New Forests 7: 63–92, 1993.

Review paper

Rationale for growing southern pine seedlings at low seedbed densities

DAVID B. SOUTH
School of Forestry and Alabama Agricultural Experiment Station, Auburn University, Alabama 36849–5418, USA

Received 3 April 1991; accepted 10 April 1992

Key words: seedling morphology, nursery, survival, growth, economics, performance potential

Application. Growing bare-root southern yellow pine seedlings at low seedbed densities can improve the morphology of the seedling by increasing diameter and root system volume without increasing seedling height. The outplanting of morphologically improved seedlings can increase the per hectare volume production at age 10 to 20 years by as much as 30 m^3/ha per mm increase in root collar diameter (within the range of 2 to 6 mm). However, the economic gains of planting these "morphologically improved" seedlings will depend on proper seedling handling and plantation management.

Abstract. Although most bare-root pine seedlings in the Southern United States are grown at seedbed densities near 300/m^2, the density used in other regions of the world is often less than 200/m^2. One rationale for growing seedlings at lower seedbed densities is based on the desire to reduce the time required for successful stand establishment. Achieving a one- to two-year advancement in stand establishment can result in an additional 15 to 30 m^3/ha within 15 to 20 years. Although seedling grade studies have demonstrated similar gains in volume production at ages 10 to 30 years, the findings from these studies are not widely known. The rationale in the Southern United States for growing at higher seedbed densities appears to be based on: (1) misinformation regarding the performance of morphologically improved seedlings; (2) a desire to minimize seedling and planting costs; and (3) density recommendations that are not based on volume growth in the field.

Introduction

The practice of growing pine seedlings at low seedbed densities has been used throughout the world. During the 1970's, *Pinus elliottii* Engelm., *P. taeda* L., and *P. radiata* D. Don seedlings were grown in bare-root nurseries in South Africa at densities of 120 to 150/m^2 (Donald 1976; Cawse and Martyn 1981; Young 1981). In China, a density of 80 to 100/m^2 was recommended for *P. elliottii* (Kuo 1965). In South America, a common density for pines in bare-root nurseries is 150/m^2 (Morales 1983; Davey

1984). In Australia and New Zealand, seedlings grown at low seedbed densities exhibit greater survival and growth than seedlings grown at densities above $200/m^2$ (Benson and Shepherd 1976; Bowles 1981). As a result, densities of 120 to $150/m^2$ are used in New Zealand (FRI 1988) while densities of 130 to $180/m^2$ are used in Australia (Ward and Johnston 1986; Donald 1991). In the Southern United States, low seedbed densities ($<120/m^2$) are used to produce morphologically improved[1] seedlings of *P. palustris* Mill. However, the trend of lowering the seedbed density for the other southern yellow pines (*P.* subsection *Australes* Loud.) has been slow to occur in the Southern United States. Prior to 1950, the recommendation by the United States Forest Service was to have densities as high as $500/m^2$ for *P. taeda* (Mattoon 1926; Wakeley 1935; Huberman 1938; Wakeley 1954). For *P. echinata*, the recommendation was as high as $750/m^2$ (Wakeley 1935). For several decades, a seedbed density of $430/m^2$ was considered preferable to lower densities due to lower production costs (Foster 1956; Shoulders 1961; Burns and Brendemuehl 1971). Consequently, during the late 1970s and early 1980's, most nurseries in the Southern United States were growing seedlings at densities greater than $300/m^2$ (Boyer and South 1988). At some nurseries the density exceeded $400/m^2$ (Marx et al. 1984; Marx and Cordell 1987). The primary reason for the high densities was due to low demand for seedlings with improved morphology. The forestry community was largely unaware of the potential growth benefits resulting from planting morphologically improved seedlings. Some experts said there is no correlation between seedling size at 9 months and later growth as adults. Finally, nursery managers were told in order to minimize seedling costs and to "fully utilize the capacity of the soil," it was important to grow seedlings at high densities.

Reevaluation of data

While it is certainly true that seedling morphology is not a perfect predictor of field survival, it is wrong to imply that seedling morphology is a poor indicator of growth potential. In fact, for an individual seedling prior to planting, seedling morphology is the best tool we have to predict the relative potential for growth. Although knowing the genotype usually does not help predict field survival, this does not mean genetically improved seedlings should not be used to improve the growth potential of a plantation. Likewise, just because seedling morphology is not a perfect predictor of field survival, this does not mean we should not use morphologically improved seedlings to improve the growth potential of our plantations.

Some who say seedling morphology is a poor predictor of survival cite old studies conducted in the 1930's when morphological standards were low and seedbed densities were high. Others cite more recent studies where other confounding variables are present. Although many studies have demonstrated a positive correlation between root-collar diameter and survival (Fig. 1), these studies are rarely cited by those who claim that seedling morphology is a poor predictor of field survival of *P. taeda*.

Old studies

Wakeley recommended growing *P. palustris* at seedbed densities as high as 370/m^2 and stated that good *P. palustris* seedlings could be produced at 430/m^2 (Wakeley 1935). As a result, the "large" seedlings from the high seedbed densities likely had a very poorly developed root system with a low root weight ratio. This could explain why seedlings with 9 mm root-collar diameters did not survive as well as seedlings with 6 mm root-collars. Wakeley stated that seedlings with root-collar diameters greater than 8 mm were inferior to seedlings in the 5 to 8 mm range (Wakeley 1949). Subsequently, nursery managers continued to grow *P. palustris* at high seedbed densities for many years. As a direct result of outplanting 5 to 8 mm *P. palustris* seedlings, many plantations failed. It was not until years later that the minimum diameter for a Grade 2 *P. palustris* seedling was increased to 10 mm (White 1981). It is now known that small-diameter *P. palustris* seedlings grown at high seedbed densities are actually inferior in growth to large-diameter seedlings grown at low seedbed densities (Derr 1955; Lauer 1987; Hatchell and Muse 1990). Even when artificially inoculated with mycorrhizae, seedlings grown at 130/m^2 produced 38 percent less volume per hectare at age 2 than did uninoculated, root-pruned seedlings grown at 65/m^2 (Hatchell 1986). Current planting recommendations call for a minimum root collar of 10 mm (Lauer 1987; Cordell et al. 1990) or 12 mm if the seedlings are stored for more than 10 days (White 1981; Anonymous 1990). Since the minimum diameter for a plantable *P. palustris* seedling has doubled, the desired seedbed spacing has been lowered to a density of 65 to 100/m^2. This is a classic example of how forest productivity can be reduced by growing seedlings at high seedbed densities.

