Two-Year Stem Curvature and Growth Responses of Three Full-Sibling Families of Loblolly Pine to Five Root/Stem Form Treatments

Michael S. Murphy, Laurence R. Schimleck, Timothy B. Harrington, and Richard F. Daniels

Alumnus, University of Georgia (UGA), Athens, GA; Professor, College of Forestry, Oregon State University, Corvallis, OR; Research Forester, U.S. Department of Agriculture, Forest Service, Olympia, WA; Professor Emeritus, UGA School of Forestry and Natural Resources Athens, GA

Abstract

To examine the effects of taproot deformity on stem curvature, 90 full-sibling loblolly pine (*Pinus taeda* L.) seedlings (30 seedlings each from 3 families) were planted with 5 root/stem form treatments: straight taproot (control treatment), straight taproot with underground obstruction, taproot planted with J-root form, taproot planted at a 45-degree angle, and a straight taproot with the stem pulled to a 45-degree angle. Significant treatment differences ($P \leq 0.05$) were found in year 1 for stem diameter and frequency of interwhorl oscillations, and all variables differed significantly among families. Although no significant treatment effects existed in year 2, family differences in diameter at breast height, height, and frequency remained significant. In addition, amplitude of stem curvature was significant for the treatment-by-family interaction in year 2. No differences were found for treatment, family, or their interaction for stem biomass. Results suggest that stem curvature responses of loblolly pine were more attributable to genetics than to root/stem form.

Introduction

Stem sinuosity in trees is defined as a series of oscillating interwhorl curves throughout the stem that usually remain for the life of the tree (Timell 1986). Campbell's (1965) definition of stem sinuosity is restricted to stem curvature within an interwhorl stem segment (figure 1). Development of such stem deformity in conifers has both genetic and environmental components. Stem straightness is an important consideration for plantation managers regardless of a stand's rotation length. Because sinuosity is associated with formation of compression wood and increased lignin content (Low 1964), it can reduce merchantable value of conifers owing to lower pulp production in young stands and lower strength and increased warping in lumber from mature trees (Koch et al. 1990) (figure 2). In a survey of 14 mature loblolly pine (*Pinus taeda* L.), Jones and Fox (2012) noted that all the trees initially exhibiting sinuosity at a juvenile age had corrected their growth pattern within 5 years, and thus all effects associated with sinuous growth were restricted to the juvenile core of the stem. Visual expression of sinuosity is dynamic in juvenile loblolly pine, however, with one-half of 1,373 surveyed seedlings showing an increased sinuosity score within a single growing season (Jones and Fox 2012).

Genetic control of stem straightness has been shown to be moderate to strong in loblolly pine (Gwaze et al. 1997), radiata pine (*Pinus radiata* D. Don) (Wu et al. 2008), and jack pine (*Pinus banksiana* Lamb.) (Weng et al. 2015). This relationship indicates that genetic selections are likely to produce significant

Figure 1. Stem sinuosity on the terminal shoot of a loblolly pine seedling in the first year after being planted with a "J"-shaped root system. (Photo by Michael S. Murphy, 2002)

Figure 2. Compression wood in a loblolly pine seedling 2 years after being planted with a straight root system. (Photo by Michael S. Murphy, 2002)

gains in stem straightness. Environmental conditions leading to fast growth or to obstruction of stem and root growth have also been implicated as causing or increasing stem sinuosity. Espinoza et al. (2012) reported increases in stem sinuosity of juvenile loblolly pine with addition of nitrogen fertilizer—a condition that was reversed when nitrogen application was combined with calcium fertilizer.

Research examining the relationship between taproot form and stem sinuosity is scarce. Most research on root deformity has focused on survival and growth responses. Haase et al. (1993) found no statistical differences in 10-year survival and growth of coast Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) planted with straight, "J"-shaped, or "L"-shaped root systems. Robert and Lindgren (2006) found that 95 percent of 3- to 10-year-old planted lodgepole pine (*Pinus contorta* Dougl. Ex Loud. var. *latifolia* Engelm.) had moderate to severe root deformities, compared with 51 percent of naturally regenerated trees. In addition, young planted trees with low or moderate root deformities had greater height and diameter growth than naturally regenerated trees (Robert and Lindgren 2006). Greater diameter growth has been reported for loblolly pines having deformed roots (Harrington et al. 1987, Hunter and Maki 1980, Seiler et al. 1990), although others found greater growth for straight-rooted trees (Harrington and Howell 1998, Harrington et al. 1999). Hay and Woods (1974) hypothesized that increased stem growth of root-deformed loblolly pine was attributable to accumulation of carbohydrates and plant hormones above the deformity.

