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Influence of Bent Taproots on Stem Sinuosity and Tree Size of Machine-Planted Loblolly and Slash Pines in Georgia



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INFLUENCE OF BENT TAPROOTS ON STEM SINUOSITY AND TREE SIZE OF MACHINE-PLANTED LOBLOLLY AND SLASH PINES IN GEORGIA

SUMMARY

During the summer of 1996, 24 machine-planted stands of loblolly pine (*Pinus taeda* L.) of ages 3 to 10 years were sampled near Athens, Georgia to determine if trees with bent taproots have greater sinuosity (oscillating curvature) of the stem and smaller size than those with straight taproots. During the summer of 1998, a study of similar design and sample size was initiated for slash pine (*Pinus elliotii* Engelm.) in southeastern Georgia. Level of stem sinuosity was quantified as low, medium, or high for each planted tree located within 11.8 ft of each of 10 sample points per site. Half or more of the trees sampled had medium to high levels of stem sinuosity. One planted tree was selected to represent each of a low level and a medium to high level of stem sinuosity ($n = 480$ trees/species). About one third of these trees ($n = 144$ trees/species) were excavated to characterize their taproot shape. For each species, over 70% of the trees with bent taproots had medium to high levels of stem sinuosity, while an equally high percentage of trees with straight taproots had a low level of stem sinuosity. Trees with bent taproots averaged 0.23 in. smaller in stem diameter and 1.6 ft shorter in height than trees with straight taproots. The horizontal angle of the taproot did not differ from planting row direction, indicating that bent taproots from machine planting remained confined to the planting slit for at least 10 years after planting. Additional measurements of slash pine indicated that the level of stem sinuosity increased with the amounts of bend in the taproot and lean in the stem. With data from 8- to 10-year-old plantations, observed levels of stem sinuosity were estimated to result in 26% to 28% reductions in volume of straight material within the lower 8 ft of bole. The research indicates that bent taproots are strongly associated with increased levels of stem sinuosity and that medium to high levels of stem sinuosity can result in substantial losses in stand quality. Guidelines for minimizing these losses are discussed, including site preparation and planting methods to reduce the incidence and severity of bent taproots and thinning methods to selectively remove trees with medium to high levels of stem sinuosity.

INTRODUCTION

Each year over one billion seedlings of southern pines are planted in the South to reforest harvested areas and

retired agricultural lands. Between 1986 and 1992, over 640,000 acres of pine plantations were established on former croplands in Georgia by the Conservation Reserve Program. Many of these acres were planted with a machine that uses a colter blade to cut a slit through the top layer of the soil, a trencher to widen the slit to a depth of 6 to 8 in., and packing wheels to close the slit firmly around the seedling's roots (18). Advantages of machine planting over hand planting include better control of spacing among individual trees and greater uniformity of planting quality. However, because the seedling is in motion during machine planting and its roots are being forced into a narrow planting slit, placement of the seedling with a bent (swept) or "L"-shaped taproot, leaning stem, and compressed root system can occur. It is important to note that either machine or manual methods can result in poor planting quality; therefore, it is the land manager's responsibility to ensure that reforestation occurs with both minimum cost and maximum quality (12).

Perhaps the most critical factor of planting quality that limits initial survival of planted pine seedlings is adequate depth of planting (5,25). However, attempts to place the root collar at a greater depth can cause the taproot to become bent, especially if the planting hole is too shallow (18,20). Traditionally, foresters have attributed increases in uprooting, water stress, and disease to the effects of bent taproots, but many of these beliefs have not been supported by research. Numerous studies on planting seedlings with bent taproots have reported no discernible effects on survival and growth (8,13,14,15,22,26), and only a few have detected reduced growth (10,12). Unfortunately, none of this research has been conclusive enough to determine whether planting seedlings with bent taproots has a long-term effect on stand quality and yield.

One question that commonly arises is whether planting seedlings with bent taproots limits their access to soil water and nutrients. Attempts to study seedling responses to bent taproots at varying levels of soil water have been limited by confounding between depth and shape of the root system (5), because bending of the taproot limits the depth to which lateral roots form. One study concluded that mid-day water stress did not differ between seedlings planted with bent versus straight taproots (23).

Research on effects of bent taproots on survival and growth of other conifer species also has shown conflicting results (9,17). Several studies on radiata pine (*Pinus radiata* D. Don) in Australia have identified a higher incidence and severity of stem sinuosity on sites that received shallow subsoiling (ripping) treatments (3,19). These studies concluded that stem sinuosity was linked to bent taproots which resulted from planting into soil conditions that restricted root growth. It was estimated that stem sinuosity reduced the number of high-quality saw logs produced by a stand of radiata pine as much as 36% (19).

Our field observations of machine-planted loblolly and slash pines in the Piedmont and Coastal Plain of Georgia suggested that a similar relationship might exist between bent taproots and stem sinuosity (Figure 1). Furthermore, our observations indicated that, when present at high levels, sinuosity occurred throughout the stem and branches of a pine tree and continued to affect its crown morphology for at least 10 years after planting. Because such tree growth responses have important implications regarding the future quality, value, and sustainability of pine plantations in Georgia, a team of scientists from the University of Georgia, Georgia Forestry Commission, and the USDA Forest Service Southern Research Station was formed to study the problem. In 1996, we initiated a study to compare stem sinuosity and tree size of loblolly pine with bent versus straight taproots (11). In 1998, we initiated a similar study for slash pine. The purpose of this report is to compare results from the loblolly and slash pine studies and discuss their management implications.

