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Glyndon E. Hatchell and H. David Muse

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Southeastern Forest Experiment Station
P.O. Box 2680
Asheville, North Carolina 28802

Nursery Cultural Practices and Morphological Attributes of Longleaf Pine Bare-Root Stock as Indicators of Early Field Performance

Glyndon E. Hatchell, Research Forester (Retired)
Institute for Mycorrhizal Research and Development
Athens, Georgia

and

H. David Muse, Professor
Department of Mathematics
University of North Alabama
Florence, Alabama

Abstract

Seven morphological characteristics of 1-0 longleaf pine (*Pinus palustris* Mill.) stock were evaluated on a total of 1,600 seedlings representing eight combinations of nursery cultural treatments. Seedlings were outplanted completely at random, with respect to rows and planting positions, on a deep sandy site in South Carolina. Field performance of individual seedlings was evaluated after two growing seasons that were extremely dry. Statistical tests were derived for determining differences in field performance of groups of seedlings, both within and between treatments. Groups of seedlings that received vertical root-pruning treatment (sidecutting) in the nursery and possessed key attributes—either 14 or more strong, first-order lateral roots for a low-fibrosity root system or a minimum of 6 strong laterals for medium- or high-fibrosity root system—met the preset goal of 80 percent survival and 60 percent of planting stock in active height growth after two growing seasons. Within a pruning treatment, all seedlings possessing these key morphological attributes, regardless of root-collar diameters, performed equally well in the field. For each of the three fibrous-root ratings, seedlings that received vertical root pruning in nursery beds had significantly higher survival than unpruned seedlings. Vertical root pruning also significantly increased the proportion of planting stock in active height growth after the second growing season.

Keywords: Seedling quality, morphological grades, vertical root pruning, *Pinus palustris*.

Introduction

Morphological and physiological characteristics of southern pine planting stock and genetic factors influence seedling quality (Wakeley 1949). The ultimate measure of seedling quality is generally considered to be field performance (Brissette 1984). The relationship of morphological characteristics of bare-root nursery stock of the southern pines to field survival has eluded researchers for the past 50 years. Their objective was to provide guides or rules for separating seedlings according to their potential for survival after transplanting. Wakeley (1954) concluded that neither the grading rules that he had developed nor morphological grades in general could be given an unqualified recommendation. He found that grade 1 seedlings usually grew best among three grades, but generally did not survive as well as grade 2 stock and sometimes did not survive as well as grade 3 stock, which ordinarily was culled. His specifications for plantable (grades 1 and 2) longleaf pine (*Pinus palustris* Mill.) stock required the culling of seedlings that (1) lacked secondary needles, (2) had a root-collar diameter (RCD) less than 4.8 mm, or (3) had a root system (taproot) less than 13 cm long. Unfortunately, he did not specify desirable characteristics of lateral roots. Planting small stock necessitates a long period in the "grass stage" until seedling RCD reaches approximately 25 mm, a size associated with height growth initiation. In one study, Wakeley (1935) found that only 11 percent of the larger grade 1 seedlings were more than 15 cm 4 years after transplanting.

South (1987) reexamined Wakeley's (1954) "critical test" of longleaf pine grades and suggested that lack of significant differences in field performance among grades may have been due to the small size (RCD ranged from 4.8 to 12.7 mm) of seedlings produced at the standard, high seedbed density (323 seedlings per m^2). More recent research has shown the benefits of producing larger longleaf pine planting stock at seedbed densities of 65 to 129 seedlings per m^2 (Derr 1955; Hatchell 1985; Scarbrough and Allen 1954; White 1981). Currently the minimum RCD specified for plantable seedlings is 12.7 mm (May 1985).

Recent nursery and outplanting studies of longleaf pine indicate that certain nursery practices, including inoculation of fumigated nursery soil with *Pisolithus tinctorius* (Pt) during spring sowing, greatly increase survival and early growth of seedlings planted on deep sandy soils (Hatchell 1985, 1986). Improved field performance also was associated with nursery cultural practices that produced a fibrous root system, such as vertical root pruning, maintaining low to medium seedbed density to give individual seedlings ample growing space, and providing enough nutrients for optimum growth. This research showed that seedlings with abundant fibrous roots and abundant ectomycorrhizae performed better in the field than seedlings with fewer fibrous roots and few ectomycorrhizae.

Unsatisfactory plantation survival and delayed initiation of height growth have led forest managers to convert most of the approximately 24 million ha that once supported virgin longleaf pine to other pine species (Mann 1969). For example, only a small portion of the approximately 3.2 million ha of forest land in the Sandhills of Georgia and the Carolinas, and of similar deep sands of northern Florida, is currently stocked with longleaf pine. Longleaf pine once dominated the Sandhills, and its deep root system probably makes it the most desirable pine to plant on these fast-draining soils. But planting longleaf pine there makes little sense unless high survival and rapid height growth initiation can be assured (Hatchell and Marx 1987).

The objectives of the research described here were (1) to test the effects of nursery cultural practices on morphological attributes of bare-root seedlings and on field performance after outplanting on a Sandhills site, and (2) to associate key morphological attributes of the seedlings with field performance for a better understanding of seedling quality and for possible use as a guide for culling poor-quality seedlings. The goal set for field performance was a minimum of 80 percent survival and 60 percent of stock in active height growth at the end of two growing seasons. Performance was observed in 1986 and 1987, two extremely dry years. Thus, stress was higher than normal and the field success we attained should be easily achievable in normal field plantings.

Methods

The nursery phase of this research involved a factorial experiment replicated in four randomized complete blocks at the Whitehall Experimental Nursery, Athens, GA, during 1985 (Hatchell 1987). The three factors and levels of each were: (1) vertical root pruning (sidecutting) three times (June 25, August 16, and September 30) to a depth of 15 cm vs. unpruned control; (2) seedbed densities of 65 (low) or 129 (medium) seedlings per m^2; and (3) spacings of seed drills at either 15 cm (single drill, current standard) or 30 cm (double drills 2.5 cm apart). The eight treatment combinations were:

Treatment number	Vertical root pruning	Seedbed density	Drill spacing (cm)
1	Pruned	Low	15
2	Pruned	Low	30
3	Pruned	Medium	15
4	Pruned	Medium	30
5	Unpruned	Low	15
6	Unpruned	Low	30
7	Unpruned	Medium	15
8	Unpruned	Medium	30

Pt vegetative inoculum was applied to the fumigated nursery soil during spring sowing (March 20, 1985). Wooden frames used to support the raised seedbeds prevented undercutting and root-wrenching treatments.

Seedlings were lifted during December 1985, and 50 seedlings that met Wakeley's (1954) minimum specification for grade 2 stock were randomly selected from each of 32 nursery plots. Numbered tags were attached to 1,600 seedlings, and seven morphological attributes of each seedling were recorded: (1) RCD (mm); (2) fresh weight (g); (3) number of strong, first-order lateral roots (NSFOLR) with diameters larger than 1 mm (Kormanik 1986); (4) visual rating of the abundance of fibrous roots as low = 1, medium = 2, or high = 3; (5) visual estimate of the percentage of short roots ectomycorrhizal with Pt; (6) visual estimate of the percentage of short roots ectomycorrhizal with all fungi; and (7) needle length (cm). Seedlings were placed in kraft bags and held in cold storage for 9 or 10 days before outplanting. Ten seedlings having grades 1 or 2 characteristics were also collected at random from each nursery plot for destructive analysis.

The outplanting site, which was located on the Savannah River Forest Station, Aiken, SC, was prepared by applying a herbicide and by burning. Brown-spot needle blight (*Scirrhia acicola* (Dearn.) Sigg.) was not a problem on the study area. The soil type is Lakeland sand (thermic, coated Typic Quartzipsamments), which is excessively well drained. A dark-gray layer of sand extends from the surface to a 10-cm depth. Below it are 2 m or more of loose sand. The soil is typical of deep sand in the Sandhills Province; it has low moisture holding capacity and low nutrient availability. Average nutrient contents (in p/m) in samples of the 0- to 15-cm depth collected in July of the second growing season were: total N, 324; available P, 10; extractable K, 34; extractable Ca, 24; and extractable Mg, 12; pH was 4.8, organic matter content was 1.8 percent, and cation exchange was 0.6 meq/100 g (Analyses by A&L Laboratories, Inc., Memphis, TN).

Seedlings were machine planted at approximately a 2- by 3-m spacing. Planting was completely randomized with respect to nursery cultural treatments and nursery plots. After planting, the number and location of each seedling were recorded to allow the association of field responses of individual seedlings with nursery cultural treatments and morphological attributes.

At the end of the second growing season, RCD and height of each seedling were measured and mortality was recorded, by seedling number. These field data, the nursery cultural treatment, and the seven morphological attributes were analyzed on an individual seedling basis. Seedling volume index (D^2H) was calculated as a nondestructive surrogate of seedling biomass (Hatchell and others 1985; Ruehle and others 1984). A stem height $\geq$10 cm was considered evidence of active height growth. The percentage of the seedling stand in active height growth was based on the number of seedlings initially planted. Thus, proportions of seedlings having certain morphological characteristics, and their performance in terms of both survival and height growth initation, had the same base.

Responses of individuals and groups of seedlings to treatments were subjected to correlation and regression analyses. Analyses of variance (ANOVA's) of the factorial experiment were made for morphological attributes and for field responses, and means were separated with Duncan's multiple range test at $P = 0.05$. For other comparisons, probability levels of 0.001, 0.01, or 0.05 were used.

The field-planting design, in which each seedling essentially constituted a plot, was selected to provide great flexibility for innovative analysis. In a forthcoming publication, Muse and Hatchell describe the design in detail, so the discussion of analysis here is brief. Large numbers of plots permitted the study of individual seedling attributes in relation to early field performance. After nursery seedling attributes that contributed to high survival and early initiation of height growth had been determined, "target zones" for desirable characteristics were established, and field performance of seedlings falling inside the target zones was compared with that of seedlings that simply qualified by Wakeley's (1954) grading criteria.