As land increases in value and population growth forces development into forested areas, land managers will have to efficiently maximize stand growth to produce superior quality products on less total acreage. Any evidence supporting the relationship between a planting practice and stem form should promote improved planting practices to maximize future returns and utility. Therefore, in early 2002, we initiated a study to investigate short-term effects of root/stem form treatments on stem curvature and growth of three full-sibling families of loblolly pine known to vary in stem straightness. Our hypothesis was that any modification in root/stem form would result in increased stem sinuosity. In addition, we compared stem form traits among families and determined if family effects interacted with the root/stem form treatments. Murphy and Harrington (2004) reported first year research results.

Methods

Study Site Description

The study was conducted at the University of Georgia's Whitehall Forest in Athens, GA. Growth of planted loblolly pine seedlings was studied both in raised beds and in an open field nursery (figure 3). Both the beds and the field were tilled to a 30-cm (12-in) depth prior to planting. The bare mineral soil was mulched with pine straw to decrease compaction and suppress development of competing vegetation. Seedlings were planted at both sites in January 2002 and grown for 2 years. To standardize resource availability among the root/stem form treatments, all seedlings were irrigated throughout two growing seasons (March through October of 2002 and 2003) with soaker hoses. A granular 10-10-10 NPK fertilizer and a micronutrient fertilizer were applied with a hand spreader once during each of the two growing seasons. Competing vegetation was removed prior to and throughout the study using spot applications of a solution of dry glyphosate in water (23 g [0.8 oz] of Roundup Pro Dry® in 3.8 L [1 gal] water). To minimize potential insect damage, seedlings were sprayed with permethrin insecticide (29.6 ml [1.0 oz] Bugstop® in 3.8 L [1 gal] water) to control the Nantucket pine tip moth (*Rhyacionia frustrana* Comstock). Three insecticide treatments were applied during each growing season (2002 and 2003) to coincide with shoot growth and egg laying cycles according to the schedule in Fettig et al. (2000).

Study Design

The experimental design was a randomized complete block with a factorial arrangement of treatments; five root/stem form treatments were applied to three full-sibling loblolly pine families. The International Paper Company (Super Tree Seedlings, Blenheim, SC), in a second-generation breeding program, selected three loblolly pine families shown to differ in stem straightness as follows—A: SCO-1 x SCO-14 < B: ATL-44 x ATL-5 < C: ATL-58 x ATL-5 (figure 4). Seedlings were grown for 1 year in the nursery and lifted as 1+0 bareroot planting stock. The root/stem form treatments were chosen to simulate typical conditions that occur during pine plantation establishment. An effort was made to create identical soil disturbance conditions for each root/stem form treatment. Each treatment by family combination was replicated 6 times (3 blocks in the raised beds and 3 blocks in the nursery field) for a total of 90 seedlings in the study. Seedlings were planted with a spacing of approximately 1.2 m (4 ft) (within row) by 2.1 m (7 ft) (between rows).

The root/stem form treatments consisted of the following planting configurations.

1. Control: straight taproot/straight stem.
2. Obstruction: straight taproot with obstruction to simulate a mineral hardpan or heavily compacted soil layer. The taproot obstruction required the use of a 45- by 45-cm (18- by 18-in) clear acrylic sheet. A square area was excavated, and the clear acrylic sheet was placed at a depth of 25 cm (10

