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Root System Structure in Planted and Seeded Loblolly and Shortleaf Pine

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ABSTRACT. Differences in root system structure attributable to stand origin were examined by pairing seeded and planted stands of loblolly (*Pinus taeda* L.) and shortleaf pine (*P. echinata* Mill.). The 17 paired stands were 3 to 9 years old and located in Arkansas, Oklahoma, and Texas on similar soil and site conditions. Root systems from 12 trees were excavated from each stand, classified by root system type and measured for number and size of first-order lateral roots and amount of root spiraling and bending. Although root systems of planted trees were commonly deformed, the most consistent difference in root system structure between planted and seeded trees was the increased distance from groundline to the uppermost lateral roots on planted seedlings. A linear discriminant function including this variable correctly classified all loblolly pine plots and 89% of the shortleaf pine plots as to whether the plot had been planted or seeded. Planted trees also had fewer first-order lateral roots less than 10 mm in diameter and exhibited greater spiraling and bending of major first-order laterals than seeded trees. Differences in root system structure between planted and seeded trees were similar for the two species. FOR. SCI. 35(2):469–480.

ADDITIONAL KEY WORDS. *Pinus echinata, Pinus taeda,* root system morphology.

ROOT SYSTEM MORPHOLOGY of tree seedlings in the field can influence survival, stability, and growth (Van Eerden and Kinghorn 1978). The root system morphology that developed from seed-in-place is a function of seedling genetics, soil characteristics, such as texture, presence and location of rocks, compaction, cementation, organic materials, fertility, and moisture content, and the severity of biotic or abiotic damaging agents, such as insects or frost. Root morphology of planted seedlings is also influenced by nursery cultural practices and planting method.

Loblolly (*Pinus taeda* L.) and shortleaf pine (*P. echinata* Mill.) are the two most widely distributed conifer species in southern Arkansas, northern Louisiana, southeastern Oklahoma, and northeastern Texas. Early reports indicated that both species develop taproots when grown in natural stands if soil drainage is adequate (Ashe 1915, Mattoon 1915, McQuilkin 1935). Available information on planted root systems of the two species (Cabrera and Woods 1975, Gruschow 1959, Hay and Woods 1974, Little and Somes 1964, Mexal and Burton 1978) is limited in scope, emphasizes loblolly pine, and is primarily qualitative rather than quantitative. The objectives of this study are: (1) to collect quantitative information on root system morphology of

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young loblolly and shortleaf pines and (2) to test if planted versus seeded stands of these species differed in root system morphology.

MATERIALS AND METHODS

Seventeen pairs of temporary 2-ha plots were established in young (3- to 9-year-old) pine stands in Arkansas, Oklahoma, and Texas. One plot in each pair had been operationally regenerated by natural or artificial seeding and the other by planting bareroot seedlings. The two plots in each pair were located so that they were: (1) on the same soil type (soil mapping unit or phase), (2) within 15 km of each other, and (3) closely matched in terms of aspect, elevation, topographic position, and type and amount of competing vegetation. Mean ages of trees in each plot pair differed by no more than 2 years. Nine of the plot pairs were shortleaf pine and eight were loblolly pine. Local seed sources had been used in the artificially regenerated stands, and none of the plots were on sites that had received site preparation treatments that would have altered rootability (e.g., ripping or bedding). Three of the planted plots in the Coastal Plain were planted by machine; all other planted plots were hand-planted.

Plot pairs of both species were split between the West Gulf Coastal Plain and Interior Highlands physiographic provinces (Figure 1). Trees sampled in the Coastal Plain were generally larger than those in the Interior Highlands because they were older and grew under more favorable site conditions. The difference in age between the physiographic provinces was related to changes in operational planting practices; for example, it was difficult to locate suitable shortleaf pine plantations in the Coastal Plain that were less than 7 years old.

Twelve trees were sampled in each plot. The location of sampling positions in a plot was generated in the office using random *X-Y* coordinates, then adjusted in the field as necessary to avoid former log landings, roads, or areas subject to shade from adjacent stands. The tallest tree out of the five trees closest to the sample point was chosen as the sample tree unless it was not typical of the species in the plot or had evidence of major top damage. The tallest tree was chosen to minimize the possibility that sample trees had been suppressed by competing vegetation. Sample trees were tagged on the north side, marked at groundline, and then excavated. Root systems were excavated down to 40 cm; lateral roots were severed about 15 cm out from the main stem. No attempt was made to sample fine root mass or length of major roots. After excavation trees were measured for total height and height growth, then their tops were cut off 15 cm above groundline. Height growth information was presented in Harrington et al. (1987).