METHODS

Study Sites

We selected 24 plantations in the Piedmont to study loblolly pine and 24 plantations in the Coastal Plain to study slash pine. The plantations had been established by machine planting one-year-old, bare-root seedlings. The sampling of sites was stratified for each species such that each age from 3 to 10 years was represented by 3 stands. The minimum age of 3 years was selected to allow sufficient time for the trees to respond to and display the hypothesized effects of bent taproots on stem sinuosity and tree size. The maximum age of 10 years was selected to document potential longer-term responses of stem sinuosity and tree size to bent taproots, yet still provide evidence to determine whether machine planting had caused the bent taproots. One 14-year-old, slash pine plantation was inadvertently measured and these data were used where appropriate.



Figure 1. A 5-year-old loblolly pine intentionally planted with a bent taproot (see 12 in References Cited for background information). Note the development of stem sinuosity at about 2 ft above the root collar

Loblolly pine plantations were randomly selected from a list of Conservation Reserve Program (CRP) stands located within a 50-mile radius of Athens, Georgia. Typical clay subsoil horizons were present near the soil surface of each Piedmont site in the study, a result of severe erosion from past agriculture (21). Because the hypothesized effects of bent taproots could be influenced by the limited penetrability of the clay subsoils, plantations in the Piedmont were selected such that about half of them had received a subsoiling (ripping) treatment and half had not.

The slash pine plantations were on lands managed by Georgia-Pacific Corporation and Union Camp Corporation in southeastern Georgia. To account for potential effects of tillage on tree responses to bent taproots (as done in the loblolly pine study), we selected one slash pine plantation of each age that had been site prepared by either single bedding, single bedding with disking, or double bedding.

Tree Measurements

To provide a uniform sample of each of the 48 plantations, a total of 10 points were located at 66-ft intervals along one or more line transects within each site. All tree measurements were conducted from late June to early August of 1996 and 1998 for loblolly and slash pine, respectively. In order to quantify levels of stem sinuosity, a visual index was used that combined the frequency and intensity of stem oscillations into a 0- to 8-point scale (11). To provide a systematic sample of stem sinuosity and tree size for each plantation, each tree located within 11.8 ft of a given sample point (0.01-acre plot) was measured for stem sinuosity and stem diameter at breast height (*DBH*, in.). Branch sinuosity also was measured for each tree using a similar approach. To simplify the presentation in this report, we grouped the index values of stem and branch sinuosity into three levels — low, medium, or high — to correspond to index values of 0 to 2, 3 to 5, and 6 to 8, respectively. Figure 2 provides photographic examples of trees with low, medium, or high levels of stem sinuosity.

Within a 33-ft radius of each sample point, one planted tree was selected to represent a low level of stem sinuosity and one planted tree was selected to represent a medium to high level of stem sinuosity ($n = 480$ trees per species). This paired-tree approach ensured that our experimental sample would include a broad enough range of stem sinuosity levels to determine whether a relationship existed between bent taproots and stem sinuosity. Trees having fusiform-rust stem cankers were avoided during selection because of stem deformities associated with this disease. *DBH* (in.), height (ft), crown density (%) (4), and levels of stem and branch sinuosity were measured on each tree. At three of the sample points per site, we excavated the paired trees described above to provide information on their root systems ($n = 144$ trees per species). The excavations were performed with hand equipment starting about three feet from the base of the stem in order to preserve the configuration of the lateral roots. Prior to excavation of slash pine, the angle between the center of the stem and ground surface was recorded in degrees. For example, 90° would indicate a vertical stem with no lean and any angle less than 90° would indicate a leaning stem.

After excavation of a given tree, the taproot was classified as either straight or bent (Figure 3). For trees with bent taproots, the horizontal direction of the taproot was recorded for comparison with the direction of the planting row. Depth (in.) of bend in the taproot also was recorded. In the slash pine study, we recorded the angle (degrees)

of bend in the taproot and noted which trees had corrected their bent taproots via downward growth instead of continued horizontal growth along the planting slit.

For each species, excavations of 7- to 10-year-old trees were performed to the depth required to determine the shape of their taproots, with a maximum depth of 24 in. For 3- to 6-year-old trees, excavations were performed to a 24-in. depth or until coarse lateral roots (lateral roots greater than 0.1-in. in diameter) were no longer detectable. On these younger trees the number of lateral roots within each of four, 6-in. depth classes was recorded. Adjacent to the excavated trees at each loblolly pine site, soil series information was recorded, including depth, color, and texture of each horizon.

For 8- to 10-year-old slash pines, the diameter of the stem at 8 ft was measured on each tree. A device having two plumb bobs mounted on a horizontal scale was attached to the tree and leveled at 8 ft above ground. We measured the maximum diameter that could be followed from 8-ft height to ground surface after compensating for irregularities in the stem due to sinuosity (Figure 4). The rationale for taking this measurement was to quantify the core of straight material within trees having various levels of stem sinuosity. We assumed that wood volume not in the core would be destined for either chipping or waste material during processing at the mill.