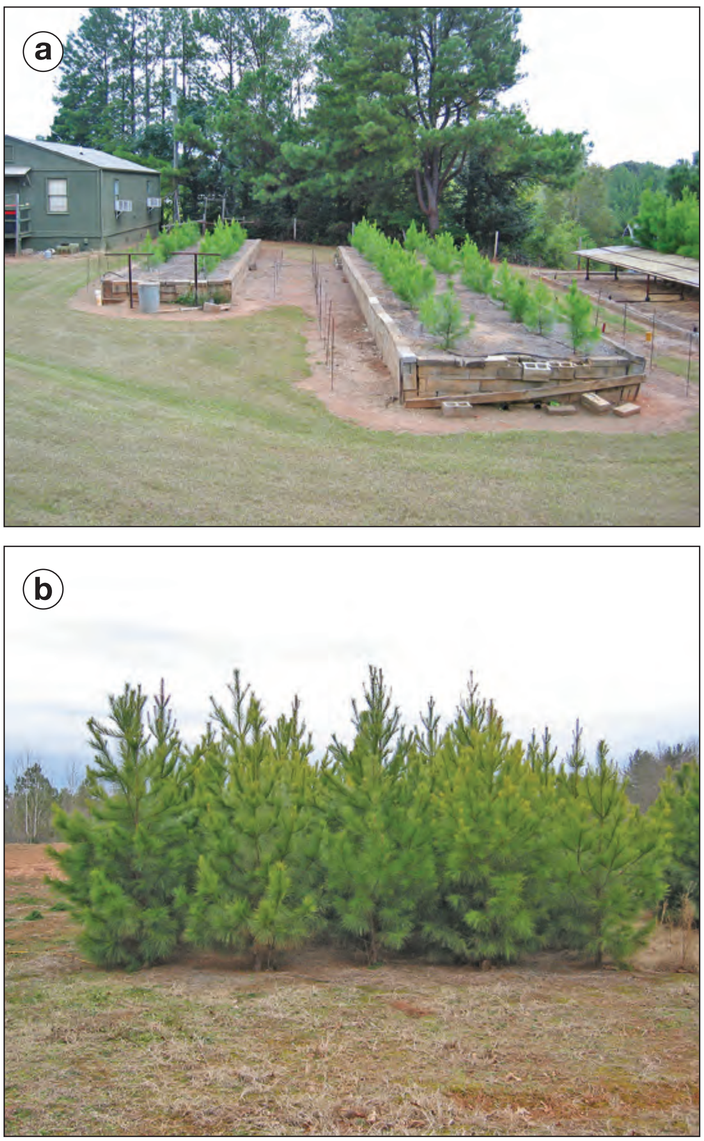

Figure 3. One-half of the study replications were planted in either (a) raised beds (year 1 shown) or (b) a nursery bed (year 2 shown). (Photos by Michael S. Murphy, 2002 and 2003)

Figure 4. Boxes from the International Paper Company containing 1-year-old bareroot loblolly pine seedlings from three full-sibling families. (Photo by Michael S. Murphy, 2002)

in). Note: The same large excavation was done for each root/stem form treatment.

3. J-root: “J”-shaped taproot to simulate improper planting of a seedling with the roots bent upward. This treatment was done by holding the root in a “J” shape as the soil was filled around it.

4. Angled: angled taproot/angled stem to simulate either hand or machine planting when the seedling stem is planted at an angle. This treatment was done by holding the entire seedling at a 45-degree angle as soil was filled around it.

5. Guy-wired: straight taproot/angled stem to simulate an aboveground deformity of the stem resulting from competing vegetation, ice, or animal damage. This treatment was done by planting the tree with a straight taproot and then pulling its stem to a 45-degree angle with a wire and maintaining it in that position by securing the wire to a wooden stake.

Measurements

One growing season after planting (October 2002), ground line diameter (GLD), height, curvature frequency, and curvature amplitude were measured on each seedling. Frequency of stem curvature was determined as the number of interwhorl curves that occurred in the main stem. Amplitude of stem curvature was measured as the distance from the peak of each stem curve and a vertically held straight edge. Curvature values were averaged for the entire stem of each tree. After the second growing season (November 2003), each seedling was measured for GLD, diameter at breast height (1.37 m [4.5 ft] above ground; DBH), height, curvature frequency, and curvature amplitude.

In February 2004, seedlings in all three raised beds were harvested (45 trees). A hydraulic front-end loader and chain were used to pull the entire tree and most of the root system out of the ground. The trees were stripped of branches and needles to leave an exposed stem and root system (figure 5) and measured for curvature frequency, curvature amplitude, total length from stem base to terminal bud (via straight edge), and actual stem length (determined by rolling a measurement wheel up one side of the stem). The ratio of actual length to total length was calculated as a sinuosity index. The stem of each tree was sectioned, bagged, dried to a constant weight at 65 °C (149 °F), and weighed.