Recent studies

Many studies with the southern yellow pines demonstrate a positive relationship between seedling size and field survival (Chapman 1948; Shipman 1958; Silker 1960; Shoulders 1961; Meekins 1964; Wakeley

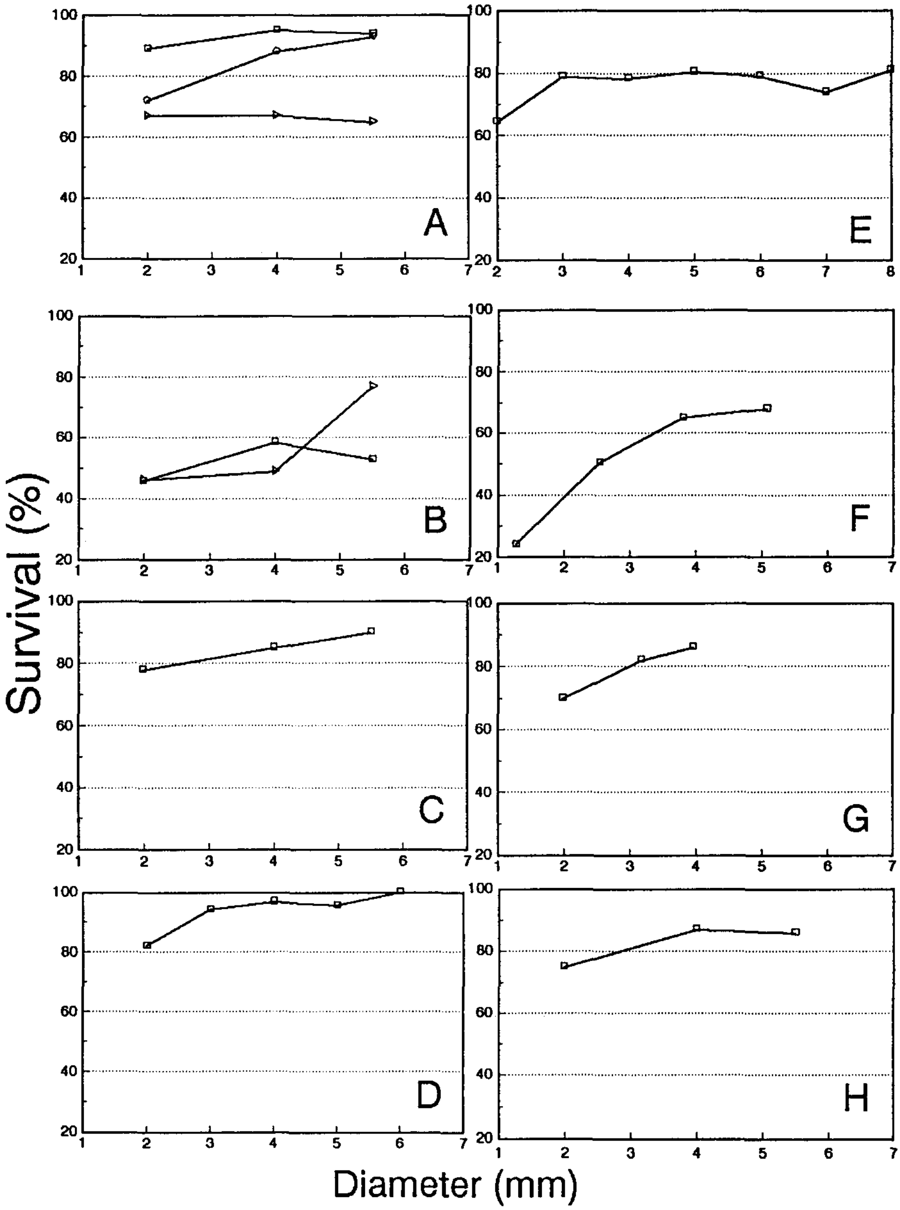

Fig. 1. The relationship between root-collar diameter (mm) and survival (%) of *P. taeda* seedlings as reported in eight studies. (A = Xydias 1981; B = Wakeley 1969; C = South et al. 1985; D = South et al. 1989; E = Shriver et al. 1990; F = Silker 1960; G = Meekins 1964; H = Blair and Cech 1974). Data from seedlings with diameters of 2 mm and less are included where Wakeley's Grade 3 seedlings were tested.

1969; Dierauf 1973; Carneiro 1976; Bacon et al. 1977; Blair and Cech 1974; White 1981; Xydias 1981; South et al. 1985; Rowan 1986; South et al. 1989; Shiver et al. 1990). However, due to various reasons, there are some reports that show no relationship between seedling diameter and survival. When citing these studies, misleading information can result when details of these studies are ignored. In one publication, it was stated that "Several researchers have failed to find a correlation between root collar diameter and field survival (Wilder-Ayers and Toliver 1987; Feret and Kreh 1985)." However, the failure of these researchers to find a correlation can be explained by a close examination of their data.

In the study by Wilder-Ayers and Toliver (1987), the authors removed approximately 44% of the roots from bare-root seedlings prior to planting. In fact, proportionally more roots were removed from the larger seedlings than from the smaller seedlings. The volumetric shoot/root ratio after pruning was 7 to 1. Under this type of treatment, one should not expect greater survival with bare-root seedlings with large diameters. The lack of a correlation for the container grown seedlings was apparently due to a lack of seedling variation. Even when a biological relationship exists, a researcher should not expect to demonstrate a correlation when there is little or no variation in seedling diameter.

In the study by Feret and Kreh (1985), seedling survival was generally high. Only 3 seedling samples out of 31 had less than 85% survival. In fact, two of the three seedling samples with low survival were air-dried for an hour or more before planting. Therefore, one should not expect a significant correlation between seedling size and survival when survival is high or when poor survival is a direct result of seedling desiccation. It is easy to misinterpret data when only part of the story is provided.

Morphologically improved seedlings survive better

There are several studies that demonstrate greater survival from morphologically improved seedlings grown at low seedbed densities (Table 1). When average survival is greater than 96%, seedbed density has little or no effect on survival. However, when the average survival is below 86%, the morphologically improved seedlings will exhibit greater survival (Fig. 2). When survival is less than optimum, planting seedlings from low seedbed densities usually increases survival by 4 to 10 percentage points over that of seedlings grown at 300/m^2 (Table 1).

There are several reasons why morphologically improved seedlings have higher survival. Seedlings grown at low seedbed densities have more root volume (Carlson 1986; Brissette and Carlson 1987; South et al. 1990), more strong first order lateral roots (Rowan 1986), more short

Table 1. Early percentage gains from growing southern pine seedlings at lower seedbed densities

Study	Species	Stand age	Density low	Density high	Survival gain	Height gain	Volume gain/ha
			plants/m²		% points	%	%
Derr 1955	palustris	1	108	215	6		
Shipman 1958	palustris	1	108	215	4		
Barnett 1991	palustris	1	108	215	3		
Scarbrough and Allen 1954	palustris	2	129	258	2	42	
Hatchell 1986	palustris	2	65	161	12	47	130
Hatchell and Muse 1990	palustris	2	65	129	0	50	68
Shoulders 1961	taeda	1	155	408	12		
	taeda	1	108	323	9		
	taeda	1	144	378	3		
	taeda	1	127	332	1		
Switzer and Nelson 1963	taeda	3	161	323		9	
	taeda	3	161	323		9	
	taeda	3	161	323		15	
Shipman 1964	taeda	2	215	430	1	18	
Carneiro 1985	taeda	2	156	278	−3	0	
Leach et al. 1986	taeda	2	215	323		9	14
	taeda	2	215	323	4	13	51
Rowan 1986	taeda	3	161	323	2	4	11
	taeda	4	161	323	8	10	32
	taeda	5	161	323	14	6	21
Shoulders 1961	elliottii	1	122	345	6		
	elliottii	1	148	364	−8		
	elliottii	1	116	340	8		
	elliottii	1	129	352	7		
Shipman 1964	elliottii	1	215	301	1	6	
Rowan 1986	elliottii	1	108	323	5	15	86
Brissette and Carlson 1987	echinata	1	123	331	2	7	52

Studies with no density less than $220/m^2$ are not included.