Data Analyses

The objectives of our data analyses were to determine if a correlation existed between bent taproots and stem sinuosity and if such an association could also affect tree growth and volume of straight material. Tree size and crown density were analyzed to determine if they differed statistically between medium to high versus low levels of stem sinuosity. Similarly, stem sinuosity, tree size, and crown density were analyzed to determine if they differed statistically between trees with bent versus straight taproots. Analyses were conducted to determine if the percentage of trees with bent taproots differed statistically among levels of stem sinuosity.

A statistical test was conducted to determine if the horizontal direction of the taproot deviated significantly from the direction of the planting row (27) to indicate whether machine planting had caused the taproot to become confined to the planting slit. Analyses were conducted to determine if the number of lateral roots of 3- to 6-year-old trees differed statistically by depth, tillage treatment, or presence versus absence of bent taproots. Relationships of stem sinuosity to the amounts of bend

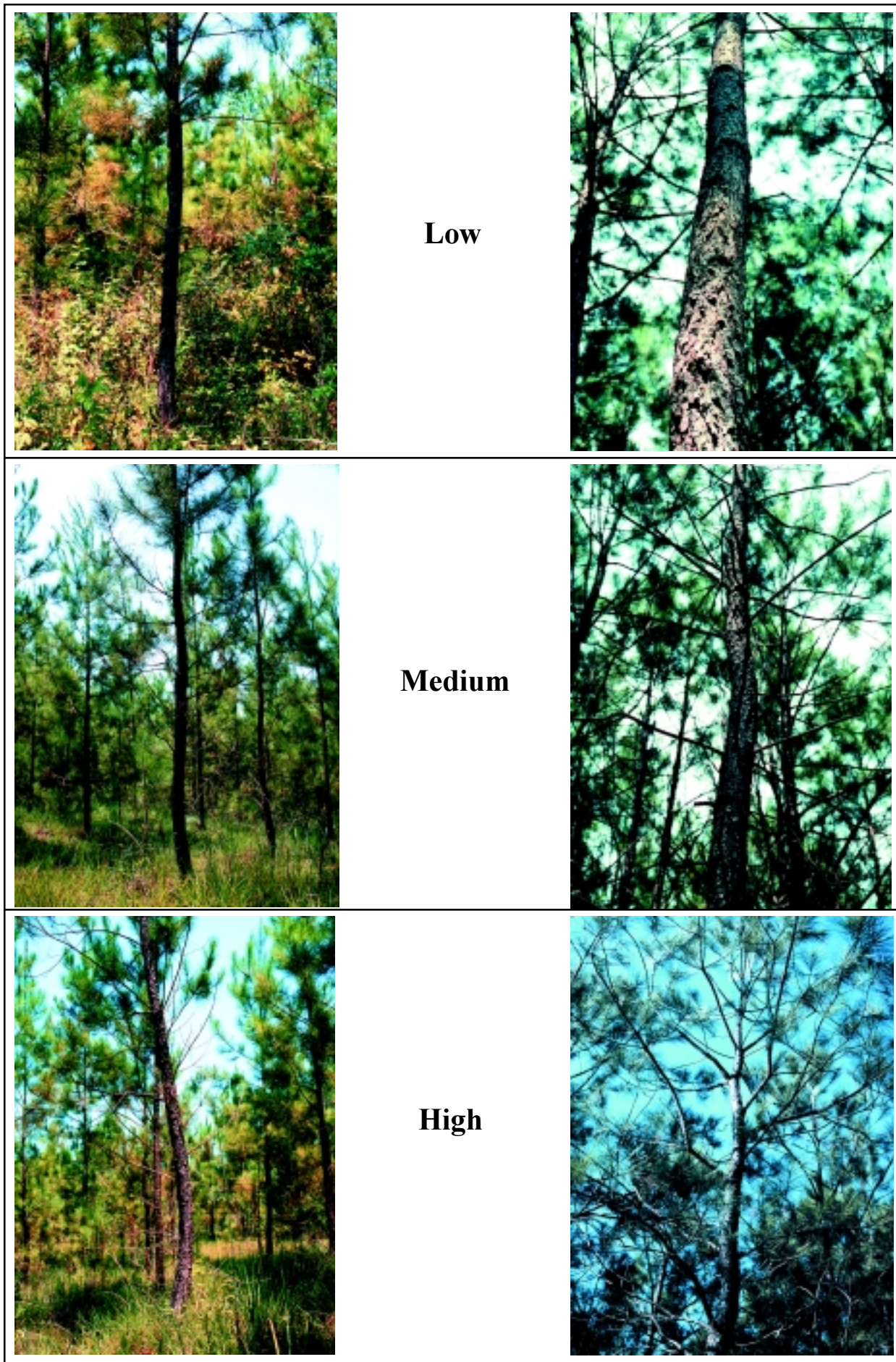


Figure 2. Examples of low, medium, and high levels of stem sinuosity for loblolly pine.