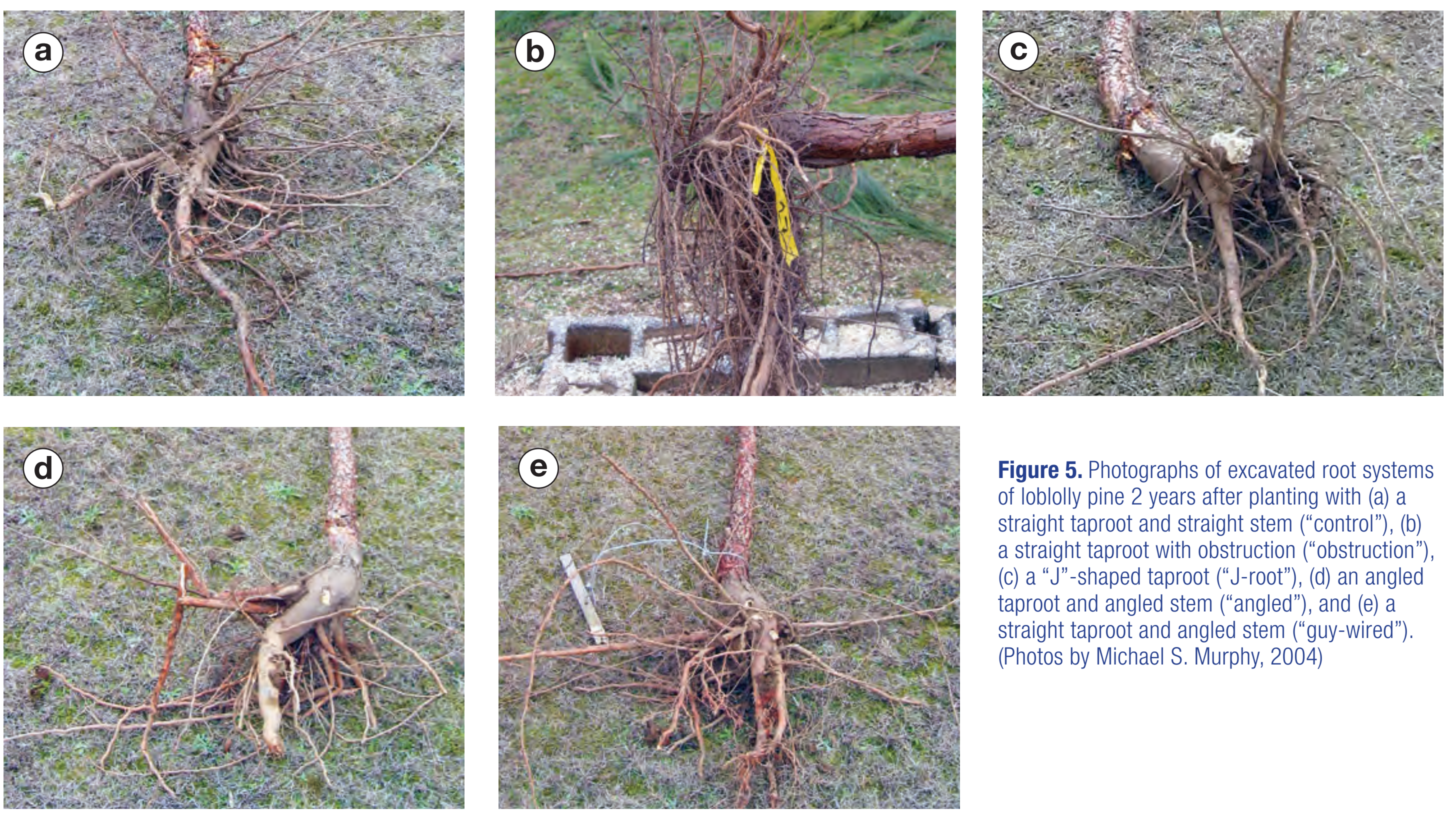

Figure 5. Photographs of excavated root systems of loblolly pine 2 years after planting with (a) a straight taproot and straight stem (“control”), (b) a straight taproot with obstruction (“obstruction”), (c) a “J”-shaped taproot (“J-root”), (d) an angled taproot and angled stem (“angled”), and (e) a straight taproot and angled stem (“guy-wired”). (Photos by Michael S. Murphy, 2004)