roots, more foliage, a greater root weight ratio (Fig. 3), and greater root growth potential (Balneaves 1983; Carlson 1986; Brissette and Carlson 1987; South et al. 1990). Seedlings that produce more new roots usually have a greater ability to take up more water (Carlson 1986; Carlson and Miller 1990). Contrary to popular belief, reducing seedbed density from $300/m^2$ to $200/m^2$ usually does not increase average seedling height for the southern yellow pines (Muntz 1944; Shoulders 1961; Shipman 1964; Dierauf and Garner 1980; Hassan 1983; Carneiro 1985; Brissette and

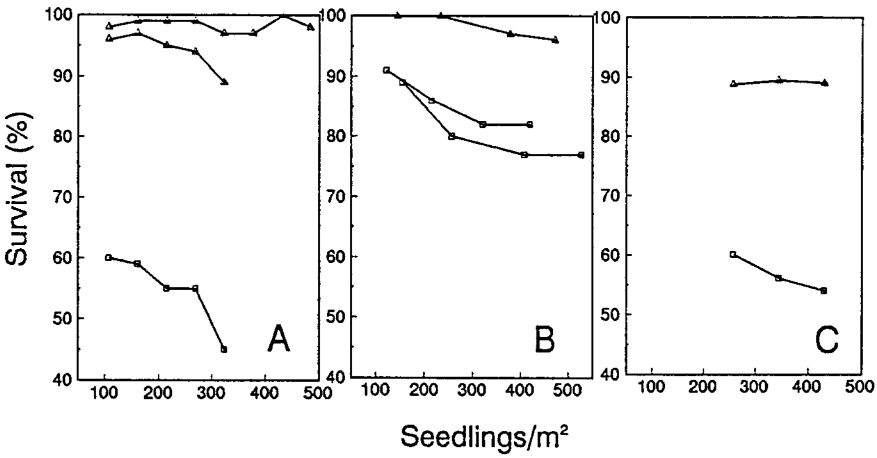

Fig. 2. Effect of seedbed density on survival of *P. taeda* seedlings when average survival is greater than 85% (△) or less than 86% (□). (A = Georgia — Rowan 1986; B = Louisiana — Shoulders 1961; C = Texas — Nebgen and Meyer 1986).

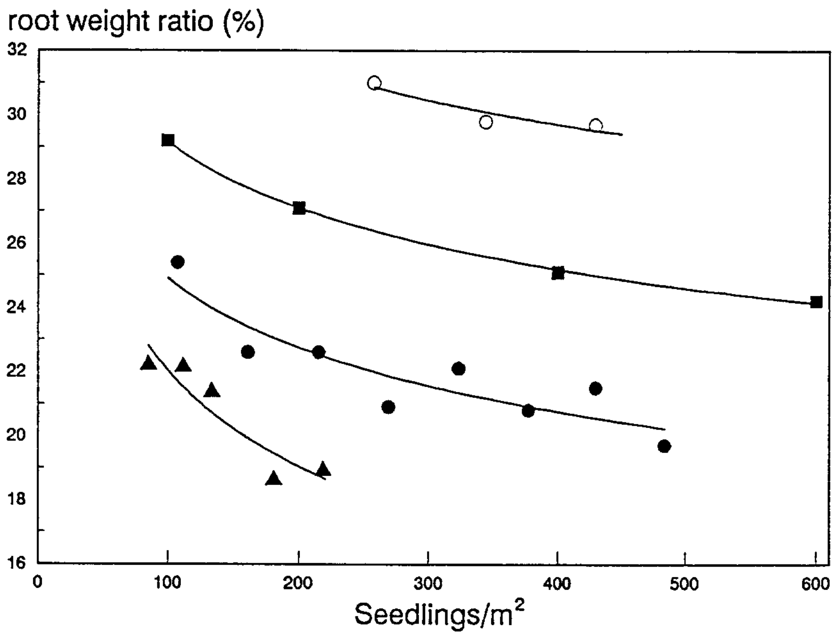

Fig. 3. The effect of seedbed density on the root weight ratio (dry weight of roots/dry weight of seedling) of *P. taeda* seedlings in Texas (0), South Carolina (■), and Georgia (•), (Harms and Langdon 1977; Nebgen and Meyer 1986; Rowan 1986) and *P. elliottii* in China (▲) (Kuo 1965).

Carlson 1987; Marx and Cordell 1989; South et al. 1990). In the past, it has been the very tall seedlings grown at high seedbed densities (and as a result, low root weight ratios) and planted out on areas with limited moisture that survived poorly. For example, Bengtson (1964) reported that *P. elliottii* seedlings that were 18 cm tall had greater survival (66% survival) than seedlings that were 33 cm tall (35% survival). When growing under high seedbed densities, the root weight ratio was likely much smaller for 33-cm trees than for 18-cm trees. This is especially true when attempting to remove a single large tree from the seedbed (as was done in Bengtson's study) instead of lifting the entire bed and then grading the seedlings.

Root weight ratio

Although lower seedbed densities can produce seedlings with larger root weight ratios, it is very important that the root weight ratio is not greatly decreased during the lifting process in the nursery. Although other nursery management practices will have a major effect, the general relationship between seedling density on root weight ratio is consistent among nurseries (Fig. 3).

Although a number of recent studies demonstrate the balance between roots and shoots is important to seedling survival, some researchers have implied that a morphological trait (such as a root weight ratio) is not important for field survival. However, the balance between root mass and shoot mass is especially important when seedlings are planted in areas or in seasons when moisture stress is likely to be severe. In fact, in one case where Grade 2 seedlings (root collar diameter 3.2 to 4.7 mm) of *P. taeda* survived better than Grade 1 seedlings (root collar diameter $>$4.7 mm), it was suggested the root weight ratio was greater for the grade 2 seedlings grown at 290/m^2 than for Grade 1 seedlings grown at the same density (Venator 1983).

A word of caution

One tree planter stated "I am a quality planter, I prune the roots to fit the planting hole." When making a small planting hole, this practice will result in pruning more roots from a large seedling than from a small seedling. This may explain in part why some operational foresters have observed that Grade 1 seedlings do not survive as well as Grade 2 seedlings. The survival benefits of growing seedlings at low seedbed densities will be destroyed if the root weight ratio is reduced by removing roots. Although pruning of roots by tree planters improves the ease of planting, it can reduce outplanting survival (Mexal and South 1991). The root growth potential of seedlings can be cut in half by stripping the roots through a closed fist only once (South and Stumpff 1990). Therefore, the results from research studies can differ greatly from that of operational studies if tree planters strip and prune roots prior to planting.

In addition, seedlings with large root systems that are not planted deep enough (from making too small a planting hole) will also not survive well. However, when planted deeply enough (either by machine or by using proper hand-planting methods), seedlings from low seedbed densities that have higher root weight ratios, more intact fibrous roots, and more foliage will usually survive better than seedlings grown at high seedbed densities (Table 1).

Morphologically improved seedlings produce more wood

Although survival benefits can result from proper planting of morphologically improved seedlings, the greatest and most consistent benefit is from an increase in growth. Realized gains in survival may occur in only one out of three years, while gains in growth can occur each year (Switzer and Nelson 1963). Therefore, the main rationale for using morphologically improved seedlings is to improve the *growth* potential of our plantations. The following review of previous research documents the fact that seedling morphology is important and seemingly small differences in seedling diameter do not "wash out" after a few years in the field.