(a)



(b)



(c)



(d)



(e)



(f)



(g)



(h)

Figure 3. Examples of taproots resulting from machine planting, including taproot angles from (a) 0° to (h) 180° . (a) A straight taproot with lateral roots compressed in the planting slit (the upward orientation of lateral roots is due to drying while in storage). (b) A straight taproot with lateral roots compressed in the planting slit and some evidence of lateral root girdling of main stem. (c) A bent (swept) taproot also with one-sided development of lateral roots resulting from machine planting. (d) A bent (swept) taproot with a compressed (two-dimensional) lateral root system resulting from machine planting. (e) A bent taproot that regained a downward orientation via spiraling. (f) A bent multiple taproot with downward orientation and lateral root girdling of main stem at ground-line. (g) A bent taproot with a balled configuration. (h) A bent taproot with a balled configuration and lateral root girdling of main stem.

Table 1. Mean *DBH*, height, and crown density of 3- to 10-year-old loblolly and slash pines with medium to high levels versus low levels of stem sinuosity (asterisks indicate significant differences).²

Variable	Loblolly pine		Slash pine	
	Medium to high	Low	Medium to high	Low
<i>DBH</i> (in.)	3.46	3.75*	3.60	3.70*
Height (ft)	18.3	19.8*	21.9	23.1*
Crown density (%)	35.6	41.4*	39.2	42.0*

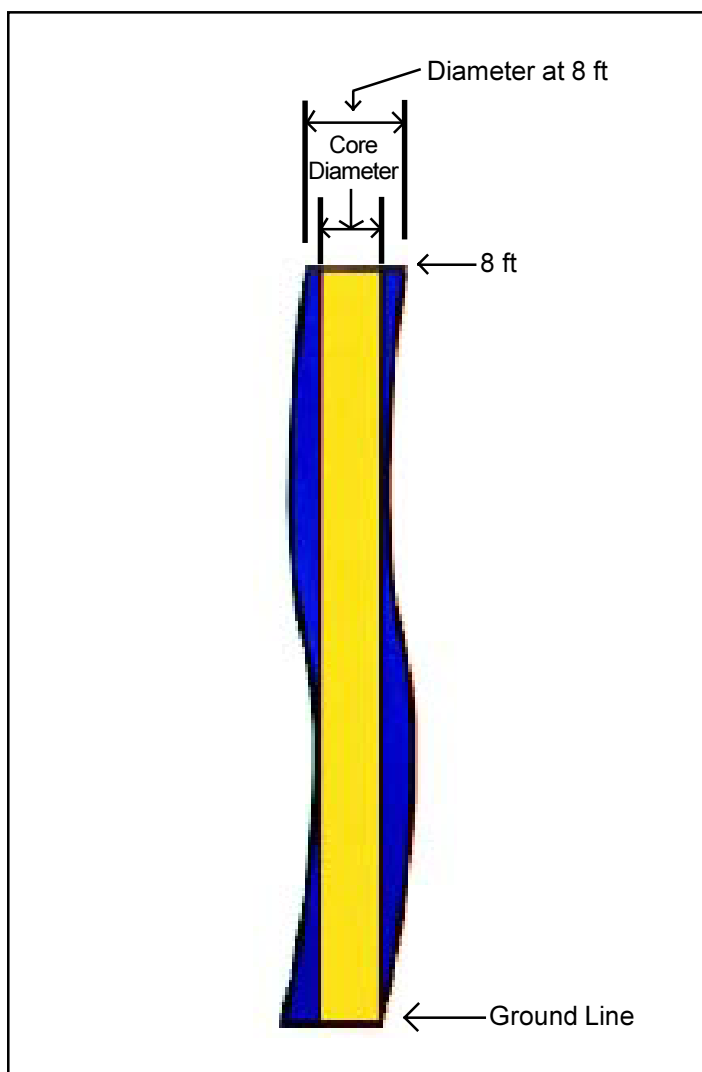


Figure 4. Method of estimating the diameter of straight core for a tree with a high level of stem sinuosity. Yellow-shaded area indicates core of straight material and blue-shaded areas indicate material to be chipped or wasted during milling.

in the taproot and lean in the stem were tested. The limiting effect of stem sinuosity on the diameter of straight material in the stems of 8- to 10-year-old slash pines was quantified. An index of total volume of straight material in the lower 8 ft of bole was calculated using observed values of stem sinuosity from the 8- to 10-year-old plantations of loblolly pine and slash pine. Reductions in stand volume resulting from stem sinuosity were calculated by comparing these results to those in which all trees in each of the stands were assumed to have a low level of stem sinuosity.

RESULTS

Our comparisons of machine-planted loblolly and slash pines revealed that trees with medium to high levels of stem sinuosity were smaller than those with low levels (Table 1). Values of *DBH*, height, and crown density averaged 0.29 in., 1.5 ft., and 5.8% smaller, respectively, for loblolly pine and 0.1 in., 1.2 ft, and 2.8% smaller, respectively, for slash pine. Similarly, trees with bent taproots were smaller than those with straight taproots, and the magnitude of the reduction was similar to that attributed to varying levels of stem sinuosity (Table 2). Values of *DBH*, height, and crown density of loblolly pine were 0.33 in., 1.4 ft, and 3.2% smaller, respectively, for trees with bent versus straight taproots. For slash pine, only height was smaller (1.8 ft) in a statistically significant way for trees with bent versus straight taproots.