Statistical Analysis

Data were analyzed using analysis of variance to determine if tree size, stem curvature, and stem biomass varied significantly ($P \leq 0.05$) among root/stem form treatments, families, or their interaction. Multiple comparisons of treatment means were conducted with Tukey's test. All analyses were performed using SAS version 6 (SAS Institute 1989).

Results

Root/stem form treatment had a significant effect for both GLD and curvature frequency (table 1). The J-root treatment resulted in the smallest GLD and differed significantly from the obstruction treatment. The angled treatment had the highest curvature frequency and differed significantly from the J-root and control treatments (table 2). In year 2, root/stem form treatment did not significantly affect any of the variables (tables 1 and 2). Although not statistically significant, the J-root treatment resulted in trees with smaller diameter and height, and the obstruction treatment had the greatest growth (table 2). Harvest data from the raised beds did not differ significantly among root/stem form treatments (tables 1 and 2).

All variables differed significantly among families in year 1 (table 1). Family A had significantly greater GLD, height, curvature frequency, and curvature amplitude compared with families B and C (table 3). Family also had a significant effect for DBH, height, and curvature frequency in year 2 (tables 1 and 3). Curvature frequency was the only variable that differed among families for the harvested trees (tables 1 and 3).

A significant root/stem form treatment by family interaction was detected for curvature amplitude in year 2 (figure 6A). The obstruction treatment for family C had a higher amplitude than the J-root treatment for family C and the guy-wired treatment for family C. A significant root/stem form treatment by family interaction was also found at harvest (year 2) for the sinuosity index (figure 6B). The obstruction treatment for family C had a greater sinuosity index than the J-root treatment for family B, the J-root treatment for family C, and the angled planting treatment for family C.

Table 1. Analysis of variance results of root/stem form treatment and family effects on first- and-second-year growth and stem curvature of loblolly pine. Probabilities shown in bold text are statistically significant ($P \leq 0.05$).

		Source of variation			
Measurement	**Variable**	**Treatment**	**Family**	**Interaction**	**Block**
		Probability > *F*			
Year 1	GLD	0.038	0.008	0.855	0.868
	Height	0.578	0.000	0.986	0.961
	Frequency	0.012	0.000	0.098	0.197
	Amplitude	0.112	0.004	0.235	0.045
Year 2	GLD	0.080	0.074	0.930	0.228
	DBH	0.581	< 0.001	0.972	0.740
	Height	0.822	< 0.001	0.838	0.965
	Frequency	0.082	0.003	0.224	0.399
	Amplitude	0.371	0.095	0.037	0.288
Harvest*	Frequency	0.796	0.001	0.106	0.375
	Amplitude	0.262	0.232	0.353	0.044
	Total length (TL)	0.780	0.182	0.922	0.489
	Actual length (AL)	0.774	0.170	0.935	0.491
	Sinuosity index (AL/TL)	0.718	0.801	0.024	0.785
	Stem biomass	0.848	0.161	0.382	0.465

DBH = diameter at breast height. GLD = ground line diameter.
*Data for years 1 and 2 are based on six replications; harvest data (year 2) include only the three replications from the raised beds.

Table 2. Effects of root/stem form treatments on 2-year growth, stem curvature, and stem biomass of loblolly pine. For variables with significant treatment effects (table 1), means followed by the same letters do not differ significantly (P > 0.05). Conversions: 1 mm = 0.0394 in; 1 cm = 0.394 in; 1 g = 0.035 oz.

