (for 20 single drills/bed). When seed are sown at the same density, seedlings growing at wider spacings will exhibit larger diameters [89], and there will be fewer culls, than when seedlings are grown closer together. This may be why seed efficiencies are better with broadcast beds than with beds sown in eight narrow drills [3, 128]. This is also why seeds have often been sown in double drills (a row of seedlings made up of two drills, 2 to 4 cm apart) since the turn of the 20th century [198].

Recently developed vacuum sowers are better at seed placement than standard drill sowers [34, 75, 215] because vacuum sowers avoid sowing seed in clumps. Therefore, when sowing in drills, the median distance between seed will be greater with vacuum sowers (especially ones designed with double drills) than with older drill sowers. The cull percentage can be reduced when seed are not sown in clumps. At some nurseries, a precision sower can pay for itself after sowing only 22 ha of seedbed (assuming a reduction in culls of 4 percentage points [34], a density of 200 seedlings/m², and a price of 3 cents/seedling). Due largely to the economics of precision sowing, more than 17 nurseries in the South now have vacuum sowers.

The value of vacuum sowers is predicated on sowing only high-quality seed. Because only one seed is sown per spot with vacuum sowers, empty or damaged seed should be removed before sowing because the median distance between pure live seed will decrease when empty seed (pops) are sown along with viable seed. For loblolly pine, pops can be removed by flotation in water because viable seed sink. Several managers of loblolly pine nurseries operationally remove pops by flotation. Liquids of various densities can be used to remove the pops from other southern pine species (see Chapter 4).

6.4.2 Time of Emergence

Seedling root-collar diameter at lifting is a function of seedling emergence date. In general, the more growing days a seedling has, the larger it will become. In fact, loblolly and slash pine seedling growth models use only the number of days since emergence to predict seedling weight [64]. Sowing loblolly or slash pine seed in March or early April results in seedlings with larger average diameters and fewer culls than sowing in May or June [31]. Fall sowing of longleaf pine not only results in larger seedlings than spring sowing, but sometimes can also improve outplanting survival [176].

Competition from early emerged seedlings can significantly impair the diameter growth of late emergers. For seedlings sown in April, a 14-day delay in emergence can reduce a seedling's diameter by 1.5 to 5% for each lost day [32, 35, 139]. Therefore, to increase seedling uniformity and reduce the number of culls, it is important to have uniform germination. Uniformity of germination can be improved by seed sizing or density grading, family sowing, and proper stratification.

In general, germination speed is related to seed size because larger seed tend to germinate quicker than small seed. Seedling uniformity can be improved by sizing seed before sowing [66]. Without sizing, the large seed would germinate first and suppress the later germinating small seed.

The relationship between germination speed and seed weight applies, to some extent, across species. For example, Wakeley [223] stated that for spring sowing, shortleaf pine (100,000 seed/kg) should be sown first, then loblolly pine (40,000 seed/kg), and finally slash pine (29,000 seed/kg). In Florida, sand pine (165,000 seed/kg) should be sown either in the fall or in March.

In general, orchard seed are larger and tend to germinate

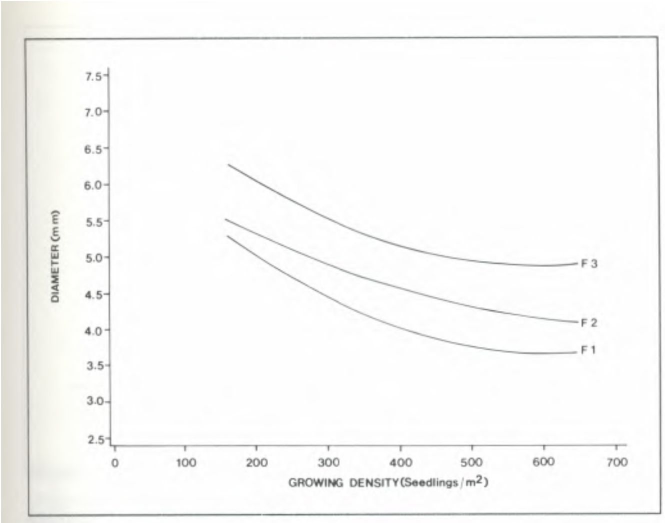

Figure 6.5. Response of loblolly pine seedling root-collar diameter to growing density and fertilization: Fl = 84 kg of nitrogen (N), 25 kg of phosphorus (P), and 70 kg of potassium (K) per hectare; F2 = 168 kg N, 49 kg P, and 139 kg K/ha ; F3 = 366 kg N, 99 kg P, and 278 kg K/ha [unpubl. data, 207].

quicker than seed collected in the woods. However, genetics can also influence emergence. Some larger seeded, half-sibling families germinate slower than other small-seeded families. This again illustrates that seedling uniformity can be further improved when sowing half-sibling families [226].

As previously mentioned, extending the length of cold stratification beyond what has traditionally been recommended (30 days for loblolly and shortleaf and 0 days for longleaf, slash, and sand pine) usually improves the speed and uniformity of germination of most good seedlots. Improving germination speed increases average seedling diameter, whereas improving germination uniformity reduces the percentage of seedlings with very small or very large diameters.

6.4.3 Nitrogen Fertilization

The available supply of nitrogen (N) affects diameter growth. The N supply, however, is affected by the type, amount, timing, and method of applying fertilizer, competition from weeds and other seedlings, level of microbial activity, soil texture, and amount of rainfall and irrigation. Up to a point, applying additional N usually increases the average diameter of loblolly seedlings (Fig. 6.5).

Additional N often improves the height:diameter ratio of seedlings. For example, shortleaf seedlings given 170 kg/ha of N were 5% larger in diameter and 6% shorter than seedlings given 110 kg/ha [37]. In Florida, slash pine seedlings given 235 kg/ha of N were 14% larger in diameter and only 3% (7 mm) taller than seedlings given 90 kg/ha [unpubl. data, 227]. At the New Kent Nursery in Virginia, 4 years of nursery studies with loblolly pine showed that increasing N from about 300 to 600 kg/ha increased diameter, but not height growth [unpubl. data, 56]. In most years, height growth decreased with extra N.

The amount of N available to any given seedling depends on how much is used by neighboring plants. When weeds are controlled, growing density plays an important role in N availability. As density increases, more fertilizer per hectare is required to maintain seedlings at a given diameter. For example, increasing fertility can compensate for increasing growing density (Fig. 6.5). For this reason, fertilizer recommendations in South Africa [63] are made on a per-seedling basis (i.e., milligrams of N per seedling) instead of on an area basis, which does not consider growing density.

Seedlings use only a percentage of the total N actually supplied. Nitrogen also is used by soil microbes and is leached by rainfall and irrigation. Extra N is required when microbes are decomposing large amounts of organic matter low in lignin or if irrigation or rainfall is excessive. N is more quickly leached from sandy than fine-textured soils.

6.4.4 Stress

The growth rate of young seedlings (5 weeks after germination) can be decreased by stress from heat and lack of moisture. Such stresses can occur in early June on sandy, unmulched soils without irrigation or where irrigation water is poorly distributed. These seedlings do not recover quickly because the severe stress causes physiological changes that are difficult to overcome with irrigation or fertilization. Subsequent growth of these seedlings is slow, and they do not catch up to unstressed seedlings. Mulching can help buffer seedlings against early stress. Use of a mulch that is not easily washed away (pine bark) can reduce soil temperatures and can help retain soil moisture. Otherwise, the nursery manager must ensure that uniform irrigation is applied to prevent early seedling stress.

Growth of older seedlings (4 to 8 months after germination) can also be decreased by a lack of soil moisture. When moisture stress occurs during the summer or fall, physiological processes such as photosynthesis, carbohydrate metabolism, and cell expansion are affected. In some cases, withholding irrigation can reduce photosynthesis to the point where root weights are decreased by 15 to 56% [116, 150, 154, 174, 229]. In Florida, the concentration of starch in the roots was decreased by reducing available water during the late fall and early winter [135]. At another nursery in Florida, withholding irrigation during the fall reduced growth and resulted in 4% more culls, equivalent to a loss in seedling sales of $2,500/ha [195]. Therefore, nursery managers should be careful not to decrease either seedling quality or quantity by overstressing seedlings.

6.5 Improving Shoot Quality

6.5.1 Shoot Mass

Average seedling shoot mass has changed tremendously since May [129] reported the effects of growing density on seedling dry weight (Fig. 6.6). The observed increase in

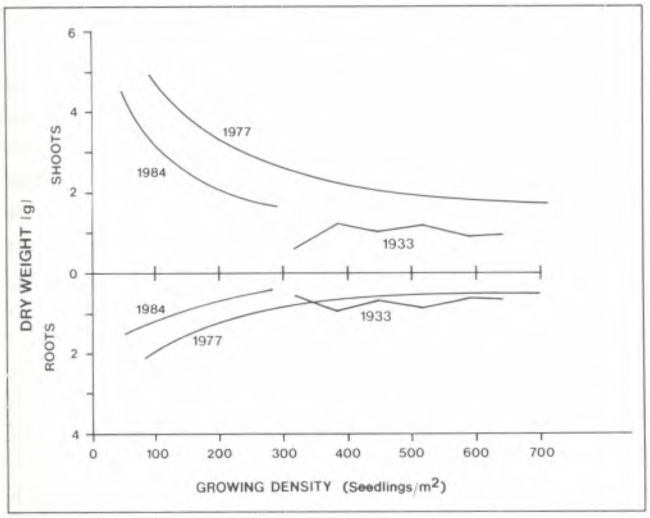

Figure 6.6. Effect of growing density on shoot and root dry weight of loblolly pine seedlings (adapted from [87, 129, 189]); note years associated with cuvres.

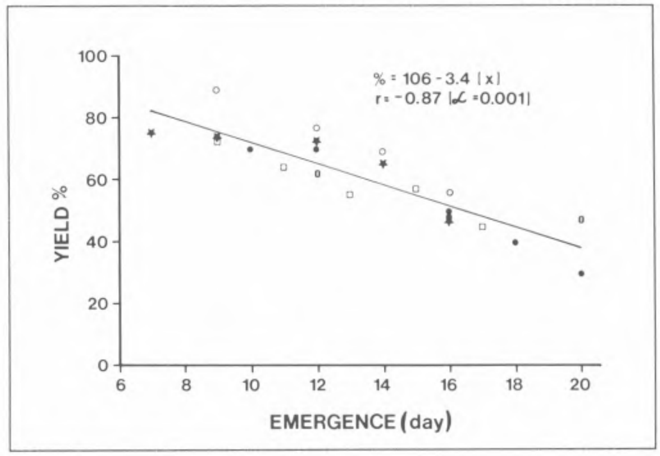

Figure 6.8. Effect of time of emergence on plantable seedling (diameter > 3 mm) yield, where yield = number of plantable seedlings per number seedlings that emerge on that date and survive until lifting; Ft. Towson, Okla. (*, 0), Magnolia, Ark. (❑, 0) and Albuquerque, N.M. (S) [147].

shoot mass of today's seedlings relative to that reported in May's study could be the result of various changes in management practices, such as seed stratification, fertilization, and improved genotypes. In addition, nursery managers are irrigating more than in the past. Regardless, the differential increase in shoot mass can affect field performance.

6.5.1.1 Sowing date

Date of sowing has a dramatic effect on shoot biomass. Mexal [139, 141] analyzed data from Rowan and Marx [unpubl. data, 169] and found that seedling biomass decreased 1% for each day sowing was postponed beyond April 15. That is, over a 60-day sowing season, seedling biomass decreased 60%. Boyer and South [32] examined sowing earlier than April 15 and found that biomass production per unit area was maximized by sowing in mid-March (Fig. 6.7).

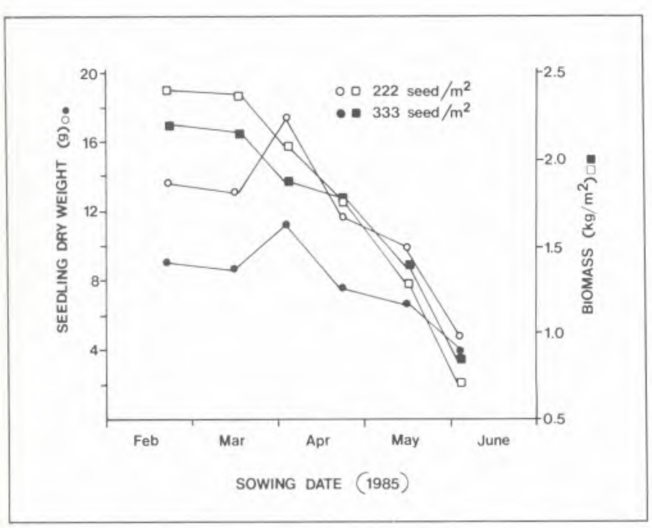

Figure 6.7. Effect of sowing date on individual seedling dry weight and biomass per unit area for loblolly pine [32].

6.5.1.2 Time of emergence

In addition to sowing date, the actual time of emergence after sowing can influence seedling size [32, 35, 139, 147]. Emergence of properly stratified loblolly pine usually begins 10 to 15 days after sowing and is complete about 20 to 25 days after sowing. Over a 10-day emergence period, seedling biomass can decrease up to 3.5%/day. That is, seedlings emerging on the last day could be about 35% smaller than those emerging on the first day. Decreased seedling size with TOE results in decreased yield (number of seedlings with diameter > 3 mm) because most culls (seedlings with diameter <3 mm) in a seedbed are a result of TOE.

Late emergers suffer greater mortality in the nursery [27, 147] than do early emergers (Fig. 6.8). In a test at three nurseries, Mexal and Fischer [147] found that nearly all early emergers survived to harvest and more than 80% were packable, whereas late emergers suffered up to 50% mortality and only 40% of the survivors were packable. As mentioned previously (6.3.2), longer stratification can reduce the variation in time of emergence.

6.5.1.3 Growing density and fertilization

Fertilization can offset the loss in seedling biomass when growing density is increased [206]. Doubling seedbed density (from 161 to 323/m^2) can reduce seedling weight by 1.7 to 2 g (Fig. 6.9). However, this weight loss can be regained by substantially increasing the fertilization rate.

6.5.2 Shoot length

The range of desired shoot length has become more restrictive since Wakeley [220] first developed seedling grades for southern pines. Wakeley [220] proposed shoot

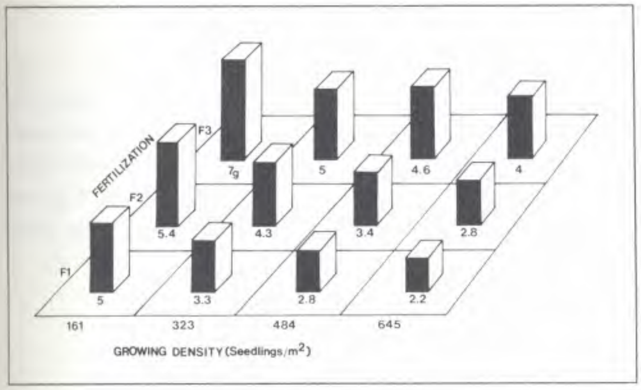

Figure 6.9. Response of loblolly pine seedling dry weight (values at base of bars, g) to growing density and fertilization: Fl = 84 kg N, 25 kg P, and 70 kg K/ha ; F2 = 168 kg N, 49 kg P, and 139 kg K/ha; F3 = 336 kg N, 99 kg P, and 279 kg K/ha [74].