Root systems were washed thoroughly and then either measured immediately or briefly stored. Stored roots were rehydrated prior to measurement by soaking in water for 1 or 2 days. Detailed root system measurements were facilitated by using a 36-cm deep cylindrical measuring frame. The frame was divided into three 12-cm horizontal zones—0 to 12 cm, 12 to 24 cm, and 24 to 36 cm. Based on common nursery undercutting practices and planting tools used in the region, we assumed that, for planted trees, roots in the upper 12-cm zone would have been influenced by nursery culture and planting technique, roots in the central zone would have been influenced somewhat in the nursery but primarily by planting, and roots in the bottom zone would have developed after planting. Each of the 3 horizontal zones was divided into 4 compass quadrants resulting in a total of 12 subquadrants (Figure 2). Root systems were positioned in the frame with the cut stump

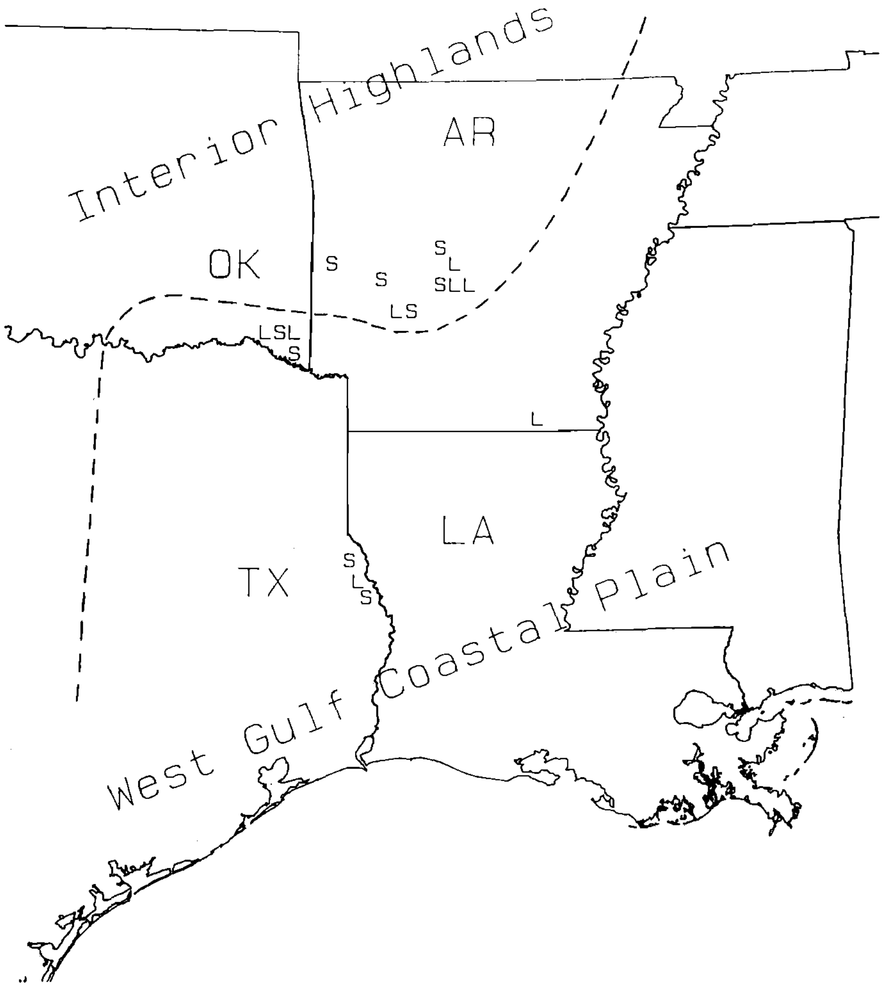

FIGURE 1. Location of paired plots excavated for root morphology study. L = loblolly pine site, S = shortleaf pine site.

facing up, the groundline mark aligned with the top of the frame, the tag centered in the north quadrant, and the longitudinal axis of the main stem oriented vertically. The measurement frame was placed over a circle divided into eighteen 20° zones.