		Root/stem form treatment				
Measurement	**Variable**	**Control**	**Obstruction**	**J-root**	**Angled**	**Guy-wired**
Year 1	GLD (mm)	27.4 ab	31.3 a	25.8 b	29.6 ab	27.4 ab
	Height (cm)	118.9	127.2	116.9	125.8	123.4
	Frequency	2.8 b	3.7 ab	2.4 b	4.7 a	2.9 ab
	Amplitude (cm)	1.0	0.9	0.7	1.1	0.7
Year 2	GLD (mm)	73.3	78.4	69.9	76.4	71.2
	DBH (mm)	37.9	39.8	35.9	38.4	36.7
	Height (cm)	345.4	358.4	342.8	347.6	346.9
	Frequency	4.1	4.3	3.6	3.4	2.5
Harvest*	Frequency	5.2	7.3	6.4	6.4	6.1
	Amplitude (cm)	1.7	3.0	1.7	1.9	1.8
	Total length (cm)	347.2	352.8	341.0	332.3	357.7
	Actual length (cm)	349.1	355.6	342.8	334.4	359.4
	Stem biomass (g)	1786.5	1927.9	1767.8	1792.7	1993.8

DBH = diameter at breast height. GLD = ground line diameter.
*Data for years 1 and 2 are based on six replications; harvest data (year 2) include only the three replications from the raised beds.

Table 3. Effects of family on 2-year growth, stem curvature, and stem biomass of loblolly pine. For variables with significant family effects, means followed by the same letters do not differ significantly (P > 0.05). Conversions: 1 mm = 0.0394 in; 1 cm = 0.394 in; 1 g = 0.035 oz.

		Family		
Measurement	**Variable**	**A (SCO–1 x SCO–14)**	**B (ATL–44 x ATL–5)**	**C (ATL–58 x ATL–5)**
Year 1	GLD (mm)	30.9 a	26.5 b	27.5 b
	Height (cm)	136.2 a	112.8 b	118.7 b
	Frequency	4.2 a	1.9 b	2.6 b
	Amplitude (cm)	1.2 a	0.7 b	0.8 b
Year 2	GLD (mm)	77.4	72.3	71.9
	DBH (mm)	43.8 a	33.8 b	35.6 b
	Height (cm)	376.0 a	329.2 b	339.5 b
	Frequency	4.5 a	3.7 ab	2.6 b
Harvest*	Frequency	9.4 a	5.7 ab	3.9 b
	Amplitude (cm)	2.3	2.3	1.5
	Total length (cm)	363.0	331.9	343.8
	Actual length (cm)	365.3	333.8	345.7
	Stem biomass (g)	2029.4	1656.7	1875.1

DBH = diameter at breast height. GLD = ground line diameter.
*Data for years 1 and 2 are based on six replications; harvest data (year 2) include only the three replications from the raised beds.