The average level of stem sinuosity of loblolly and slash pines with bent taproots was two to three times greater, respectively, than that of trees with straight taproots

²Excerpts from this table are forthcoming from *Southern Journal of Applied Forestry* (1999) published by the Society of American Foresters, 5400 Grosvenor Lane, Bethesda, MD 20814-2198. Not for further reproduction.

Table 2. Mean *DBH*, height, and crown density of 3- to 10-year-old loblolly and slash pines with bent versus straight taproots (asterisks indicate significant differences).³

Variable	Loblolly pine		Slash pine	
	-----Taproot shape-----			
	Bent	Straight	Bent	Straight
<i>DBH</i> (in.)	3.31	3.64*	3.57	3.70
Height (ft)	18.0	19.4*	21.4	23.2*
Crown density (%)	36.0	39.2*	40.3	41.7

(Figure 5). Statistically significant differences also were detected for branch sinuosity, but of a smaller magnitude. Slash pines with bent taproots that regained a downward direction had about half the level of stem sinuosity as those with taproots that remained horizontal.

For each species, a strong association was found between the percentage of trees with bent taproots and level of stem sinuosity. Of trees with bent taproots, 73% to 77% had medium to high levels of stem sinuosity, while of trees with straight taproots, 71% to 78% had low levels of stem sinuosity (Figure 6). A total of 1327 loblolly pines and 1496 slash pines were measured for stem sinuosity. Based on this systematic sample of trees from the study sites, 49% of loblolly pines and 57% of slash pines had medium to high levels of stem sinuosity (Figure 7).

The average depth of bend in the taproot was 11.2 in. and 7.3 in. for loblolly and slash pine, respectively. The horizontal direction of bent taproots for each species did not differ significantly from planting row direction, indicating that machine planting had caused the taproot to remain confined to the planting slit for at least 10 years after planting. Stem sinuosity of slash pine was found to increase with the amounts of bend in the taproot and lean in the stem.

Lateral root frequency decreased with soil depth for each species, but only root systems of loblolly pine were affected by the tillage treatments. For loblolly pine, lateral root frequency in the 0-6 in. depth was less in

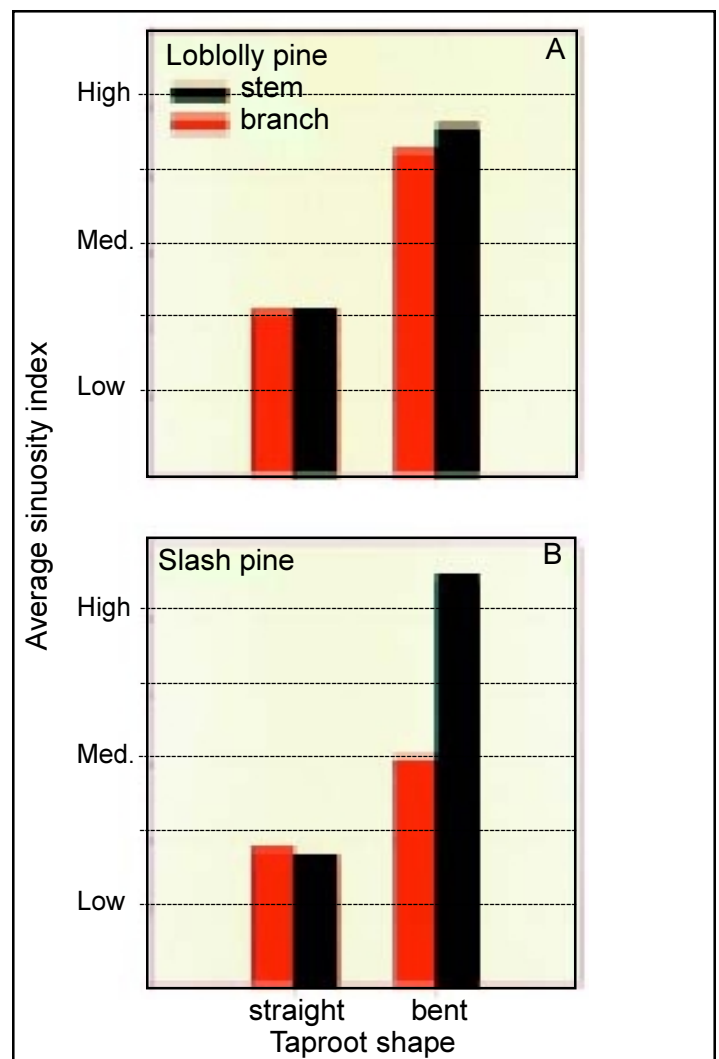


Figure 5. Average levels of sinuosity for stems and branches of 3- to 10-year-old (a) loblolly and (b) slash pines with straight versus bent taproots. Differences between straight and bent taproots were statistically significant.