Where appropriate, the usual two-sample independent proportions test was applied. For comparisons involving partially dependent samples, the test statistic was adjusted to account for the associated correlation between sample proportions. For example, all target-zone seedlings also met Wakeley's criteria for standard seedlings. Therefore, comparisons of sample proportions involved seedlings common to each group as well as non-target-zone Wakeley's (1954) standard seedlings. The associated adjusted test statistic was given by

$$t = W/ Var(W)$$

Where

$W = X_1/n_1 - (X_1 + X_2)/(n_1 + n_2)$,

X_1 = number of surviving (or active height growth) target-zone seedlings,

n_1 = total number of target-zone seedlings,

X_2 = number of surviving (or active height growth) non-target-zone Wakeley's standard seedlings,

n_2 = total number of non-target-zone Wakeley's standard seedlings,

$X_1 + X_2$ = number of surviving (or active height growth) Wakeley's standard seedlings,

$n_1 + n_2$ = total number of Wakeley's standard seedlings,

$f_1 = X_1/n_1$, $f_2 = X_2/n_2$,

and

$$Var(W) = n_2^2[f_1(1-f_1)/n_1+f_2(1-f_2)/n_2]/(n_1+n_2)^2.$$

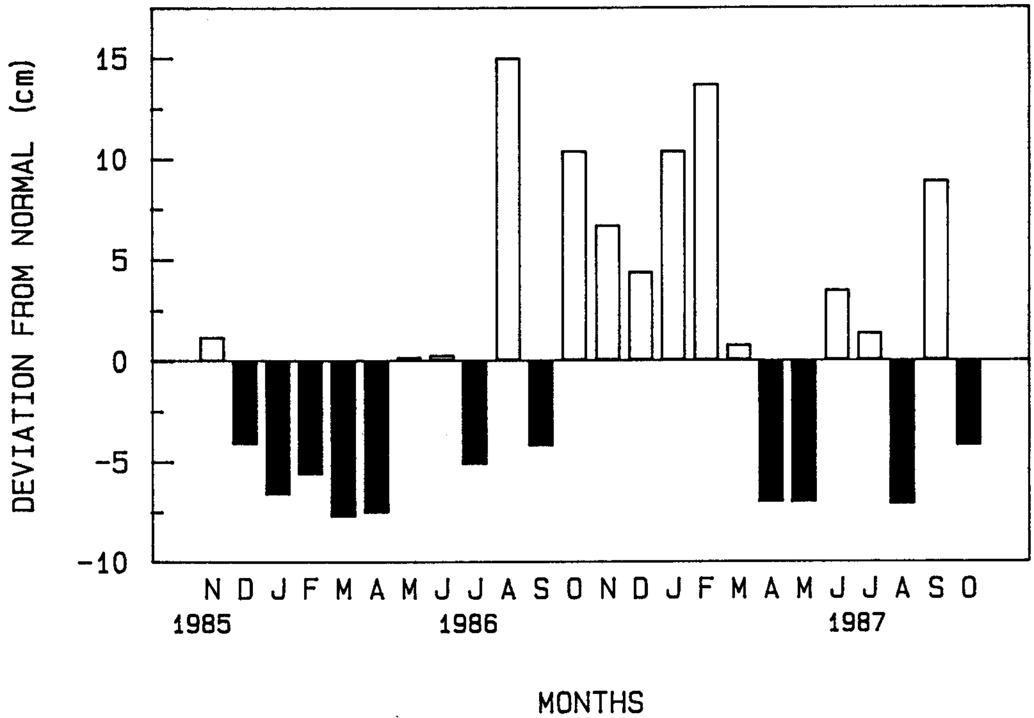


Figure 1—Deviation of monthly precipitation from normal precipitation. Data were recorded at a weather station 7.2 km from the study area.

Results and Discussion

The 1986 and 1987 growing seasons were very dry (fig. 1). In the spring and early summer of 1986, the rainfall deficit was more than 20 cm before heavy rain occurred in August. Furthermore, average daily temperature was high, especially during July when the record for the past century was broken.

Results 1 year after outplanting were reported (Hatchell 1987). Vertical root pruning and seedbed density altered morphological attributes of seedlings (Hatchell 1987). Seedling survival and vigor were strongly correlated with abundance of fibrous roots, NSFOLR, and the interaction of these attributes. Vertical root pruning significantly increased survival (mean = 71.6%) compared with unpruned seedlings (51.2%).

At the end of the second growing season, seedling survival dropped only slightly from the first year (69.1% for pruned vs. 47.8% for unpruned); however, no nursery treatment combination reached the goals of 80 percent survival and 60 percent of initial stand in active height growth. Without culling of unsatisfactory nursery seedlings, therefore, planters cannot anticipate satisfactory initial longleaf survival in the Sandhills in dry years. Producing satisfactory seedlings at nurseries requires a combination of appropriate cultural practices and appropriate grading criteria.

Effects of Nursery Cultural Practices

Vertical root pruning significantly ($P = 0.001$) increased not only the fibrosity of seedling root systems but also the second-year survival and growth of seedlings (table 1). Seedbed density significantly affected all morphological attributes except needle length. Seedbed density also significantly affected initiation of height growth but not survival. At the low and medium densities, respectively, average values for morphological attributes were: RCD, 12.6 vs. 10.2 mm; fresh weight, 108 vs. 69 g; NSFOLR 9.3 vs. 5.1; fibrous root rating, 1.7 vs. 2.0; Pt ectomycorrhizae, 54 vs. 62 percent; and all ectomycorrhizae, 62 vs. 68 percent. Among the eight nursery cultural treatments, the combination of low seedbed density, vertical root pruning, and the 15-cm drill spacing was the only one that resulted in 60 percent of stock in active height growth at age 2. The only significant effect ($P = 0.05$) of drill spacing was observed at the wider spacing where total fresh weight was increased 4 g, apparently due to additional root mass.

Certain data obtained in destructive analysis of seedlings; e.g., shoot dry weight, root dry weight, and shoot-root ratio, provided little help for interpreting field performance of outplanted stock. Shoot-root ratio (with overall mean of 3.72) was not affected by nursery cultural practices and did not affect field performance. A similar shoot-root ratio was observed for spring-sown longleaf pine produced at medium seedbed density (Hatchell 1986).

Effects of Morphological Attributes

Linear correlations among six morphological attributes of vertically root-pruned or unpruned seedlings are presented in table 2; needle-length data are omitted because they were not correlated with the other attributes and they were not related to the field responses of seedlings. With 800 observations for each pruning treatment, several correlations that were statistically significant had relatively low r values. But some of these relationships may be useful in the understanding of seedling quality. RCD was positively correlated with total fresh weight and NSFOLR. RCD and fibrous root rating were negatively correlated. NSFOLR and total fresh weight had high positive correlations ($r \geq 0.77$). The fibrous root rating was positively correlated with the two ectomycorrhizal attributes and was negatively correlated ($r = -0.16$) with NSFOLR.

Linear correlations between field response variables and morphological attributes of vertically root-pruned and unpruned stock presented in table 3 were based on individual seedlings or on the 25-seedling groups used in computing the percentage of seedlings surviving or in active height growth after two growing seasons. To investigate a single curve form, reciprocals of independent variables and certain interaction variables were tested. Survival of pruned seedlings was significantly ($P = 0.05$) correlated with the reciprocal of the ectomycorrhizal variables. Survival of unpruned seedlings was correlated with the reciprocal of fibrous root rating and percentage of short roots ectomycorrhizal either with Pt or with all fungi. High correlations ($r \geq 0.45$) were observed between percentage of seedling stands in active height growth and the interaction variable, NSFOLR X the fibrous root rating. Height, RCD, and D^2H of individual seedlings were significantly correlated with nearly all of the independent variables.

Although multiple linear regression analyses based on first-year data showed promise with regard to identifying useful indicators of seedling quality (Hatchell 1987), subsequent analyses using second-year data were unacceptable because of relatively low multiple correlation coefficients ($R^2 < 0.41$ for survival and $R^2 < 0.66$ for active height growth). The difficulty in developing reliable regressions arose from the intercorrelation of morphological attributes (table 2) and from the limited number of significant linear relationships with respect to survival and height growth initiation (table 3).

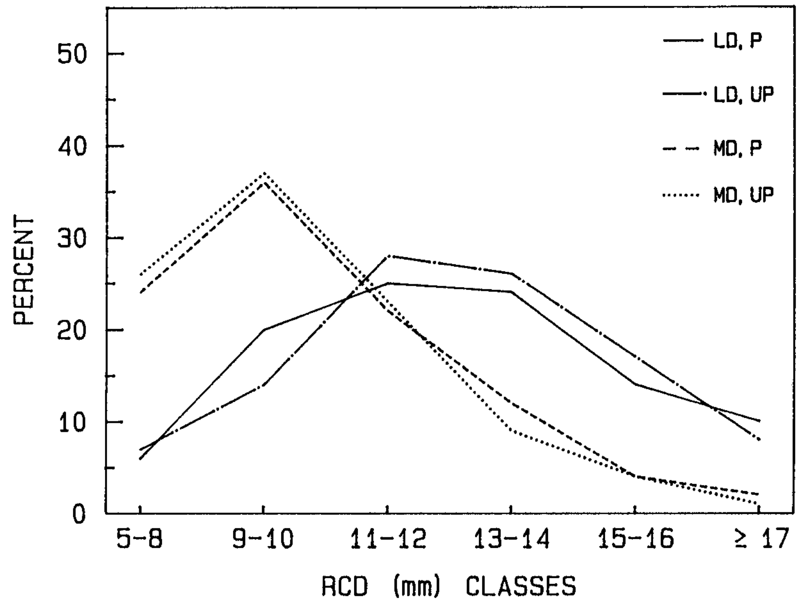


Figure 2—Percent distributions of planting stock among root-collar diameter (RCD) classes after specific nursery treatments. Nursery cultural treatments: LD = low seedbed density; MD = medium seedbed density; P = vertical root pruning; UP = unpruned roots.

RCD as Indication of Field Performance

Figure 2 shows the frequency distributions of RCD at outplanting time for combinations of seedbed density and vertical root-pruning treatments. Pruning had little effect on the distributions. The RCD class with the highest frequency was 11-12 mm for low seedbed density and 9-10 mm for medium seedbed density. An average of 6 percent of the planting stock had a RCD of 5 to 8 mm at the low seedbed density compared with 25 percent at the medium seedbed density. Some 9 percent of the seedlings produced at the low seedbed density had an RCD of 17 mm or larger compared with only 2 percent at the medium density.

Percentages of both survival and planting stock in active height growth after 2 years in the field are shown in figure 3. Among seedlings whose roots were pruned, the only RCD classes that approached the goals of 80 percent survival and 60 percent height growth initiation at age 2 were: at low seedbed density, 13-14 mm RCD (79% survival and 62% in active height growth) and 15-16 mm RCD (80 and 73%, respectively), and at medium seedbed density, 11-12 mm (80 and 57%, respectively), and 13-14 mm (73 and 60%, respectively). For seedlings with unpruned roots, all RCD classes were well below the performance goal.