Density studies

Although early seedbed density studies were conducted (May 1933; Muntz 1944), the seedlings were not outplanted. In the early 1950s, researchers began to demonstrate that rapid growth of *P. palustris* could be achieved by improving seedling morphology with low seedbed densities (Table 1). Soon afterwards, density studies with *P. taeda* and *P. elliottii* showed similar results. However, usually only survival and/or gains in height growth were initially reported (Switzer and Nelson 1963; Burns and Brendemuehl 1971; Dierauf and Garner 1980; Nebgen and Meyer 1986). After 1980, researchers finally began to report the volume gains achieved by lowering seedbed densities (Balneaves 1983; Carneiro 1985; Rowan 1986; Leach et al. 1986; Brissette and Carlson 1987; Hatchell 1986; Hatchell and Muse 1990). This progression of data reporting (nursery data only — 1933—1950; nursery data plus field survival —

1950—1960; survival plus height growth data 1954—1985; survival, height growth and early volume growth — 1980—present) is partly responsible for the delay in reducing the target seedbed density. However, it is the long-term growth data that will finally determine if researchers will recommend lower seedbed densities.

Fortunately, Autry (1972) was able to collect some long-term growth data from two density studies installed by Switzer. Treatments were planted in adjacent rows spaced 1.2 m apart. After an early pre-commercial thinning, seedlings were 1.8 m apart within the rows. Total dry weight of the nursery seedlings at lifting was correlated with final tree volume (r = 0.83 for study 1 and 0.65 for study 2). The morphologically improved seedlings (those grown at $161/m^2$) were 18 to 22% larger in tree volume than seedlings grown at $323/m^2$ (Fig. 4). These gains are solely due to differences in nursery management and are not confounded with genetic differences. These two studies demonstrate that substantial long-term gains in volume can be achieved by outplanting morphologically improved seedlings. As a result of the long-term gains, Mexal (1981) was among the first in the Southern United States to recommend reducing the target density to $200/m^2$.

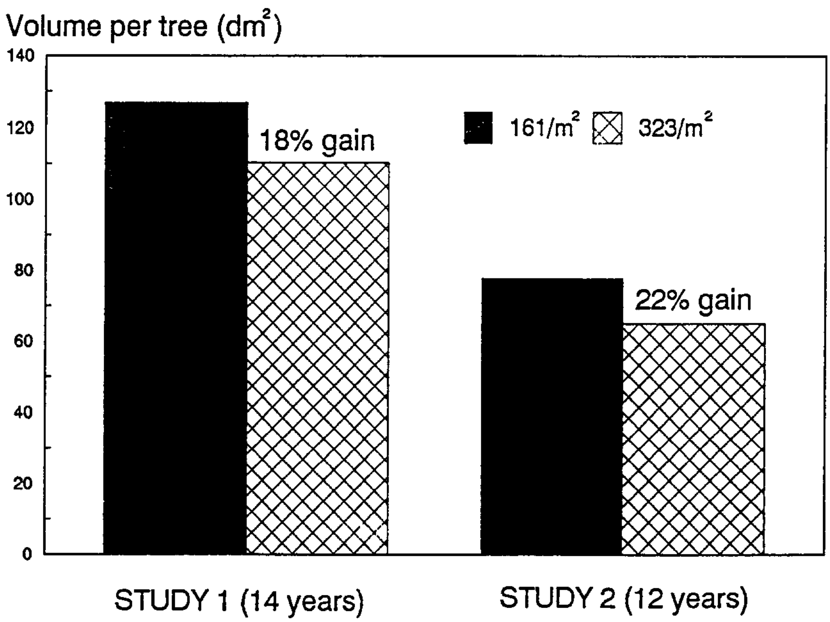

Fig. 4. The effect of lowering seedbed density on average tree volume of *P. taeda* in Mississippi (Autry 1972).

Seedling grade studies

There are a number of row-plot or single-tree-plot studies that report growth differences due to differences in seedling morphology (Silker 1960; Hunt 1967; Wakeley 1969; Blair and Cech 1974). Although row plots are sometimes used to calculate volume per hectare (Wakeley 1969; Talbert 1982; Hodge et al. 1989), row-plot tests are not good for making such estimations since the potential for exaggerated differences with intense competition is real. This could lead to substantial differences between theoretical and realized volume gains (Lowerts 1987). Block plots should be used when the goal is to measure yield per unit area (Zobel and Talbert 1984). Fortunately, there are several seedling grade studies that employ block plots. Although these were not seedbed density studies, they are useful in determining potential gains from planting seedlings with large diameters.

Australia

In Australia, a seedling grade study was installed in 1969 using *P. elliottii* seedlings raised from orchard seed (Bacon et al. 1977; Bacon 1979). This study compared six different seedling grades. Each plot contained 49 trees (7 rows with 7 trees/row) that were planted on a 2.4 by 2.4 m spacing. Each treatment was replicated six times. Measurements were made after 10 years in the field (Fig. 5). In this study, the volume gains are due solely to survival differences.

Florida

In 1977, a *Pinus elliottii* seedling grade study was established on ITT—Rayonier's Nassau Forest (Jacobson 1980). Each plot consisted of 49 trees (7 rows of 7 trees; 2.0 by 3.4 m spacing) with 25 measurement trees. Each treatment was replicated 4 times. Seedlings were separated into 3 grades according to Wakeley's diameter limits. At age 10, average tree volume was 70, 65, and 59 cubic decimeters for the Grades 1, 2, and 3, respectively. Although Grade 1 seedlings were 17% greater in volume per hectare than Grade 3 seedlings, there was no difference between Grade 1 and Grade 2 seedlings.

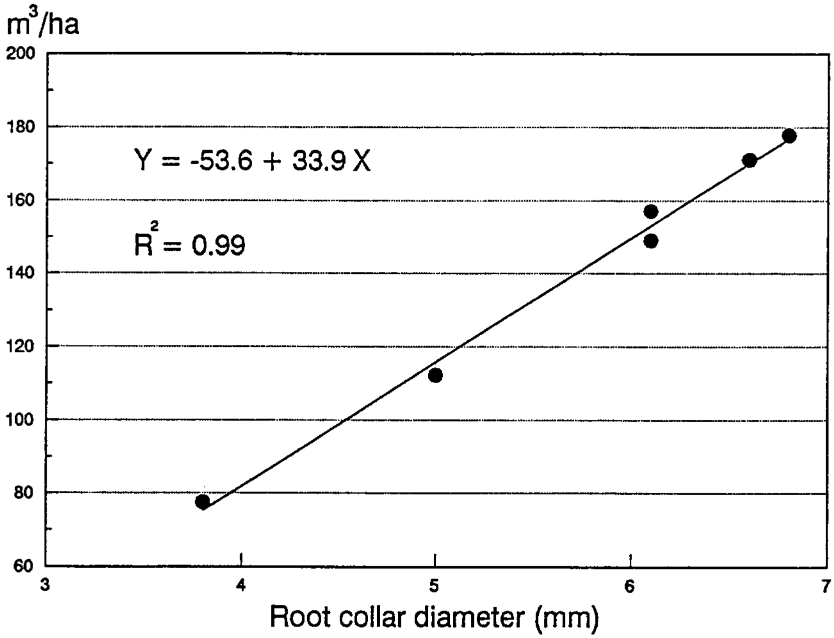

Fig. 5. The relationship between root-collar at time of outplanting and total volume production of *P. elliottii* after 10 years in the field (Bacon 1979).