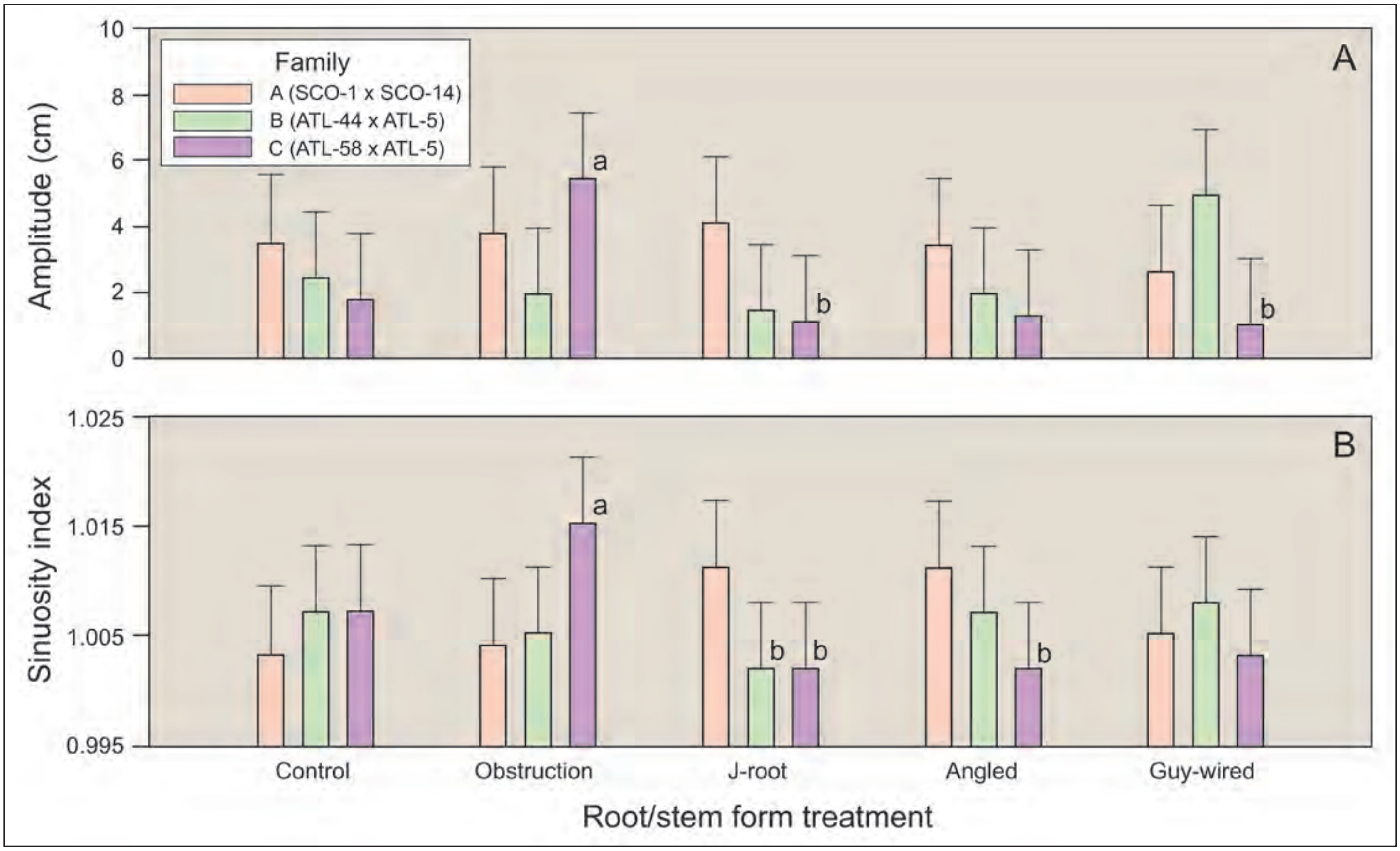

Figure 6. Mean values (± 95% confidence intervals) for the interaction of root/stem form treatment by family for (a) curvature amplitude in year 2 and (b) sinuosity index (actual stem length via measurement wheel/total length via straight-edge measurement) at harvest (year 2) for planted loblolly pine. For a given variable, lowercase letters indicate significant differences ($P \leq 0.05$), and all other means do not differ significantly from those with letters.

Discussion

In this 2-year study, an attempt was made to maintain a high level of soil water and nutrient availability to the planted loblolly pine seedlings. As a result, potential issues associated with shallow or deformed roots were eliminated, or at least alleviated, by the irrigation and fertilization treatments. Likewise, potential damage from tip moths was eliminated via the insecticide applications. Although the experimental approach provided an adequate system for comparing genetic influences on loblolly pine seedling growth and stem curvature, it did not provide an operationally meaningful evaluation of the consequence of poor planting practices. We would expect a different set of results if the treatments were replicated on sites of different soil qualities with no nutrient, water, or pest control amendments. Nonetheless, in our approach, we were able to distinguish important differences between seedling responses attributable to family effects versus those attributable to root/stem form treatment effects.

Root/Stem Form Treatment Effects

The significant effects of root/stem form treatment on stem diameter and curvature frequency in the first year suggest a relationship between taproot deformity and stem form, yet this relationship was not observed in subsequent measurements. Growth differences, however, may be longer term. For example, seedlings in the J-root treatment had the least growth throughout the 2-year study. The J-root treatment caused the taproot to wind on itself and turn into a ball because of grafting among lateral roots. This formation leads to a diminished ability of roots to seek out and absorb nutrients and water. Seiler et al. (1990), however, found that J-rooting did not significantly lower the water potential of loblolly pine or eastern white pine (*Pinus strobus* L.) seedlings. They concluded that the shallow planting of a J-root planted tree caused reduced water potential, but this effect did not continue as the root system grew enough to compensate for the initial shallow placement. In their 3-year study, they also found greater height growth for J-root planted seedlings when compared with straight-root planted seedlings. Harrington et al. (1999) excavated 3- to 10-year-old planted loblolly pine to determine if taproots were bent or straight and if taproot form was related to stem form. They found that trees with bent taproots had medium to high levels of stem sinuosity, and those with straight taproots had low levels. Harrington and Howell (1998) found that loblolly pine seedlings planted with deformed ("balled") roots with the slit method had less growth than those planted with straight roots using the dug-hole method. Trees planted with a "J"-shaped root system may also have decreased wind resistance (Hunter and Maki 1980, Lindström and Rune 1999).