Because White (1981) had found that only seedlings with RCD ≥13 mm survived up to 3 weeks of cold storage without loss in survival, May (1985) recommended planting of stock with minimum RCD of 13 mm. May's (1985) recommendation was intended to direct nurseries away from Wakeley's (1954) recommendations for high seedbed density and specifications for RCD ≥6.4 mm for grade 1 and RCD ≥4.8 mm for grade 2 stock. Lauer (1987) reported that longleaf pine stock with RCD <11 mm was slow to initiate height growth and that the highest response at age 2 was from stock with RCD ≥19 mm. Smaller stock (RCD, 5 to 11 mm) was more susceptible to damage by brown-spot needle blight.

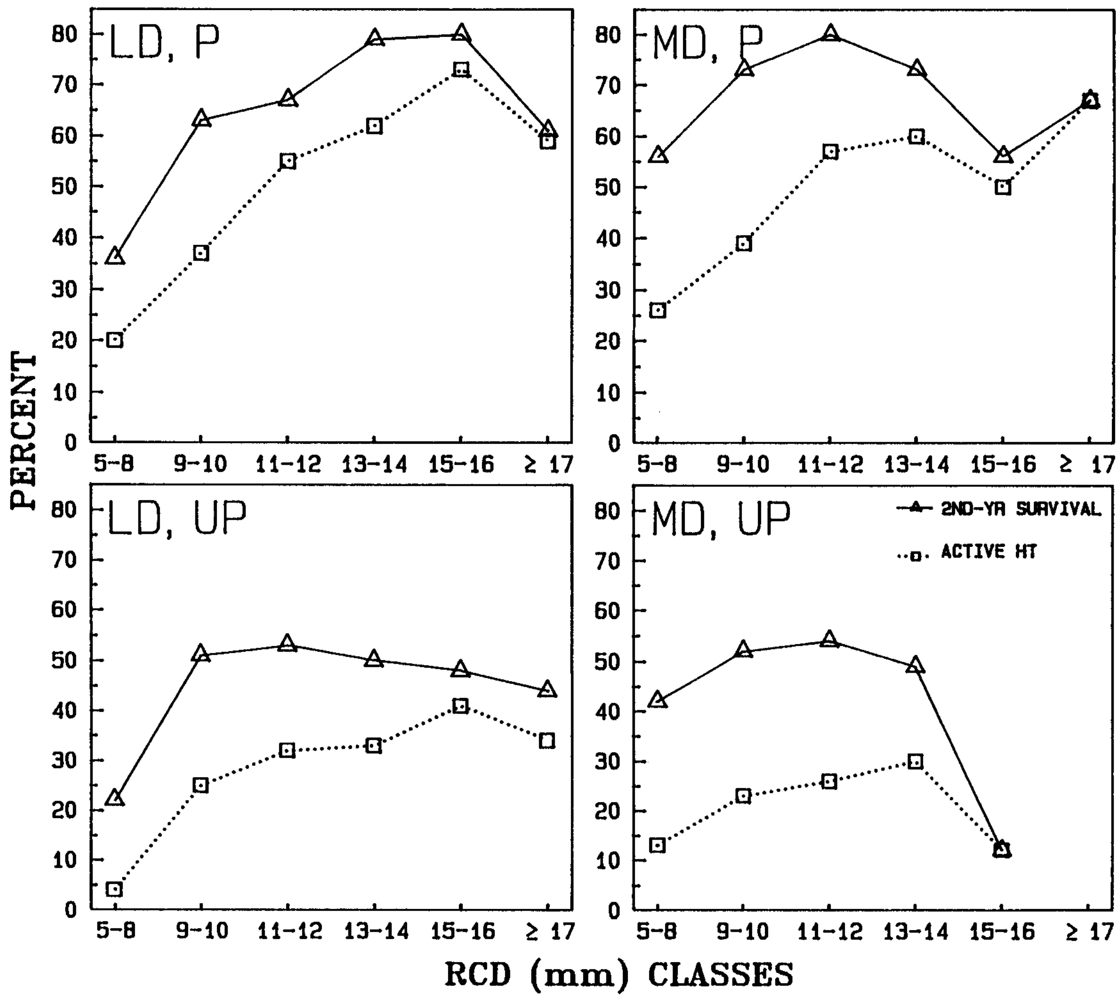


Figure 3—Percent survival and percent of longleaf pine seedlings in active height growth 2 years after planting, by root-collar diameter (RCD) of stock. Nursery cultural treatments: LD = low seedbed density; MD = medium seedbed density; P = vertical root pruning; UP = unpruned roots.

Effects of Root Morphology

Root fibrosity and NSFOLR strongly influenced the performance of individual seedlings in this study. Vertical root pruning increased fibrosity of roots. Visual fibrosity ratings were 18.5 percent low, 60.2 percent medium, and 21.2 percent high for pruned seedlings and 39.2 percent low, 52.6 percent medium, and 8.1 percent high for unpruned seedlings. Furthermore, for any of the three fibrosity ratings, seedlings receiving vertical root pruning performed significantly better than unpruned seedlings. Perhaps, vertical root pruning improved field performance by altering certain physiological characteristics. Although vertical root pruning influenced key morphological attributes and seedling performance in the field, it did not alter the frequency distributions of either NSFOLR or RCD. To simplify the data set and to derive statistical analyses, we listed the data as frequency distributions consisting of (1) the number of grades 1 and 2 (Wakeley 1954) seedlings that were randomly selected from the nursery for outplanting, (2) the number or proportion of stock surviving the second growing season, and (3) the number or proportion of seedlings in active height growth at age 2. This concept is illustrated in figure 4, with 10 classes of NSFOLR, 3 fibrosity classes, and pruned vs. unpruned treatments. These data are also presented in figure 5 as a percentage of initial stand surviving or in active height growth at age 2 for combinations of seedbed density and pruning treatments. These illustrations

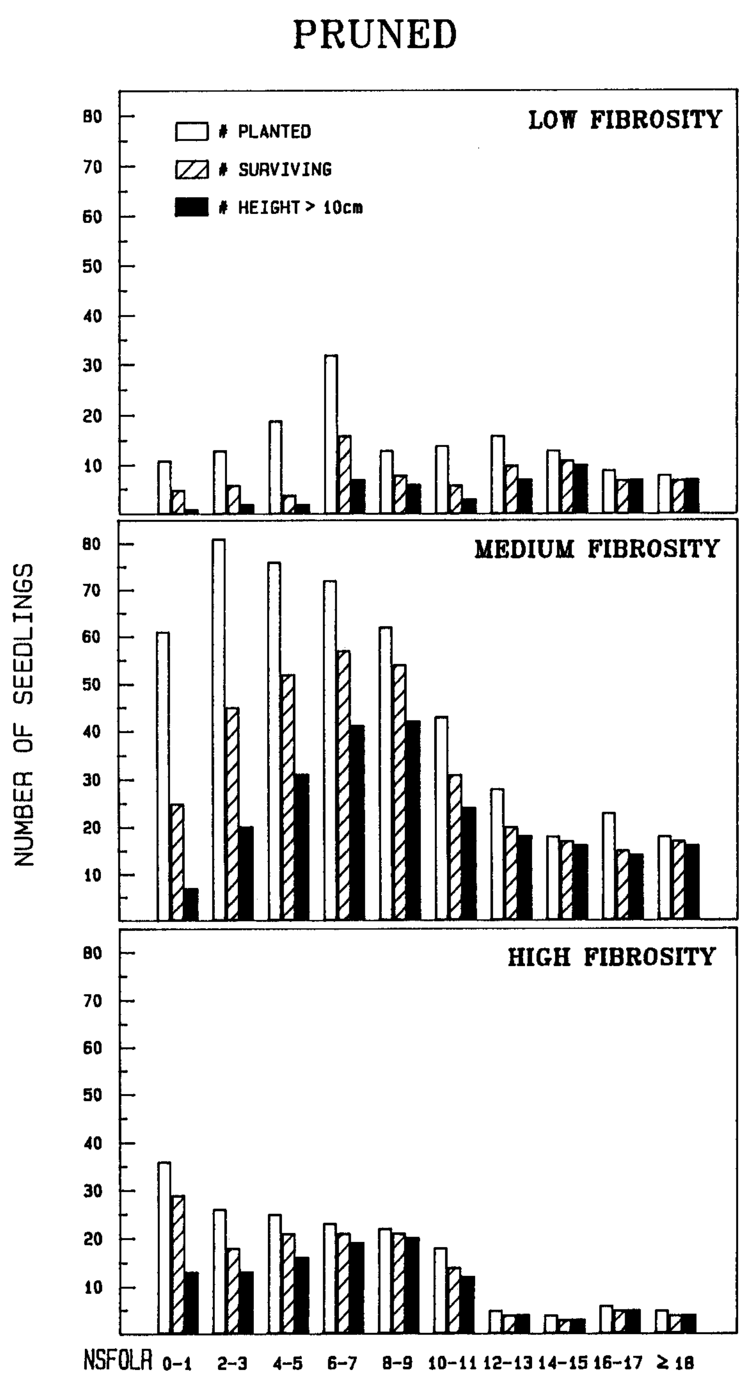
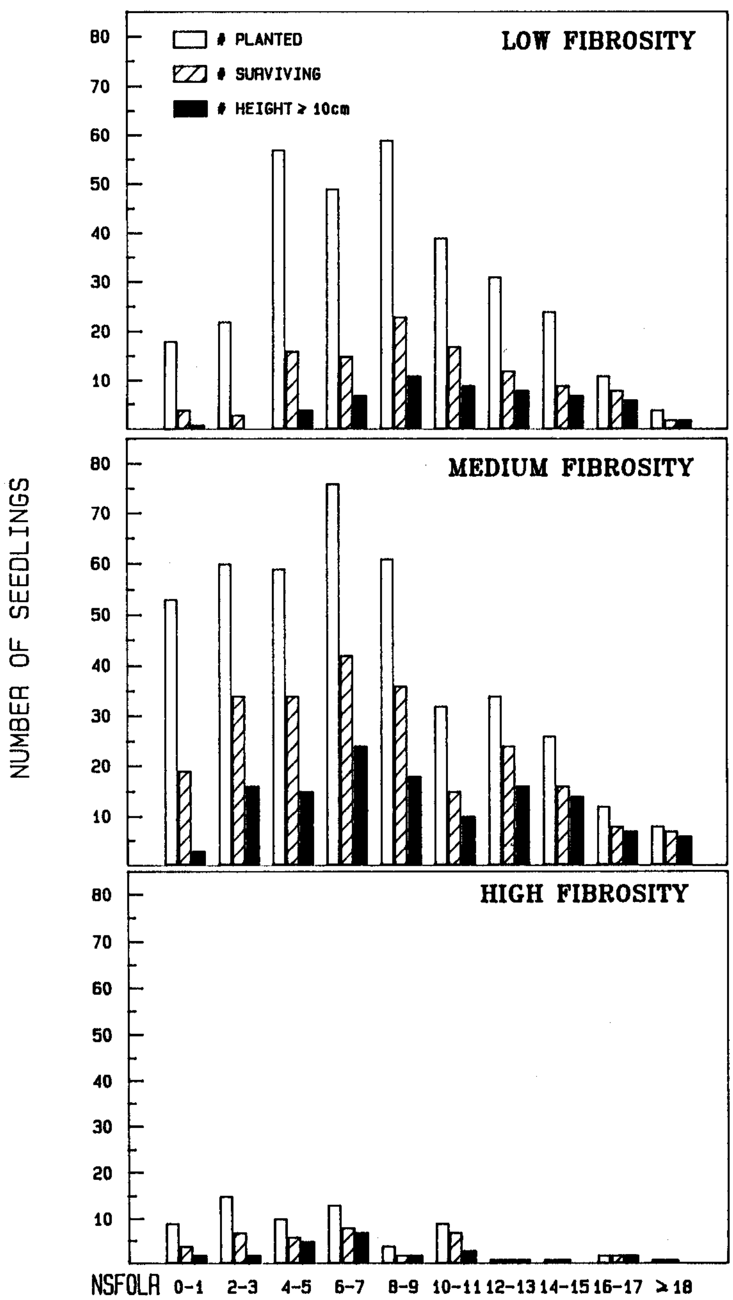