Georgia

At Calloway Gardens in Georgia, a seed size study was installed in 1954 using "select" versus "average" *P. taeda* seedlings (Sluder 1979). The "select" seedlings were apparently larger in diameter at time of outplanting since there were little or no differences in average height (e.g. 254 mm vs. 259 mm for "select" and "average" seedlings from large seed). Two seed sizes and two seedling sizes made up a 2 × 2 factorial. Each plot consisted of 20 trees (4 rows of 5 trees/row) at a 3.0 by 3.0 m spacing. Seedling size had a significant effect on survival for the medium seed but not for the large seed. Therefore, with the medium seed, the 27 percent volume gain is attributable to both an increase in survival and an increase in tree growth. However, with the large seed, the 14 percent volume gain was solely due to additional tree growth.

Louisiana

A seedling grade study was installed in 1967 on an extremely productive site (South et al. 1985). The *P. taeda* seedlings used in this study were raised from six different seed sources. Each plot contained 36 trees (6 rows with 6 trees/row) that were planted on an 2.4 by 2.4 m spacing. Each treatment was replicated four times for a total of 72 plots. Measurements were made after 13 years in the field. In four sources, the per hectare growth gains for planting Grade 1 seedlings (as opposed to Grade 2 seedlings) ranged from 14 to 26 percent and were due to both increases in survival and tree growth. However, for two sources, the gains (10 and 17 percent) were solely due to differences in tree growth.

Missouri

Three latin-square studies involving seedling grades of *P. echinata* were established in southern Missouri from 1939 until 1941 (Clark and Phares 1961). The spacing was 1.8 by 1.8 m with either four (1940) or six replications. The size of the plots for each grade varied with the study but were either 4 rows of 4 trees or 5 rows of 5 trees. The seedlings were sorted into grades according to both height and diameter measurements. All three studies were measured in 1959 and volume measurements were calculated. In each study, the larger diameter seedlings exhibited greater survival and, therefore, volume production per hectare was greater. The per hectare volume differences (between 3.8 and 5.1 mm classes) for the 19- and 21-year-old plantations were 20 and 26 percent, respectively. For the 20-year-old plantation, there was a 19 percent difference between the 2.5-mm and 3.8-mm seedlings.

South Carolina

In the 1950s, a study involving seedling size was conducted on the Santee Experimental Forest (Hatchell et al. 1972). Although the block plots were small (3 rows of 4 trees per row; planted on a 1.8 by 1.8 m spacing), they were replicated both in space (two replications per grade) and time (three years). Height was the only seedling characteristic measured. Mean heights were 30.5 and 13.5 cm for the two *P. taeda* grades. The *P. elliottii* grades were 29.5 and 14.5 cm tall at planting. After 10 years in the field, survival was approximately the same for the *P. elliottii* (tall = 76% and short = 74%). However, the per hectare volume was 80% greater for the tall grade. For the *P. taeda* grades, survival was slightly lower for the taller grade (tall = 81% and short = 86%). Despite this, the per hectare volume difference was 92% greater for the taller grade. In both studies, the additional volume was solely due to additional tree growth.

Predicting per hectare volume gains

It is clear from the above studies that per hectare volume gains can be made at ages 10 to 20 years by planting seedlings with large diameters. In most cases, the gains will result from both greater survival and greater average tree growth. In some cases the gains are solely attributable to greater tree growth. In only two cases (Clark and Phares 1961; Bacon 1979) were the gains primarily due to greater survival. In no case did Grade 1 seedlings grow less (on an individual tree basis) than the Grade 2 seedlings. In one case where lower per hectare volume production occurred by planting Grade 1 seedlings (Blair and Cech 1974), the losses were attributable only to poorer survival (likely a result of poorer root weight ratios or inexperience in planting larger stock).

Gains per mm increase in root-collar diameter

It is not enough to say "if you want more wood, carefully raise and carefully plant stock with large diameters and root mass." What the practical forester needs is some estimate of how much volume gains can be expected. One way to do this is to estimate the volume gain per mm increase in seedling diameter, which is provided for the above examples in Table 2. In one case where there were 6 diameter classes, the slope of the regression was used (Fig. 5). In two studies where diameters were measured prior to planting (Clark and Phares 1961; South et al. 1989), the differences between the top two diameter classes were compared. When seedling diameters were not reported, it was assumed the average root-collar diameters for a Grade 1 and Grade 2 seedling were 6 mm and 4 mm, respectively. Therefore, the observed volume difference between the two grades was divided by 2 to get an estimate of the volume gain per mm. Until additional data are collected, 6 mm should be tentatively considered the upper range for this relationship. This method of estimating volume gains was used to obtain the volume gains listed in Table 2. However, there are three other methods that have been used to estimate volume gains.

Percent gain

Geneticists often predict the per hectare volume gains calculating a percentage of the volume expected from a local unimproved source. A certain "% gain" is estimated for first-generation seedlings and a higher "% gain" is estimated for second-generation seedlings. Although this is a tempting method to use due to its simplicity, it can be very misleading since the "%

Table 2. Effect of increasing average root-collar diameter of southern pine seedlings by one mm on observed gains in height and volume

Study	Stand Age	Plot shape	Average height	Height gain	Volume gain
			- - m - -	-dm/mm-	m^3/ha/mm
Wakeley 1969	30	row	18.6	0.1	8.7
	30	row	16.8	8.2	68.3*
	30	row	18.0	6.3	123.8*
	30	row	16.6	3.2	−1.1**
Clark and Phares 1961	21	block	9.7	1.2	40.5
	20	block	9.1	1.2	23.4
	19	block	8.8	0.0	41.2
Sluder 1979	15	block	14.6	3.6	15.3
	15	block	14.0	2.1	8.3
South et al. 1989	15	row	9.5		8.5
South et al. 1985	13	block	17.3	1.5	30.0
Blair and Cech 1974	13	row			19.5
	13	row			18.6
	13	row			26.4
	13	row			0.0
	13	row			−26.8***
Hatchell et al. 1972	10	block	8.8	16.4	28.8
	10	block	8.8	7.9	24.9
Bacon 1979	10	block	14.3	1.5	33.9
ITT (unpublished)	10	block	10.3	0.0	0.0
Silker 1960	10	row	6.4	2.7	7.8
Hunt 1967	9	row	8.5	3.0	5.0
	9	row	8.8	3.0	4.1

* These values are likely too high due to use of row plots.
** Low due to poor initial survival of Grade 1 seedlings that were infected with scale insects (Wakeley 1935).
*** Low due to poor survival of Grade 1 seedlings.

gain" usually decreases with age (Talbert 1982). The "% gain" in per hectare volume observed at age 10 years will not be the same as that for unthinned plantations at age 20, 30, 40, 50, etc. The following example illustrates that the percentage gain in average tree volume due to planting larger stock will decrease with age.

These data are from a seed source study in Texas (South et al. 1989). The absolute difference in size between a 3-mm and 5-mm seedling may appear small, but the 5-mm seedling can be more than 200% larger in volume than the 3-mm seedling. However, with time, the absolute difference in tree volume increases while the percentage difference in volume decreases (Fig. 6). At age 15 years, the average tree volume was 20% greater for the 5-mm seedling (a percentage difference similar to that reported by others) (Autry 1972; Sluder 1979; South et al. 1985). At age 30, the difference is reduced to 6.5%. Therefore, to avoid overestimating expected volume gains, the percentage difference observed at a young age should never be extrapolated to older trees (Zobel and Talbert 1984).