Root systems were first classified into one of four general orientation classes (Figure 3). Orientation class 1 was a root system with one major root oriented downward; no attempt was made to distinguish between undisturbed taproots and a major root that may have grown downward after the original taproot was cut or damaged. Orientation 1 also included taproots with major turns if the overall direction of the root system was primarily downward; thus, this category would have included trees with straight (vertical) taproots and trees with a taproot originally "L" or "J" rooted that recovered or corrected itself and grew downward. Orientation 2 was for root systems having one major root, but the root system was not directed downward. This included root systems having an "L" or "J" configuration that had been maintained. Orientation 3 was applied to root systems that had a downward orientation but with more than one major root involved. This

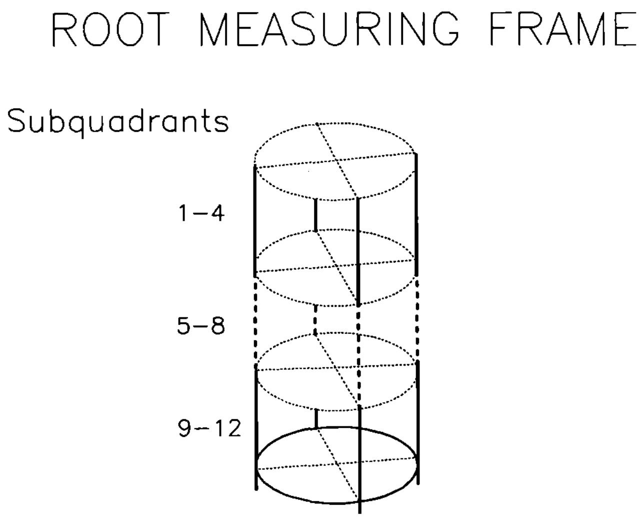

FIGURE 2. Root measuring frame illustrating location of subquadrants.

included root systems with two to four large "sinker" roots as well as more fibrous root systems with a strong downward orientation. Orientation 4 was for root systems without a major root and with the orientation of the laterals primarily outward rather than downward.

Tree diameter at groundline was measured for all trees, and diameters of the tap or main root (if present) were measured at 12, 24, and 36 cm below the original groundline. The number of major turns made by a taproot between the top and where it exited the frame was recorded. Major turns were defined as changes in root direction of 60° or more. The length of the taproot was measured from the top of the frame to where it split into two or more major roots or to where it exited the frame, whichever came first. Taproots exiting the bottom of the frame were assigned a length of 37 cm. A count was also made of the number of first-order lateral roots exiting the bottom of the measurement frame.

Several measurements were also taken on first-order lateral roots by quadrant or subquadrant. The distance from groundline to the uppermost lateral root in each of the four compass quadrants was measured first. Next, the following measurements were taken on the largest first-order lateral root in each of 12 subquadrants: *diameter* measured about 1 cm out from where it originated on the taproot; the *angle* between the lateral root and the taproot (an angle of 180° would mean the lateral root was growing straight down); the number of *major turns* made by the lateral root between the taproot and where it exited the side of the frame; and the number of *20° zones* the root crossed from its origination on the main root and where it exited the side of the frame. The diameter of the measuring frame was 25 cm for trees from the Interior Highlands and 50 cm for trees from the Coastal Plain. We used a larger diameter frame for the Coastal Plain trees because they had substantially larger groundline diameters. The number of major turns is a measure of root deformation; the number of 20° zones crossed by the root quantifies the spiraling of lateral roots. Root diameters were measured with calipers; for visibly out-of-round roots, two measurements were taken at right angles from each other and averaged. The number of roots per subquadrant was also tallied by size class: <10 mm, 10 to 20 mm, and >20 mm in diameter. Root system measurements in this study were similar to those presented by Preisig et al. (1978); our measurements were somewhat modified from theirs to accommodate the larger root systems being measured.

Statistical analyses contrasted root system characteristics of planted and seeded trees of each species. No statistical tests were made between species because initial plot selection was done independently for the two species. Differences among compass quadrants were tested using analysis of variance. For both species, the effect of quadrant was nonsignificant for most variables; thus the mean of the values from the four subquadrants in each horizontal zone was used in the other statistical analyses rather than keeping the four individual values as separate variables. Differences in root system characteristics between planted and seeded stands were tested with univariate paired t-tests (Snedecor and Cochran 1980). Differences between planted and seeded stands in the distribution of root systems into root orientation classes were tested using the chi-square test of independence (Snedecor and Cochran 1980). Stepwise discriminant analyses were used to select a subset of the original variables for inclusion in several nonstepwise discriminant analyses (Morrison 1976). Discrete or class variables were not included in the discriminant analyses. All statistical analyses except that of root orientation class were done using plot means.