Seedlings in the obstruction treatment had vigorous taproot and lateral root development in the upper soil layer, generally resulting in a broad, flattened root system (figure 5B). From visual observation, these root systems had a large number of far reaching laterals near the surface. This lateral expansion likely increased the surface area available for water and nutrient uptake, hence the greater growth that was observed. Although the clear acrylic sheet used for the obstruction was installed at an angle to minimize water pooling, some water and nutrients may have collected on its impermeable surface, giving trees in this treatment an advantage. Analogously, in the sandhill region of the South, site quality for southern pines decreases gradually with depth to a fine-textured horizon, because the clay layer traps soil water and increases its availability to plants (Duryea and Dougherty 1991). Balneaves and De La Mare (1989) did not find growth differences for radiata pine grown in an area with a mineral hardpan that limited root penetration to a maximum depth of 48 cm (18.9 in). In their study, growth was compared between a control and a series of ripping depths where the soil was mechanically penetrated. Because the Whitehall study trees were irrigated, the broad root expansion near the surface was advantageous for water capture. In the field, an obstruction may be a disadvantage as it limits root exploration for deeper water sources.

The angled plantings had greater diameter growth than any other treatment except the control at all three measurement dates. Manual bending increases xylem and bark production at the point of bending leading to a possible effect on stem form (Valinger et al. 1995). Likewise, preventing stem bending by staking results in decreased diameter growth (Dean 1991). Decreased height growth has been observed for Fraser fir (*Abies fraseri* [Pursh] Poir.) trees that were subjected to wind stress or mechanical perturbation (Telewski and Jaffe 1986).

Family Effects

Genetic variation among families was evident in growth and stem curvature for years 1 and 2. At harvest (year 2), only curvature frequency differed significantly among families. One family (family A) significantly outgrew the others in height and stem diameter during both seasons. Vargas-Hernandez et al. (2003) evaluated family heritability of growth traits for coast Douglas-fir seedlings and consistently found height to be under stronger genetic control than stem diameter, top weight, or stem curvature. Bail and Pederick (1989) found no correlation between mean height and stem deformity characteristics among 44 full-sibling families of radiata pine.

Family C, which had the least stem curvature and growth of all families, showed an interaction with the obstruction treatment resulting in the largest values for curvature amplitude (year 2) and sinuosity index (harvest). Although we are unable to explain the mechanism for this response, we can infer that this family was particularly sensitive to taproot obstruction, and hence, it responded disproportionately to the treatment compared with the other families.

Conclusions

Our study suggests that genetic variation is a greater factor than root/stem form treatment in affecting stem straightness. We cannot conclude that variations in root and stem form during planting practices are a cause of stem curvature. It is likely that stem curvature responses are the result of genetics and site conditions. Trees that are more genetically prone to irregular growth may show an intensified response owing to poor planting practices, reinforcing the importance of selecting high quality genotypes, proper site preparation, and careful planting practices.

Research results also suggest a potential exists to select genotypes that are best adapted to site conditions restricting root growth, such as soils with a compacted layer. In our study, family C was noted to show a significant increase in stem curvature in response to the obstruction treatment. The study also emphasizes the resilience of loblolly pine, and likely many other tree species, to environmental stress. Despite our attempts to create planting conditions likely to stimulate increases in stem curvature, the seedlings differed little in their development among the root/stem form treatments. However, in no way should the results of our research be taken as a justification for limiting planting quality. Instead, our work highlights the importance of seed source and genetic selection, breeding, or both; adequate planting depth; and proper vertical alignment of the seedling within the planting hole

Address correspondence to—

Michael S. Murphy, 3311 Woodside Court NE, Olympia, WA 98506; email: mmurphy112@gmail.com; phone: 706–338–0775.

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