Stem Sinuosity Changes in Young and Merchantable Stands of *Pinus taeda*

P. David Jones
Thomas R. Fox

Abstract

A survey of stem sinuosity severity and occurrence was conducted on six sites in North Carolina and South Carolina (USA) in *Pinus taeda* stands approximately 2 years after establishment. Approximately 1,400 trees on each site were measured for height, diameter, and degree of sinuosity in the stem at the beginning of the growing season and again after the completion of the growing season. Fifty-two percent of the trees increased in sinuosity over the growing season. Using stand records and observations by local foresters, two mature stands of loblolly pine (*Pinus taeda*) were located in the Atlantic Coastal Plain, where excessive stem sinuosity was reported to be present at ages 1 to 3 years. Seven trees were felled from each site. The 2.4-m butt logs were removed from each tree along with a 0.61-m bolt from the remaining felled tree. Slices were then cut through the log progressing through the pith. A single veneer containing the pith from each log was then selected for calculation of log volume, juvenile wood volume, and the volume of sinuous growth. Seven trees at the two sites were found to have had severe sinuosity earlier in their lives. Of the seven sinuous trees, three trees took only 1 year to correct the sinuous growth and return to a normal growth pattern. Two trees took an additional year to return to cylindrical growth, one tree returned to normal growth after the third year, and a single tree returned to a straight appearance by the end of the fifth year after the initiation of sinuous growth. Therefore, the sinuous portions of all seven trees were entirely contained within the juvenile core of the tree. Clear static bending specimens were machined and tested. Trees that were found to be nonsinuous produced mature wood that was significantly stiffer than the sinuous trees.

Loblolly pine (*Pinus taeda*) is the most widely planted species in the United States because of its ability to grow on a wide range of sites and its use in a variety of wood products, including pulp, oriented strand board, medium-density fiberboard, chip-n-saw, sawtimber, plywood, and poles (Wear and Greis 2002). Genetic improvements have increased the growth and yield of managed loblolly plantations an estimated 14 to 23 percent (Li et al. 1999). Intensive silvicultural practices, including site preparation, weed control, and fertilization, have also increased the growth and financial return from plantation management (Allen et al. 2005, Fox et al. 2007). A side effect of increased growth rates appears to be the occurrence of stem sinuosity, particularly in species such as *Pinus radiata* (Turvey et al. 1993).

Stem sinuosity is defined as the displacement of the stem from vertical within an internode or growth flush (Campbell 1965). Several studies have examined deformities similar to sinuosity that do not fit Campbell's definition (Gatch et al. 1999, Harrington et al. 1999, Murphy and Harrington 2004). Various studies have examined causes of sinuosity in *P. radiata* and other species, with varying results (Downes and Turvey 1990, Turvey et al. 1993, Spicer et al. 2000, Gartner and Johnson 2006).

There are a variety of stem defects that decrease the yield of usable chip-n-saw, sawtimber, and veneer logs in pine plantations. These include, but are not limited to, crook, sweep, cankers, large limbs, and associated knots, and it is thought that sinuosity also poses a problem (US Forest Products Laboratory 2000).

The obvious appearance of stem sinuosity in juvenile loblolly pines has led to many foresters and scientists holding the view that trees that exhibit the deformity will be deformed at the time of harvest. If this is the case, sinuosity would cause a deduction in log grade and a loss of value on par with other defects. Consequently, trees with stem sinuosity are frequently culled from breeding populations during the evaluation of genetic trials (P. Dougherty, personal communication, July 2006). This conclusion was

---

The authors are, respectively, Assistant Extension Professor, Dept. of Forest Product, Mississippi State Univ., Mississippi State (pdjones@cfr.msstate.edu [corresponding author]); and Professor, Dept. of Forest Resources and Environmental Conservation, Virginia Polytechnic Institute and State Univ., Blacksburg (tfox@vt.edu).
This paper was received for publication in May 2012. Article no. 12-00051.