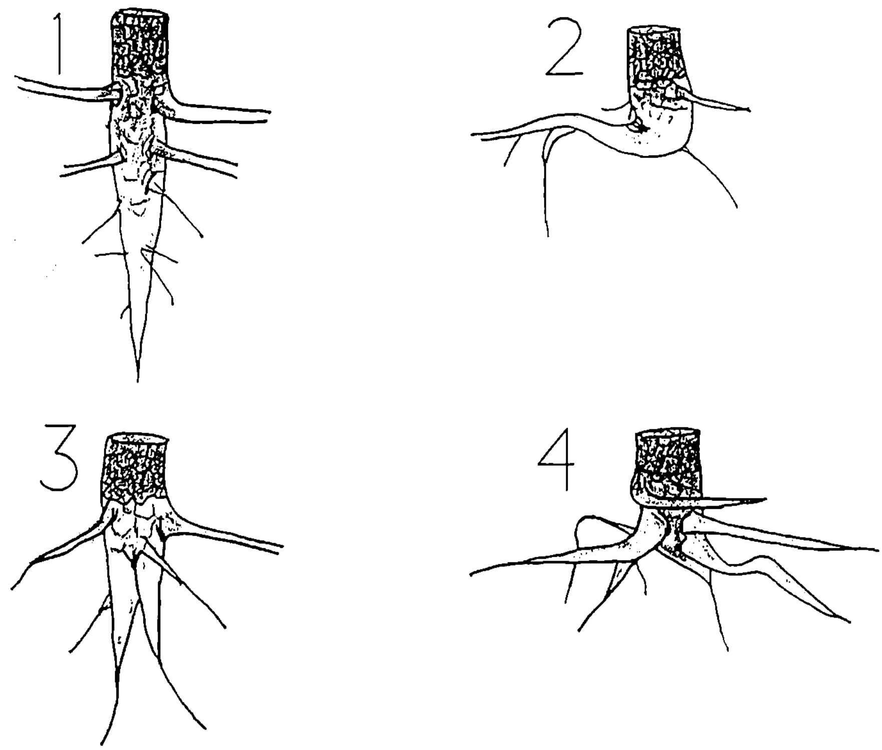

FIGURE 3. Orientation classes used to classify root systems.

RESULTS

Several root system characteristics differed between planted and seeded trees (Table 1). For both species, planting decreased the percentage of trees with downward-oriented root systems. The percentage of trees in root orientation class 1 (one major root, oriented downward) was particularly decreased by planting; the other three root classes were all increased (for a more detailed analysis of root orientation classes, see Harrington et al. 1987). The shorter mean taproot length for planted trees (Table 1) reflects the increase in root systems not having one major taproot, rather than indicating that taproot length within a root orientation class was shorter. For loblolly pine, planting also increased the mean number of turns per tree in the taproot (Table 1). In addition, the percentage of trees with major taproot turns was higher for both species on sites in the Interior Highlands than in the Coastal Plain (Table 2); this may reflect the increased presence of obstacles to rooting such as rocks and clayey soil layers present at many Interior Highland sites.

Values for distance from groundline to the uppermost lateral roots were greater in planted than seeded trees (Table 1). Most planted root systems clearly showed deformation associated with planting, as indicated by the greater number of turns in the taproot, turns in the largest lateral roots, and the number of 20° zones the largest lateral roots crossed. Multiplying the mean number of 20° zones by 20 results in an estimate of the amount that the largest lateral roots were displaced or spiraled around the root stock; this value was 36° for seeded and 64° for planted loblolly pine, and 38° for seeded and 80° for planted shortleaf pine. The number of zones crossed and turns made by the largest lateral roots were higher for planted trees than for seeded trees (Figures 4A, 4B); however, at least for number of turns, the differences between planted and seeded trees generally decreased with tree size. The mean angle between the taproot and the largest upper lateral roots was somewhat larger in planted than in seeded stands, particularly for loblolly pine.