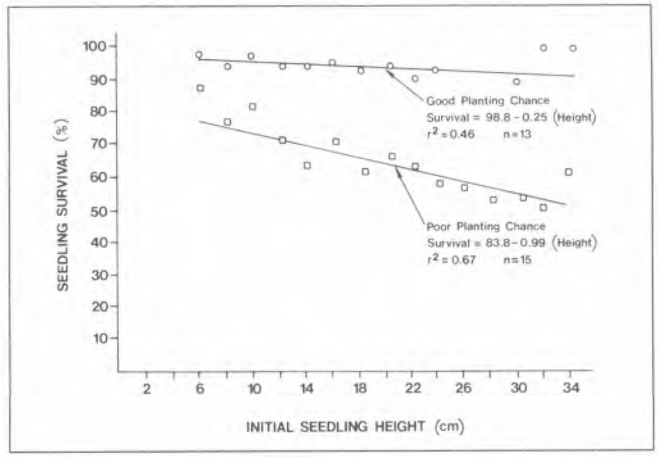

Figure 6.10. Relationship between seedling survival after two seasons and initial seedling height after planting for poor and good planting chances [212].

lengths of 12 to 36 cm; more recent recommendations are 20 to 25 cm [45]. However, Hunt and Gilmore [97] found that seedlings up to 60 cm (in length) grew more than shorter seedlings. Baker et al. ([9], cited in [192]) found seedling length to have no effect on survival or growth on wet to mesic sites. However, tall seedlings (mean height = 31 cm) did not survive or grow as well as shorter seedlings (mean height < 20 cm) on droughty sites.

Tuttle et al. [211, 212] found strong negative correlations between seedling survival and seedling height after planting on sites where survival was < 75% (Fig. 6.10). Where survival was > 75%, initial height minimally affected survival. Furthermore, height growth was best when heights after planting were 15 to 20 cm. Because seedlings are usually planted below the original groundline, actual seedling heights in this study may have been 2 to 4 cm greater than reported. To obtain high survival with poor planting and maximum growth with good planting, the optimum seedling height from nursery groundline should be 15 to 25 cm.

Many factors can influence seedling height in the nursery. Growing density is one of the few that usually does not, at least for densities of 100 to 800/m^2. However, sowing date can exert strong control over seedling height [32, 100]. Obviously, the longer the growing season, the taller the seedling. Late-sown seedlings simply run out of short nights (night length regulates height growth). However, the growing phenology can be different [32]. Seedlings sown in early April completed more than 90% of their height growth by September 1; however, seedlings sown in early June completed only 50%.

Irrigation can sometimes be used to control height growth. Stem elongation is sensitive to mild water stress [201]. When rainfall patterns permit, height growth may be regulated by withholding irrigation during summer months. When rainfall keeps soil moisture high, roots can be undercut (during active shoot elongation) to limit height growth. However, if seedlings have already set bud in late summer, undercutting will have no effect on shoot length [140, 219].

Top pruning can also control height, but must be timed properly. Late top pruning may prevent terminal bud formation before lifting. Seedlings top pruned early have time to recover and may exhibit greater height growth at the end of the season than their unpruned neighbors [146].

6.5.3 Nutrient Content

Although seedling survival can be increased when nursery fertilization increases root volumes, root weights, or root-growth potential, survival is usually not strongly correlated with foliar N levels [112, 113]. However, foliar nitrogen can be important for early growth. Third-year height of loblolly seedlings has been positively correlated with the amount of foliar N [112, 206]. Some recommend late-season fertilization to improve the nutrient status of seedlings before lifting [21, 41, 62, 95]. In some cases, growth responses from nursery fertilization have lasted 8 to 16 years [4, 74, 95].

6.5.4 Secondary Needle Development

Few studies have examined the importance of needle development on seedling survival and growth. Young emerging seedlings develop only primary or juvenile needles. In mid- to late June, secondary or fascicled needles develop in the axis of primary needles [223], intermittently at first and then, as the seedling elongates, in many of the axes in the upper part of the shoot. After outplanting, secondary needles can be important for growth because, when under moderate stress, most of the primary needles desiccate and become nonfunctional.

Grigsby [82] developed seedling shoot classes that included only needle and terminal bud development. After 10 years in the field, the best grades produced 47% more volume than "typical 1+0 nursery stock." The grade which grew poorest was likely the smallest in overall size, had no terminal bud, and had only primary needles (turkey feather). The best grades were likely the largest in overall size and had long secondary needles and/or long terminal buds.

6.5.5 Terminal Bud Development

During the year, the terminal bud passes through several morphological and physiological stages (see Chapter 8, this volume). However, bud dormancy status cannot be determined simply by examining bud morphology. For some tree species, a bud can pass from an ecodormant state (regulated by insufficient soil moisture), to a paradormant state (regulated by photoperiod), to an endodormant state (regulated by internal hormonal status), and back to an ecodormant state (regulated by temperature), without changing morphologically [109]. Although terminal buds of loblolly pine may remain closed for approximately 6 months, they may be in a relatively dormant state (as measured by rate of budbreak in a greenhouse) for a relatively small portion of the time [33, 230].

Under some situations, bud dormancy status can be correlated with survival. Larsen et al. [111, 113] reported greater field survival and greater root-growth potential when terminal buds were apparently in an ecodormant state (buds flushed quickly under greenhouse conditions). Johnson and Barnett [99] also reported root-growth potential to be greater on seedlings that broke bud quickly after transplanting. However, for the southern pines, a causal relationship probably does not exist between bud dormancy and root-growth potential. Although loblolly pine seedlings lifted with terminals in an endodormant state may not tolerate cool storage as well as seedlings that have passed through that stage, it is likely that the stage of bud dormancy does not directly affect the seedling's ability to withstand cool storage [44].

Although some consider the presence of a winter bud a requirement of a quality seedling [18, 36, 38, 49], most studies that compare seedlings with winter buds to those with immature buds support Wakeley's [223] conclusion that lack of a winter bud seldom explains low initial survival [54, 82, 83, 173]. In one study, survival and growth were poorer for seedlings with immature buds than for seedlings that had a bud, or a bud that had broken dormancy, or a bud that was actively reshooting [7]. However, other studies also comparing seedlings of equal size found that presence of a winter bud did not increase early growth in the field [54, 222; pers. commun., 148].

For loblolly pine, the formation of winter buds depends to some extent on seedling size. Even under long photoperiods, once a loblolly pine seedling reaches a critical size, or plastochron age, it will stop elongating and set a bud [32, 43]. Therefore, winter buds are "almost never present" on small cull seedlings [223]. However, winter buds are often present on plantable seedlings unless they have been sown late or top pruned after mid-September. Because the formation of a winter bud is related in part to seedling size, studies that compare bud types should either compare seedlings of equal size [e.g., 54, 222] or use covariance analysis [e.g., 230] instead of confounding seedling size with bud type [e.g., 82].

Cultural practices that affect seedling size (e.g., sowing date and high seedbed density) can affect the percentage of seedlings that form buds. Bud formation is also influenced by practices such as undercutting, and withholding irrigation and fertilization. In addition, a chemical growth regulator (benzyladenine) can be used to quickly cause seedlings to form buds.

6.6 Maintaining Shoot Quality

6.6.1 Top Pruning

Southern pine seedlings grown in the nursery often cease terminal growth in midsummer. If conditions are favorable, the bud elongates and initiates a summer shoot. Consequently, more than 90% of nursery managers top prune seedlings [68], most from June through August, some as late as October. Most nursery managers prune to control height; others prune to increase the R:S ratio or improve uniformity.

Late top pruning may preclude the formation of a new terminal bud before lifting. While the presence of a well-formed terminal bud *per se* is not requisite for successful reforestation, the presence of an apical dome can be important to height growth during the first field growing season. Time required to produce a new terminal on a seedling top pruned late can delay the initiation of height growth.

Top pruning may be beneficial because it improves the uniformity of seedling height and shoot fresh weight [146]. However, it does not improve root-weight uniformity, and if care is not taken to regulate height growth following top pruning, the effects on uniformity may be lost. Top-pruned seedlings are the tallest in the nursery bed and, consequently, have a great capacity for growth after transplanting. Despite the 3-week check in height growth caused by top pruning [55], these seedlings may still be the tallest in the nursery at the end of the growing season. Mexal and Fisher [146] reported top-pruned seedlings grew 11 cm after pruning. Unpruned plantable seedlings in the same population grew only 5 cm, and cull seedlings grew < 4 cm after pruning. In this study, minimal N was applied, and therefore cull seedlings were not released by top pruning and did not grow into packable size.

Although top pruning removes little stem biomass, it can remove many secondary needles [146]. On harsh sites this may be beneficial [55] because survival can be improved by decreased transpirational surface area. However, on mesic sites this can reduce early growth potential. The greater the needle surface area, the greater the growth, and removing too many secondary needles will reduce root-growth potential.

6.6.2 Storage

With sufficient chilling, seedlings are usually not harmed

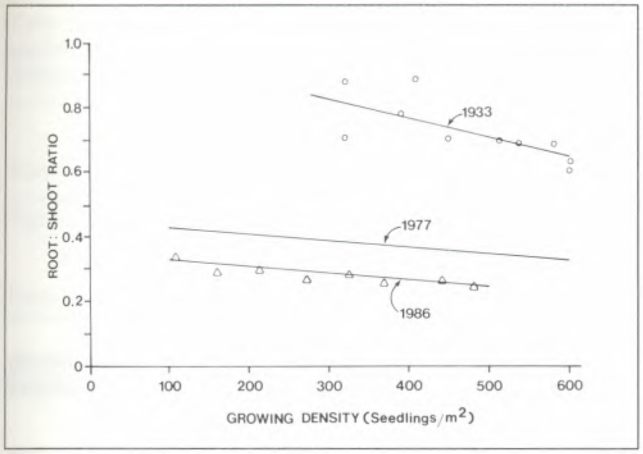

Figure 6.11. Relationship over time (note years associated with curves) between growing density and root and shoot weight for loblolly pine (adapted from [87, 129, 1661).

by up to 12 weeks of cool (1 to 2°C) storage [44, 76]. However, shoots may be damaged if clay slurry accumulates in the bottom of the bag. Seedlings left too long in standing water (with or without clay) will die regardless of storage temperature. Furthermore, seedlings with insufficient moisture in either bags or bundles can desiccate, so moisture during cool storage should be monitored carefully (see Chapter 16).

6.7 Improving Root Quality

6.7.1 Root Mass

Earlier stock-quality studies virtually ignored root parameters. Most morphological traits referred exclusively to the shoot [82, 221, 223]. This failure to quantify differences in the root system might have explained the occasional instance of Grade 2 seedlings from one bed surviving better than Grade 1 seedlings from another [185].

For a given seedbed density, root mass of the average southern pine seedling has not changed dramatically since 1933 (see Fig. 6.6). The lack of improvement in root weight, coupled with large increases in shoot weight, has substantially changed the balance between roots and shoots of seedlings. The R:S ratio of loblolly pine seedlings has decreased greatly over time, regardless of growing density (Fig. 6.11). In 1933 [129], the R:S ratio ranged from 0.61 at the highest density (600/m^2) to 0.89 at the lowest density (320/m^2); by 1986, it had decreased to 0.25 (480/m^2) to 0.34 (110/m^2) [166].

This decrease in seedling R:S ratio with increasing seedling size is inconsistent with the concept that R:S ratio tends to increase with increasing size [116]. However, Satoo [171] reported that the R:S ratio of three conifer species remained relatively constant as size increased. For loblolly pine, Boyer and South [29, 32] reported smaller R:S ratios for taller seedlings. In all of these studies, attempts were made to estimate or capture all root biomass.

Table 6.2. Effect of root pruning loblolly pine after lifting on field performance [59, unpubl. data, 84; 142].

Location	Pruning regime	Age in field, yr	Mortality, %	Height, cm
Alabama				
(Piney Flats)		2		
	None		9	75
	Moderate		12	77
	Severe		16	72
(Piney Flats South)		2		
	None		3	64
	Moderate		4	56
	Severe		5	58
(Germany Branch)		1		
	None		4	31
	Moderate		7	29
	Severe		11	28
Arkansas[1]		1		
	None		0	16
	Light		0	13
	Medium		5	13
	Heavy		16	11
Virginia				
(Ideotype A seedlings)		3		
	None		5	159
	Moderate		8	154
	Severe		13	143
Virginia				
(Cull seedlings)		3		
	None		20	126
	Moderate		19	125
	Severe		26	124

[1] Height data for Arkansas are reported as height growth.

In reality, up to half of the root system can be lost during the lifting process [224]. It is, therefore, reasonable to assume that the larger seedlings may have suffered disproportionately more root loss during lifting. Even though the roots of larger seedlings may have explored greater rooting volume during the growing season, the volume of roots lifted at harvest may be the same, regardless of seedling size. For example, although studies with loblolly pine have demonstrated that inoculation with *Pisolithus tinctorius* can increase seedling size, the R:S ratio (fresh-weight basis) decreased in half of the studies (see 6.7.5). Apparently, attempts to increase concomitantly both root and shoot biomass may be frustrated by physical limitations when operationally lifting roots.

Few studies have examined the effect of root biomass *per se* on field performance. For most studies, root biomass is confounded with either growing density [91, 166, 206], root pruning regime [59, 144], nursery [111, 113, 167], or genotype [20, 83]. However, in general, seedlings with more roots tend to survive better than those with fewer roots (Table 6.2).

6.7.1.1 Sowing date

The length of the growing season influences total seedling biomass [32, 141] and biomass partitioning. Root biomass can be decreased when sowing is delayed until

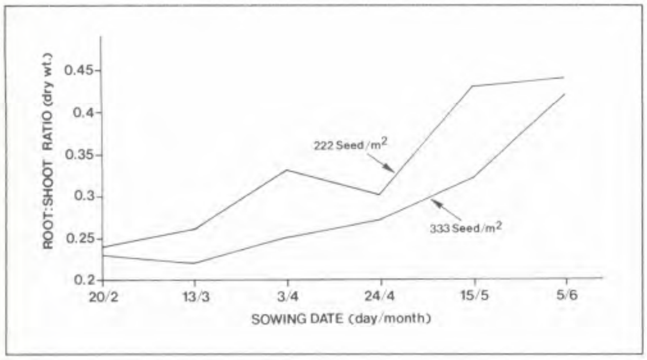

Figure 6.12. Effect of sowing date and density on root:shoot ratio of loblolly pine seedlings lifted in February. Seedlings were not undercut or root wrenched [32].

May [140] or June [32]. However, a delay in sowing decreases shoot biomass more than root biomass. Consequently, late sowing tends to increase the R:S ratio (Fig. 6.12), possibly because shoot growth can be inhibited in the summer by the stress of high temperatures, and in the fall by declining photoperiods. In addition, root weight usually increases substantially in the fall and winter with cool nighttime temperatures.

Time of sowing not only influences biomass partitioning but also the type of root formed. A 23-day delay in sowing reduced lateral root biomass 40% and increased taproot biomass 9% [140]. Apparently, delayed sowing tends to create more of a carrot like taproot to the detriment of lateral root development. A lack of lateral root development can decrease field survival (see 6.8.1).