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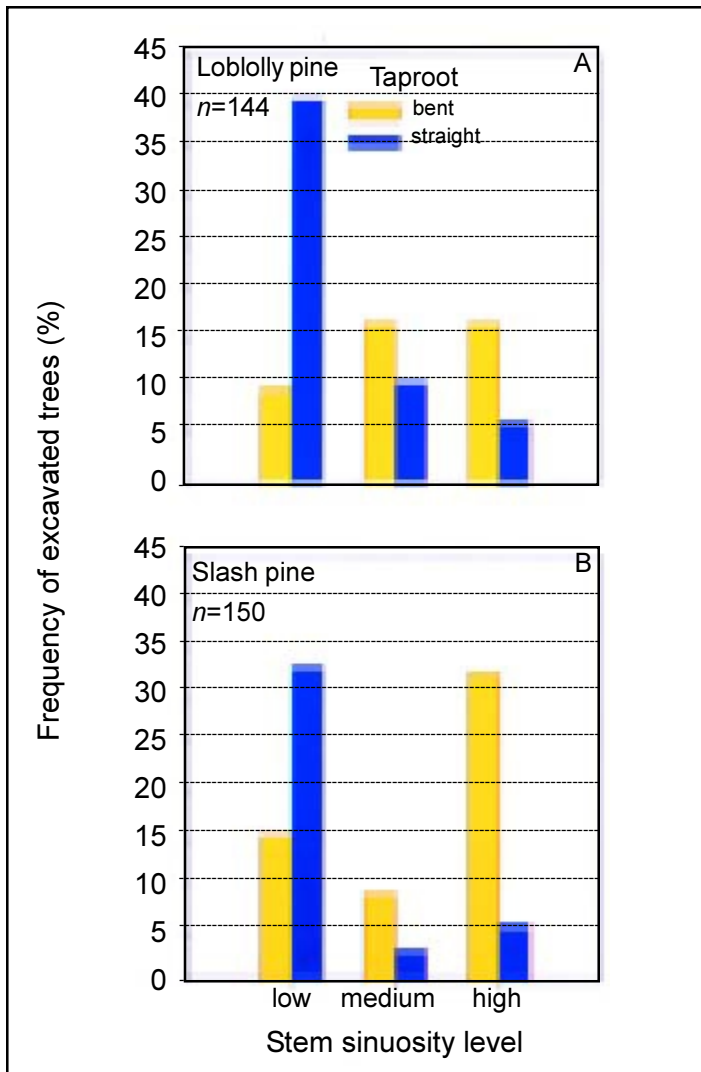


Figure 6. Frequency of excavated (a) loblolly and (b) slash pines by each of low, medium, and high levels of stem sinuosity. Data analyses for each species revealed that a disproportionately high number of trees with bent taproots had medium to high levels of stem sinuosity, while a disproportionately high number of trees with straight taproots had low levels of stem sinuosity.

the presence (10 lateral roots) versus absence (14 lateral roots) of subsoiling. However, total lateral root frequency was not affected by subsoiling, indicating that the treatment had shifted the distribution of lateral roots to a greater soil depth. The frequency by depth and total number of lateral roots was not affected by the presence versus absence of a bent taproot. The probability of a loblolly pine having a bent taproot increased with percentage of clay content of the soil (7). For example, as clay content increased from 20% to 60%, the probability of a tree having a bent taproot increased from 0.35 to 0.66.

For a given *DBH*, the diameter of straight material of 8- to 10-year-old slash pines averaged 1.3 in. greater for trees with low versus medium to high levels of stem

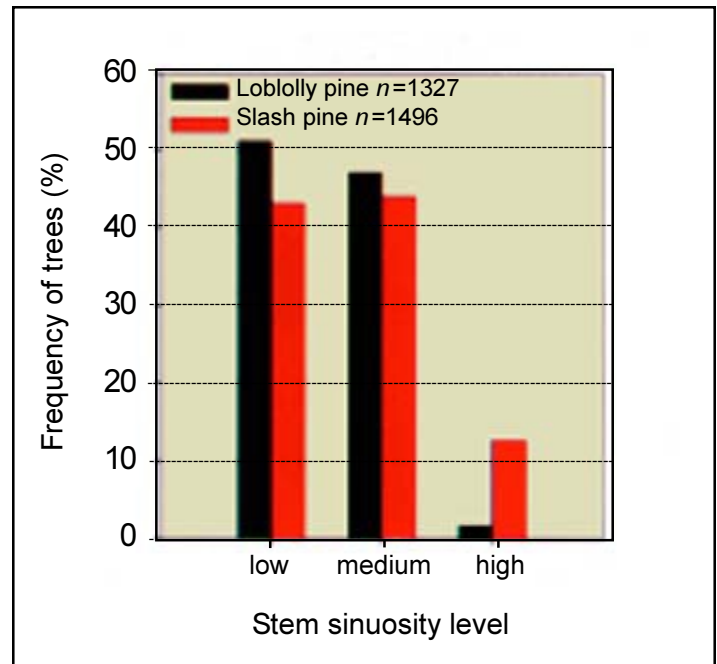


Figure 7. Percentage of loblolly and slash pines having each of low, medium, and high levels of stem sinuosity. For a given species, stem sinuosity was measured on all trees located within each of 240 hundredth-acre plots.