Diameter at groundline did not differ between planted and seeded trees; however, there were differences in the number and size of lateral roots (Table 1). Seeded trees had more first-order lateral roots per tree than planted trees; most of this difference can be accounted for by the number of first-order lateral roots <10 mm in diameter located in the top 12 cm of soil. Planted trees, especially loblolly pine, generally had fewer but somewhat larger first-order lateral roots than seeded trees; this was shown by the greater mean diameter of the largest lateral root in subquadrants 1 through 4 and the greater number of lateral roots that were more than 20 mm in diameter.

Planted trees generally exhibited greater variability in most root system characteristics than seeded trees. The range of characteristics seen in each of the subquadrants was usually greater for planted than seeded trees. Shortleaf pine exhibited greater variability than loblolly pine in many root system characteristics. This greater variability could be inherent in the species or it may reflect less uniform rooting conditions associated with the rocky soils at some of the shortleaf pine sites.

Discriminant analysis resulted in several linear discriminant functions that correctly classified all or most plots into the correct stand origin group (Table 3). Mean distance from groundline to the uppermost lateral roots correctly classified all the loblolly pine plots. No other one-variable function

TABLE 1. Summary of root system measurements by species and stand origin. Significance levels are based on paired t-test or chi-square tests for each species.

Root system characteristic	Loblolly pine			Shortleaf pine		
	Seeded	Planted	P	Seeded	Planted	P
Age at GL[a] (yr)	6.0	5.7	0.4356	5.3	4.8	0.0919
Height (m)	3.7	3.2	.3017	2.7	2.5	0.7934
Diameter at GL (mm)	79	81	.7782	57	56	0.8784
Diameter at 12 cm (mm)	68	78	.0383	49	53	0.6369
Taproot length[b] (cm)	33	26	.0016	29	25	0.1277
Taproot turns (no.)	0.3	0.9	.0565	0.4	1.0	0.7715
Orientation—% downward[c]	91.0	74.0	.0006	86.0	71.0	0.0648
Distance from GSL to uppermost lateral roots (cm)	4.2	7.9	.0008	4.7	7.9	0.0002
For top 12-cm zone:						
Diameter LLR[d] (mm)	16	21	.0118	14	15	0.3907
Angle LLR + taproot (°)	102	91	.0475	107	103	0.3969
20° zones for LLR (no.)	2.8	4.2	.0227	2.9	5.0	0.0003
Major turns for LLR (no.)	0.2	1.1	.0093	0.5	1.3	0.0149
LR[e] <10 mm diam. (no.)	10.9	5.8	.0001	10.4	8.0	0.0079
LR 10–20 mm diam. (no.)	4.7	3.9	.0736	3.8	3.4	0.1606
LR >20 mm diam. (no.)	1.4	2.3	.1109	1.0	1.2	0.2158
Total LR/tree (no.)	29.4	22.8	.0011	25.9	22.8	0.0290
Total LR <10 mm diam. (no.)	20.4	11.9	.0001	18.4	14.6	0.0083
Total LR 10–20 mm diam. (no.)	6.7	6.5	.6432	5.8	5.8	0.9470
Total LR >20 mm diam. (no.)	2.3	4.3	.0020	1.8	2.4	0.2153
Total LR in top 12 cm (%)	59.1	53.7	.1231	59.9	57.2	0.3982

[a] GL = groundline.
[b] Maximum length 37 cm.
[c] Percentage of root systems in orientation classes 1 and 3, p value based on chi-square analysis of all 4 orientation classes.
[d] LLR = mean of largest first-order lateral root in subquadrants 1 through 4.
[e] LR = first-order lateral roots.

TABLE 2. Percentage of trees by species, province, and stand origin with one or more major turns recorded for the taproot.

Pine species	Physiographic province	Stand origin	
		Seeded	Planted
		(%)	
Loblolly	Interior Highlands	31.9	47.9
	West Gulf Coastal Plain	2.2	17.0
Shortleaf	Interior Highlands	27.5	40.0
	West Gulf Coastal Plain	12.5	23.5

was as accurate; however, alternative functions incorporating number of lateral roots and turns in lateral roots misclassified only one or two plots. For shortleaf pine, the number of zones crossed by lateral roots and distance from groundline to the uppermost lateral roots were the best variables in one-variable functions. Two three-variable functions correctly classified all shortleaf pine plots; these functions used number of lateral roots <10 mm and number of zones, plus either distance from groundline or angle between the taproot and the largest lateral roots in the upper subquadrants.