6.7.1.2 Growing density

Regardless of sowing date, sowing at a low seedbed density improves the R:S ratio (Figs. 6.11, 6.12, and 6.13). This could explain why seedlings grown at low seedbed densities usually survive better when outplanting conditions

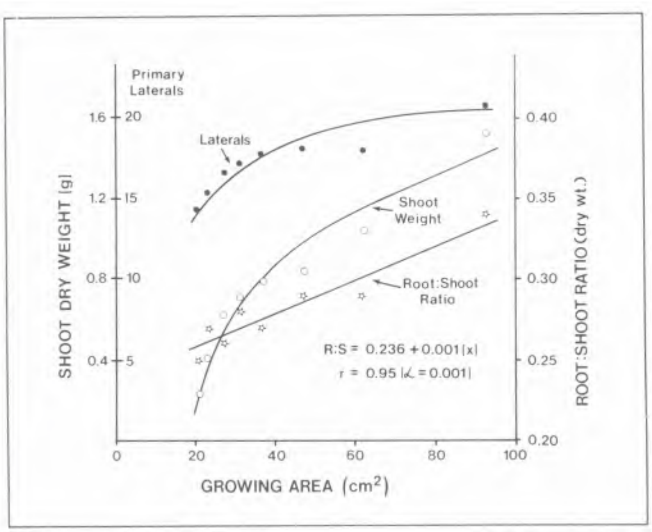

Figure 6.13. Effect of growing area on shoot dry weight, number of primary laterals, and root:shoot ratio of loblolly pine seedlings (adapted from [166]).

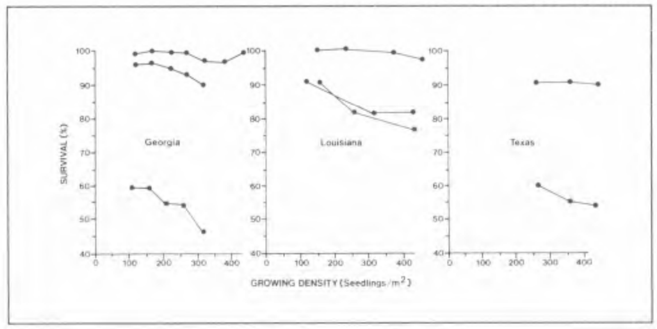

Figure 6.14. Effect of growing density on survival of loblolly pine seedlings in Georgia, Louisiana, and Texas (adapted from [152, 166, 178]).

are less than ideal for good survival (Fig. 6.14). The improvement in the R:S ratio occurs because growing density is perhaps the strongest determinant of root biomass (Fig. 6.6). Reducing the growing density from 400 to 160/m² can increase the proportion of roots by 65 to 100% [37, 45, 166]. However, root biomass is relatively insensitive to growing densities above 400/m²; below 400/m² it responds curvilinearly to decreasing density. For southern pines (except longleaf), Mexal [138] proposed a growing density of 200/m² to maximize seedling size with minimum loss of seedling yield. This density also tends to optimize seedling root biomass.

6.7.1.3 Fertility

Increasing N fertility generally results in larger seedlings with a correspondingly greater root biomass [80, 96, 205, 208]. Switzer and Nelson [206] reported that both seedling weight and root weight at lifting were highly correlated with height growth 3 years after outplanting. Root weight accounted for more than 81% of the variation in height growth after 3 years. Furthermore, this difference in initial seedling morphology was correlated with individual-tree volume differences at 16 years [4].

6.7.1.4 Root pruning

Root pruning in the seedbed includes wrenching, undercutting, and lateral root pruning (root pruning after lifting is covered in 6.8.1). In wrenching and undercutting (the terms often are used interchangeably in the U.S.), the taproot is severed; however, wrenching causes greater soil disturbance because a fixed, thick (> 10 mm) blade is used. Few nurseries in the South practice true undercutting, which uses a reciprocating, thin (< 8 mm) blade. However, a reciprocating blade is usually required when cutting the taproot at a shallow depth (to about 8 cm). Lateral root pruning is accomplished with rolling coulters run between seed drills.

Undercutting usually does not alter the amount of roots harvested at lifting [140, 209, 225]. However, it does alter the ratio of lateral root biomass to taproot biomass. Tanaka et al. [209] reported that frequent wrenching increased the proportion of lateral roots from 43% for unwrenched

Table 6.3. Mortality caused by root removal for three southern pine species; base survival adjusted to 100% [adapted from 124, 144, 223].

Root part	Treatment	Mortality, %	
		Loblolly/Slash	Longleaf
Taproot	Prune to 15 cm	0	0
	Prune to 10 cm	0	0-10
	Prune to 5 cm	7-11	8-15
Primary laterals	Prune to 5 cm	Up to 25	Up to 15
	Remove 1/2	40-53	1-36
	Remove all	44-99	27-82
Mycorrhizae	Remove 1/3	15	17
	Remove 2/3	30	33
	Remove all	42	48

seedlings to 60% for seedlings wrenched monthly. Mexal [136] found that timing and frequency of undercutting could increase the proportion of lateral roots up to 80%.

This increase in lateral root weight is not accompanied by an increase in number of primary lateral roots, but rather is the result of greater fibrosity of the secondary and tertiary laterals. Greater root fibrosity yields greater hydraulic conductivity [45], which should lead to improved survival and growth.

6.7.2 Taproot

Southern pine seedlings have dominant taproots. However, with the exception of longleaf pine, their primary purpose in the nursery is to serve as the scaffold for lateral root attachment. Taproots can be pruned to 5 cm with few deleterious effects (Table 6.3). It is unnecessary for taproots to be any longer than 15 cm; in fact, there are probably disadvantages to having taproots longer. Long, flexible taproots are difficult to place in the planting hole correctly. Consequently, J- or L-rooting is more prevalent with long taproots. Under certain situations, this could result in future instability and windthrow.

Stiffness of the taproot is a function of length and root-collar diameter. Ideally, the distal tip of the taproot should be at least 1.5 mm in diameter to have enough stiffness to preclude J-rooting. To meet this target, a seedling should have a minimum root-collar diameter of 3 mm and a taproot length of 12 cm, or a diameter of 4 mm and a taproot of 15 cm [unpubl. data, 142].

6.7.3 Primary Lateral Roots

The number of primary lateral roots formed on a seedling is apparently under genetic control [20; pers. commun., 106] and cannot be increased by lateral root pruning [217]. However, radial growth of the primary laterals can be affected by growing density [91, 159, 166], fumigation [85], soil texture [176], and, possibly, soil temperature [151].

Decreasing seedbed density increases the number of large, first-order lateral roots for all southern pines, including longleaf [91]. In one study with loblolly pine, the number of laterals increased from 14 at a growing area of 21 cm^2 to 21 at a growing area of 92 cm^2 (Fig. 6.13). However, this effect may be simply due to differences in seedling size. Growing area had no effect on the number of lateral roots when seedlings of the same size were compared [85]. In situations where seedling size is increased by soil fumigation, the number of large, lateral roots will also be increased [85].

Shipman [176] reported that longleaf pine seedlings grown in sandy soils had 10 more laterals than seedlings grown in sandy clay soil. As a result, survival following outplanting was lowest when the seedlings were grown in soil with < 40% sand. Thus, nursery soil texture can affect longleaf seedling quality.

Nambiar et al. [151] indicated that the number of lateral primordia per unit length of taproot was a function of temperature. At higher temperatures, greater elongation resulted in fewer primordia per unit length; the opposite occurred at lower temperatures. Therefore, earlier sowing would tend to maximize the number of primary lateral roots over the upper 15 cm of taproot.

The baseline number of primary laterals is important to future seedling survival and growth [91, 165, 166]. Unavoidably, some laterals are lost during lifting, sorting, packaging, storage, and planting. However, a 50% reduction from a baseline of 20 laterals is much less severe than the same loss from a base of only 10 laterals. More than 30 years ago, Wakeley [223] showed the importance of lateral roots to survival (see 6.8.2). Furthermore, Mexal and Burton [143] reported that height up to 4 years from planting was correlated with the number of laterals. These authors also noted that no new primary laterals developed from the original root system; they developed instead on new roots formed after planting.

6.7.4 Higher Order Laterals

Higher order lateral roots are secondary long roots emanating from primary laterals and tertiary long roots emanating from secondary laterals. These fine roots are involved directly in nutrient and water absorption and support mycorrhizae (see 6.7.5). During the establishment phase of bareroot seedlings, such roots absorb water until new roots develop. Carlson [45] reported a seedling with well-developed, higher order laterals may have 3.5 times more root volume, but can absorb 7 times more water. This greater root volume also increases root-growth potential [45], presumably because there are more sites from which new roots can develop.

The number of higher order laterals (fibrosity) can be increased by lowering seedbed density, by undercutting, and, for some species, by lateral root pruning. Rowan [166] found that "small root weight" could be doubled by increasing the growing area from 25 to 63 cm^2/seedling (growing densities of 400 to 160/m^2, respectively). Undercutting not only reduces shoot growth, but also increases root fibrosity [152]. The subsequent improvement in R:S ratio improved survival of seedlings planted on

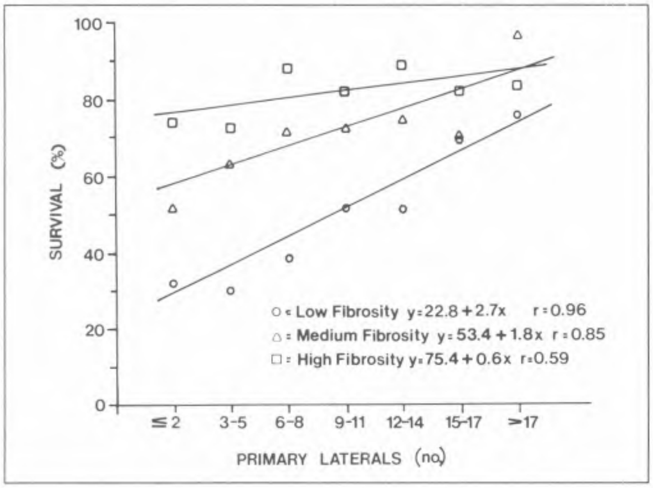

Figure 6.15. Interaction between root fibrosity and number of primary lateral roots for first-year survival of longleaf pine seedlings (adapted from [91]).

droughty sites [152]. For longleaf pine, both root fibrosity and field survival can be greatly increased with lateral root pruning [90, 91].

For survival of longleaf pine seedlings, Hatchell [91] found a strong interaction between root fibrosity and number of primary laterals (Fig. 6.15). Survival of seedlings with low fibrosity increased 1.3% for each additional lateral root. However, survival of seedlings with high fibrosity was not significantly improved by increasing the number of primary laterals.

6.7.5 Mycorrhizae

The mycorrhizal structure is a symbiotic association between the tree root and a fungus. This symbiosis promotes absorption of water and phosphorus (P). However, the symbiosis can sometimes be lacking at nurseries when ectomycorrhizal seedlings are grown for the first time on new ground (soil that has not previously produced such a crop) [5, 194]. The stunted seedlings exhibit classical symptoms of P deficiency. In seedbeds that have previously produced ectomycorrhizal seedlings, the mycorrhizal inoculum normally is adequate, even after fumigation with a combination of methyl bromide and chloropicrin. Although effective fumigation can destroy much of the natural inoculum in upper soil layers, it usually does not eliminate that in soil below 15 cm. While fumigation may delay the timing of mycorrhizal infection [52, 127], it typically does not prevent it.

Many studies have examined the response to artificial inoculation with the mycorrhizal fungus *Pisolithus tinctorius* (Pt). Depending upon the objectives, the nursery manager may choose vegetative inoculum [123], spores [126, 127], or spore pellets [119]. However, since the use of the fungicide triadimefon can greatly reduce the amount of infection with Pt [121], alternative fungicides to control rust may be required when using artificial inoculation.

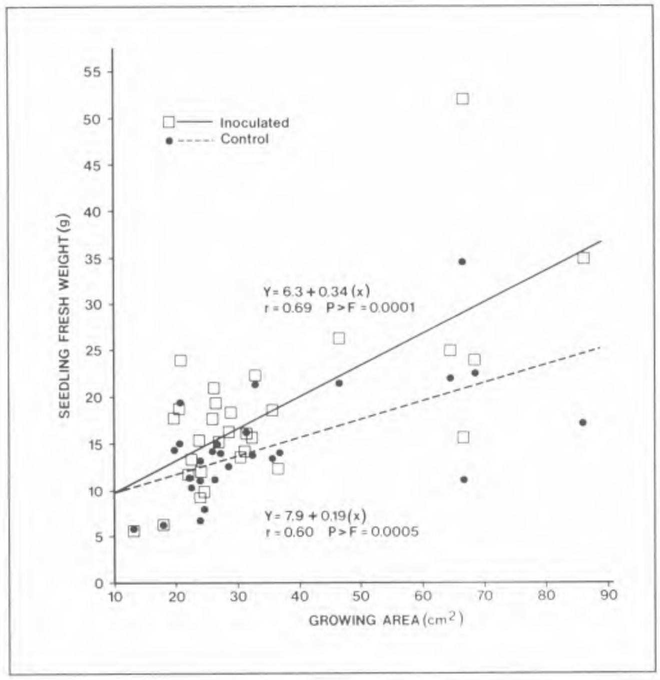

Figure 6.16. Interaction between growing area and inoculation with *Pisolithus tinctorius* for weight of southern pine seedlings (loblolly, slash, Virginia, and shortleaf) (adapted from [123]).

6.7.5.1 Nursery response to *Pisolithus tinctorius*

A nationwide trial with commercially produced Pt inoculum [123] illustrated a diversity of nursery-management practices. Therefore, the benefits of artificial inoculation with Pt were not universal. The number of plantable seedlings was significantly increased in less than half the studies with southern pines (Table 6.4). In 13 of 20 tests with loblolly pine, inoculation with Pt after fumigation resulted in significantly increased seedling biomass, compared to natural infection (Table 6.4).

However, growth response from artificial inoculation with Pt may depend on seedbed density. A trend toward greater increase in seedling weight was evident at lower seedbed densities (Fig. 6.16). At a growing area of 50 cm²/seedling, inoculation increased average seedling fresh weight by 32%. However, at a growing area of 25 cm², inoculation increased fresh weight by only 17%. This reduction in weight increase is probably the result of reduced photosynthate production at the higher density. Apparently, when insufficient photosynthate is translocated to the root, the fungal symbiont can actually become semiparasitic [69].

6.7.5.2 Field response to *Pisolithus tinctorius*

Although the presence of ectomycorrhizae on seedlings can be important for survival [179], there is little information available about the amount of natural mycorrhizal inoculum required for adequate survival on adverse sites [124]. Most outplanting studies in the South have been conducted with seedlings that vary in biomass, as well as degree of infection with Pt.

Table 6.4. Effect of inoculation with *Pisolithus tinctorius* (U.S.D.A. Forest Service inoculum at 1.08 1.1m²) on average seedling diameter, fresh weight, root:shoot (R:S) ratio (fresh weight), and production of plantable seedlings (adapted from [123]).