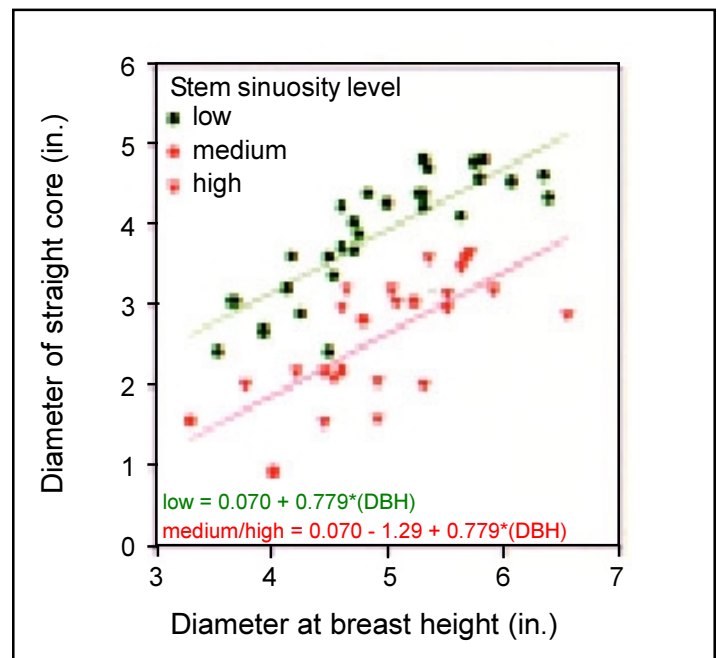


Figure 8. Relationships of the diameter of the core of straight material to diameter at breast height for 8- to 10-year-old slash pines with low versus medium to high levels of stem sinuosity. Lines indicate predicted values from the regression model.

sinuosity (Figure 8). Using stand data collected from each 8- to 10-year-old plantation, we calculated an index of total volume (ft³/acre) of straight material in the lower 8 ft of bole using the linear relationships depicted in Figure 8. The observed volume index of each stand averaged 26% and 28% lower for loblolly and slash

Table 3. Index of potential volume of straight material and percentage loss due to observed levels of stem sinuosity in 8- to 10-year-old plantations of loblolly and slash pines.

Stand	Age (yr)	Loblolly pine		Slash pine	
		Potential volume of straight material (ft ³ /acre) ⁴	Loss from stem sinuosity (%) ⁵	Potential volume of straight material (ft ³ /acre)	Loss from stem sinuosity (%)
1	8	495	-40	199	-29
2	8	305	-28	330	-31
3	8	200	-34	277	-35
4	9	536	-25	387	-26
5	9	421	-24	328	-40
6	9	873	-18	409	-32
7	10	490	-17	491	-28
8	10	447	-30	310	-31
9	10	565	-20	315	-32
Averages		481	-26	305	-28

loblolly pines, respectively, than that assuming all trees had a low level of stem sinuosity (Table 3).

DISCUSSION AND CONCLUSIONS

Comparisons of research results for loblolly and slash pines demonstrated each species had similar reductions in size and crown density for trees with medium to high versus low levels of stem sinuosity and for trees with bent versus straight taproots. Also, trees with bent taproots had two to three times the level of stem sinuosity as those with straight taproots. Slash pines with bent taproots that corrected themselves with vertical growth had lower levels of stem sinuosity than trees with bent taproots that continued to grow horizontally.

For both species, a vast majority of trees with bent taproots (77% and 73% for loblolly and slash pines, respectively) had medium to high levels of stem sinuosity. Conversely, an equally high percentage of trees with straight taproots (71% and 78% for loblolly and slash

loblolly pines, respectively) had low levels of stem sinuosity. For a given *DBH*, the diameter of straight material in trees of medium to high levels of stem sinuosity was 1.3 in. less than that of trees with low levels of stem sinuosity.

Taproot direction of loblolly and slash pines did not differ from planting row direction for either species, indicating that after being bent from machine planting, the taproot remained confined to the planting slit for at least 10 years after planting. Regardless of whether this confinement has resulted from the dragging of the taproot in the planting slit by the planting machine or from growth of the taproot along the tilled soil of the planting slit, the observed restrictions in taproot growth can be attributed to the effects of machine planting.

Effects of tillage during site preparation differed between the two species. For loblolly pine, subsoiling shifted development of lateral roots to a greater soil depth, while different combinations of bedding and disking had no effect on the spatial distribution of lateral roots for slash

⁴The total volume in the lower 8 ft of bole of all trees, assuming a low level of stem sinuosity. The diameter of the core of straight material was predicted for each tree from the regression model depicted in Figure 8, and it was used to calculate the volume of a cylinder.

⁵Percentage difference in volume of straight material for the observed levels of stem sinuosity versus that assuming all trees had a low level of stem sinuosity.

pine. These differences in the benefits of tillage on lateral root development are most likely attributable to the restricted penetrability of Piedmont clay soils versus the much higher penetrability of many Coastal Plain sandy soils.

Our results are similar to those found for radiata pine in Australia in which stem sinuosity increased with decreasing depth of root penetration and with decreasing straightness of the taproot (3). Although we were unable to identify the biological mechanism linking stem sinuosity to bent taproots, our research indicates a strong association between the two characteristics for the two most commercially prominent species of southern pines. One possible mechanism linking stem sinuosity to bent taproots is the formation of compression wood in the response to bending of the stem (16). The parallel responses of stem and branch sinuosity to bent taproots suggest that plant growth regulators could play an important role in the development of sinuosity. Other factors that have been associated with stem sinuosity of radiata pine in Australia include greater soil nitrification of pasture versus clearcut sites (6), rapid rates of juvenile growth on fertile sites (24), and genetic heritability (2). Bent taproots may play an important role in facilitating these responses. For example, it is believed that increases in stem sinuosity from deficiencies in micronutrients, such as boron, are most likely to occur if trees have shallow root systems (from bent taproots) that are unable to tap resources from the deeper soil horizons (1).