Figure 4—Initial distribution of nursery stock, number of surviving seedlings, and seedlings in active height growth 2 years after planting, by fibrosity class and number of strong, first-order lateral roots (NSFOLR) for vertical root-pruned and unpruned (page 11) seedlings.

show that even with the vertical root-pruning treatment, seedlings with limited NSFOLR, regardless of fibrosity rating, performed poorly. However, seedlings with low fibrosity and an exceedingly large NSFOLR performed well. Distributions are tabulated henceforth as seven classes of NSFOLR and two classes of fibrosity, with the medium and high ratings combined, thereby increasing the number of observations at the extremities.

UNPRUNED



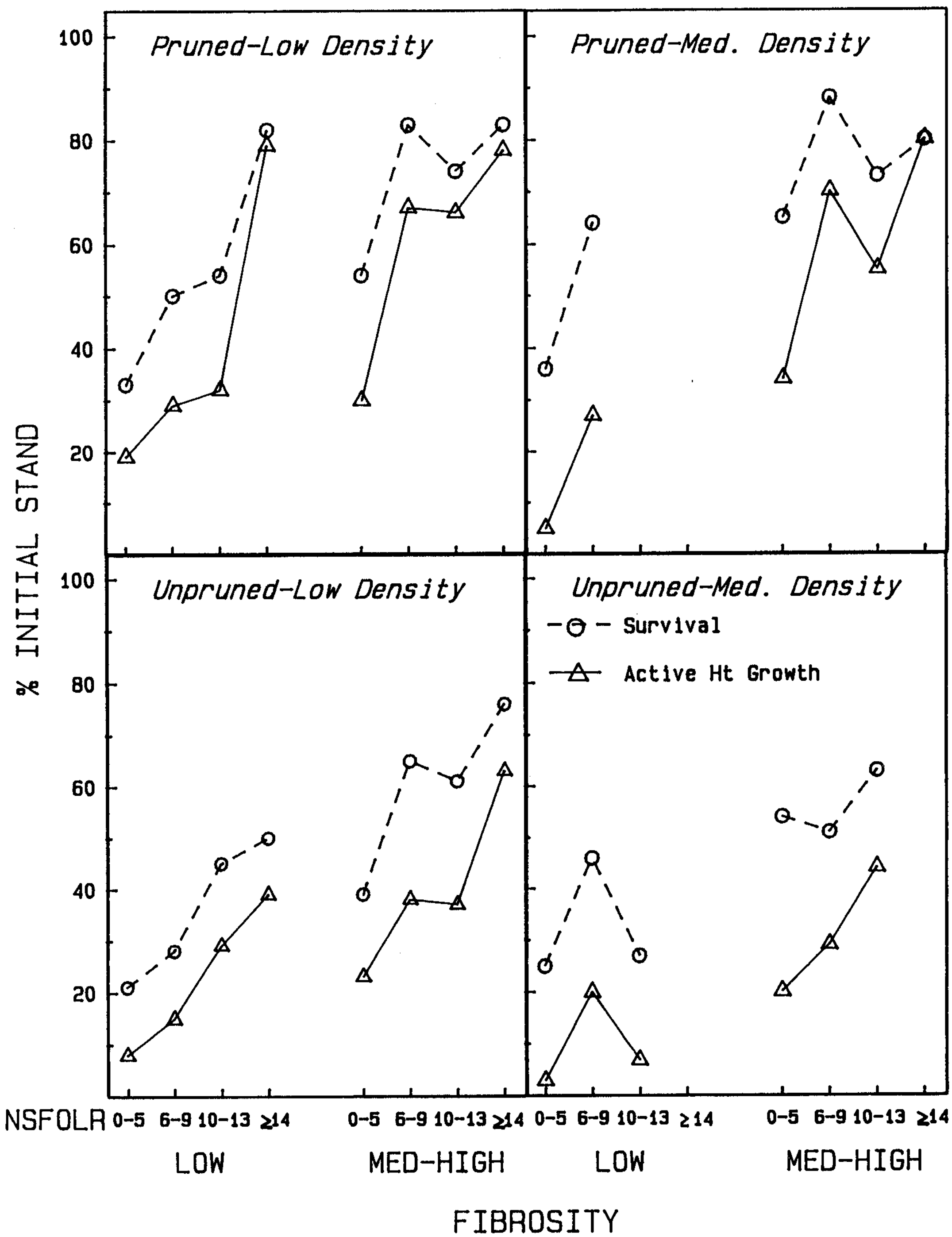


Figure 5—Percent survival and percent of longleaf pine seedlings in active height growth 2 years after planting, by fibrosity class and number of strong, first-order lateral roots (NSFOLR).

Identification of Target Zone

Mexal and South, in press, discussed the concept of an ideotype—an ideal target seedling, having minimum RCD, etc. In the present study, the "target zone" included the ranges in key morphological attributes for which seedling field performance under critical moisture stress met or closely approached the standards of 80 percent survival and 60 percent of planting stock in active height growth at the end of the second growing season. All target seedlings met Wakeley's (1954) specifications for grade 1 stock based on RCD ≥6.4 mm.

The initial distribution of 800 vertically root-pruned seedlings is listed in table 4, by NSFOLR and fibrosity classes and distributions of surviving seedlings and seedlings in active height growth at age 2. RCD is also tabulated with the key attributes to show its distribution and to test the hypothesis that seedlings meeting minimal quantities of the key attributes perform alike regardless of whether their RCD was ≥13 mm. The range of RCD within the target zone for vertically root-pruned seedlings was 8 to 17 mm or larger. The target zone is shown by the underlined counts of seedlings that met the performance standards previously described for combinations of key morphological attributes. The target-zone characteristics included 14 or more NSFOLR with low root fibrosity and 6 or more NSFOLR with medium to high fibrosity. The reduction in NSFOLR for a medium- to high-fibrosity system was supported by a significant ($P = 0.01$) positive correlation between active height growth and the fibrosity X NSFOLR interaction variable for both vertically pruned and unpruned stock (table 3).

The overall field performance of the 800 vertically root-pruned seedlings was 69.1 percent survival and 48.8 percent in active height growth. Performance of the 377 seedlings in the target zone was 81.7 percent survival and 69.5 percent in active height growth (table 4). The significance levels observed in the comparison of these correlated proportions were 0.001 for both survival and height growth initiation. Within the target zone were 170 seedlings with initial RCD of 8 to 12 mm whose 2-year performance was 85.3 percent survival and 67.6 percent active height growth. Among the 207 target-zone seedlings with initial RCD ≥13 mm, 78.7 percent survived and 71.0 percent were in active height growth at age 2. The probability that these two RCD groups had statistically similar field performance is 0.093 for survival and 0.478 for height growth initiation.

The overall field performance of the 800 unpruned control seedlings was 47.8 percent survival and 26.0 percent in active height growth. The 319 seedlings in the target zone showed 58.9 percent survival and 39.2 percent active height growth (table 5). Comparison of these proportions resulted in significance at the 0.001 level for survival and also for active height growth. Within the target zone, 153 seedlings with initial RCD of 8 to 12 mm showed a 2-year performance of 62.7 percent survival and 37.3 percent active height growth; 166 seedlings with initial RCD ≥13 mm showed 55.4 percent survival and 41.0 percent active height growth. The probability that these two RCD groups had statistically similar field performance is 0.1836 for survival and 0.4966 for active height growth.

Testing Effectiveness of Target Zone

Distributions of initial seedling stands, of surviving stands, and of seedlings in active height growth 2 years after outplanting, by fibrosity rating, NSFOLR, and RCD, are presented in tables 6-13 for each of the eight nursery cultural treatments. The seedlings within the previously defined target zone were denoted to provide the counts or percentage of seedlings within the target zone for various distributions. These statistics were used in tests designed to answer two questions: (1) Did seedlings in the target zone perform significantly better than the overall performance shown for the treatment? (2) Was performance of target seedlings with an RCD of 8 to 12 mm significantly different from that of seedlings with RCD ≥13 mm? Counts for treatment Nos. 1 and 3, each with an overall survival of 74.0 percent, provided interesting contrasts.