		Control seedlings				Increases for inoculated seedlings			
State/year location	Seedbed density no./m²	Stem diam., mm	Wt./ plantable seedling, g	R:S ratio	Cull, %	Stem diam., %	Wt./ seedling, %	R:S ratio, %	Plantable seedlings, no./100
				Loblolly Pine					
SC-1980	116	5.3	17.0	0.60	53	8*[1/]	105*	8[2/]	41*
SC-1978	150	7.9	34.4	0.61	17	20*	51*	−1	11*
MS-1978	215	5.4	21.5	0.34	39	6	22	−19	21*
SC-1977	280	5.3	13.3	0.28	6	−2	39*	−10	−1
AL-1977	303	5.4	21.4	0.36	10	−2	4	14	0
SC-1979	308	5.3	13.8	0.37	12	8	13*	−3	0
AR-1978	320	5.1	16.4	0.21	20	−8	−14	0	−2
GA-1977	344	3.8	13.1	0.16	12	18*	39*	14	−2*
SC-1980	352	4.9	12.5	0.39	15	8*	30*	−1	0
OK-1977	370	4.4	14.0	0.32	20	5	8*	−13	−2
OK-1978	376	4.8	14.7	0.26	27	13*	31*	16	1
GA-1978	380	4.2	11.1	0.44	23	29*	88*	12	9*
IL-1978	383	5.1	14.2	0.30	13	12	24	4	0
VA-1977	406	3.9	7.8	0.47	7	8	25*	−2	−1
AR-1977	418	4.4	13.2	0.26	30	7	16	−9	14*
MS-1979	442	4.4	10.3	0.32	29	7*	29*	−13	6
OK-1977	451	3.9	11.4	0.26	42	3	2	−2	18
AL-1978	477	5.5	19.5	0.30	24	11	23*	5	12*
GA-1979	487	5.5	14.7	0.26	9	9*	27*	3	−1
VA-1878	561	3.3	5.9	0.44	13	0	3	11	4
				Slash Pine					
FL-1978	273	4.5	13.9	0.20	13	−7	0	7	6
FL-1980	327	4.8	13.5	0.29	14	0	9	0	0
FL-1977	417	3.0	6.6	0.22	12	17*	38*	19	7*
FL-1979	419	4.0	11.0	0.20	10	5	−12	−4	2
				Shortleaf Pine					
KY-1977	146	6.0	22.3	0.39	56	5	7	5	32*
MS-1977	37–305	5.8	21.3	0.84	70	7	25	22	12*
MO-1978	760	3.4	6.0	0.54	29	−3	−8	−2	2
				Virginia Pine[3]					
TN-1977	150	3.2	11.0	0.43	25	19	42	−17	9*
IN-1978	155	3.4	21.8	0.69	14	−3	15	7	3
IN-1979	317	4.0	14.9	0.52	49	−3	7	5	9*
NC-1977	503	3.4	14.5	0.34	16	15*	21	19	9*
				Longleaf Pine					
LA-1978	168	10.2	30.2	0.51	66	3	31*	10	9
NC-1977	5–237	9.7	32.1	0.57	11	−4	−26	2	3
LA-1977	116–236	8.7	25.3	0.38	11	−7	−19	−7	−8
				Sand Pine					
FL-1977	254	2.5	6.7	0.20	32	12	42*	22	18*
				Averages					
Loblolly	357	4.9	15.0	0.35	21	8	28	1	6
Slash	359	4.1	11.3	0.23	12	4	9	6	4
Shortleaf	—	5.1	16.5	0.59	52	3	8	8	15
Virginia	281	3.5	15.6	0.50	26	7	21	4	8
Longleaf	—	9.5	29.2	0.49	29	−3	−5	2	1

[1] * = significant treatment response ($\alpha = 0.05$).
[2] Statistical differences were not calculated for R:S ratios.
[3] *Pinus virginiana* Mill.

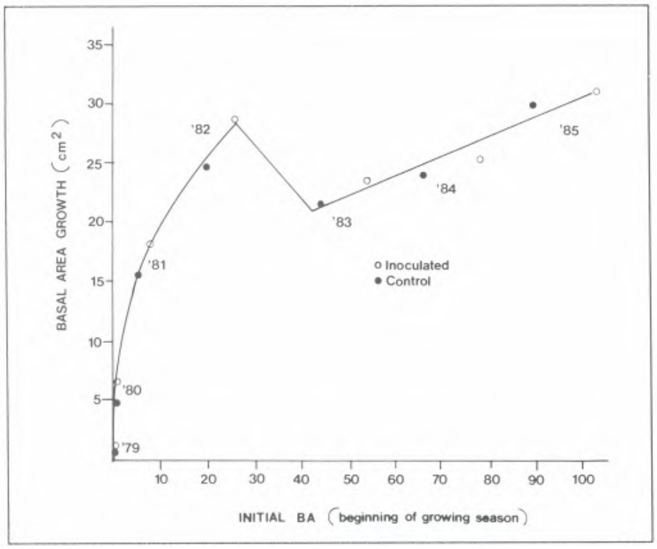

Figure 6.17. Effect of initial basal area, BA, and inoculation with *Pisolithus tinctorius* on annual basal-area growth of loblolly pine (adapted from [123]).

Because artificial inoculation with Pt can increase seedling biomass in the nursery, it may improve seedling survival following outplanting [90, 102]. In some cases, such inoculation may improve survival on routine reforestation sites by as much as 40%, although increases in survival of 5 to 20% are more common [90, 120, 125, 137, 170]. Marx et al. [123] reported that, for survival to consistently improve, seedlings must have Pt on at least 50% of the infected roots (a Pt index of 50% or more). However, Mexal [137] suggests that survival will improve only if Pt inoculation improves seedling morphology. For example, in one study where the morphology of control seedlings (Pt index of 0%) was equal to that of artificially inoculated seedlings (Pt index of 78%), there was no lasting difference between treatments in growth or survival of loblolly pine [92].

Barnett [14] also noted that mycorrhizal response trials are often confounded by seedling size. He found that the larger, well-fertilized, noninoculated seedlings grew better after outplanting than the smaller inoculated seedlings. The difference in fertility regimes of the two treatments masked any potential response to inoculation. Barnett said that in order to have a valid test of the hypothesis (that Pt affects field performance), inoculated and control seedlings should have similar morphology at time of outplanting. As far as the nursery manager is concerned, these two arguments are probably compatible because many treatments (including mycorrhizal inoculation) that improve seedling morphology will likely improve performance where outplanted seedlings are stressed.

Marx et al. [122] reported that Pt inoculation could result in a prolonged growth benefit. They concluded that additional growth during the fifth year after planting was due to residual Pt on the root system. However, it is also possible that growth improvements were simply a function of the initial establishment success and not a prolonged benefit of the fungus *per se*. Examining basal area growth as a function of basal area at the beginning of each growing season indicates that artificial and natural inoculation results in similar growth habits (Fig. 6.17). The only difference is that artificial inoculation appears to give the trees a 6-month head start. Therefore, during the fifth year, the bigger trees grew more in basal area because they were bigger at the beginning of the year.

Regardless of the mode by which Pt influences field performance, the mycorrhizal association is beneficial. When economical, nursery cultural practices should be used to either improve the efficacy of the endemic fungus population or alter the species composition (e.g., artificial inoculation). Furthermore, care during lifting and post-harvest handling should ensure that nursery efforts to increase mycorrhizae are not wasted.

6.7.6 Root-Growth Potential

For the southern pines, Wakeley [222] was among the first to recognize the relationship between rapid root growth following outplanting and seedling survival. Later, Stone [199] developed procedures to measure a seedling's ability to grow roots under laboratory conditions. One measure of root-growth potential (RGP) is the number of new roots a seedling can produce within a 4-week period in the laboratory. At times, RGP has been correlated with survival of outplanted pine seedlings (see Chapter 8, this volume). However, the laboratory test of RGP should not be confused with actual root activity in the field. For example, root growth of undisturbed seedlings in a seedbed may be low in January, although the RGP of those seedlings may be high [162]. Likewise, root growth of seedlings planted in cold soil is lower than that of seedlings placed in a warm greenhouse. Environmental conditions following outplanting can determine the degree of correlation between the RGP test and survival [71]. Correlations would be expected to be higher in late fall or early spring when soils are warmer than during cold winter months. In studies where either survival is high [i.e., 39, 62] or RGP is uniformly high, there will likely be poor correlation between RGP and survival.

For the South, RGP generally has been measured after seedlings are outplanted. It is yet to be determined if RGP measurements made before planting will prove useful in indicating whether various seedling lots should be outplanted. Because RGP can change rapidly (during a 2-week period, RGP of seedlings might increase by 100% or decrease by 50%), the time required to make the test reduces its usefulness as a method of evaluating seedling lots before outplanting.

Management practices that increase RGP are the same practices that affect root mass and photosynthesis. For example, seedlings with more potential sites for new root growth (more primary, secondary, and tertiary laterals) can express a higher RGP than seedlings with a limited number of roots [11, 83]. Therefore, seedlings grown at lower

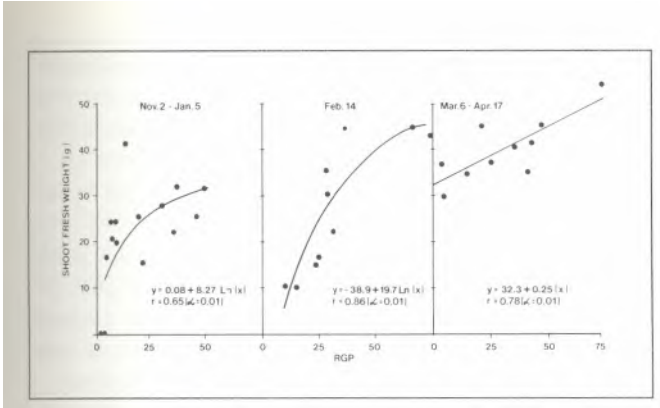

Figure 6.18. Relationship between root-growth potential (RGP; measured as number of new roots) and shoot fresh weight (SFW) after one growing season (adapted from [145]). The relationship differs for season of planting; however, one equation can be fitted to the overall relationship SFW = 14.29 + 0.51 (RGP), r = 0.65, p > r < 0.001.

seedbed densities will have more roots and will exhibit both greater RGP [10, 37, 45, 189] and greater survival (see Fig. 6.14). Also, because RGP in conifers depends on the production of current photosynthate [216], new root growth can be increased with nitrogen fertilization [41, 72, 205] or decreased if foliage is removed (79, 222]. Desiccation of seedlings can also reduce RGP [73].

Because bud dormancy is sometimes negatively correlated with RGP [99, 111, 113], initial shoot growth can also be correlated with RGP under certain conditions. For example, Feret et al. [71] found that RGP and initial growth were correlated only for seedlings lifted after March 1. In contrast, Mexal and Dunlap [145] found RGP and initial growth to be correlated during fall, winter, and spring (Fig. 6.18).

6.8 Maintaining Root Quality

6.8.1 Root Pruning

Root pruning in the seedbed and root pruning by tree planters can have opposite effects on outplanting survival. Root pruning (or, more correctly, root culturing) in the seedbed can improve the R:S ratio, whereas root pruning in the field only decreases it. Subsequently, root pruning in the field can decrease survival (see Table 6.2). In one study, pruning the taproot to 20 cm and the laterals to 5 cm reduced root volume by 44% and decreased the R:S ratio (volumetric basis) from 0.23 to 0.17 [228]. In addition, pruning by tree planters is usually uncontrolled. Seedlings may be pruned in bundles, so some may be unintentionally pruned excessively. Field pruning also takes time; and the longer roots are exposed, the more desiccated they become, resulting in root mortality. There are no studies to show that root pruning in the field improves outplanting survival.

Wakeley [223] illustrated the deleterious effects of root pruning. The taproot *per se* is relatively insensitive to severe pruning. Indeed, the taproot of some southern pines can be pruned as short as 5 cm before increasing mortality (see Table 6.3). However, pruning of primary lateral roots has a much greater impact on seedling survival. Severe pruning of the laterals can result in up to 35% mortality [144, 165, 223]. Furthermore, complete removal of the laterals can result in total plantation failure. Wakeley [223] reported that removing 50% of the laterals killed up to 53% of the seedlings, removing all the laterals up to 99% (Table 6.3).

6.8.2 Root Stripping

Root stripping, a modified form of pruning, refers to the inadvertent removal of higher order laterals and mycorrhizae. Unfortunately, stripping is inherent is nursery harvest operations because it is impossible to lift, sort, and separate seedlings for planting without removing some of the finer roots. Rowan [167] found that lifting often removes 35 to 77% of the small roots; Wakeley [224] stated that 50% of the roots can be lost during lifting. In some cases, root stripping caused during machine lifting has increased seedling mortality by 5 to 50 percentage points [12, 110, 233].

However inadvertent stripping may be, it is still damaging. The fine roots improve water uptake and root growth following outplanting of seedlings [45]. Stripping of mycorrhizae also reduces survival. Marx and Hatchell [124] found seedling mortality to be correlated with the proportion of mycorrhizae removed (Table 6.3). Removing one-third of the mycorrhizae resulted in 15 to 17% seedling mortality, removing all mycorrhizae 42 to 48% mortality.

Mortality induced by root stripping probably results from the roots' inability to absorb sufficient moisture to continue basic physiologic functions. Although stripping creates an open wound and may increase the production of ethylene [98], there is no evidence that it increases susceptibility to disease [2].

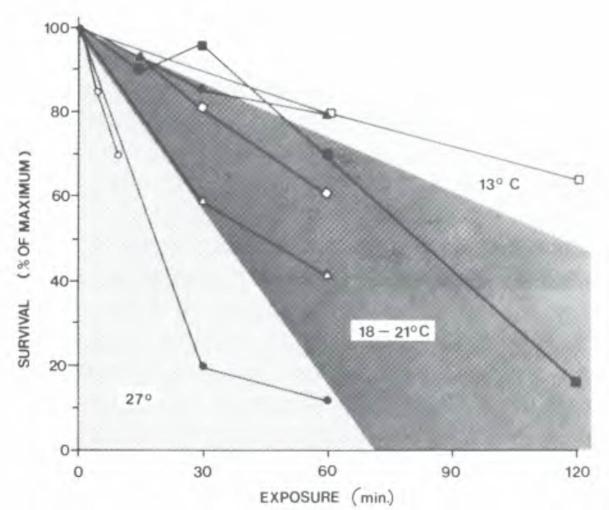

Figure 6.19. Effect of root exposure on loblolly pine survival over various temperature ranges (adapted from [60, 73, 142, 181, 204, 231]).

6.8.3 Exposure

An often unconsidered effect of culling, handling, and pruning is the damage resulting from root exposure (see Chapter 16, this volume). Roots can lose up to 20% of moisture in 5 minutes at 7°C, and more than 50% at 21°C [pers. commun., 65, cited in 70]. Slocum and Maki [181] found that exposures of up to 2 hours reduced survival 35%. However, Williston [231] found that exposures of only 30 minutes reduced survival 80%. It is possible the discrepancies among the various exposure studies reflect differences in the ambient temperature (Fig. 6.19) and, possibly, wind speed at time of exposure. Short exposure to warm temperatures (27°C) results in heavy mortality, whereas even long exposure to low temperatures (13°C) results in little mortality.

Exposure apparently results in root mortality, and reduced RGP [73] can lead to seedling mortality. The effects of slight desiccation can be mitigated to some extent by dipping the roots in water before planting [58]. Daniels [51] found that exposure before cold storage was alleviated over time by absorption of moisture from the clay slurry. Apparently, some effects of desiccation are reversible if steps are taken to rehydrate before planting. However, this is often not done operationally in the field. Therefore, precautions should be taken to minimize exposure and maintain seedling hydration (see Chapter 16, this volume).

6.9 Integration of Root- and Shoot-Quality Practices

Because roots and shoots grow in concert, management practices to modify their growth must be integrated. The R:S ratio is sometimes used to evaluate the relative balance between roots and shoots, and one R:S value is often given as optimum for a specified planting stock. However, practitioners should be aware that the value can vary greatly, depending on how and when it is calculated. The R:S ratio is often calculated on a weight basis and sometimes on a volumetric basis; it is not determined by dividing taproot length by shoot length.