Forest Prod. J. 62(5):354–358.

not based on examination of stands that had displayed sinuosity and were harvested for processing into products, but rather the appearance of the young stems only. Sinuosity in many cases is visible in juvenile trees but is not visible after the tree reaches a merchantable size. Therefore, it is important to examine if sinuosity extends outside of the juvenile portion of the tree. Our study had three objectives:

1. To determine the occurrence of sinuosity in young stands that show signs of sinuosity
2. To determine if sinuous growth leads to significant changes in volume, such as increased juvenile core size or log volume
3. To determine if significant differences exist in stiffness and strength of wood from sinuous trees and their nonsinuous counterparts

Materials and Methods

Sinuosity survey

Six sites were selected for a survey of the prevalence and severity of sinuosity in young stands. Five of the sites were located in North Carolina, in Beaufort and Martin counties. The remaining site was located in South Carolina in Berkley County. The sites were chosen because of the sinuosity found within the stands, their age (younger than 3 years), and their distribution (areas known locally for the occurrence of sinuosity). The South Carolina site was located in a progeny test that spanned several hectares, and there were approximately 800 trees measured on the site. On the North Carolina sites, plots of approximately 25 by 25 m were randomly located in five stands; approximately 600 of the trees measured were located in North Carolina. Each tree was numbered to allow repeated measures of the trees during the growing season. All of the trees were measured for height, diameter, and degree of sinuosity in the stem at the beginning of the growing season and once again after the completion of the active growing season. Height was measured using a stadia rod placed next to the stem and read at the top of the apical meristem. Diameter was measured at breast height (1.37 m) using digital calipers. Degree of sinuosity was visually estimated by using the stadia rod as a vertical reference and looking at the displacement of the stem from vertical between the internodes. Degrees of sinuosity were ranked based on the following scale: 0 = vertical internode, 1 = slight displacement to 2 cm, 2 = 2 to 3.8 cm, 3 = 3.8 to 5.7 cm, and 4 = >5.7 cm. A reference sheet was used to make the estimations more consistent throughout the study sites. A total of 1,373 trees were measured for the survey.

Data collected was analyzed using an analysis of variance approach to determine if differences in height and diameter growth between sinuosity classes occurred. Tukey's mean separation was used to examine significant differences at the $\alpha = 0.05$ level. All statistics were calculated using SAS 9.2 (SAS Institute, Cary, North Carolina).

Sinuosity effects

Site and tree selection.—Using stand records and observations by local foresters, two mature stands of loblolly pine were located in the Atlantic Coastal Plain, where high stem sinuosity was present at ages 1 to 3 years. One site was located in North Carolina, and the other was in South Carolina. The North Carolina site was in Washington County and was planted in 1991 at approximately 1,112 trees per ha; the trees were first pruned at 8 years and then again at 9 years. A first thinning was performed in 2002, reducing the trees to 334/ha. A second thinning was then performed in 2007 reducing the stocking to 183 trees per ha. There was no application of fertilizer to the site. The soils at this site are the poorly drained Bayboro series (fine, mixed, semiactive, thermic Umbric Paleaquults). The stand age was 16 years when the trees were selected for this study.

The second site was located in Dorchester County, South Carolina. It was hand planted in 1987 to a density of approximately 1,730 trees per ha. The stand did not receive fertilizer. The soil at the site was somewhat poorly drained Wahee series (fine, mixed, semiactive, thermic Aeric Endoaquults). The stand age was 21 years when the trees were selected for this study.

Seven trees were selected, with their orientation relative to the direction of sinuosity marked (as observed in the lower limbs), and felled from each site; trees were selected to represent a range of merchantable diameters. The 2.4-m butt logs were removed from each tree along with a 0.61-m bolt from the remaining felled tree, immediately adjacent to the butt log, and transported to Virginia Tech for processing.

Log volume.—The lower 2.4-m logs were cut into thin radial slices using a Timber King (Kansas City, Missouri) portable band sawmill. Logs were positioned so that the logs were oriented with the direction of sinuosity in the forest parallel to the saw blade and so that the log was also level. Slices were then cut by cutting through the log progressing through the pith. On average, section thickness was 5 mm, with the thinnest being approximately 2 mm and the thickest being 7 mm. The green sections were stacked and dried outside from February 16 until June 1, 2007. Once the sections had lost a considerable amount of moisture, they were restacked indoors prior to measurement.