Table 6 lists data for treatment No. 1 (vertical root pruning, low seedbed density, and 15 cm-drill spacing). Some 117 of 200 seedlings receiving the treatment were in the target zone. Survival of target-zone seedlings was 84.6 percent, and 74.4 percent were in active height growth at age 2 (see table 6 footnote). Thus, the 117 target seedlings exceeded the performance standards. The target seedlings showed increases ($P = 0.001$) of 10.6 percentage points in survival and 14.4 percentage points in active height growth compared with Wakeley's (1954) standard stock (table 14). For treatment 1, the 43 seedlings with an RCD of 8 to 12 mm had 83.7 percent survival, and 69.7 percent were in active height growth at age 2. Of 74 treatment 1 seedlings with an RCD ≥13 mm, 85.1 percent survived and 77.0 percent had initiated height growth by age 2. There was no significant difference in the field performance between seedlings with RCD of 8 to 12 mm and seedlings with RCD ≥13 mm ($P = 0.841$ for survival and $P = 0.134$ for percent of initial stand in active height growth).

Table 8 lists data for treatment No. 3 (vertical root pruning, medium seedbed density, and 15 cm-drill spacing). Some 67 of the 200 seedlings receiving treatment 3 were in the target zone. Survival of target seedlings was 89.6 percent, and 76.1 percent were in active height growth. Compared with standard stock, target seedlings had 15.6 percentage points higher survival and the proportion in active height growth was 30.1 percentage points higher (table 14). The differences were statistically significant at $P = 0.001$. In the target zone, 42 seedlings with initial RCD of 8 to 12 mm had 88.1 percent survival and 73.8 percent active height growth at age 2. Twenty-five seedlings with initial RCD ≥13 had 92.0 percent survival and 80.0 percent in active height growth (table 8). There was no significant difference in the performance of the two RCD groups ($P = 0.596$ for survival and $P = 0.555$ for active height growth).

Testing differences in second-year performance of target-zone seedlings vs. Wakeley's (1954) standard grades 1 and 2 stock showed: for vertically root-pruned seedlings, target-zone seedlings had significantly ($P = 0.01$ or 0.001) higher performance than standard stock, with ranges among the four treatments (Nos. 1-4) from 10.6 to 15.6 percentage points higher in terms of survival and 14.4 to 30.1 percentage points higher for active height growth; and for unpruned seedlings (treatment Nos. 5-8), only seedlings produced at the low density (treatments 5 and 6) had both significantly higher survival and height growth initiation, with an advantage of 11.9 to 18.4 percentage points for survival and of 8.1 to 17.0 percentage points for height growth initiation (table 14). Treatment 8 did show a significant advantage of 15.7 percentage points in terms of height growth initiation, but the performance for the target zone (37.7%) was far below the standard goal of 60 percent.

In each of the eight nursery cultural treatments, no significant differences were observed in the field performance of the two RCD groups (8 to 12 mm vs. ≥13 mm), either in terms of survival or height growth initiation (table 15). This finding strengthens the conclusion that root fibrosity and NSFOLR were key morphological attributes affecting field performance.

Two-sample independent proportion tests were conducted on the performance of target-zone seedlings by the RCD group to determine significant ($P = 0.05$) differences among individual nursery cultural treatments receiving either vertical root pruning or the unpruned control (table 15). However, emphasis should be placed on the performance of vertically root-pruned seedlings because even the unpruned control seedlings having target-zone attributes failed to meet standards set for field performance. The 8-12 mm RCD group did not significantly differ in performance among treatments 1, 2, 3, and 4 and the performance standards were met, with ranges of 83.0 to 88.1 percent for survival and of 57.9 to 73.8 percent for height growth initiation; however, for the ≥13 mm group, the survival goal (80%) was not reached with treatments No. 2 (72.7%) and No. 4, (67.7%) and the latter did differ significantly from treatment No. 3 (92.0%). Poorer survival associated with the greater drill spacing of treatment Nos. 2 and 4 may have been due to a potential problem in planting seedlings with longer lateral roots (vertical cutting laterals at approximately 15 cm from drills with the 30-cm drill spacing of treatment Nos. 2 and 4 vs. vertical cutting at approximately 7.5 cm with the 15-cm drill spacing of treatment Nos. 1 and 3). However, closer seed spacing within the double seed drills of treatment Nos. 2 and 4 may have adversely affected the physiological characteristics of stock.

Summary and Conclusions

Results strongly indicate that root fibrosity and NSFOLR are key morphological attributes affecting seedling field performance of longleaf pine during the critical first 2 years after outplanting. The effects of RCD tended to be indirect because of the strong relationship between RCD and NSFOLR, and this relationship was modified by seedbed density. Thus, statistical comparisons, similar to those used in this study, should be made in future studies of the effects of nursery cultural practices and morphological attributes on performance after outplanting.

This study supports several important conclusions about the field performance of longleaf pine bare-root stock:

(1) Abundance of fibrous roots and NSFOLR are key morphological attributes for estimating the field performance of nursery stock.

(2) Vertical root pruning in the nursery increases field survival and the proportion of seedlings that initiate height growth within 2 years after outplanting.

(3) Among root-pruned seedlings, low-fibrosity seedlings with 14 or more NSFOLR or medium- to high-fibrosity seedlings with 6 or more NSFOLR can be expected to have 80 percent survival and 60 percent or more can be expected to be in active height growth 2 years after outplanting on a deep sandy site.

(4) Conventional statistical analyses, including ANOVA's of treatment effects in a factorial experiment, the correlations of seedling attributes with field response, and regression of attributes and response variables, failed to provide conclusive information about seedling quality.

(5) Single-tree plots in field plantings permit statistical evaluation of seedling distributions, both initially and as surviving stands and seedlings in active height growth.

(6) Seedlings having target attributes perform significantly better than Wakeley's (1954) standard grades 1 and 2 seedlings.

(7) Field performance of target-zone seedlings with RCD of 8 to 12 mm is not significantly different from that of seedlings with RCD ≥13 mm. Thus, nurserymen should place less importance on the current longleaf pine ideotype of RCD ≥13 mm (Mexal and South, in press) and focus more attention on increasing root fibrosity in combination with NSFOLR.

(8) The statistical procedures for comparing groups of seedlings within the target zone vs. average performance or the performance of target-zone seedlings among various cultural treatments should have application to other species, especially when testing two or more morphological attributes.

Vertical root pruning of longleaf pine seedlings in the nursery markedly improves seedling quality and should be a standard practice. When pruning is done, culling planting stock based on certain key morphological attributes should further enhance seedling quality and subsequent field performance.

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Tables

Table 1--Means and significance levels of ANOVA's of the effects of nursery cultural practices on the morphological attributes of longleaf pine planting stock and on field responses of seedlings 2 years after outplanting on a deep sandy site

Nursery cultural treatment: (No.) vertical root pruning, seedbed density, and spacing of seed drills	Morphological attributes of 1-0 stock						Field responses at age 2				
	Root-collar dia.	Fresh weight	Strong, first-order laterals	Fibrous-root rating[1]	Short roots ecto-mycorrhizal with-- Pt	All fungi	Survival	Active height growth	Height	Root-collar dia.	D^2H
	mm	g	No.		%	%	%	%	cm	mm	(cm^2)
					Treatment means[2]						
Vertical pruning											
Density, drills											
Low, 15 cm (1)	12.5a	104a	9.3a	1.8b	56ab	63ab	74.0a	60.0a	31.0a	35.1a	476a
Low, 30 cm (2)	12.6a	109a	9.3a	1.8b	57ab	64ab	63.0a	48.0b	27.9a	34.6ab	439a
Medium, 15 cm (3)	10.1bc	64b	4.6b	2.2a	63ab	69ab	74.0a	46.0b	20.6b	32.5abc	284b
Medium, 30 cm (4)	10.5b	71b	5.1b	2.2a	66a	72a	65.5a	41.0bc	20.9b	31.9bc	286b
Unpruned controls											
Density, drills											
Low, 15 cm (5)	12.6a	108a	9.1a	1.5c	53b	60b	49.0b	33.5cd	21.9b	31.8bc	281b
Low, 30 cm (6)	12.7a	110a	9.5a	1.6bc	52b	59b	47.5b	28.5de	19.5b	32.2abc	275b
Medium, 15 cm (7)	9.9c	68b	5.2b	1.9b	60ab	66ab	47.0b	20.0e	12.3c	29.5cd	158c
Medium, 30 cm (8)	10.3bc	72b	5.6b	1.8bc	61ab	67ab	47.5b	22.0de	13.5c	27.9d	158c
Source of variation						Significance level					
Pruning (P)	0.561	0.167	0.347	0.001	0.094	0.076	0.001	0.001	0.001	0.001	0.001
Density (D)	.001	.001	.001	.001	.001	.002	.971	.001	.001	.001	.001
Drill spacing (S)	.080	.033	.258	.784	.586	.595	.142	.085	.394	.384	.619
P x D	.291	.993	.365	.226	.852	.958	.744	.930	.706	.627	.202
P x S	.882	.447	.798	.837	.633	.628	.184	.225	.707	.938	.716
D x S	.348	.494	.778	.343	.641	.662	.744	.225	.132	.460	.596
P x D x S	.814	.926	.625	.632	.942	.887	.971	1.000	.974	.469	.700

Means within a column followed by a common letter are not significantly different at $P = 0.05$.

[1] Low fibrosity = 1; medium fibrosity = 2; high fibrosity = 3.

[2] Means for morphological attributes are based on measurements of 50 seedlings per nursery plot with four replications in a randomized block design; means for field responses are based on 8 groups of 25 seedlings with seedlings randomly distributed throughout study area.

Table 2--Linear correlation coefficients among morphological attributes of 1-0 longleaf pine seedlings, by vertical root-pruning treatments

Morphological attributes of stock	Root-collar diameter	Total fresh weight	No. of strong first-order lateral roots	Fibrous-root rating	% short roots with Pt ectomycorrhizae	% short roots with all ectomycorrhizae
	- - - - - -	- - - - r value and	significance level	- - - -	- - - -	- - - -
			Pruned seedlings			
Root-collar diameter	--	+0.799***	+0.785***	-0.142***	+0.059	+0.064
Total fresh weight	+0.799***	--	+.814***	-.192***	-.025	-.020
NSFOLR[1]	+.785***	+.814***	--	-.156***	+.039	+.045
Fibrous-root rating	-.142***	-.192***	-.156***	--	+.601***	+.612***
% short roots with Pt ecto.	+.059	-.025	+.039	+.601***	--	+.992***
% short roots with all ecto.	+.064	-.020	+.045	+.612***	+.992***	--
			Unpruned seedlings			
Root-collar diameter	--	+.842***	+.758***	-.178***	-.029	-.017
Total fresh weight	+.842***	--	+.774***	-.183***	-.119***	-.103**
NSFOLR[1]	+.758***	+.774***	--	-.157***	-.027	-.020
Fibrous-root rating	-.178***	-.183***	-.157***	--	+.578***	+.596***
% short roots with Pt ecto.	-.029	-.119***	-.027	+.578***	--	+.991***
% short roots with all ecto.	-.017	-.103**	-.020	+.596***	+.991***	--

***, **, and * significant at 0.1%, 1%, and 5% level, respectively; N = 800 for each pruning treatment.

[1] NSFOLR = Number of strong, first-order lateral roots with diameter >1 mm.