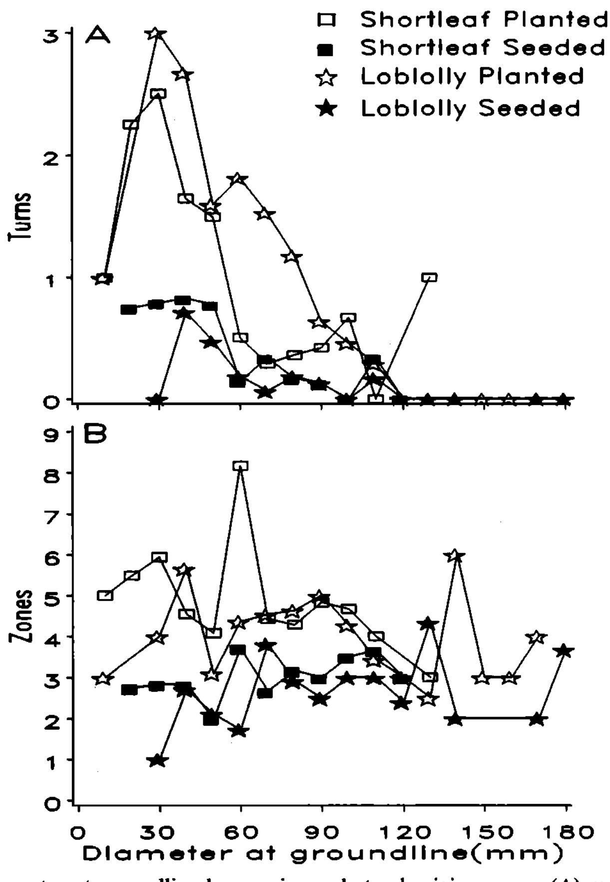

FIGURE 4. Diameter at groundline by species and stand origin versus: (A) mean number of turns made by LLR-12 (largest lateral root per quadrant in the top 12 cm soil zone) and (B) mean number of 20° zones crossed by LLR-12.

TABLE 3. Root system variables in linear discriminant functions that best separated planted and seeded plots.

Pine species	Variables in function[a]	Plots misclassified	
		Seeded	Planted
		.... *(No. plots)*	
Loblolly	Distance GL	0	0
	LR <10	0	1
	LR <10, Turns	0	1
	LR <10, Turns, LR >20	0	0
	LR >20, Turns	1	1
Shortleaf	Distance GL	1	1
	Distance GL, Turns	1	0
	Distance GL, Zones	1	0
	Distance GL, LR <10	1	1
	Distance GL, LR <10, Zones	0	0
	Zones	0	1
	Zones, Angle	0	1
	Zones, Angle, LR <10	0	0

[a] Distance GL = distance from groundline to the uppermost first-order lateral root; LR <10 = total first-order lateral roots per tree <10 mm in diameter; LR >20 = total first-order lateral roots per tree >20 mm in diameter; Turns = number of major turns made by LLR-12 (the largest lateral roots per quadrant in the top 12-cm soil zone); Zones = number of 20° zones crossed by LLR-12; Angle = angle between LLR-12 and the vertical axis of the taproot.

DISCUSSION

In our study, planted loblolly and shortleaf pines had fewer first-order lateral roots per tree, especially small roots (<10 mm in diameter) than seeded trees. The lower total number of roots per planted root system may be related to the greater average depth to the uppermost lateral roots associated with planted trees; that is, because the root collar of planted trees was generally deeper than that of seeded trees, the length of root stock between the root collar and the bottom of the measuring frame would have been somewhat less for planted trees than for seeded trees. In contrast with our findings, however, planted conifers in Washington and Oregon have been reported to have more lateral roots per root system than corresponding seeded trees (Long 1978, Preisig et al. 1979, Carlson et al. 1980). The differences in results among studies may indicate differences among species in response to nursery practices or planting that affect the number of first-order lateral roots produced or retained.