Measurements.—The slices of each log containing the pith were analyzed as follows (Fig. 1). First, a reference line was drawn by stretching a string from the center of the bottom of the veneer to the center of the top; this line is represented by the heavy dashed line in Figure 1. Several internodes or growth flushes were visible on each of the veneers. Each deviation of the pith was measured, but it was determined that the maximum sinuous deviation controlled the overall volume affected by the displacement. The maximum deviation of the pith was then determined by measuring the distance of the pith from the center reference line. The number of rings affected by sinuosity was then counted by finding the latewood band of the first ring that was vertical and not displaced. The distance from the reference line was then measured; this boundary is represented by the black dashed lines to either side of the reference line in Figure 1. The juvenile wood boundary was then measured by counting to the 10th ring from the pith both at the top of the veneers and the bottom and then measuring from the reference line to the boundary; this is represented by the dotted black line. Research has shown that the juvenile period for loblolly pine in Florida is 5 to 7 years. This period increases as one goes north and west resulting in a juvenile period of 15 years for the upper Western Gulf Region. Therefore, 10 years is the appropriate juvenile period for the Carolinas (Larson et al. 2001). Finally the width at the top and bottom of each veneer was measured.

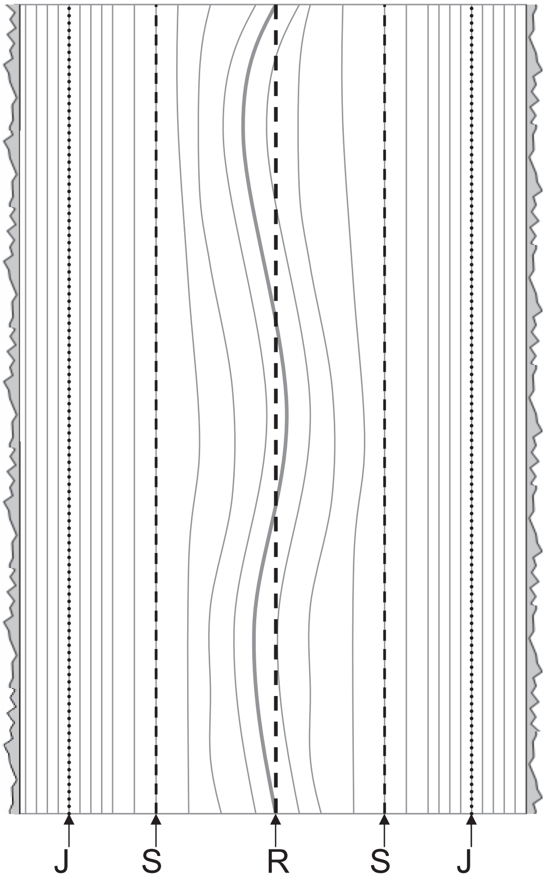

Figure 1.—Measurements performed on each veneer. Reference line (heavy black dashed line [R]), sinuous core (black dashed lines [S]), and juvenile core (black dotted lines [J]).

Total volume was calculated using the formula for a frustum. Juvenile wood volume was calculated in a similar manner by using the frustum formula. Sinuosity volume was estimated by taking the measurements of the rings affected and calculating the volume of a cylinder.

Wood properties

A 50-mm slab was cut from each 0.61-m section from bark to bark with the pith centered. This thickness was to allow for shrinkage from drying and machining. The slabs were dried to 12 percent moisture content prior to being processed into 25.4 by 25.4 by 406-mm static bending specimens in accordance with ASTM D143-09 (ASTM International 2010). Juvenile wood samples were cut from rings 2 through 4 on each side of the pith, while the mature wood samples were cut from each edge next to the bark. This resulted in two juvenile wood samples and two mature wood samples from each tree. With 14 trees, there were 28 juvenile wood samples and 28 mature wood samples. The 56 static bending samples were conditioned to 12 percent equilibrium moisture content (EMC) before testing.

The clear static bending samples were tested at 12 percent EMC over a 355.6-mm span with center loading on a MHS 10G/L static bending machine, following the procedures for alternate sample size under ASTM D143. A continuous load was applied at a head speed of 1.78 mm/min, rather than 1.29 mm/min to reduce test time. Modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated using procedures outlined in ASTM D143. After testing, the ends of each sample were removed and oven dried at 103°C, a weight was recorded along with a measure of volume, and density was calculated using ovendry mass and volume. The static bending and density data were analyzed using the SAS 9.2 analysis of variance procedure.

Results

Sinuosity survey in young stands

Many of the trees in this study did not stay in the same sinuosity class from the beginning of the growing season until the end. Table 1 illustrates the changes in sinuosity. Fifty-two percent of the trees increased in sinuosity over the growing season; the majority of these (30%) were trees that showed no sinuosity at the beginning of the study, but had sinuosity at the end of the season. Thirty-seven of the trees in Class 1 at the beginning of the study moved lower, to Class 0. This indicates that movement can occur in both directions (increasing and decreasing sinuosity rating).