Table 3--Linear correlations between response variables of longleaf pine 2 years after outplanting on a deep sandy site and morphologial attributes of bare-root stock, based on 25-seedling groups or individual seedlings, and listed by vertical root-pruning treatments

Morphological attributes of stock, the reciprocal of attributes, and certain interaction variables	Field response 2 years after outplanting based on-- 25-seedling groups[1] Survival	Active height growth	Height (H)	Root-collar dia. (D)	D^2H	Individual seedlings [2] Height (H)	Root-collar dia (D)	D^2H
	- - - - r value and significance level - - - -							
Pruned seedlings								
Root-collar diameter (RCD)	-0.072	+0.287	+0.484**	+0.333	+0.520**	+0.453***	+0.355***	+0.428***
1/RCD	+.073	-.265	-.443*	-.316	-.492**	-.429***	-.348***	-.402***
Total fresh weight	-.080	+.277	+.517**	+.326	+.557***	+.458***	+.324***	+.436***
1/total fresh weight	+.129	-.208	-.412*	-.239	-.447*	-.310***	-.239***	-.282***
NSFOLR[3]	-.074	+.340	+.592***	+.430*	+.626***	+.490***	+.355***	+.470***
1/NSFOLR	+.137	-.240	-.468**	-.379*	-.513**	-.329***	-.287***	-.312***
RCD x NSFOLR interaction	-.061	+.345	+.590***	+.417*	+.617***	+.492***	+.352***	+.457***
Fibrous-root rating (FRR)	+.330	+.105	-.146	+.026	-.230	+.109*	+.097*	+.080
1/FRR	-.342	-.124	+.121	-.079	+.201	-.097*	-.107*	-.074
NSFOLR x FRR interaction	+.044	+.459**	+.658***	+.570***	+.662***	+.519***	+.373***	+.485***
% short roots with Pt ecto.	+.286	+.192	+.113	+.073	+.009	+.212***	+.165***	+.189***
1/% short roots with Pt ecto.	-.442*	-.394*	-.202	-.203	-.127	-.159***	-.138***	-.151***
% short roots with all ecto.	+.290	+.186	+.092	+.077	-.008	+.210***	+.171***	+.192***
1/% short roots with all ecto.	-.439*	-.360*	-.181	-.188	-.105	-.179***	-.151***	-.169***
Unpruned seedlings								
Root-collar diameter (RCD)	-.065	+.313	+.638***	+.543**	+.630***	+.382***	+.311***	+.373***
1/RCD	+.020	-.350*	-.639***	-.551**	-.626***	-.349***	-.302***	-.332***
Total fresh weight	-.134	+.235	+.596***	+.485**	+.586***	+.411***	+.307***	+.405***
1/total fresh weight	+.078	-.264	-.569***	-.404	-.552**	-.348***	-.305***	-.330***
NSFOLR[3]	+.113	+.414*	+.619***	+.452**	+.642***	+.391***	+.276***	+.365***
1/NSFOLR	+.042	-.123	-.334	-.163	-.340	-.219***	-.164**	-.186***
RCD x NSFOLR interaction	+.060	+.402*	+.653***	+.498**	+.667***	+.420***	+.299***	+.399***
Fibrous-root rating (FRR)	+.346	+.150	-.141	-.065	-.131	+.117*	+.154**	+.147**
1/FRR	-.379*	-.207	+.094	+.006	+.078	-.113*	-.138**	-.141**
NSFOLR x FRR interaction	+.284	+.480**	+.540**	+.396*	+.590***	+.413***	+.330***	+.421***
% short roots with Pt ecto.	+.402*	+.401*	+.150	+.222	+.157	+.147**	+.176***	+.166**
1/% short roots with Pt ecto.	-.274	-.428*	-.356*	-.383*	-.323	-.112*	-.114*	-.125*
% short roots with all ecto.	+.385*	+.401*	+.175	+.263	+.174	+.141**	+.171***	+.158**
1/% short roots with all ecto.	-.373*	-.435*	-.277	-.316	-.261	-.123*	-.129*	-.133**

***, **, and * significant at 0.1%, 1%, and 5% level, respectively.

[1] With 25-seedling groups, N = 32 for each pruning treatment.

[2] Initially, 800 seedlings represented each pruning treatment; however, evaluations on surviving seedlings after two growing seasons were: N = 553 for pruned seedlings and N = 282 for unpruned seedlings.

[3] NSFOLR = Number of strong, first-order lateral roots.

Table 4--Initial distribution of 800 vertically root-pruned longleaf pine seedlings (treatment Nos. 1-4) and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
	Initial number of seedlings															
5-8	6	2			1			9	100	9	1					110
9-10	16	11	13	1	2			43	82	50	31	15	4		1	183
11-12		5	13	4	3	1	2	28	17	28	46	43	17	4	6	161
13-14	1		5	6	5	5	11	33	3	13	15	18	28	20	14	111
15-16		1	1	2	2	7	5	18	2		2	5	7	4	34	54
≥17	1				1	3	12	17		1		3	5	5	19	33
Totals	24	19	32	13	14	16	30	148	204	101	95	84	61	33	74	652
	Number of seedlings surviving at age 2															
5-8	3	0			1			4	52	5	1					58
9-10	7	2	9	1	0			19	54	38	29	14	2		1	138
11-12		2	4	1	0	0	2	9	9	24	36	39	12	3	6	129
13-14	1		3	4	4	5	10	27	1	5	12	16	22	15	13	84
15-16		0	0	2	1	3	5	11	1		0	3	6	3	30	43
≥17	0				0	2	8	10		1		3	3	3	11	21
Totals	11	4	16	8	6	10	25	80	117	73	78	75	45	24	61	473
	Number of seedlings in active height growth at age 2															
5-8	2	0			1			3	21	4	1					26
9-10	1	1	3	1	0			6	25	20	22	12	1		1	81
11-12		1	2	1	0	0	2	6	6	18	28	30	9	3	6	100
13-14	0		2	3	1	2	9	17	1	4	9	14	18	14	12	72
15-16		0	0	1	1	3	5	10	0		0	3	5	2	29	39
≥17	0				0	2	8	10		1		3	3	3	10	20
Totals	3	2	7	6	3	7	24	52	53	47	60	62	36	22	58	338

[1] Underlined numbers denote the "target zone." There were initially 377 seedlings in the target zone, and after two growing seasons in the field 308 seedlings survived (81.7% survival) and 262 seedlings (69.5%) were in active height growth. Within the target zone, 170 seedlings with initial RCD of 8-12 mm showed 85.3% survival and 67.6% in active height growth at age 2, and 207 seedlings with initial RCD ≥13 showed 78.7% survival and 71.0% in active height growth; tests of differences in responses between these RCD groups showed that $P = 0.093$ for survival and $P = 0.478$ for active height growth, based on the two-tailed alternative hypothesis.

Table 5--Initial distribution of 800 unpruned control longleaf pine seedlings (treatment Nos. 5-8) and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
								Initial number of seedlings								
5-8	17	12	2					31	84	9	5				1	99
9-10	15	24	15	6	2	1		63	47	37	40	11	7	1		143
11-12	6	15	23	29	14	4		91	6	17	37	30	8	10	3	111
13-14	2	6	6	14	11	13	11	63		3	5	15	17	16	21	77
15-16			2	8	9	11	18	48		3	1	7	6	4	17	38
≥17			1	2	3	2	10	18			1	2	3	4	8	18
Totals	40	57	49	59	39	31	39	314	137	69	89	65	41	35	50	486
								Number of seedlings surviving at age 2								
5-8	3	1	0					4	37	6	2				0	45
9-10	3	9	7	4	1	1		25	25	23	20	9	3	1		81
11-12	1	5	7	12	7	3		35	2	10	24	20	5	9	3	73
13-14	0	1	1	5	6	4	5	22		1	4	7	10	11	15	48
15-16			0	1	2	4	10	17		0	0	2	4	2	10	18
≥17			0	1	1	0	4	6			0	0	0	2	6	8
Totals	7	16	15	23	17	12	19	109	64	40	50	38	22	25	34	273
								Number of seedlings in active height growth at age 2								
5-8	0	0	0					0	11	1	2				0	14
9-10	1	3	4	1	0	1		10	11	11	12	3	1	1		39
11-12	0	1	3	5	3	1		13	1	7	15	10	4	6	3	46
13-14	0	0	0	3	4	3	3	13		1	2	5	5	7	12	32
15-16			0	1	1	3	10	15		0	0	2	3	1	9	15
≥17			0	1	1	0	2	4			0	0	0	2	5	7
Totals	1	4	7	11	9	8	15	55	23	20	31	20	13	17	29	153

[1] Underlined numbers denote the "target zone." There were initially 319 seedlings in the target zone, and after two growing seasons 188 seedlings survived (58.9% survival) and 125 seedlings (39.2%) were in active height growth. Within the target zone, 153 seedlings with initial RCD of 8-12 mm showed 62.7% survival and 37.3% in active height growth at age 2, and 166 seedlings with initial RCD ≥13 showed 55.4% survival and 41.0% in active height growth; tests of differences in responses between these RCD groups showed that $P = 0.1836$ for survival and $P = 0.4966$ for active height growth, based on the two-tailed alternative hypothesis.