Because the moisture content of needles is often greater than that of roots, the R:S ratio can be greater on a dry-weight than on a fresh-weight basis. The ratio will also be different if calculated on a volumetric basis [81, 157]. In addition, when the number of observations is small, the ratio can vary, depending on how it is calculated [158]. The value will be different if calculated as a mean of ratios instead of a ratio of means. In addition, the R:S ratio of most southern pine seedlings will progressively improve during the fall and winter (Fig. 6.20) because root weights increase under cool nighttime temperatures while shoot weights remain relatively the same [93, 94]. Because the specific gravity of the root system increases more during the winter than does that of shoots [160], much of the weight gain in roots apparently results from an increase in carbohydrates rather than an increase in root volume.

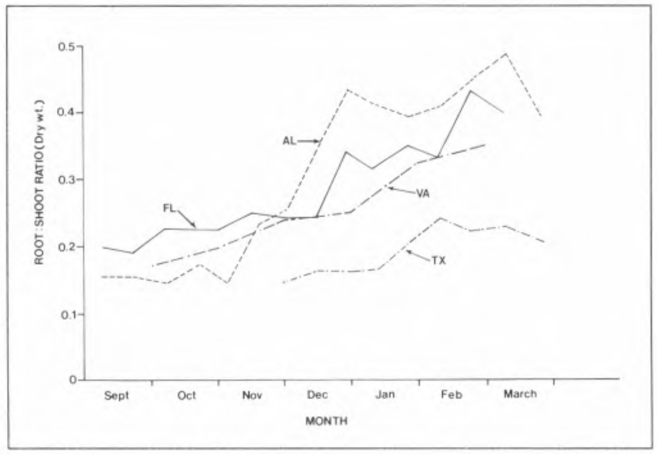

Figure 6.20. Effect of time on root:shoot ratio: AL, loblolly pine [unpubl. data, 196]; FL, slash pine [135]; TX, loblolly pine [22]; and VA, loblolly pine [56].

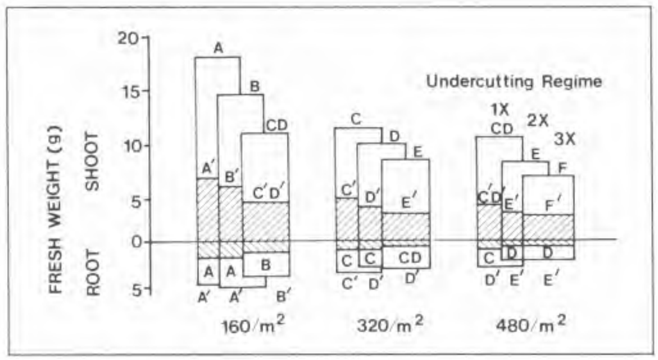

Figure 6.21. Effect of frequency of undercutting (1X = once, 2X = twice, 3X = thrice) on biomass partitioning of loblolly pine seedlings (family 8-74) grown at three densities [140]. For shoots, the open areas represent foliage and the hatched areas stem. For roots, the open areas represent lateral roots and the hatched areas taproot. Within each component, weights with the same letter designation do not differ significantly at the 0.05 level.

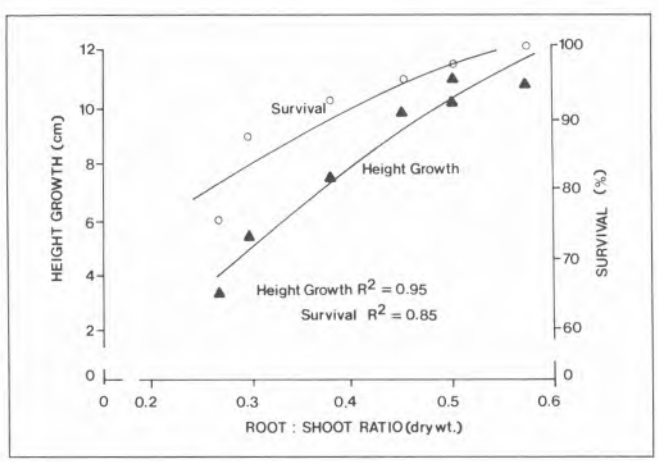

Figure 6.22. Relationship between root:shoot ratio of loblolly pine seedlings and first-year survival and height growth [144].

Regardless, these factors indicate that the optimum R:S ratio can vary, depending on the time of lifting seedlings as well as the method of determining the ratio.

As previously mentioned (see 6.7.1.2), growing area is one of the strongest determinants of the R:S ratio [87, 96, 138, 166]. Moreover, additional fertilization will sometimes improve the R:S ratio of southern pine species [80, 95, 208]. In contrast, van den Driessche [214] showed that applying 235 kg/ha of N slightly lowered the R:S ratio for three northern conifer species.

Seedling balance can be modified by undercutting to regulate shoot growth [140]. Timing and frequency of undercutting can hold shoot biomass in check without affecting root biomass (Fig. 6.21). Undercutting has the greatest impact on needle fresh weight and can be effective regardless of growing density. Obviously, the magnitude of growth affected is less at higher densities because the weight of individual seedlings is density dependent.

Altering seedling balance by reducing growing density or undercutting can have a profound impact on seedling performance. Mexal and Dougherty [144] found that survival and early season growth were correlated to seedling R:S ratio (Fig. 6.22). The mortality occurred before a water stress treatment began and presumably was caused by the physiological condition of the stock rather than environment. They determined that performance was best if the R:S ratio (dry weight) was at least 0.45. Others [29, 71, 111, 113, 167, 228] reported that survival was correlated with the R:S ratio at time of planting.

Southern pine seedlings lifted in fall have lower R:S ratios than seedlings lifted in winter (see Fig. 6.20). This could partially explain lower survival often experienced with early fall planting. Ideally, selected seedlots scheduled for early planting should be cultured to improve root mass and survival potential. Altering the R:S ratio for early planting by combining early sowing with lower bed densities and undercutting could provide a seedling with an acceptable size and R:S ratio.

Performance after outplanting is positively correlated with R:S ratio, but only up to a point. Romero et al. [163] proposed that there may be an optimum R:S ratio beyond which shoot performance declines. For bareroot loblolly pine seedlings, the optimum may lie between 0.45 and 0.60 (dry-weight basis). This would yield a root system sufficient for rapid establishment as well as a shoot large enough to allow maximum root and shoot growth.

6.10 Economic Considerations

Adopting new nursery-management practices often alters production costs. Nursery managers may adopt practices that reduce production costs more readily than those that increase costs, regardless of benefit, because many southern pine nurseries are managed as cost centers instead of profit centers [47]. Production costs that do not directly affect seed efficiency (yield) may be difficult to justify. As a result, only a few nurseries (e.g., Ashe Nursery) sow to achieve densities of 200/m^2; many nurseries grow seedlings at densities above 300/m^2 (Table 6.4). If the perceived value of the large Ideotype A seedlings is not greater than that for the smaller Ideotype B seedlings, there is no incentive for the nursery manager to produce more Ideotype A seedlings. A nursery manager producing a high proportion of Ideotype A may even get complaints regarding increased cost, increased bag weights, and too many roots to plant easily. Such criticisms, coupled with no positive economic incentives, preclude production of a high proportion of Ideotype A.

However, most nursery managers would custom-grow Ideotype A seedlings specifically for regeneration foresters who request them ahead of time (before sowing). In Oklahoma, such requests resulted in the nursery manager producing loblolly pine at two different seedbed densities (i.e., 200 and 300/m^2) [pers. commun., 65].

It has long been recognized that different management practices are required to produce high-quality longleaf pine seedlings. Likewise, different practices are required to grow Ideotype A seedlings. In some cases, the practices increase production costs by a few dollars per thousand; in other cases (where seed efficiency is increased and culling costs are eliminated), there may be little or no difference in production costs. In Oklahoma, the regeneration forester was willing to pay the additional cost of producing the higher quality seedlings. The economic objective of the regeneration forester, then, ultimately is the deciding factor when selecting which ideotype to plant.

Foresters who want to minimize the cost of wood (delivered to the mill) may decide to use Ideotype A seedlings, which allow lower outplanting densities because of better field survival. As a result, establishment costs might be reduced, and the lower densities would yield greater piece (log) sizes at harvest which, in turn, would lower harvesting costs [25]. However, other regeneration foresters may have incentives that would not favor using seedlings with the potential for better survival. For example, some foresters are rewarded solely on the number of hectares planted each year and for keeping regeneration costs low, regardless of the percentage of replants!

The return on investing in increased seedling performance (better seedling quality) depends on several economic and biological factors. For example, when survival of regular seedlings averages above 60%, increasing seedling performance will have higher returns for lands with high site index than for lands with low site index. Where survival is adequate, higher seedling quality is more economically important for short (6- to 25-year) rotations than for longer (60-year) rotations. Likewise, commercial thinning at age 15 will support the economics of using better quality seedlings, as will use of herbicides for weed control [149]. Higher stumpage values and lower interest rates improve the value of using higher quality seedlings. Increasing seedling quality will have higher returns when the effect of piece size on cost of harvesting is considered.

There will be large savings if the use of high-quality seedlings significantly reduces the number of sites that have to be replanted.

Regeneration failures with loblolly pine rarely are attributed to poor seedling quality at time of lifting. The cause is more often poor handling and/or poor planting practices [167]. Therefore, investing money to improve seedling quality will be of no value unless seedling handling and planting are well supervised (see Chapters 16 and 17, this volume).

Assuming good handling and planting (and survival > 60%), how much money can a nursery manager afford to spend on practices to increase seedling survival? Growth and yield models predict (over planting densities ranging from 1,200 to 2,000/ha) that a 5% increase in survival at planting will increase volume production at year 25 by about 4 to 7 m^3/ha (on site index 60 land). Therefore, if the discounted value of a cubic meter of wood (harvested in 25 years) is $2, one could spend $4 to $7/thousand seedlings to increase average seedling survival by 5%. As a result, Bailey [8] states "...rather dramatic increases in the cost per thousand seedlings could be justified if improved survival resulted."

The probability of increasing survival by using only Ideotype A seedlings depends on the site and environmental conditions during and following planting. On sites that traditionally have < 72% survival with Ideotype B seedlings, proper planting of Ideotype A will likely increase average survival by about 11% [24]. However, where survival with Ideotype B seedlings averages above 92%, Ideotype A may increase average survival by only 2%.

Regardless of the effect on survival, additional early growth can be expected by planting seedlings with larger diameters. Wakeley [223] stated that the better morphological grades "generally made the best *growth..."* If they do not suffer transplant shock (from being too tall in relation to the proportion of roots planted), seedlings that start out ahead usually remain ahead [193]. If planting Ideotype A seedlings increases final volume at harvest (at year 25) by just 4% (an additional 9 m^3/ha), then one could spend up to $10 more/thousand for Ideotype A seedlings (assuming a discounted value of wood to be $2/$m^3$ and an outplanting density of 1,800 seedlings/ha).

There will be many ways to improve seedling performance in the future. Some will be relatively inexpensive ($0.10 to $4.00/thousand), others far more costly ($75 to $200/thousand). Researchers are usually the ones who claim that we should be making large investments to improve seedling performance. However, most regeneration foresters are aware that not all attempts to improve seedling performance are economical. There is a simple calculation that can be made to determine if an investment is likely to be economical. First, select a real interest rate and a realistic, uninflated, future stumpage value. With these values, determine the present discounted value of a cubic meter of wood harvested in 25 years (e.g., $2/$m^3$). Divide the investment cost per hectare by the discounted value of a cubic meter of wood (e.g., $90/$2) to give the number of additional cubic meters per hectare required at harvest. Divide this value (45 m^3) by the level of wood production at harvest without the increase in seedling performance (45/220 = 0.20) to give the percentage gain in wood volume required for the investment to be economical. If this value seems unreasonable, before investing, the regeneration forester should ask researchers for data substantiating use of the practice in question (also see Chapter 2, this volume).

6.11 Future Improvements in Cultural Practices

Predicting cultural practices that will be used to produce planting stock in the future can be risky because the choices will depend greatly on the future value of wood. The value of wood relative to other consumer goods could rise (energy shortages or increased food production) or fall (smaller population growth of U.S. or more competition from exports). However, on the basis of performance, it is likely that value of pulpwood will remain relatively constant in comparison to the values of other consumer goods.

Sowing practices may change. Because current seedbed densities often exceed 300/m^2 (Table 6.4), the production of cull seedlings usually exceeds 10% and can average above 20% [30, 31]. In the future, nursery managers may choose to sow a large proportion of their seedbeds at rates to achieve densities close to 200/m^2. This will not only reduce the cull percentage, but also increase the percentage of Ideotype A seedlings. Sowing date in the nursery may also be modified with the intent of widening the outplanting "window." For example, loblolly or slash pine seedlings that are destined to be outplanted on wet sites in October may be sown in March. Various management practices may be used to reduce the variation in seedling diameter within a seedbed (below a standard deviation of 1 mm for loblolly and slash pine).

In the future, a morphological index will describe the stages of seedling development for the southern pines. Such an index may be used by nursery managers to determine timing of cultural practices such as initial herbicide application, undercutting, and late-season fertilization. Similar indexes have been developed for other tree species [86, 114].

Fertilization practices will likely be different in the future. Most fertilizer recommendations are not based on results from outplanting studies. Therefore, recommended annual rates of nitrogen application may be increased to improve field growth of seedlings. Use of liquid fertilizers might increase for economic reasons. Liquid fertilizers may be tank-mixed with herbicides and applied weekly.

Advances in biotechnology will certainly impact nursery management. However, to be operationally implemented, such advances must prove economical. McKeand [132] determined that, for average sites, vegetatively propagated plants can cost no more than 7.5 cents apiece (if both a 10% interest rate and a 25% gain in pulpwood growth are expected). Genetic engineering for southern pines could be employed by incorporating selected genes into seed orchard trees and locating the seed-orchards in areas free of native pine pollen (see Chapter 5 and 11, this volume).

Some inexpensive biotechnological advances will include use of chemicals that cost < 50 cents/thousand seedlings. Antitranspirants [50, 153, 168, 180], shoot growth regulators [78], root growth regulators [118, 155], root dips [62, 200, 218], ethylene absorbers [13], and fungicidal treatments [17, 101, 102] can affect seedling performance under certain conditions. The percentage of short roots infected with ectomycorrhizae can even be increased with applications of certain compounds [186]. Some chemicals may be applied at the nursery to repel deer and/or insects. Use of enzyme-activated temperature monitors can help pinpoint problems during transportation and storage [210].

One practice that may be widely applied is the use of growth regulators to control seedling height growth, one of the biggest problems of nursery managers today. Controlling height growth with plant growth regulators would allow nursery managers more flexibility in their use of other practices.

In the future, there will be less concern about having all seedlings within a nursery look alike because differences in environment, genotype, plant growth regulators, and soil types can alter seedling morphology. However, within a seedlot or seedbed, cultural practices may result in reduced morphological, physiological, and genetic variation [203]. Such practices may begin before seed collection to maintain strict parental identity and follow through to matching seedling types to outplanting sites. Seedlings to be planted under adverse conditions may be cultured differently to improve their morphological and physiological status (see Chapter 8). However, for this scheme to be effectively implemented, the regeneration forester must inform the nursery manager, before sowing, on which sites the seedlings will be planted [62].