A shift in site index

Some researchers use a shift in site index to predict the gains from genetics (Buford 1986) or various cultural practices (Hughes et al. 1979). This method is attractive since one could utilize growth and yield models to predict volume gains. However, there can either be a temporary "lift" in site index or the "lift" can be permanent (Hughes et al. 1979; Sprinz 1987). If the "lift" is permanent, then the carrying capacity (i.e. the maximum amount of pine volume the stand can support when the current

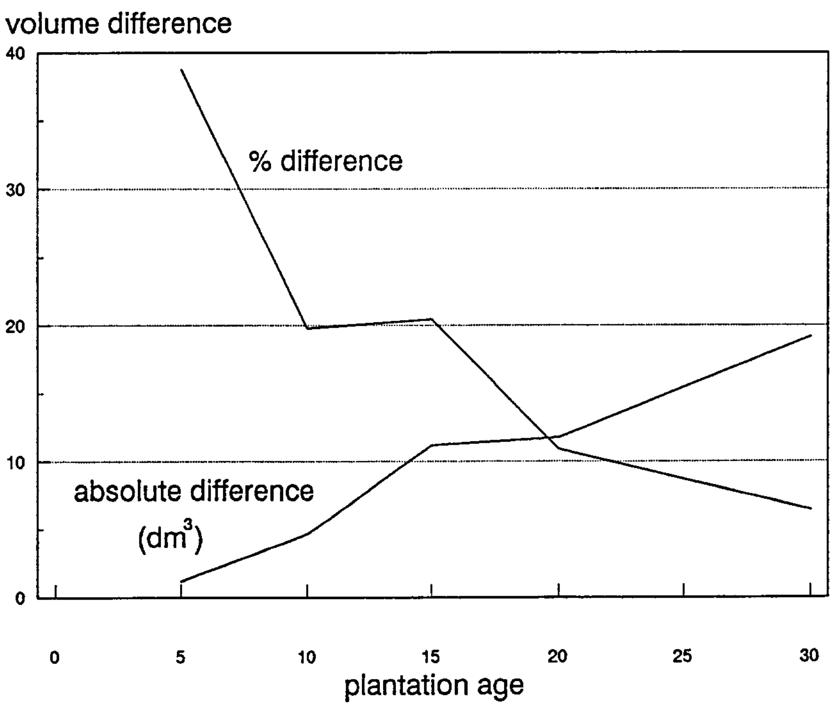

Fig. 6. The percentage difference and absolute difference in average tree volume between 3-mm seedlings and 5-mm seedlings of *P. taeda* planted in Texas (South et al. 1989).

annual increment (m^3/ha) reaches zero) will be increased, and use of growth and yield models to project this increase will be appropriate for long rotations. However, when considering volume gains from planting morphologically improved seedlings, it is difficult to visualize why an increase in carrying capacity would occur. Therefore, the volume gains due to planting seedlings with larger diameters are likely due to a temporary "lift." This means that for a 50-year rotation, estimating the gains by increasing the site index value would result in an overestimation of volume gains.

A shift in age

A fourth method of predicting volume gain is to advance the stand age. In other words, getting the trees off to a faster start could result in a 10-year-old stand that would have the same stand structure and would grow the same as a "normal" stand at age 11 or 12 (Gordon and Duryea 1985). This method is more appropriate when a temporary "lift" in site index occurs. For unthinned *P. taeda* at age 50, this method would not show much (if any) difference in per hectare volume production due to advancing early stand development. Although this method can be used with any growth and yield program, a modification of PTAEDA2 (Burkhart et al. 1987) incorporates this as an option. This model allows the user to include a 1- to 3-year "boost" in stand establishment.

A growth and yield model was used to estimate the % gain in per hectare volume predicted for a 1- or 2-year advance in stand development (Fig. 7). As expected, the % gain declines with time. However, unlike the "shift in site index" method, the percent gain eventually reaches zero. Some data from several studies are also plotted. In general, the gains appear to fall within what should be expected for a 1- or 2-year gain in age. Even the data by Hatchell et al. (1972) seem less surprising when plotted in this manner.

How to obtain a one- and two-year age shift

A 1-year advance in stand development could be achieved by one of two methods. One way would be to purchase seedlings from the local nursery and grade out all seedlings that have a root collar diameter greater than 4.7 mm. The results from this method should be similar to past studies where only Grade 1 seedlings were planted. However, a major disadvantage would be that these seedlings were grown at densities near 300/m^2 and therefore would not be morphologically improved and, as a result,

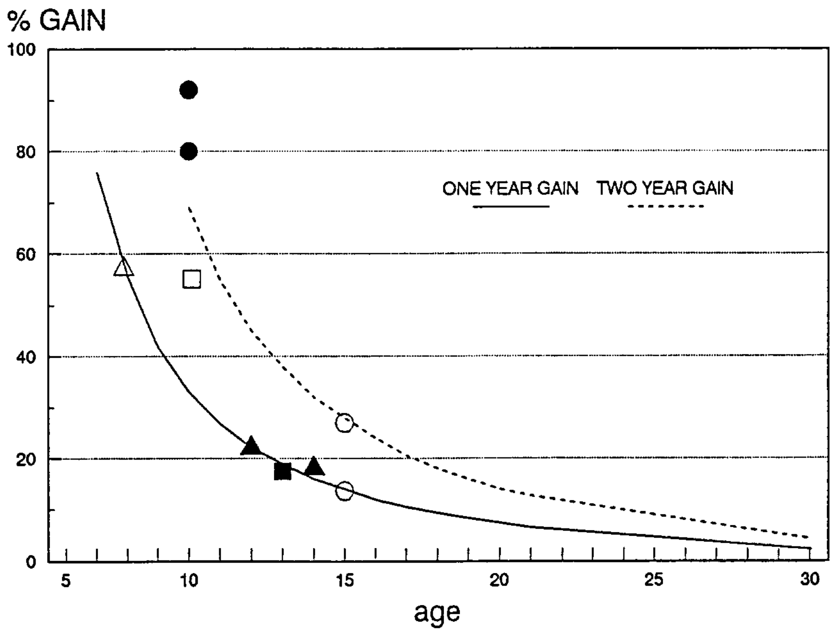

Fig. 7. Predicted percent gain in merchantable volume per acre by advancing the stand age by one or two years. Real data from various studies are plotted for purposes of illustration. Gain achieved by: ▲ = lowering seedbed density to $161/m^2$ (Autry 1972) ■ = planting seedlings >4.7 mm vs. seedlings $\leqslant 4.7$ mm (South et al. 1985) ○ = planting larger diameter seedlings (Sluder 1979) △ = planting mycorrhizal inoculated seedlings (Marx et al. 1988) □ = planting 6.8-mm seedlings instead of 5.1-mm seedlings (Bacon 1979) • = planting seedlings >4.7 mm vs. seedlings $\leqslant 4.7$ mm (Hatchell et al. 1972)

might not have a good root volume or root weight ratio. Since a tall Grade 1 seedling with a low root weight ratio will normally have a poorer chance of surviving a drought than a short Grade 2 seedling with high root weight ratio (Bengtson 1964; Venator 1983; Carlson and Miller 1990), these seedlings should be planted in moist soil and deeper than normal to help ensure good survival.

The recommended method would be to have a nursery manager grow seedlings at low seedbed densities (a target density of 150 to $200/m^2$ for *P. taeda*, *P. elliottii*, and *P. echinata*). The seedlings should be cultured so that they produce many fibrous roots and should be carefully lifted to retain both a good root weight ratio and fibrous roots. All cull seedlings (those with root-collar diameters less than 3.2 mm) would be removed and the remainder outplanted. This method should produce gains similar to those reported by Autry (1972).