MANAGEMENT IMPLICATIONS AND FUTURE RESEARCH

Forest regeneration sites should be assessed for their potential to cause high levels of stem sinuosity. A simple method to determine this risk is to classify stem sinuosity for a sample of volunteer pines growing on a given site (see Figure 2). Evidence that volunteer trees will develop medium to high levels of stem sinuosity generally becomes visible by the fifth year after seed germination. Other methods for quantifying high-risk sites include sampling the soil to detect the presence of a hard pan or a high clay content. For sites with these characteristics, subsoiling (ripping) should be used to loosen restrictive soil layers that limit planting depth and root penetrability. Use of light weight machine planters should be avoided on soils with high clay contents, even when converting farm land or pasture sites to plantations. This is because the colter blade and trencher will not be able to penetrate to the 8 in. depth required to accommodate the root system of typical nursery-grown stock.

Although planting seedlings deeper than the root collar can promote their initial survival, doing so can lead to bent taproots if the planting hole is not deep enough. Regardless of soil type, when using a machine planter, care should be taken to operate the machine at a reasonably slow speed to encourage vertical placement of the seedlings in the planting slit. Operating the planting machine at a high rate of speed will cause seedlings to be dragged in the planting slit, resulting in bent taproots and leaning stems.

If commercial thinning is to be included in the management regime, the stand should be evaluated for stem sinuosity prior to thinning. Unfortunately, current prescriptions for thinning pine plantations (e.g., fifth row removal with “operator select” in adjacent areas) generally differentiate crop trees from removal trees on the basis of tree size (*DBH*), not stem quality. Thinning should be conducted as selectively as possible in order to remove all high-risk trees because of the benefits in stand quality and vigor likely to result from their removal. As shown in Table 3, medium to high levels of stem sinuosity greatly reduced the volume of straight material of a pine plantation. Therefore, the cutting of trees with medium to high levels of stem sinuosity will remove trees of lesser value and increase growing space for trees of good form. Trees with medium to high levels of stem sinuosity also may be more susceptible to drought, insects, and disease (7).

The following are general guidelines for evaluating plantations for thinning based on the stem sinuosity levels shown in Figure 2:

1. If the stand contains at least 70 ft²/acre of basal area in trees with low levels of stem sinuosity and these trees are evenly spaced throughout the stand, then all trees with medium to high levels of stem sinuosity should be removed.
2. If the stand does not contain at least 70 ft²/acre of basal area in trees with low levels of stem sinuosity or if these trees are not evenly distributed throughout the stand then either:
 - a. Thin by removing, first, all trees with high levels of stem sinuosity, then remove some trees with medium levels of stem sinuosity to leave a residual basal area of 70 ft²/acre that is evenly distributed throughout the stand. The landowner should expect a reduction in sawtimber volume because many of the remaining trees with medium levels of stem sinuosity will qualify only as pulpwood.

- b. Alternatively, a residual basal area greater than 70 ft²/acre could be left by removing only trees with high levels of stem sinuosity and leaving trees with low to medium levels of stem sinuosity evenly distributed throughout the stand. The stand should then be managed primarily for chip-n-saw and pulpwood material.
3. Finally, if it appears that an inadequate number of trees exist with low to medium levels of stem sinuosity to leave a high-quality residual stand, then do not thin, and instead, manage strictly for pulpwood.

One approach for conducting a pre-thinning sample to evaluate stem sinuosity is to determine the stand basal area in each of low, medium, and high sinuosity classes (see Figure 2). First, locate at least one 0.01-acre plot (11.8-ft radius) per acre, and on each tree within the plot measure *DBH* and level of stem sinuosity. Second, calculate the stand basal area (ft²/acre) represented by each tree ($BA = 100 \times [0.005454 \times DBH^2]$). Finally, calculate the stand basal area within each sinuosity class. If two-thirds of the sample points contain at least 70 ft²/acre of stand basal area in the low sinuosity class, it

can be assumed that crop trees are distributed evenly enough to apply the first thinning guideline described above.

The results of the loblolly and slash pine studies, hopefully, will stimulate further research into the biological mechanisms underlying the observed tree responses. Specifically, we need to know how bending of the taproot or leaning of the stem during planting triggers the onset of stem sinuosity. In addition, our results prompt the need for research on planting practices, machine and hand tool designs, and seedling root specifications to determine if they can be modified to reduce the incidence and severity of bent taproots and leaning stems from planting.

If the current prevalence of medium to high levels of stem sinuosity goes unchecked (i.e., half or more of all planted trees, as observed in this study), significant losses in potential forest productivity are likely to continue. If we assume that half of the one billion pine seedlings planted in the South each year will develop medium to high levels of stem sinuosity due to poor planting practices, the sustainability of high-quality sawtimber as an important forest product could be in jeopardy.

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