In the future, southern pine seedlings will likely not be separated into morphological or physiological grades during the packaging process. In only very special cases will it be necessary to cull diseased or small seedlings. However, seedlings samples could be taken and packages labeled as to the approximate percentages of ideotypes (e.g., A-75%; B-20%) in the seedlot. Electronic devices could be developed to help speed the sampling procedure [1, 108, 134]. Some organizations will package seedlings soon after lifting with minimal handling.

Wakeley [222] proposed that "The ultimate solution of the whole grading problem would be to learn how to achieve high physiological grade at will, so that there would be no low-grade seedlings to throw away... The next step should be to identify the exact elements of site-selection, soil management, and general nursery techniques that have produced the desired results..." In the future, researchers may conduct outplanting studies under rain shelters (e.g., stress houses) where soil moisture could be controlled to measure the ideotype response to imposed stress. Results from such studies could help to identify the optimum nursery regimes for producing high-quality seedlings. These results may show that consistent production of high-quality seedlings for given planting dates and site conditions depends on proper timing of cultural regimes.

References

1. Ardalan, S. A., and A. E. Hassan. 1982. Automatic feeding and sorting of bare root seedlings. Trans. ASAE 25:266-270.
2. Armson, K. A. 1978. Roots of the new forest. Pages 325-328 *In* Proc. Root Form of Planted Trees Symposium (E. Van Eerden and J. M. Kinghorn, eds). Victoria, B. C.
3. Arnold, I. 1956. Drill vs. broadcast sowing. Tree Planters' Notes 26:5-6.
4. Autry, L. L. 1972. The residual effects of nursery fertilization and seed bed density levels on the growth of 12-, 14-, and 16-year old loblolly pine stands. M.S. thesis, MississippiState Univ., Starkville. 59 p.
5. Auten, J. T. 1945. Response of shortleaf and pitch pines to soil amendments and fertilizers in newly established nurseries in the Central States. J. Agric. Res. 70:405-426.
6. Bacon, C. G., and D. B. South. 1989. Chemicals for control of common insect and mite pests in southern pine nurseries. South. J. Appl. Forestry 13:112-116.
7. Bacon, G. J., P. J. Hawkins, and D. Jermyn. 1977. Morphological grading studies with 1-0 slash pine seedlings. Aust. Forestry 40(4):293-303.
8. Bailey, R. L. 1986. Rotation age and establishment density for planted slash and loblolly pines. South. J. Appl. Forestry 10:162-168.
9. Baker, K. A., D. A. Idem, and J. G. Mexal. 1979. The effects of seedling morphology and planting date on survival and early growth of loblolly pine in the Oklahoma region. Weyerhaeuser Co., Hot Springs, Ark. Tech. Rep. 042-2008/79/35.10 p.
10. Balneaves, J. M. 1983. Effect of precision sowing on growth of *Pinus radiata* seedlings at Edendale Nursery. N. Z. J. Forestry 28(1):93-99.
11. Barden, C. J. 1987. Root growth potential and outplanting performance of loblolly pine seedlings raised at two nurseries. M.S. thesis, Virginia Polytechnic Institute and State Univ., Blacksburg. 124 p.
12. Barnard, E. L., C. A. Hollis, and W. L. Pritchett. 1981. A comparative evaluation of seedling quality in commercial forest nurseries in Florida. Pages 34-41 *In* Proc. 1980 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.
13. Barnett, J. P. 1981. Ethylene absorbent increases storability of loblolly pine seedlings. Pages 86-88 *In* Proc. 1980 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.
14. Barnett, J. P. 1982. Relating field performance of containerized longleaf and shortleaf pine seedlings to mycorrhizal inoculation and initial size. Pages 358-367 *In* Proc. 7th North American Forest Biology Workshop (B. A. Thielges, ed.). Univ. of Kentucky, Dep. of Forestry, Lexington.
15. Barnett, J. P. 1986. Techniques for improving performance

of southern pine seed in nurseries. Pages 102-112 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.

16. Barnett, J. P., J. C. Brissette, and W. C. Carlson. 1986. Artificial regeneration of shortleaf pine. Pages 64-88 *In* Proc. Symposium on the Shortleaf Pine Ecosystem (P. A. Murphy, ed.). Arkansas Cooperative Extension Serv., Monticello.
17. Barnett, J. P., J. C. Brissette, A. G. Kais, and J. P. Jones. 1988. Improving field performance of southern pine seedlings by treating with fungicides before storage. South. J. Appl. Forestry 12:281-285.
18. Barnett, J. P., T. E. Campbell, and P. M. Dougherty. 1984. Seedling establishment - artificial methods. Pages 109-125 *In* Proc. Symposium on the Loblolly Pine Ecosystem (West Region) (B. L. Karr, J. B. Baker, and T. Monaghan eds.). Mississippi Cooperative Extension Serv., Mississippi State.
19. Barton, L. V. 1928. Hastening the germination of southern pine seeds. J. Forestry 26:774-785.
20. Beineke, W. F., and T. O. Perry. 1965. Genetic variation in ability to withstand transplanting shock. Pages 106-109 *In* Proc. 8th Southern Conference on Forest Tree Improvement. Savannah, Ga.
21. 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.
22. Bilan, M. W., and E. R. Ferguson. 1986. Root regeneration in out-planted loblolly pine *(Pines taeda* L.) seedlings. Pages 329-341 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.
23. Blair, R., and F. Cech. 1974. Morphological seedling grades compared after thirteen growing seasons. Tree Planters' Notes 25(1):5-7.
24. Blake, J. I. 1987. The impact of seedling diameter and root mass on the performance of Douglas fir *(Pseudotsuga menziesii* Mirb. Franco) and associated conifers and their economic significance in regeneration management. Unpubl. manuscript, School of Forestry, Auburn Univ., Auburn, Ala.
25. Bowling, D. 1987. Twenty-year slash pine spacing study: what to optimize? Pages 300-304 *In* Proc. 4th Biennial Southern Silvicultural Research Conference (D. R. Phillips, ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N. C. Gen. Tech. Rep. SE-42.
26. Boyce, J. S. 1948. Forest Pathology. McGraw-Hill, New York. 550 p.
27. Boyer, J. N., S. E. Duba, and D. B. South. 1987. Emergence timing affects root-collar diameter and mortality in loblolly pine seedbeds. New Forests 1:135-140.
28. Boyer, J. N., and D. B. South. 1984. Forest nursery practices in the South. South. J. Appl. Forestry 8:67-75.
29. Boyer, J. N., and D. B. South. 1987a. Excessive seedling height, high shoot-to-root ratio, and benomyl root dip reduce survival of stored loblolly pine seedlings. Tree Planters' Notes 38(4):19-22.
30. Boyer, J. N., and D. B. South. 1987b. The influence of seedbed density on loblolly and slash pine seedling grade distributions. Pages 189-197 *In* Proc. 4th Biennial Southern Silvilcultural Research Conference (D. R. Phillips, ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-42.
31. Boyer, J. N., and D. B. South. 1988. Loblolly pine seedling morphology and production at 53 southern nurseries. Tree Planters' Notes 39(3): 13-16.
32. Boyer, J. N., and D. B. South. 1989a. Date of sowing and emergence timing affect growth and development of loblolly pine seedlings. New Forests 3:13-28.
33. Boyer, J. N., and D. B. South. 1989b. Seasonal changes in intensity of bud dormancy in loblolly pine seedlings. Tree Physiol. (in press).
34. Boyer, J. N., D. B. South, C. A. Muller, and H. Vanderveer. 1985a. A comparison of nursery sowers. Tree Planters' Notes 26(3):20-24.
35. Boyer, J. N., D. B. South, C. Muller, H. Vanderveer, W. Chapman, and W. Rayfield. 1985b. Speed of germination affects diameter at lifting of nursery-grown loblolly pine seedlings. South. J. Appl. Forestry 9:243-247.
36. Brissette, J. C., and J. P. Barnett. 1987. Relating nursery to field performance of shortleaf pine seedlings. Pages 180-186 *In* Proc. 1986 Southern Forest Nursery Ass. (R. A. Schroeder, ed.). Pensacola, Fla.
37. Brissette, J. C., and W. C. Carlson. 1987. Effects of nursery density on shortleaf pine. Pages 36-41 *In* Proc. Intermountain Forest Nursery Assoc. (T. D. Landis, ed.). U.S.D.A. Forest Serv., Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo. Gen. Tech. Rep. RM-151.
38. Brissette, J. C., and C. W. Lantz. 1983. Seedling quality. Pages 303-305 *In* Proc. 1982 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga. Tech. Publ. R8-TP4.
39. Brissette, J. C., and R. C. Roberts. 1984. Seedling size and lifting date effects on root growth potential of loblolly pine from two Arkansas nurseries. Tree Planters' Notes 35(1):34-38.
40. Brissette, J. C., *F.* Vande Linde, and J. P. Barnett. 1983. Producing, storing, and handling quality slash pine seedlings. Pages 150-164 *In* Proc. The Managed Slash Pine Ecosystem (E. L. Stone, ed.). School of Forest Resources and Conservation, Univ. of Florida, Gainesville.
41. Bryan, M. B. 1954. Some effects of winter applications of inorganic fertilizers to pine seedlings in the nursery. M.S. thesis, North Carolina State Univ., Raleigh. 70 p.
42. 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., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-77. 7 p.
43. Cannell, M. G. R. 1986. Physiology of southern pine seedlings. Pages 251-274 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.
44. Carlson, W. C. 1985. Effects of natural chilling and cold storage on budbreak and root growth potential of loblolly pine *(Pious taeda* L.). Can. J. Forest Res. 15:651-656.
45. Carlson, W. C. 1986. Root system considerations in the quality of loblolly pine seedlings. South. J. Appl. Forestry 10:87-92.
46. Carlson, W. C., J. G. Anthony, and R. P. Plyler. 1987. Polymeric nursery bed stabilization to reduce seed losses in forest nurseries. South. J. Appl. Forestry 11:116-119.
47. Caulfield, J. P., D. B. South, and J. N. Boyer. 1987. Nursery seedbed density is determined by short-term or long-term objectives. South. J. Appl. Forestry 11:152-157.
48. Clark, B. F., and R. E. Phares. 1961. Graded stock means greater yields for shortleaf pine. U.S.D.A. Forest Serv., Central States Forest Exp. Sta. Tech. Pap. 181.5 p.
49. Cleary, B. D., R. D. Greaves, and P. W. Owston. 1978. Seedlings. Pages 63-97 *In* Regenerating Oregon's Forests (B. D. Cleary, R. D. Greaves, and R. K. Hermann, eds.). Oregon State Univ. Extension Serv., Corvallis.
50. Colombo, S. J., and K. D. Odium. 1987. Efficacy of six

antitranspirants on black spruce container seedlings. New Forests 3:239-244.
51. Daniels, T. G. 1978. The effect of winter plant moisture stress on survival and growth of 2+0 Douglas-fir seedlings. M.S. thesis, Oregon State Univ., Corvallis. 86 p.
52. Danielson, R. M., and C. B. Davey. 1969. Microbial colonization of a fumigated nursery soil. Forest Sci. 15:368-380.
53. Derr, H. J. 1955. Seedbed density affects longleaf pine survival and growth. Tree Planters' Notes 20:28-29.
54. Dierauf, T. A. 1973. Loblolly pine seedlings grade, growth and survival. Virginia Division of Forestry, Charlottesville. Occasional Rep. 40.6 p.
55. Dierauf, T. A. 1976. Top clipping in the nursery bed. Pages 37-43 *In* Proc. 1976 Southeastern Area Nurserymen's Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Doraville, Ga.
56. Dierauf, T. A. 1987. Personal communication, Virginia Dep. of Forestry, Charlottesville.
57. Dierauf, T. A., and L. J. Apgar. 1988. A two year study comparing five sowing depths for loblolly pine seed. Virginia Dep. of Forestry, Charlottesville. Occasional Rep. 73.9 p.
58. Dierauf, T. A., and L. C. Edwards. 1985. A three-year study of immersing stored loblolly pine seedlings in water before planting. Virginia Division of Forestry, Charlottesville. Occasional Rep. 66.7 p.
59. Dierauf, T. A., and J. W. Garner. 1978. Root pruning loblolly pine seedlings effect on survival and growth. Virginia Division of Forestry, Charlottesville. Occasional Rep. 52.4 p.
60. Dierauf, T. A., and R. L. Marler. 1971. Effect of exposure, clay treatment, and storage on survival and growth of loblolly pine seedlings. Virginia Division of Forestry, Charlottesville. Occasional Rep. 34.10 p.
61. Dixon, W. N., and J. L. Foltz. 1984. Integrated pest management in nurseries - insects and mites. Pages 226-237 *In* Proc. Integrated Forest Pest Management Symposium (S. J. Branham and G. D. Hertel, eds.). Univ. of Georgia, Athens.
62. Donald, D. G. M. 1983. Plant characteristics affecting survival and early growth. Medeleling, Fakulteit Bosbou, Universiteit Stellenbosch. 98(I):246-268.
63. Donald, D. G. M. 1986. South African nursery practice - the state of the art. Pages 25-47 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.
64. Donald, D. G. M., and I. Young. 1982. The growth of pine seedlings in South African forest nurseries. South African Forestry J. 123:36-50.
65. Dougherty, P. 1987. Personal communication, Univ. of Georgia, Athens.
66. Dunlap, J. R., and J. P. Barnett. 1983. Influence of seed size on germination and early development of loblolly pine *(Pious taeda* L.) germinants. Can. J. Forest Res. 13:40-44.
67. Dunlap, J. R., and J. P. Barnett. 1984. Manipulating loblolly pine *(P. taeda* L.) seed germination with simulated moisture and temperature stress. Pages 61-74 *In* Seedling Physiology and Reforestation Success (M. L. Duryea and G. N. Brown, eds.). Martinus Nijhoff/Dr. W. Junk Publishers, Boston, Mass.
68. Duryea, M. L. 1987. Shoot and root pruning at southern nurseries. Pages 114-120 *In* Proc. 1986 Southern Forest Nursery Assoc. (R.A. Schroeder, ed.). Pensacola, Fla.
69. Ekwebelam, S. A., and C. P. P. Reid. 1984. Effect of light, nitrogen fertilization, and mycorrhizal fungi on growth and photosynthesis of lodgepole pine seedlings. Can. J. Forest Res. 13:1099-1106.
1. Fancher, G. A., J. G. Mexal, and F. B. Widmoyer. 1986. Planting and handling conifer seedlings in New Mexico. New Mexico State Univ., Las Cruces. CES Circ. 526.10 p.
2. Feret, P. P., R. C. Freyman, and R. E. Kreh. 1986. Variation in root growth potential of loblolly pine from seven nurseries. Pages 317-328 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.
3. Feret, P. P., R. E. Kreh, and L. E. DeWald. 1985a. Root growth potential - one tool for measuring loblolly pine seedling quality. Pages 129-137 *In* Proc. 1984 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.
4. Feret, P. P., R. E. Kreh, and C. Mulligan. 1985b. Effects of air drying on survival, height, and root growth potential of loblolly pine seedlings. South. J. Appl. Forestry 9:125-128.
5. Fisher, J. T., and J. G. Mexal. 1984. Nutrient management: a physiological basis for yield improvement. Pages 271-299 *In* Seedling Physiology and Reforestation Success (M. L. Duryea and G. N. Brown, eds.). Martinus Nijhoff/Dr. W. Junk Publishers, Boston, Mass.
6. Forest Research Institute. 1981. Precision seed sowing becomes a reality. N. Z. Forest Serv., Forest Res. Institute, Rotarua. What's New in Forest Res. No. 96.4 p.
7. Garber, M. P., and J. G. Mexal. 1980. Lift and store practices: their impact on successful establishment of southern pine plantations. N. Z. J. Forestry Sci. 10:72-82.
8. Gibson, I. A. S. 1956. Sowing density and damping-off in pine seedlings. The East African Agric. J. 21:183-188.
9. Gill, J. J. 1979. Use of the growth retardant "Maintain" by Georgia Kraft Company. Pages 69-77 *In* Proc. 1978 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga. Tech. Publ. SA-TP6.
10. Gilmore, A. R. 1965. The apparent source of a root growth stimulus in loblolly pine seedlings. Illinois Agric. Exp. Sta., Urbana. Forestry Note 112.4 p.
11. Gilmore, A. R., and L. H. Kahler. 1965. Fertilizers and organic additives in pine nursery seedbeds: effects on field survival, field growth, and chemical content of foliage. Tree Planters' Notes 73:21-27.
12. Glerum, C., and J. G. Boufford. 1979. A comparison between top-root ratio determinations by oven-dry weight and volume displacement. Ontario Ministry of Natural Resources. Forest Res. Note 22.4 p.
13. Grigsby, H. C. 1971. Nursery morphology of loblolly pines as an indicator of field performance. Pages 148-153 *In* Proc. 11th Conference on Southern Forest Tree Improvement.
14. Hallgren, S. W., and C. G. Tauer. 1988. Effects of lift date, storage and family on early survival and root growth potential of shortleaf pine. Pages 87-92 *In* Proc. Intermountain Forest Nursery Assoc. (T. D. Landis, ed.). U.S.D.A. Forest Serv., Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo. Gen. Tech. Rep. RM-151.
15. Hamm, M. F. 1986. Unpublished data, Tenneco, Counce, Tenn.
16. Hansbrough, T., and J. P. Hollis. 1959. The effect of soil fumigation on the growth and yield of loblolly pine seedlings in the nursery. Tree Planters' Notes 37:13-16.
17. Hanson, P. J., R. E. Dickson, J. G. Isebrands, T. R. Crow, and R. K. Dixon. 1986. A morphological index of *Quercus* seedling ontogeny for use in studies of physiology and growth. Tree Physiol. 2:273-281.
18. Harms, W. R., and 0. G. Langdon. 1977. Competition-density effects in a loblolly pine seedling stand. U.S.D.A. Forest Serv., Southeast Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-161. 8 p.
88. Hartley, C. 1918. Stem lesions caused by excessive heat. J. Agric. Res. 14:595-604.