Obtaining a 2-year shift in age should be relatively easy to obtain with

P. palustris because of the "grass stage" growth habit. However, for the other southern pines, the probability of actually achieving a 2-year gain is less certain because it takes a sound understanding of regeneration practices to consistently obtain such a gain. An integrated approach to regeneration would be required so that no "weak link" spoils the efforts. First, the nursery cultural practices should be followed to produce an average root-collar diameter of near 6 mm without being too tall (Fig. 8).

The seedling culling standard should be raised to at least 4 mm. In order to be economical, this will mean growing at low seedbed densities and will likely involve fall fertilization with nitrogen. Most important is to avoid late winter planting (late February and March). In fact, if the soil moisture is adequate at time of planting, the two-year shift in age will be easier to achieve if the seedlings can be planted in late October or early November (Wakeley 1954; South and Mexal 1984; Kainer and Duryea 1990; Stumpff and South 1991). This would require little or no storage between lifting in the nursery and outplanting. However, the practice can be very successful on an operational scale (e.g. as carried out by St. Regis in Florida and Union Camp in Georgia). Proper depth of planting is most

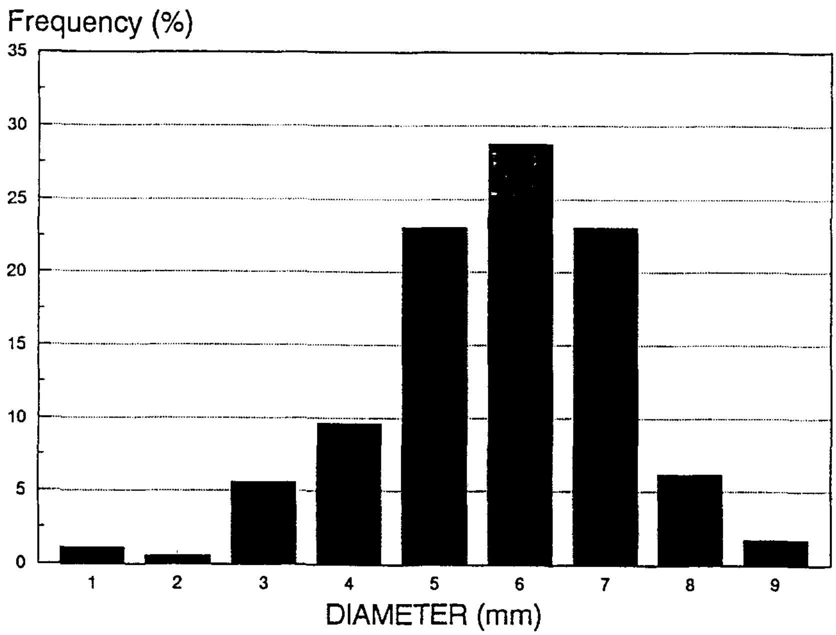

Fig. 8. Morphologically improved *P. elliottii* seedlings grown at a density of 161/m^2 at the Superior Trees Nursery at Lee, Florida. Average height of the seedlings that were greater than 5 mm was 257 mm.

important. Seedlings should be provided with a sufficiently deep hole and should be planted at least 5 cm deeper than the level at which they were grown in the nursery (Blake and South 1991; Long 1991). However, obtaining a sufficiently deep planting hole can be difficult when using a dibble bar or hoedad. Therefore, the use of shovels is recommended when hand planting seedlings with large root systems (Long 1991).

Economics

In the past, landowners have purchased genetically improved seedlings which cost more than "regular" seedlings. In some cases, the difference between "woods run" and "genetically improved" seedlings was $8 per thousand plantable seedlings (South 1988). However, most landowners are usually willing to pay extra for "genetically improved" seedlings since researchers had predicted the long-term growth gains would be worth the additional cost.

Block plot studies have demonstrated that additional volume growth can be expected from morphologically improved seedlings. Like genetically improved seedlings, they also cost more to produce. However, due to fixed costs and to increased seed efficiency, the additional cost of growing at low seedbed densities is often less than might be expected. It does not cost twice as much per thousand to grow seedlings at $60/m^2$ as compared to $120/m^2$ (Fig. 9). Depending on whether the seedlings are sold at cost or for a profit, a nursery manager may charge $3 to $10 more for a thousand *P. taeda* seedlings grown at low seedbed densities ($200/m^2$) than at higher densities ($375/m^2$). At one private nursery, seedlings grown at $160/m^2$ only cost the customer $18 more than seedlings grown at $375/m^2$.

In addition to increased seedling costs, transportation and planting costs might also be increased. The increase in transportation cost will be proportional to the additional volume required (assuming the cargo capacity is fully utilized when transporting the smaller stock). On some sites, tree planting productivity might be reduced by 10% when hand planting seedlings with a root mass of 2.1 g instead of 0.6 g (Blake and South 1991). However, planting costs should not increase with machine planting. The data in Tables 3 and 4 can be useful in determining if the additional costs are worth the investment.

The discounted value of a cubic meter of wood at several harvest ages and interest rates are presented in Table 3. By using Table 3 and estimating the additional cubic meters of wood produced, one can calculate how much increase in value can be obtained by planting morphologically improved seedlings. For example, if an additional 25 m^3 of wood was

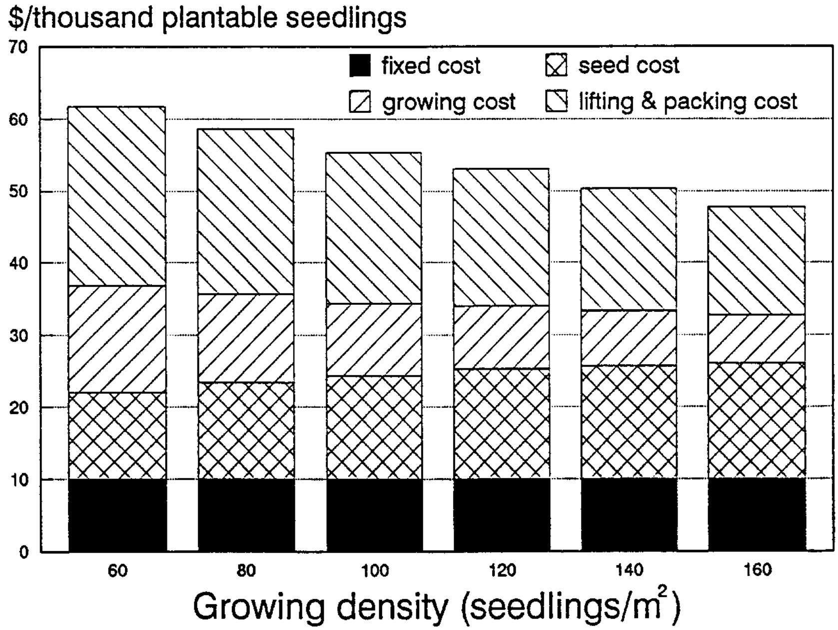

Fig. 9. An example of the effect of growing density (plantable seedlings plus culls) on cost of producing 1000 plantable *P. palustris* seedlings.