Table 6--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 1 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
	Initial number of seedlings															
5-8	1	1						2	10	3						13
9-10	3	5	5		2			15	12	5	11		1			29
11-12		1	3		2		1	7	1	7	10	12	6	1	1	38
13-14			2	4	3	2	6	17		1	6	4	6	8	5	30
15-16		1		1		5	2	9				1			14	15
≥17						3	5	8				1	3	2	11	17
Totals	4	8	10	5	7	10	14	58	23	16	27	18	16	11	31	142
	Number of seedlings surviving at age 2															
5-8	1	0						1	5	2						7
9-10	0	2	4		0			6	9	3	11		0			23
11-12		1	1		0		1	3	0	5	6	11	5	1	1	29
13-14			2	3	3	2	6	16		0	4	4	4	6	5	23
15-16		0		1		3	2	6				1			14	15
≥17						2	5	7				1	2	1	8	12
Totals	1	3	7	4	3	7	14	39	14	10	21	17	11	8	28	109
	Number of seedlings in active height growth at age 2															
5-8	1	0						1	2	2						4
9-10	0	1	3		0			4	4	2	9		0			15
11-12		0	1		0		1	2	0	4	5	9	4	1	1	24
13-14			2	3	1	2	5	13		0	3	3	4	5	4	19
15-16		0		0		3	2	5				1			14	15
≥17						2	5	7				1	2	1	7	11
Totals	1	1	6	3	1	7	13	32	6	8	17	14	10	7	26	88

[1] Underlined numbers denote the "target zone." There were initially 117 seedlings in the target zone, and after two growing seasons 99 seedlings survived (84.6% survival) and 87 seedlings (74.4%) were in active height growth. Within the target zone, 43 seedlings with initial RCD of 8-12 mm showed 83.7% survival and 69.8% in active height growth at age 2, and 74 seedlings with initial RCD ≥13 showed 85.1% survival and 77.0% in active height growth; tests of differences in responses between these RCD groups showed that *P* = 0.841 for survival and *P* = 0.134 for active height growth, based on the two-tailed alternative hypothesis.

Table 7--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 2 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
								Initial number of seedlings								
5-8									8	2						10
9-10	3	3	3					9	10	10	1	5	1		1	28
11-12		3	6	3	1	1	1	15		3	14	17	3		4	41
13-14			3	2	2	3	4	14		2	3	6	12	8	4	35
15-16			1	1	2	1	3	8	1		1	1	4	3	14	24
≥17					1		6	7		1			2	1	5	9
Totals	3	6	13	6	6	5	14	53	19	18	19	29	22	12	28	147
								Number of seedlings surviving at age 2								
5-8									0	1						1
9-10	2	0	1					3	3	9	1	4	1		1	19
11-12		1	2	0	0	0	1	4		1	12	14	1		4	32
13-14			1	1	1	3	3	9		1	2	5	10	6	4	28
15-16			0	1	1	0	3	5	1		0	1	3	3	11	19
≥17					0		2	2		1			1	1	1	4
Totals	2	1	4	2	2	3	9	23	4	13	15	24	16	10	21	103
								Number of seedlings in active height growth at age 2								
5-8									0	0						0
9-10	1	0	0					1	1	5	0	2	1		1	10
11-12		1	0	0	0	0	1	2		1	10	12	1		4	28
13-14			0	0	0	0	3	3		1	2	4	8	6	4	25
15-16			0	1	1	0	3	5	0		0	1	3	2	10	16
≥17					0		2	2		1			1	1	1	4
Totals	1	1	0	1	1	0	9	13	1	8	12	19	14	9	20	83

[1] Underlined numbers denote the "target zone." There were initially 124 seedlings in the target zone, and after two growing seasons 95 seedlings survived (76.6% survival) and 83 seedlings (66.9%) were in active height growth. Within the target zone, 47 seedlings with initial RCD of 8-12 mm showed 83.0% survival and 68.1% in active height growth at age 2, and 77 seedlings with initial RCD ≥13 showed 72.7% survival and 66.2% in active height growth; tests of differences in responses between these RCD groups showed that $P = 0.168$ for survival and $P = 0.826$ for active height growth, based on the two-tailed alternative hypothesis.

Table 8--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 3 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD (mm)	Low fibrosity and NSFOLR of-- 0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	Medium or high fibrosity and NSFOLR of-- 0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
	Initial number of seedlings															
5-8	3	1			1			5	41	1	1					43
9-10	4	1	2	1				8	35	13	12	6	1			67
11-12		1	1	1				3	8	9	14	5	3			39
13-14									2	8	3	4	5	3	4	29
15-16												1	1		2	4
≥17												1		1		2
Totals	7	3	3	2	1	—	—	16	86	31	30	17	10	4	6	184
	Number of seedlings surviving at age 2															
5-8	2	0			1			3	27	0	1					28
9-10	1	0	2	1				4	25	10	10	6	0			51
11-12		0	1	1				2	5	9	12	5	3			34
13-14									1	2	3	4	5	2	3	20
15-16												1	1		2	4
≥17												1		1		2
Totals	3	0	3	2	1	—	—	9	58	21	26	17	9	3	5	139
	Number of seedlings in active height growth at age 2															
5-8	1	0			1			2	8	0	1					9
9-10	0	0	0	1				1	12	3	7	6	0			28
11-12		0	1	1				2	4	6	10	4	3			27
13-14									1	2	2	4	3	2	3	17
15-16												1	1		2	4
≥17												1		1		2
Totals	1	0	1	2	1	—	—	5	25	11	20	16	7	3	5	87

[1] Underlined numbers denote the "target zone." There were initially 67 seedlings in the target zone, and after two growing seasons 60 seedlings survived (89.6% survival) and 51 seedlings (76.1%) were in active height growth. Within the target zone, 42 seedlings with initial RCD of 8-12 mm showed 88.1% survival and 73.8% in active height growth at age 2, and 25 seedlings with initial RCD ≥13 showed 92.0% survival and 80.0% in active height growth; tests of differences in responses between these RCD groups showed that P = 0.596 for survival and P = 0.555 for active height growth, based on the two-tailed alternative hypothesis.

Table 9--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 4 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	>14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	>14	Totals
	Initial number of seedlings															
5-8	2							2	41	3						44
9-10	6	2	3					11	25	22	7	4	1			59
11-12			3					3	8	9	8	9	5	3	1	43
13-14	1						1	2	1	2	3	4	5	1	1	17
15-16						1		1	1		1	2	2	1	4	11
>17	1						1	2				1		1	3	5
Totals	10	2	6	—	—	1	2	21	76	36	19	20	13	6	9	179
	Number of seedlings surviving at age 2															
5-8	0							0	20	2						22
9-10	4	0	2					6	17	16	7	4	1			45
11-12			0					0	4	9	6	9	3	2	1	34
13-14	1						1	2	0	2	3	3	3	1	1	13
15-16						0		0	0		0	0	2	0	3	5
>17	0						1	1				1		0	2	3
Totals	5	0	2	—	—	0	2	9	41	29	16	17	9	3	7	122
	Number of seedlings in active height growth at age 2															
5-8	0							0	11	2						13
9-10	0	0	0					0	8	10	6	4	0			28
11-12			0					0	2	7	3	5	1	2	1	21
13-14	0						1	1	0	1	2	3	3	1	1	11
15-16						0		0	0		0	0	1	0	3	4
>17	0						1	1				1		0	2	3
Totals	0	0	0	—	—	0	2	2	21	20	11	13	5	3	7	80

[1] Underlined numbers denote the "target zone." There were initially 69 seedlings in the target zone, and after two growing seasons 54 seedlings survived (78.3% survival) and 41 seedlings (59.4%) were in active height growth. Within the target zone, 38 seedlings with initial RCD of 8-12 mm showed 86.8% survival and 57.9% in active height growth at age 2, and 31 seedlings with initial RCD >13 showed 67.7% survival and 61.3% in active height growth; tests of differences in responses between these RCD groups showed that $P = 0.057$ for survival and $P = 0.772$ for active height growth, based on the two-tailed alternative hypothesis.

Table 10--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 5 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
	Initial number of seedlings															
5-8	3	1						4	8		1					9
9-10	4	7						11	6	3	7	1	1			18
11-12		2	10	10	7	3		32	2	4	8	9	4	2		29
13-14	1	2	4	4	2	7	5	25		1	3	5	2	6	7	24
15-16			1	3	3	4	13	24			1	1	2	1	7	12
≥17				1	1	1	4	7					2		3	5
Totals	8	12	15	18	13	15	22	103	16	8	20	16	11	9	17	97
	Number of seedlings surviving at age 2															
5-8	1	0						1	1		1					2
9-10	0	4						4	1	2	6	1	1			11
11-12		1	2	6	2	2		13	1	2	5	6	3	2		19
13-14	0	0	0	1	1	3	3	8		1	3	3	0	6	5	18
15-16			0	0	0	2	7	9			0	1	2	0	5	8
≥17				0	1	0	2	3					0		2	2
Totals	1	5	2	7	4	7	12	38	3	5	15	11	6	8	12	60
	Number of seedlings in active height growth at age 2															
5-8	0	0						0	0		1					1
9-10	0	1						1	1	1	4	1	0			7
11-12		0	1	3	1	1		6	1	2	4	4	2	1		14
13-14	0	0	0	1	0	2	2	5		1	2	2	0	4	5	14
15-16			0	0	0	2	7	9			0	1	1	0	4	6
≥17				0	1	0	1	2					0		2	2
Totals	0	1	1	4	2	5	10	23	2	4	11	8	3	5	11	44

[1] Underlined numbers denote the "target zone." There were initially 95 seedlings in the target zone, and after two growing seasons 64 seedlings survived (67.4% survival) and 48 seedlings (50.5%) were in active height growth. Within the target zone, 33 seedlings with initial RCD of 8-12 mm showed 75.8% survival and 51.5% in active height growth at age 2, and 62 seedlings with initial RCD ≥13 showed 62.9% survival and 50.0% in active height growth; tests of differences in responses between these RCD groups showed that $P = 0.180$ for survival and $P = 0.889$ for active height growth, based on the two-tailed alternative hypothesis.