89. Hassan, A. E. 1983. Nursery equipment development for automatic feeding of bare root seedlings. Pages 246-266 *In* Proc. 1982 Southern Nursery Conferences *(J.* Brissette and C. Lantz, eds.). U.S.D.A. Forest Serv., Atlanta, Ga. Tech. Publ. R8-TP4.
90. Hatchell, G. E. 1986. Nursery cultural practices affect field performance of longleaf pine. Pages 148-156 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.
91. Hatchell, G. E. 1987. Nursery cultural practices, seedling morphology, and field performance of longleaf pine. Pages 61-66 *In* Proc. 4th Biennial Southern Silvicultural Research Conference. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-42.
92. Hatchell, G. E., and D. H. Marx. 1987. Response of longleaf, sand, and loblolly pines to *Pisolithus* ectomycorrhizae and fertilizer on a sandhills site in South Carolina. Forest Sci. 33:301-315.
93. Hellmers, H. 1962. Temperature effect on optimum tree growth. Pages 275-287 *In* Tree Growth (T. T. Kozlowski ed.). Ronald Press Co., New York.
94. Hellmers, H., and D. A. Rook. 1973. Air temperature and growth of radiata pine seedlings. N. Z. J. Forestry Sci. 3(3):271-285.
95. Hinesley, L. E., and T. E. Maki. 1980. Fall fertilization helps longleaf pine nursery stock. South. J. Appl. Forestry 4:132-135.
96. Hodgson, T. *J.* 1977. Preliminary investigations on the manipulation of pine seedling growth and development. M.S. thesis, Univ. of Stellenbosch, Republic of South Africa. 193 p.
97. Hunt, E. V., Jr., and G. Gilmore. 1967. Taller loblolly pine seedlings grow faster in a Texas plantation. Tree Planters' Notes 18(2):25-28.
98. Johnson, J. D. 1983. Ethylene accumulation during cold storage of pine seedlings: is it a problem? Pages 224-231 *In* Proc. 1982 Southern Nursery Conferences (J. C. Brissette and C. W. Lantz, eds.). U.S.D.A. Forest Serv., Atlanta, Ga. Tech. Publ. R8-TP4.
99. Johnson, J. D., and J. P. Barnett. 1985. Loblolly pine seedlings vigor based on bud development. Pages 138-144 *In* Proc. 1984 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.
100. Jones, E. P. 1971. Season of sowing for direct seedling slash pine in the middle and upper coastal plains of Georgia. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-151.7 p.
101. Kais, A. G., C. E. Cordell, and C. E. Affeltranger. 1986. Benomyl root treatment controls brown-spot disease on longleaf pine in the southern United States. Forest Sci. 32:506-511.
102. Kais, A. G., G. A. Snow, and D. H. Marx. 1981. The effects of benomyl and *Pisolithus tinctorius* ectomycorrhizae on survival and growth of longleaf pine seedlings. South. J. Appl. Forestry 5(4):189-195.
103. Karrfalt, R. P. 1989. Stratification of longleaf pine. Pages 46-49 *In* Proc. 1988 Southern Forest Nursery Association (R. Hagwood, ed.). South. Forest Nursery Assoc., Charleston, S.C.
104. Kelley, W. D. 1985. An improved method for treating pine seeds with Bayleton. Pages 89-90 *In* Proc. 1984 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.
105. Kelley, W. D., and J. C. Williams. 1984. Effects of two systemic fungicides as seed dressings on fusiform rust of loblolly pine seedlings. Phytopathology 74:802-803.
106. Kormanik, P. P. 1988. Personal communication, U.S.D.A. Forest Serv., Athens, Ga.
107. Kormanik, P. P., and J. L. Ruehle. 1987. Lateral root development may define nursery seedling quality. Pages 225-229 *In* Proc. 4th Biennial Southern Silvicultural Research Conference (D. R. Phillips, ed.). U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SE-42.
108. Kranzler, G. A., and M. P. Rigney. 1988. Grading pine seedlings with machine vision. Pages 100-104 *In* Proc. Intermountain Forest Nursery Assoc. (T. D. Landis, ed.). U.S.D.A. Forest Serv., Rocky Mountain Forest and Range Exp. Sta., Fort Collins, Colo. Gen. Tech. Rep. RM-151.
109. Lang, G. A., J. D. Early, R. L. Darnell, and G. C. Martin 1987. Endo-, para-, and ecodormance: physiological terminology and classification for dormancy release. HortScience 22:372-377.
110. Langdon, 0. G. 1954. Skillful lifting technique increases seedling survival. Tree Planters' Notes 18:23-24.
111. Larsen, H. S., D. B. South, and J. N. Boyer. 1986. Root growth potential, seedling morphology and bud dormancy correlate with survival of loblolly pine seedlings planted in December in Alabama. Tree Physiol. 1:253-263.
112. Larsen, H. S., D. B. South, and J. N. Boyer. 1988. Foliar nitrogen content at planting correlates with early growth of loblolly pine seedlings from 20 nurseries. South. J. Appl. Forestry 12:181-185.
113. Larsen, H. S., D. B. South, H. M. Williams and *J.* N. Boyer. 1989. Survival and early growth of loblolly pine seedlings from six nurseries. *In* Proc. 4th Biennial Southern Silvicultural Research Conference (J. H. Miller, ed.). U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. (in press).
114. Larson, P. R., and J. G. Isebrands. 1971. The plastochron index as applied to developmental studies of cottonwood. Can. J. Forest Res. 1:1-11.
115. Lauer, D. K. 1987. Seedling size influences early growth of longleaf pine. Tree Planters' Notes 38(3):16-17.
116. Ledig, F. T., F. H. Bormann, and K. F. Wenger. 1970. The distribution of dry matter growth between shoot and roots in loblolly pine. Bot. Gaz. 131:349-359.
117. MacKinney, A. L., and W. E. McQuilkin. 1938. Methods of stratification for loblolly pine seeds. *J.* Forestry 36:1123-1127.
118. Maki, T. E., and H. Marshall. 1945. Effects of soaking with indolebutyric acid on root development and survival of tree seedlings. Bot. Gaz. 107:268-276.
119. Marx, D. H., and W. Bell. 1985. Formation of *Pisolithus* ectomycorrhizae on loblolly pine seedlings with spore pellet inoculum applied at different times. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-249. 6 p.
120. Marx, D. H., W. C. Bryan, and C. E. Cordell. 1977. Survival and growth of pine seedlings with *Pisolithus* ectomycorrhizae after two years on reforestation sites in North Carolina and Florida. Forest Sci. 23:363-373.
121. Marx, D. H., and C. E. Cordell. 1986. Bayleton (triadimefon) affects ectomycorrhizal development on slash and loblolly pine seedlings in nurseries. Pages 460-475 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.
122. Marx, D. H., C. E. Cordell, and A. Clark III. 1988. Eight-year performance of loblolly pine with *Pisolithus tinctorius* ectomycorrhizae on a good-quality site. South. J. Appl. Forestry 12:275-280.
123. Marx, D. H., C. E. Cordell, D. S. Kenney, J. G. Mexal, J. D. Artman, J. W. Riffle, and R. J. Molina. 1984. Commercial vegetative inoculum of *Pisolithus tinctorius* and inoculation techniques for development of ectomycorrhizae on bare-root tree seedlings. Forest Sci. Monogr. No. 25. 101 p.

124. Marx, D. H., and G. E. Hatchell. 1986. Root stripping of ectomycorrhizae decreases field performance of loblolly and longleaf pine seedlings. South. J. Appl. Forestry 10:173-179.
125. Marx, D. H., A. Hedin, and S. F. P. Toe. 1985. Field performance of *Pinus caribaea* var. *hondurensis* seedlings with specific ectomycorrhizae and fertilizer after three years on a savanna site in Liberia. Forest Ecol. Manage. 13:1-25.
126. Marx, D. H., J. G. Mexal, and W. G. Morris. 1979. Inoculation of nursery seedbeds with *Pisolithus tinctorius* spores mixed with hydromulch increases ectomycorrhizae and growth of loblolly pines. South. J. Appl. Forestry 3:175-178.
127. Marx, D. H., W. G. Morris, and J. G. Mexal. 1978. Growth and ectomycorrhizal development of loblolly pine seedlings in fumigated and nonfumigated soil infested with different fungal symbionts. Forest Sci. 24:193-203.
128. Mattoon, W. R. 1940. Slash pine. Government Printing Office, Washington, D.C. U.S.D.A. Farmers' Bull. No. 1256 (rev.). 57 p.
129. May, J. T. 1933. Effects of density of stocking on the growth and development of longleaf, loblolly and slash pine seedlings. M.S. thesis, Univ. of Georgia, Athens. 52 p.
130. May, J. T. 1985. Seedling quality, grading, culling and counting. Pages 9-1 - 9-10 *In* Southern Pine Nursery Handbook (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Southern Region, Atlanta, Ga.
131. May, J. T., H. H. Johnson, and C. S. Walsh. 1961. Growth of pine seedlings in relation to soil moisture in nursery seedbeds. Georgia Forestry Commission, Macon. Georgia Forest Res. Pap. No. 5.6 p.
132. McKeand, S. E. 1981. Loblolly pine tissue culture: present and future uses in southern forestry. School of Forest Resources, North Carolina State Univ., Raleigh. Tech. Rep. No. 64.50 p.
133. McLemore, B. F., and F. J. Czabator. 1961. Length of stratification and germination of loblolly pine seed. J. Forestry 59:267-269.
134. McLendon, B. D., and J. M. Allison. 1986. Field evaluation of pine seedling counter. American Society of Agric. Engineers, St. Joseph, Mich. Pap. No. 86-1094.11 p.
135. McNabb, K. L. 1985. The relationship of carbohydrate reserves to the quality of bare-root *Pinus elliottii* var. *elliottii* (Engelm.) seedlings produced in a northern Florida nursery. Ph.D. dissertation, Univ. of Florida, Gainesville. 147 p.
136. Mexal, J. G. 1980a. Growth of loblolly pine seedlings. I. Morphological variability related to day of emergence. Weyerhaeuser Co., Hot Springs, Ark. Forest Res. Tech. Rep. 042-2008/6.26 p.
137. Mexal, J. G. 1980b. Aspects of mycorrhizal inoculation in relation to reforestation. N. Z. J. Forest Sci. 10:208-217.
138. Mexal, J. G. 1981. Seedling bed density influences seedling yield and performance. Pages 89-95 *In* Proc. 1980 Southern Nursery Conference (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga. Tech. Pub. SA-TP17.
139. Mexal, J. G. 1982a. Growth of loblolly pine seedlings. II. Early sowing improves nursery yield. Weyerhaeuser Co., Hot Springs, Ark. Tech. Rep. 050-1422/3.10 p.
140. Mexal, J. G. 1982b. Growth of loblolly pine seedlings. III. Response to competition and root pruning. Weyerhaeuser Co., Hot Springs, Ark. Tech. Rep. 050-1422/4.24 p.
141. Mexal, J. G. 1984. Integrated pest management in southern pine nurseries. Pages 267-279 *In* Proc. Integrated Forest Pest Management Symposium (S. J. Branham and G. D. Hertel, eds.). Univ. of Georgia, Athens.
142. Mexal, J. G. 1982. Unpublished data, New Mexico State Univ., Las Cruces.
143. Mexal, J. G., and S. Burton. 1978. Root development of planted loblolly pine seedlings. Pages 85-90 *In* Proc. Root Form of Planted Trees Symposium (E. V. Eerdem amd J. M. Kinghorn, eds.). Victoria, B. C.
144. Mexal, J. G., and P. M. Dougherty. 1983. Growth of loblolly pine seedlings. IV. Performance in a simulated drought environment. Weyerhaeuser Co., Hot Springs, Ark. Tech. Rep. 050-1422/6.26 p.
145. Mexal, J. G., and J. R. Dunlap. 1982. First-year survival and shoot growth of loblolly pine *(Pinus taeda):* influence of lift date, time in storage and seed source. Weyerhaeuser Co., Hot Springs, Ark. Tech. Rep. 050-1422/5.20 p.
146. Mexal, J. G., and J. T. Fisher. 1985. Pruning loblolly pine seedlings. Pages 75-83 *In* Proc. 1984 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.
147. Mexal, J. G., and J. T. Fisher. 1987. Size hierarchy in conifer seedbeds. I. Time of emergence. New Forests 1:187-196.
148. Miller, A. E. 1987. Personal communication, Clemson Univ., Clemson, S.C.
149. Mitchell, R. J., B. R. Zutter, and D. B. South. 1988. Interaction between weed control and loblolly pine, *Pinus taeda,* seedling quality. Weed Technol. 2:191-195.
150. Morris, W. G., and M. S. Greenwood. 1977. Control of nursery seedling growth and development: controlled water stress versus wrenching. Weyerhaeuser Co., Hot Springs, Ark. Tech. Rep. 041-2009/77/3.4 p.
151. Nambiar, E. K. S., G. D. Bowen, and R. Sands. 1979. Root regeneration and plant water status of *Pious radiata* D. Don seedlings transplanted to different soil temperatures. J. Exp. Bot. 30:1119-1131.
152. Nebgen, R. J., and J. F. Meyer. 1986. Seed bed density, undercutting, and lateral root pruning effects on loblolly seedling morphology, field survival, and growth. Pages 136-147 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. South, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.
153. Paul, J. T. 1966. The influence of transpiration suppressants on slash pine seedlings. M.S. thesis, Univ. of Georgia, Athens. 144 p.
154. Pharis, R. P., and P. J. Kramer. 1964. The effect of nitrogen and drought on loblolly pine seedlings. Forest Sci. 10:143-150.
155. Plank, D. K. 1939. Root response of slash pine seedlings to indolebutyric acid. J. Forestry 37:497-498.
156. Plass, W. T. 1974. Factors affecting the establishment of direct-seeded pine on surface-mine spoils. U.S.D.A. Forest Serv., Northeast. Forest Exp. Sta. Res. Pap. NE-290. 5 p.
157. Racy, G. D., C. Glerum, and R. E. Hutchison. 1983. The practicality of top-root ratio in nursery stock characterization. Forestry Chron. 59(4):240-243.
158. Raj, D. 1968. Sampling Theory. McGraw-Hill, New York. 302 p.
159. Reineke, L. H. 1942. Effect of stocking and seed on nursery development of eastern white pine seedlings. J. Forestry 40:577-578.
160. Retzlaff, W. A. 1984. Effect of soil moisture on *Pinus taeda* L. seedling morphology. M.S. thesis, Auburn Univ., Auburn, Ala. 99 p.
161. Retzlaff, W. A., and D. B. South. 1985. High soil moisture level in the nursery can adversely affect loblolly pine seedling morphology. Pages 158-167 *In* Proc. Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.
162. Ritchie, G. A., and J. R. Dunlap. 1980. Root growth potential: its development and expression in forest tree seedlings. N.Z.J. Forestry Sci. 10(1):218-248.
163. Romero, A. E., J. Ryder, J. T. Fisher, and J. G. Mexal.