Table 3. Present value of one cubic meter of wood at various harvest ages, harvest values, and interest rates

Stumpage value ($/m^3 at time of harvest)	Harvert age	Real interest rate	
		6%	8%
9	15	3.76	2.84
	20	2.81	1.93
	25	2.10	1.31
	30	1.57	0.89
11	15	4.89	3.47
	20	3.43	2.36
	25	2.56	1.61
	30	1.91	1.09
13	15	5.42	4.10
	20	4.05	2.79
	25	3.03	1.90
	30	2.26	1.29

Table 4. Projected merchantable volume gains by achieving a one- and two-year advance in stand development and subsequent gains in present value from planting *P. taeda* stock capable of achieving such gains

Year advance	Stand age	Stand height	Planted seedlings per hectare					
			750	1500	3000	750	1500	3000
	-yr-	-m-	----	m^3 gain/ha	----	$ gains/1000 seedlings		
one								
	15	12	13.7	17.3	17.9	89	56	29
	20	16	14.2	15.0	11.3	65	34	13
	25	19	12.6	10.4	7.3	43	18	6
	30	21	10.1	5.7	2.8	26	7	2
two								
	15	13	27.8	34.5	34.8	181	112	57
	20	17	28.3	29.0	21.2	129	66	24
	25	19	24.8	19.7	13.6	85	34	18
	30	21	19.7	14.2	4.8	50	18	3

Volume gain/ha calculated from the North Carolina State University Plantation Management Simulator for site index 20 m (base age 25).
Assuming a 6% real interest rate and a stumpage value of $11/$m^3$.

harvested at age 15 years and sold for $11/$m^3$, the present value (at a 6% real interest rate) would be increased by $122 per hectare (25 m^3 × $4.89/$m^3$). Assuming that morphologically improved seedlings cost $10 more per thousand than "regular" stock, and transportation and planting costs were increased by $5.25 per thousand, then the benefit/cost ratio would equal 8 (assuming 1000 trees were planted per hectare).

The economic advantage of using morphologically improved seedlings will depend on site quality (Caulfield et al. 1987) and on how the plantation is managed. Both spacing in the plantation and the timing of the first thinning will affect seedling value. Since the use of morphologically improved seedlings does not cause a permanent "lift" in site index, their use in unthinned plantations on very long rotations is not recommended in areas where acceptable survival and early growth can be achieved with "regular" seedlings. For example, in Table 4, the predicted volume gain from planting 1500 morphologically improved seedlings per hectare (resulting in a 1-year gain in stand development) is only 5.7 m^3/ha for an unthinned stand at age 30. If the *additional* costs of using morphologically improved seedlings is more than $7 per thousand, then this investment would result in less than a 6% return on investment. In contrast, the economics can be very favorable if all the additional volume gains due to using morphologically improved seedlings are harvested with a commercial thinning (Blair and Cech 1974; South et al. 1985; Caulfield et al. 1987). Capturing the same amount of additional volume at age 15 years would be worth twice as much as waiting till age 30 to harvest.

The outplanting density will also affect the economics of using morphologically improved seedlings. Some (Mattoon 1926; Wakeley 1935; Bailey 1986; Borders et al. 1991) have recommended outplanting as many as 3200 *P. taeda* trees per hectare (TPH), while others (Vardaman 1989; Bowling 1987; Caulfield et al. 1992) recommend outplanting 750 to 1000 TPH. Therefore, the additional cost per hectare for morphologically improved seedlings can vary from less than $7.50 (at 750 TPH) to $32 (at 3200 TPH). Due to density related competition, merchantable volume production at ages above 20 years are not strictly proportional to the number of trees planted. In fact, on some sites, merchantable volume may even be the same for trees planted at 750 TPH (Harms and Lloyd 1982; Sarigumba 1985) or 1075 TPH (Arnold 1978; Bowling 1987; Jones 1987) than for trees planted at 3000 TPH. Therefore, the incremental gains from planting morphologically improved seedlings will not be proportionately increased by planting 4 times as many trees per hectare. As a result, the economic advantage of using morphologically improved seedlings is much greater when outplanting densities are low. The present value of 1000 morphologically improved seedlings planted at 750 TPH can be up to 13 times greater than when seedlings are planted at 3000 TPH (Table 4).

Summary

By ignoring potential gains in volume production, some researchers have used short-term economics to justify growing seedlings at high densities. However, growth gains of only 15 m^3/ha at age 15 years could easily justify spending an additional $28 or more to plant a thousand morphologically improved seedlings. Actual data from block plots indicate that planting 6-mm seedlings instead of 4-mm seedlings can increase volume production by up to 60 m^3/ha. Therefore, researchers who consider long-term economics recommend growing southern yellow pine seedlings at densities of 200/m^2 or less (Mexal 1981; Caulfield et al. 1987).

Individuals who choose to plant morphologically improved seedlings with larger root-collar diameters should consider the following points:

1) *P. taeda*, *P. elliottii*, and *P. echinata* seedlings are considered to be "morphologically improved" if (1) they are grown at low seedbed densities $\leqslant 200/m^2$, (2) half or more of the plantable seedlings have root-collar

diameters greater than 5 mm and none less than 3.2 mm, (3) have a median root volume greater than 3 cm^3, and (4) have been cultured and lifted to produce and retain fibrous roots. In addition, the morphologically improved seedlings are (5) not taller than and (6) have a higher root weight ratio than "regular" seedlings grown at higher densities.

2) Survival of properly planted morphologically improved seedlings will usually be greater than seedlings grown at high seedbed densities. Although there may be no difference in survival when conditions for survival are favorable (>96% survival), an increase of 7 (±3) percentage points increase is very possible when survival of "regular" seedlings is less than 86%.

3) Although relatively easy to machine plant, morphologically improved seedlings may require more time to plant properly by hand. Therefore, supervision will be essential to prevent tree planters from (1) reducing the root weight percentage by pruning and stripping roots prior to planting; (2) cramming the large roots in a shallow planting hole; and (3) failing to plant the roots 5 to 10 cm deeper than the level grown in the nursery.

4) When planted properly, morphologically improved seedlings can result in an advancement of stand development by one year. A 2-year advancement is possible if such seedlings are planted in wet soil during October or early November and if the root-collar diameter limit for cull seedlings is raised to 4 mm.

5) The use of morphologically improved seedlings are most economical when (1) incremental gains are captured during the first commercial thinning (prior to age 20) and (2) outplanting densities are less than 1200 trees per hectare.

6) Although vague and often undefined, the term "fully utilizing the bed space" is used in context with the production of aboveground biomass. However, the roots will "fully utilize" the upper soil horizon prior to when the shoots achieve complete canopy closure. Therefore, attempting to "fully utilize above ground bed space" will often result in producing seedlings with a lower root weight ratio. Seedbed densities that are based on long-term economics will appear to some to be wasting bed space. When densities are based on short-term economics, it will be difficult to see bare soil between drills at lifting time.

Acknowlements

This review was conducted under the auspices of the Auburn University Southern Forest Nursery Management Cooperative. Special thanks are due to Gary Bacon, Department of Forestry, Queensland; J.G.A. Carneiro, University of Parana, Brazil; Gregory Leach, Champion International, Florida; Marshall Jacobson, ITT-Rayonier, Florida; and John Brissette, U.S. Forest Service, Louisiana, for supplying unpublished data.

Note

[1] Terms lacking operational definitions, no matter how intuitively clear and familiar they may seem, can lead to meaningless statements and questions (Puttonen 1989). For this reason, the often-used term "seedling quality" is not used in this review. The term "morphologically improved" is used to describe pine seedlings grown at low seedbed densities to promote a greater root volume, a greater root weight ratio (dry weight of root/total dry weight of plant; *sensu* Margolis and Brand 1990), a larger root-collar, a lower height/diameter ratio, and more secondary foliage development than "regular" seedlings that are grown at high seedbed densities (i.e. $>200/m^2$ for most *Pinus* species or $>120/m^2$ for *P. palustris*).

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