We found planted loblolly and shortleaf pines to be fairly consistent in having greater depths to uppermost lateral roots than seeded pines. A similar relationship has been reported for Douglas-fir (Preisig et al. 1979). Although the mean differences in depth to uppermost lateral roots between planted and seeded trees were not great in our study (3–4 cm), some planted trees had mean depths to uppermost lateral roots that exceeded 15 cm. It is common practice in the southern United States to plant bareroot seedlings deeper than they had been growing in the nursery. Thus, we assume that the greater distance from groundline to uppermost lateral roots for planted trees is primarily a reflection of this planting practice. It is possible, however, that early development or retention of surface lateral roots may differ between planted and seeded trees (see discussion below on spiraling). The functional consequences of root system differences such as reduced number of small roots and increased depth to the first lateral root are not known, but differences in depth and number of roots could result in altered water relations during drought. Deep planting increases the probability of root system deformation (Greaves 1978, Mexal and Burton 1979) but may have beneficial effects on initial survival and growth (Sutton 1967, Hay and Woods 1974). The long-term effects of an initial deformation on growth may depend on whether or not the root system recovers and develops a more normal configuration. We previously reported (Harrington et al. 1987) that root systems with bent taproots not oriented downward had poorer growth than corresponding root systems with bent taproots that recovered and grew downward.

Planted trees in our study exhibited greater spiraling and turning (or kinking) of major lateral roots than seeded trees. This agrees with results reported for other species (Van Eerden and Kinghorn 1978, Preisig et al. 1979, and Carlson et al. 1989). Minor spiraling of lateral roots is probably unimportant, but spiraling of most major roots can decrease root system stability (Lindgren and Orlander 1978) and could result in a root system with few lateral roots close to the surface. The presence of surface lateral roots may be beneficial to tree growth because these surface roots can take advantage of light summer showers that do not penetrate the soil layers surrounding deeper roots (Carlson et al. 1988, Hay and Woods 1974, Hoover et al. 1953). Bending or kinking of the root system can also restrict photosynthate movement, resulting in carbohydrate buildup above the point of restriction (Hay and Woods 1968, 1975). As the main root stock increases in diameter with time, twisted roots are commonly overgrown or occluded (Hagner 1978). This obscures the actual location of lateral root initiation and results in an apparent decrease in the amount of spiraling with an increase in diameter. Similarly, bends or kinks (turns) located close to the original root stock can also be overgrown. After the roots fuse and are covered with a common xylem sheath, any physiological effects associated with bends or constrictions should diminish. Consequently the overgrowth that obscures the original extent of root system deformation may also result in a reduction of possible problems associated with deformation.

Studies of root system morphology have historically emphasized the importance of wind firmness (Sutton 1969). *Pinus radiata* (D. Don) with straight-grained taproots (i.e., taproots without turns) are more stable under periodic wind stress than trees with bent or hooked taproots (Mason 1985). In our study, planted loblolly pines had more turns in the taproot than seeded trees and thus would have had less straight grain. If Mason's results are applicable to southern pines, this would imply that poorly planted trees with several taproot turns would be most likely to have problems with wind firmness. Our study was not designed to evaluate wind firmness; however, we did notice infrequent toppling of some planted but none of the seeded trees. Excavation of these trees revealed: (1) the taproot had been bent or J-rooted at planting (two or more major turns present), and (2) major lateral roots were largely absent from one side of the tree. Apparently the turns in the taproot served as pivots or rocking points under stress, and the unbalanced distribution of major lateral roots allowed the pivot or rocking motion to develop. The lack of stability associated with such gross root morphologies probably does not become evident until tree crown mass surpasses some critical size and one or more environmental stress factor increases (e.g., high wind or heavy snow). This hypothesis is consistent with the observation of many foresters that toppling is often observed in plantations the year after precommercial thinning; trees large enough to be left after thinning would have surpassed critical size, and thinning would have resulted in reduced intertree crown support and increased wind speeds. However, root system configurations that are potentially unstable during one time period can grow into more stable configurations as root systems spread out spatially and grow over bends and turns.

Planting quality is very important to plantation establishment and can influence early survival (Rudolf 1939) and growth (Harrington et al. 1987). Because our study was limited to trees that had been in the field for at least three growing seasons, it did not include root system configurations associated with early mortality. In addition, our sampling system avoided trees with the poorest growth rates, which may have reduced the variety of root morphologies sampled. We did, however, characterize the root system structure of young planted and seeded loblolly and shortleaf pine in the western portion of their ranges and identified several individual variables and multivariate functions that were effective in separating root systems by stand origin. In general, the differences in root system structure between planted and seeded stands were similar for loblolly and shortleaf pine.

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