There were some difference between the heights and diameters of the stems based on sinuosity level. Table 2 contains the mean heights and diameters of the stems in the different sinuosity classes. Diameter at breast height was significantly larger in sinuosity Class 4 than in Classes 0, 1, and 2. The mean heights between the sinuosity classes were not significantly different; this may be a function of height lost in the higher sinuosity classes because of the displacement from vertical.

Sinuosity effects in older trees

The number of older trees in this study was rather small. Of the 14 trees sampled, only seven of the older trees at the two sites in North Carolina and South Carolina were found to have had sinuous growth during the first several years

Table 1.—Number of trees in each sinuosity class as they were measured at the beginning and end of the study.

Sinuosity class at the beginning	Sinuosity class at the end				
	0	1	2	3	4
0	264	111	61	9	3
1	226	149	82	19	0
2	96	78	74	20	5
3	30	31	44	36	11
4	1	4	4	9	6

Table 2.—Results from analysis of variance of diameter and height of trees measured.

Sinuosity class	No. of trees	Diameter at breast height (mm)	Tukey[a]	Mean height (m)[b]
0	617	55.13	B	4.0
1	373	55.17	B	3.9
2	265	55.87	B	3.9
3	93	58.22	AB	3.9
4	25	63.81	A	4.1

[a] Values with the same letter are not significantly different at the $\alpha = 0.05$ level.

[b] Mean height was not significantly different.

after plantation establishment. The remaining seven trees appear to have never had any sinuous growth. Of the seven sinuous trees, three trees only took 1 year to correct the sinuous growth and return to a normal growth pattern. Two trees took an additional year to return to cylindrical growth, one tree returned to normal growth after the third year, and a single tree returned to a straight appearance by the end of the fifth year after the initiation of sinuous growth. This indicates that by the sixth year of growth, none of the trees would have had any outward appearance of sinuous growth. Regardless of time required to mask or cover the sinuous growth in the stem, it was found in this limited study that all sinuous distortions were contained in the juvenile wood core of the stem.

There was no significant differences between the log volumes of the trees harvested from North Carolina and South Carolina ($P = 0.297$). Interestingly, there was no significant difference between the size of the juvenile core of trees that were previously sinuous and those that were not ($P = 0.199$). There was also no difference between the total volume of trees with sinuous growth rings and those lacking sinuousity ($P = 0.816$).

Table 3 summarizes the results; mean separations were performed using Tukey's mean separation. There were no significant differences between the combined juvenile and mature wood data or the juvenile data alone. It was found that there was a difference between the mean MOE measurements of the mature wood. Trees that were found to be nonsinuous produced mature wood that was significantly stiffer than the sinuous trees ($P = 0.0016$). Density and MOR were found to not be significantly different between trees with sinuosity and trees without.

Discussion

Through the survey of over 1,300 juvenile *P. taeda* trees, it appears that there is a growth-related response or mechanism that causes trees to be susceptible to sinuous growth. Trees in the higher sinuosity classes had larger diameter growth than the lower rated trees. This may indicate that the trees were growing at a faster rate or that the trees were laying down compression wood that could have caused increased diameter growth. During this study it was noted that in stands that exhibited sinuous growth flushes in a large percentage of the trees, the majority of the displacements were in approximately the same direction. This may indicate that whatever the mechanism that initiated the sinuous growth in the trees—possibly wind events or the movement of the sun across the sky—acted upon all of the stems in the same direction.

Sinuous growth in *P. taeda* at a young age gives the impression that volume is compromised by the displacements of vertical. This study indicated that volume is only slightly affected by sinuosity. These results are similar to those of Spicer et al. (2000) for *Pseudotsuga menziesii,* for which a smaller-than-expected volume of individual logs was affected by sinuous growth.

Unlike sweep and crook, where the volume affected could reach as high as 100 percent (causing the log to be rejected for use at a sawmill), sinuosity only affects a relatively small portion of the log. One tree in this study had 25 percent of the total volume affected by sinuousity. Even though a relatively large volume was sinuous, all of the curvatures were contained within the first 5 years of growth and thus were contained within the juvenile core of the tree.