Table 11--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 6 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
	Initial number of seedlings															
5-8	3	3						6	5	1	1				1	8
9-10	2	3	3					8	1	6	6	3	3	1		20
11-12	2	3	8	5	4	1		23	2	3	6	9	1	4	3	28
13-14		2	2	8	7	4	6	29		1	1	2	6	7	8	25
15-16			1	5	3	5	5	19		1		3	1	2	7	14
≥17			1	1	2	1	5	10				1	1	3	5	10
Totals	7	11	15	19	16	11	16	95	8	12	14	18	12	17	24	105
	Number of seedlings surviving at age 2															
5-8	0	0						0	2	1	0				0	3
9-10	0	1	0					1	1	3	4	3	1	1		13
11-12	0	1	3	0	4	1		9	0	2	4	5	0	4	3	18
13-14		0	1	4	4	1	2	12		0	1	0	2	3	8	14
15-16			0	1	2	2	3	8		0		1	1	2	4	8
≥17			0	1	0	0	2	3				0	0	2	4	6
Totals	0	2	4	6	10	4	7	33	3	6	9	9	4	12	19	62
	Number of seedlings in active height growth at age 2															
5-8	0	0						0	0	0	0				0	0
9-10	0	1	0					1	1	1	1	1	0	1		5
11-12	0	1	1	0	2	0		4	0	2	1	3	0	3	3	12
13-14		0	0	2	4	1	1	8		0	0	0	0	2	5	7
15-16			0	1	1	1	3	6		0		1	1	1	4	7
≥17			0	1	0	0	1	2				0	0	2	3	5
Totals	0	2	1	4	7	2	5	21	1	3	2	5	1	9	15	36

[1] Underlined numbers denote the "target zone." There were initially 101 seedlings in the target zone, and after two growing seasons 60 seedlings survived (59.4% survival) and 37 seedlings (36.6%) were in active height growth. Within the target zone, 38 seedlings with initial RCD of 8-12 mm showed 65.8% survival and 34.2% in active height growth at age 2, and 63 seedlings with initial RCD ≥13 showed 55.6% survival and 38.1% in active height growth; tests of differences in responses between these RCD groups showed that $P = 0.303$ for survival and $P = 0.689$ for active height growth, based on the two-tailed alternative hypothesis.

Table 12--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 7 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
	Initial number of seedlings															
5-8	6	6	1					13	38	5	3					46
9-10	4	8	5	2	1	1		21	19	14	16	3	3			55
11-12	1	3	2	6				12	2	4	9	3	2	1		21
13-14		2		1	1	1		5				6	6	3	2	17
15-16					2	1		3		2		2	1	1		6
≥17							1	1								
Totals	11	19	8	9	4	3	1	55	59	25	28	14	12	5	2	145
	Number of seedlings surviving at age 2															
5-8	1	1	0					2	17	3	1					21
9-10	1	2	3	2	0	1		9	10	8	5	3	1			27
11-12	1	2	0	2				5	1	3	8	2	1	1		16
13-14		1		0	1	0		2				4	5	2	0	11
15-16					0	0		0		0		0	1	0		1
≥17							0	0								
Totals	3	6	3	4	1	1	0	18	28	14	14	9	8	3	0	76
	Number of seedlings in active height growth at age 2															
5-8	0	0	0					0	7	0	1					8
9-10	1	0	2	1	0	1		5	3	4	2	0	1			10
11-12	0	0	0	1				1	0	3	4	1	1	0		9
13-14		0		0	0	0		0				3	2	1	0	6
15-16					0	0		0		0		0	1	0		1
≥17							0	0								
Totals	1	0	2	2	0	1	0	6	10	7	7	4	5	1	0	34

[1] Underlined numbers denote the "target zone." There were initially 62 seedlings in the target zone, and after two growing seasons 34 seedlings survived (54.8% survival) and 17 seedlings (27.4%) were in active height growth. Within the target zone, 40 seedlings with initial RCD of 8-12 mm showed 55.0% survival and 25.0% in active height growth at age 2, and 22 seedlings with initial RCD ≥13 showed 54.5% survival and 31.8% in active height growth; tests of differences in responses between these RCD groups showed that P = 0.968 for survival and P = 0.575 for active height growth, based on the two-tailed alternative hypothesis.

Table 13--Initial distribution of 200 longleaf pine seedlings receiving treatment No. 8 and distributions in terms of survival and height-growth initiation 2 years after outplanting, by fibrosity rating, number of strong, first-order lateral roots (NSFOLR) of stock, and root-collar diameter (RCD)[1]

RCD	Low fibrosity and NSFOLR of--								Medium or high fibrosity and NSFOLR of--							
(mm)	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals	0-3	4-5	6-7	8-9	10-11	12-13	≥14	Totals
	Initial number of seedlings															
5-8	5	2	1					8	33	3						36
9-10	5	6	7	4	1			23	21	14	11	4				50
11-12	3	7	3	8	3			24		6	14	9	1	3		33
13-14	1			1	1	1		4		1	1	2	3		4	11
15-16					1	1		2				1	2		3	6
≥17											1	1		1		3
Totals	14	15	11	13	6	2	—	61	54	24	27	17	6	4	7	139
	Number of seedlings surviving at age 2															
5-8	1	0	0					1	17	2						19
9-10	2	2	4	2	1			11	13	10	5	2				30
11-12	0	1	2	4	1			8		3	7	7	1	2		20
13-14	0			0	0	0		0		0	0	0	3		2	5
15-16					0	0		0				0	0		1	1
≥17											0	0		0		0
Totals	3	3	6	6	2	0	—	20	30	15	12	9	4	2	3	75
	Number of seedlings in active height growth at age 2															
5-8	0	0	0					0	4	1						5
9-10	0	1	2	0	0			3	6	5	5	1				17
11-12	0	0	1	1	0			2		0	6	2	1	2		11
13-14	0			0	0	0		0		0	0	0	3		2	5
15-16					0	0		0				0	0		1	1
≥17											0	0		0		0
Totals	0	1	3	1	0	0	—	5	10	6	11	3	4	2	3	39

[1] Underlined numbers denote the "target zone." There were initially 61 seedlings in the target zone, and after two growing seasons 30 seedlings survived (49.2% survival) and 23 seedlings (37.7%) were in active height growth. Within the target zone, 42 seedlings with initial RCD of 8-12 mm showed 57.1% survival and 40.5% in active height growth at age 2, and 19 seedlings with initial RCD ≥13 showed 31.6% survival and 31.6% in active height growth; tests of differences in responses between these RCD groups showed that $P = 0.052$ for survival and $P = 0.496$ for active height growth, based on the two-tailed alternative hypothesis.

Table 14--Comparison of field performance of Wakeley's (1954) standard grades 1 and 2 longleaf pine seedlings vs. seedlings having values of key morphological attributes within the "target zone for higher quality," by nursery cultural treatment

Nursery cultural treatment: (No.) vertical root pruning, seedbed density, and spacing of seed drills	Field performance through two growing seasons on deep sandy site				Difference and significance level in performance of seedling within target zone vs. standard stock	
	Grade 1 and 2		Target seedlings[1]			
	Survival	Active height growth	Survival	Active height growth	Survival	Active height growth
Vertical pruning	% of initial		% of initial target seedling		Percentage points and P	
Density, drills						
Low, 15 cm (1)	74.0	60.0	84.6	74.4	+10.6***	+14.4***
Low, 30 cm (2)	63.0	48.0	76.6	66.9	+13.6***	+18.9***
Medium, 15 cm (3)	74.0	46.0	89.6	76.1	+15.6***	+30.1***
Medium, 30 cm (4)	65.5	41.0	78.3	59.4	+12.8**	+18.4***
Unpruned controls						
Density, drills						
Low, 15 cm (5)	49.0	33.5	67.4	50.5	+18.4***	+17.0***
Low, 30 cm (6)	47.5	28.5	59.4	36.6	+11.9***	+8.1**
Medium, 15 cm (7)	47.0	20.0	54.8	27.4	+7.8	+7.4
Medium, 30 cm (8)	47.5	22.0	49.2	37.7	+1.7	+15.7***

***, **, *, Significant at 0.1%, 1%, and 5% level, respectively, based on the two-tailed alternative hypothesis.

[1] See tables 6-13 for seedling distributions, by treatments.

Table 15--Comparison of second-year field response of target-zone planting stock having root-collar diameter (RCD) of 8-12 mm vs. RCD ≥13 mm, by nursery cultural treatment[1]

Nursery cultural treatment: (No.) vertical root pruning, seedbed density, and spacing of seed drills	Initial number of seedlings with RCD of--			Field performance after two growing seasons							
				Survival by RCD group			Active height growth by RCD			Difference in performance of stock with RCD of 8-12 mm vs. >13 mm	
	8-12 mm	≥13 mm	All	8-12 mm	≥13 mm	All	8-12 mm	≥13 mm	All	Survival	Height growth
Vertical pruning	Number (% of total)[2]			% of initial target seedlings[3]						Percentage points (P^4)	
Density, drills											
Low, 15 cm (1)	43	74	117(58.5)	83.7a	85.1ab	84.6ab	69.8a	77.0a	74.4a	-1.4 (0.841)	-7.2 (0.134)
Low, 30 cm (2)	47	77	124(62.0)	83.0a	72.7b	76.6b	68.1a	66.2a	66.9ab	+10.3 (0.168)	+1.9 (0.826)
Medium, 15 cm (3)	42	25	67(33.5)	88.1a	92.0a	89.6a	73.8a	80.0a	76.1a	-3.9 (0.596)	-6.2 (0.555)
Medium, 30 cm (4)	38	31	69(34.5)	86.8a	67.7b	78.3ab	57.9a	61.3a	59.4b	+19.1 (0.057)	-3.4 (0.772)
Unpruned controls											
Density, drills											
Low, 15 cm (5)	33	62	95(47.5)	75.8a	62.9a	67.4a	51.5a	50.0a	50.5a	+12.9 (0.180)	+1.5 (0.889)
Low, 30 cm (6)	38	63	101(50.5)	65.8a	55.6ab	59.4ab	34.2ab	38.1a	36.6b	+10.2 (0.303)	-3.9 (0.689)
Medium, 15 cm (7)	40	22	62(31.0)	55.0a	54.5ab	54.8ab	25.0b	31.8a	27.4b	+0.5 (0.968)	-6.8 (0.575)
Medium, 30 cm (8)	42	19	61(30.5)	57.1a	31.6b	49.2b	40.5ab	31.6a	37.7ab	+25.5 (0.052)	+8.9 (0.496)

[1] See tables 6-13 for seedling distributions, by treatments.

[2] Percentage of seedlings having target-zone attributes = (number in target zone divided by 200) x 100.

[3] Within a pruning treatment, means in a column followed by a common letter are not significantly different at $P = 0.05$.

[4] Based on the two-tailed alternative hypothesis.

Hatchell, Glyndon E.; Muse, H. David. 1990. Nursery cultural practices and morphological attributes of longleaf pine bare-root stock as indicators of early field performance. Res. Pap. SE-277. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 34 pp.

Longleaf pine seedlings performed satisfactorily after planting on deep sands in South Carolina in dry years when: (1) They were vertically root-pruned in the nursery. (2) They had 14 or more first-order lateral roots and nonfibrous root systems. (3) They had six or more first-order lateral roots and highly fibrous root systems.

Keywords: Seedling quality, morphological grades, vertical root pruning, *Pinus palustris*.

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