1986. Root system modification of container stock for arid land plantings. Forest Ecol. Manage. 16:281-290.

164. Rowan, S. J. 1980. Planting depth and seedbed mulch affect germination of slash pine seeds. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Note SE-292. 3 p.

165. Rowan, S. J. 1983. Loss of feeder roots lowers seedling survival more than severe black root rot. Tree Planters' Notes 34(1):18-20.

166. Rowan, S. J. 1986. Seedbed density affects performance of slash and loblolly pine in Georgia. Pages 126-135 *In* International Symposium on Nursery Management Practices for the Southern Pines (D. B. south, ed.). Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala.

167. Rowan, S. J. 1987. Nursery seedling quality affects growth and survival in outplantings. Georgia Forestry Commission, Macon. Georgia Forest Res. Pap. No. 70.15 p.

168. Rowan, S. *J.* 1989. Vapor-gard affects survival and growth of outplanted pine seedlings. Pages 27-32 *In* Proc. 1988 Southern Forest Nursery Assoc. (R. Hagwood, ed.). Charleston, S.C.

169. Rowan, S. J., and D. H. Marx. 1989. Unpublished data, U.S.D.A. Forest Serv., Athens, Ga.

170. Ruehle, J. L., D. H. Marx, J. P. Barnett, and W. H. Pawuk. 1981. Survival and growth of container-grown and bare-root shortleaf pine seedlings with *Pisolithus* and *Thelephora* ectomycorrhizae. South. J. Appl. Forestry 5:20-24.

171. Satoo, T. (Edited and revised by H. A. I. Madgwick.) 1982. Forest Biomass. Martinus Nijhoff/Dr. W. Junk Publisher, The Hague, The Netherlands. 152 p.

172. Scarbrough, N. M., and R. M. Allen. 1954. Better longleaf seedlings from low-density nursery beds. Tree Planters' Notes 18:29-30.

173. Schubert, G. H., and R. S. Adams. 1971. Reforestation practices for conifers in California. California Dep. of Conservation, Division of Forestry, Sacramento. 359 p.

174. Seiler, J. R., and J. D. Johnson. 1985. Moisture stress conditioning of containerized loblolly pine. Pages 60-65 *In* Proc. 1984 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.

175. Seymour, C. P., and C. E. Cordell. 1979. Control of charcoal root rot with methyl bromide in forest nurseries. South. J. Appl. Forestry 3(3):104-108.

176. Shipman, R. D. 1958. Planting pine in the Carolina sandhills. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Pap. 96.43 p.

177. Shipman, R. D. 1964. Low seedbed densities can improve early height growth of planted slash and loblolly pine seedlings. J. Forestry 62:814-817.

178. Shoulders, E. 1961. Effect of nursery bed density on loblolly and slash pine seedlings. *J.* Forestry 59:576-579.

179. Shoulders, E., and J. R. Jorgensen. 1969. Mycorrhizae increase field survival of planted loblolly pine. Tree Planters' Notes 20(1):14-17.

180. Simpson, D. G. 1984. Filmforming antitranspirants: their effect on root growth capacity, storability, moisture stress avoidance, and field performance of containerized conifer seedlings. Forestry Chron. 60:335-339.

181. Slocum, G. K., and T. E. Maki. 1956. Exposure of loblolly pine planting stock. J. Forestry 54:313-315.

182. South, D. B. 1984. Integrated pest management in nurseries-vegetation. Pages 247-265 *In* Proc. of the Integrated Forest Pest Management Symposium. Univ. of Georgia, Athens.

183. South, D. B. 1986a. Economic aspects of nursery seed efficiency. South. J. Appl. Forestry 10:106-109.

184. South, D. B. 1986b. Herbicides for southern pine seedbeds. South. J. Appl. Forestry 10:152-157.

185. South, D. B. 1987a. A re-evaluation of Wakeley's "critical tests" of morphological grades of southern pine nursery stock. South African Forestry J. 142:56-59.

186. South, D. B. 1987b. Sulfometuron-methyl increased ectomycorrhizae at two loblolly pine nurseries in Arkansas. Page 181 *In* Proc. 40th Annual Meeting of the Southern Weed Science Society (A. D. Worsham, ed.). South. Weed Sci. Society, Champaign, Ill.

187. South, D. B. 1988. Nursery management affects the efficiency of a tree improvement program. Pages 203-209 *In* Proc. WGFTIP Tree Improvement Short Course (W. J. Lowe, ed.). Texas Forest Serv., Western Gulf Forest Tree Improvment Program, College Station.

188. South, D. B., J. N. Boyer, and L. Bosch. 1985. Survival and growth of loblolly pine as influenced by seedling grade: 13-year results. South. J. Appl. Forestry 9(2):76-81.

189. South, D. B., C. W. Brewer, H. S. Larsen, W. D. Kelley, and J. N. Boyer. 1984. 1983-84 annual report: Auburn University Southern Forest Nursery Management Cooperative. Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala. 102 p.

190. South, D. B., and H. S. Larsen. 1985. Seed efficiency in southern pine nurseries. Alabama Agric. Exp. Sta., Highlights of Agric. Res. 33(2):5.

191. South, D. B., and J. G. Mexal. 1983. Effects of bifenox and oxyfluorfen on emergence and mortality of loblolly seedlings grown under growth chamber conditions. Pages 418-426 *In* Proc. 2nd Biennial Southern Silvicultural Research Conference (E.P. Jones, Jr., ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-24.

192. South, D. B., and *J.* G. Mexal. 1984. Growing the "best" seedling for reforestation success. Alabama Agric. Exp. Sta., Auburn Univ., Auburn, Ala. 11 p. Forestry Departmental Series No. 12.

193. South, D. B., J. G. Mexal, and J. P. van Buijtenen. 1989. The relationship between seedling diameter at planting and long-term growth of loblolly pine seedlings in east Texas. *In* Proc. 10th North American Forest Biology Workshop. Vancouver, B.C.

194. South, D. B., R. *J.* Mitchell, R. K. Dixon, and M. S. Vedder. 1988. New ground syndrome - an ectomycorrhizal deficiency in pine nurseries. South. J. Appl. Forestry 12:234-239.

195. South, D. B., and H. M. Williams. 1988. Should fall irrigation be applied at nurseries located on sands? South. J. Appl. Forestry 12:273-274.

196. South, D. B., H. M. Williams, and J. N. Boyer. 1987. Unpublished data, Auburn Univ., Auburn, Alabama.

197. Stanley, H. 1987. Top pruning. Pages 130-135 *In* Proc. 1986 Southern Forest Nursery Ass. (R. A. Schroeder, ed.). Pensacola, Fla.

198. Sterling, E. A. 1906. How to grow young trees for forest planting. Pages 183-192 *In* Yearbook of the United States Department of Agriculture. Government Printing Office, Washington, D.C.

199. Stone, E. C. 1955. Poor survival and the physiological condition of planting stock. Forest Sci. 1:90-94.

200. Stange, C. M., and C. R. Venator. 1985. Testing superabsorbent treatments for loblolly pine seedlings. Pages 174-177 *In* 1984 Proc. Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.

201. Stransky, J. J., and D. R. Wilson. 1964. Terminal elongation of loblolly and shortleaf pine seedlings under soil moisture stress. Soil Sci. Soc. Amer. Proc. 28:439 440.

202. Stransky, *J.* J., and D. R. Wilson. 1967. Soil moisture and

texture affect root and shoot weights of transplanted pine seedlings. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. Note SO-62. 3 p.

203. Sutton, R. F. 1979. Planting stock quality and grading. Forest Ecol. Manage. 2:123-132.

204. Switzer, G. L. 1960. Exposure and planting depth effects of loblolly pine planting stock on poorly drained sites. J. Forestry 58:390-391.

205. Switzer, G. L. 1962. Some effects of nursery soil fertility on loblolly pine *(Pinus taeda* L.) planting stock. Ph.D. dissertation, State Univ. of New York, Coll. of Forestry, Syracuse Univ., Syracuse. 181 p.

206. 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. Soc. Amer. Proc. 27:461-464.

207. Switzer, G. L., and L. E. Nelson. 1964. Unpublished data, Mississippi State Univ., Starkville.

208. Switzer, G. L., and L. E. Nelson. 1967. Seedling quality strongly influenced by nursery soil management, Mississippi study shows. Tree Planters' Notes 18(3):5-14.

209. Tanaka, Y., J. D. Walstad, and J. E. Borrecco. 1976. The effect of wrenching on morphology and field performance on Douglas fir and loblolly pine seedlings. Can. J. Forest Res. 6:453-458.

210. Taylor, R., and J. P. Barnett. 1985. Use of time-temperature monitors for controlling seedling quality in storage. Pages 178-183 *in* Proc. 1984 Southern Nursery Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga.

211. Tuttle, C. L., D. B. South, M. S. Golden, and R. S. Meldahl. 1987. Relationship between initial seedling height and survival and growth of loblolly pine seedlings during a droughty year. South. J. Appl. Forestry 11:139-143.

212. Tuttle, C. L., D. B. South, M. S. Golden, and R. S. Meldahl. 1988. Initial *Pinus taeda* seedling height relationships with early survival and growth. Can. J. Forest Res. 7:867-871.

213. U.S.D.A. Forest Service. 1988. 1987 U.S. forest planting report. Government Printing Office, Washington, D.C. 1988-201-023:60605/FS. 13 p.

214. 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.

215. Van den Driessche, R. 1984. Seedling spacing in the nursery in relation to growth, yield, and performance of stock. Forestry Chron. 60:345-355.

216. Van den Driessche, R. 1987. Importance of current photosynthate to new root growth of rooted cuttings compared with seedlings. Can. J. Forest Res. 17:157-164.

217. Venator, C. R. 1983. Effect of lateral root pruning on development of nursery-grown longleaf pine seedlings. Tree Planters' Notes 34(2):17-19.

218. Venator, C. R., and J. C. Brissette. 1983. The effectiveness of superabsorbent materials for maintaining southern pine seedlings during cold storage. Pages 240-245 *In* Proc. 1982 Southern Nursery Conferences (J. C. Brissette and C. W. Lantz, eds.). U.S.D.A. Forest Serv., Atlanta, Ga. Tech. Publ. R8-TP4.

219. Venator, C. R., and J. G. Mexal. 1981. The effect of wrenching and planting date on the survival of loblolly pine. Pages 20-24 *in* Proc. 1st Biennial Southern Silvicultural Research Conference (J. P. Barnett, ed.). U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-34.

220. Wakeley, P. C. 1935. Artificial reforestation in the southern region. Government Printing Office, Washington, D.C. U.S.D.A. Tech. Bull. 429.115 p.

221. Wakeley, P. C. 1938. Planting southern pines. Government Printing Office, Washington, D.C. U.S.D.A. Leaflet 159.8 p.

222. Wakeley, P. C. 1949. Physiological grades of southern pine nursery stock. Pages 311-323 *In* Proc. of the 1948 Society of American Foresters Annual Meeting (H. L. Shirley ed.). Society of American Foresters, Washington, D.C.

223. Wakeley, P. C. 1954. Planting the southern pines. Government Printing Office, Washington, D.C. U.S.D.A. Agric. Monogr. No. 18.233 p.

224. Wakeley, P. C. 1965. The less obvious problems of nursery stock production. Pages 77-92 *In* Proc. Nursery Soil Improvement Sessions (A. L. Leaf, ed.). State Univ. of New York, Coll. of Forestry, Syracuse Univ., Syracuse.

225. Walstad, J. D., J. H. Breland, and J. G. Mexal. 1977. Application of wrenching and lateral pruning in loblolly pine nurseries. Weyerhaeuser Co., Hot Springs, Ark. Forest. Res. Tech. Rep. 042-2008/77/10.7 p.

226. Wasser, R. G. 1979. Tree improvement research - pure vs. random sowing study. Pages 15-19 *In* Proc. 1978 Southern Nurserymen's Conferences (C. W. Lantz, ed.). U.S.D.A. Forest Serv., Atlanta, Ga. Tech. Publ. SA-TP6.

227. Webb, A. 1987. Unpublished data, Superior Trees Inc., Lee, Fla.

228. Wilder-Ayers, J. A., and J. R. Toliver. 1987. Relationships of morphological root and shoot characteristics to the performance of outplanted bareroot and containerized seedlings of loblolly pine. Pages 206-211 *In* Proc. 4th Biennial Southern Silvicultural Research Conference (D. R. Phillips, ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N. C. Gen. Tech. Rep. SE-42.

229. Williams, H. M., and D. B. South. 1988. Effects of fall irrigation at a sandy nursery on morphology and root growth potential of loblolly pine seedlings. South African Forestry J. 147:1-5.

230. Williams, H. M., D. B. South, and G. R. Glover. 1988. Effect of bud status and seedling biomass on root growth potential of loblolly pine seedlings Can. J. Forest Res. 18:1635-1640.

231. Williston, H. L. 1967. Clay slurry root dip impairs survival of loblolly pine seedlings in Mississippi. Tree Planters' Notes l8(4):28-30.

232. White, J. B. 1981. The influence of seedling size and length of storage on longleaf pine survival. Tree Planters' Notes 32(4):3-4.

233. Xydias, G. K. 1981. Plantation survival studies of Continental Forest Industries. Pages 8-15 *In* Proc. 1st Biennial Southern Silvicultural Research Conference (J.P. Barnett, ed.). U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans. Gen. Tech. Rep. SO-34.