Table 3.—Results from analysis of variance.[a]

				Tukey	
Analysis	P value	Not sinuous	Sinuous	Not sinuous	Sinuous
Total					
MOE (MPa)	0.0716	6,549.02	5,428.49	A	A
MOR (MPa)	0.8354	54.32	53.47	A	A
Density (kg/m^3)	0.9594	557.75	479.18	A	A
Juvenile wood					
MOE (MPa)	0.8569	4,464.45	4,359.44	A	A
MOR (MPa)	0.2847	41.07	45.38	A	A
Density (kg/m^3)	0.1238	554.84	443.29	A	A
Mature wood					
MOE (MPa)	0.0016	8,633.59	6,497.53	A	B
MOR (MPa)	0.1445	67.57	61.56	A	A
Density (kg/m^3)	0.2483	554.84	525.74	A	A

[a] Values with the same letter are not significantly different at the $\alpha = 0.05$ level. MOE = modulus of elasticity; MOR = modulus of rupture.

Because there appears to be no difference between the strength and stiffness of the juvenile wood found in the trees used in this study (whether sinuous or not), it could be reasoned that the lower wood properties of the juvenile wood core are more of an issue than sinuosity; therefore, the culling of trees from breeding programs may be unwarranted. Mature wood of sinuous trees has decreased stiffness according to the results found in this small study. This may be an effect of the sinuosity, but is more likely tied to the cause of the sinuous growth. The juvenile wood of the sinuous trees likely had a lower MOE at the time of the initial deflection from vertical, but at the moment of the deflection, the tree began producing compression wood to correct the problem, therefore masking the initial decreased stiffness of the wood. The mature wood of the sinuous trees forms after the tree as a whole has significant stiffness to resist any further deflections.

Literature Cited

Allen, H. L., T. R. Fox, and R. G. Campbell. 2005. What is ahead for intensive pine plantation silviculture in the south? *South. J. Appl. Forestry* 29:62–69.

ASTM International. 2010. Standard methods for small clear specimens of timber. ASTM D143-09. ASTM International, West Conshohocken, Pennsylvania.

Campbell, R. K. 1965. Phenotypic variation and repeatability of stem sinuosity in Douglas-fir. *Northwest Sci*. 39:47–59.

Downes, G. M. and N. D. Turvey. 1990. The effect of nitrogen and copper on characteristics of wood tissue in *Pinus radiata*. *Can. J. Forest Res*. 20:1369–1377.

Fox, T. R., H. L. Allen, T. J. Albaugh, R. Rubilar, and C. A. Carlson. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. Forestry* 31:5–11.

Gartner, B. L. and G. R. Johnson. 2006. Is long primary growth associated with stem sinuosity in Douglas-fir? *Can. J. Forest Res*. 36:2351–2356.

Gatch, J. A., T. B. Harrington, T. S. Price, and M. B. Edwards. 1999. Stem sinuosity, tree size, and pest injury of machine-planted trees with and without bent taproots: A comparison of loblolly and slash pine. General Technical Report. USDA Forest Service, Southern Research Station, Asheville, North Carolina.

Harrington, T. B., J. A. Gatch, and T. S. Price. 1999. Stem sinuosity, tree size, and pest injury of machine-planted loblolly pine with bent versus straight taproots. *South. J. Appl. Forestry* 23:197–202.

Larson, P. R., D. E. Kretschmann, A. I. Clark, and J. G. Isebrands. 2001. Formation and properties of juvenile wood in southern pines: A synopsis. General Technical Report FPL-GTR-129. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 42 pp.

Li, B., S. McKeand, and R. Weir. 1999. Tree improvement and sustainable forestry—Impact of two cycles of loblolly pine breeding in the U.S.A. *Forest Genet*. 6:229–234.

Murphy, M. S. and T. B. Harrington. 2004. Stem sinuosity of loblolly pine seedlings as influenced by taproot shape. USDA Forest Service, Southern Research Station, Asheville, North Carolina. pp. 465–468.

Spicer, R., B. L. Gartner, and R. L. Darbyshire. 2000. Sinuous stem growth in a Douglas-fir (*Pseudotsuga menziesii*) plantation: Growth patterns and wood-quality effects. *Can. J. Forest Res*. 30:761–768.

Turvey, N. D., G. M. Downes, P. Hopmans, N. Stark, B. Tomkins, and H. Rogers. 1993. Stem deformation in fast grown *Pinus radiata*—An investigation of causes. *Forest Ecol. Manag*. 62:189–209.

US Forest Products Laboratory. 2000. Wood Handbook: Wood as an Engineering Material. University Press of the Pacific, Honolulu, Hawaii.

Wear, D. N. and J. G. Greis. 2002. Southern forest resource assessment. General Technical Report SRS 53. USDA Forest Service, Southern Research Station, Asheville, North Carolina.