THE INFLUENCE OF TAPROOT SHAPE ON STEM FORM IN LOBLOLLY (*Pinus taeda* L.) AND SLASH PINE (*Pinus elliottii* Engelm.)

by

MICHAEL S. MURPHY

(Under the direction of Richard F. Daniels)

ABSTRACT

Two studies were completed to evaluate the influence of taproot shape on stem form in loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.). In the first study, measurements were collected on loblolly pine seedlings after each growing season. These seedlings were comprised of three full-sibling families subjected to five taproot treatments: a straight taproot (control treatment), straight taproot with underground obstruction, taproot planted with J - form, taproot planted at a 45 degree angle, and a straight taproot with the stem guy-wired to a 45 degree angle. Growth and stem form measurements were evaluated to determine the effect family, taproot treatment, or their interaction had on stem form. In the first year, there were significant family and taproot treatment effects on growth and form, while in the second year only family effects were significant. There was a significant interaction of family and taproot for one stem form measurement (amplitude) in year two. Significant growth variation was found among families in a post harvest measurement. A stem form sinuosity index interaction effect was also found to be significant.

In the second study, measurements were collected on slash and loblolly pine aged three to six years old planted at six locations throughout Georgia. J, L, and straight taproot treatments were applied to these trees in split plots with fertilization and weed control. Growth and stem form measurements were collected during the winter of 2003. Measurements were evaluated to determine the effects of taproot treatment, split-plot treatment or their interaction for each of the six sites. Significant differences were found among the taproot treatment at two locations. No split-plot or interaction differences were found.

INDEX WORDS: taproot form, stem form, family, full-sibling, J-root, sinuosity

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The following thesis presents a literature review compiling past research efforts into stem form and growth in chapter 1 and two studies that were designed to determine the relationship between taproot shape and stem form in chapters 2 and 3. A summary and discussion of silvicultural implications concludes in chapter 4.

The results of the Whitehall seedling study are presented in Chapter 2. For this study, we tested the hypotheses that there would be stem form and growth variation among five taproot treatments, there would be stem form and growth variation among families, and there would be stem form and growth variations among the taproot treatment and family interaction. Three full-sibling loblolly pine (*Pinus taeda* L.) seedlings were subjected to five taproot treatments: a 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 guy-wired to a 45 degree angle. Growth and stem form measurements were collected twice, once after each growing season (2002 and 2003), and evaluated for the effects of family, taproot treatment, or their interaction.

The results of the older plantation study are presented in Chapter 3. For this study we tested the hypotheses that there would be stem form and growth variation among three taproot treatments, there would be stem form and growth variation among plots split by whether they had received weed control and fertilization or not, and there would be stem form and growth variation among the taproot treatment and split plot interaction. This study was comprised of three to six year old trees subjected to three root treatments: a straight taproot (control treatment), taproot planted with a J-root form, and taproot planted with an L-root form planted among split plots with fertilization and weed control. Growth and stem form measurements of loblolly and slash pine (*Pinus elliottii* Engelm.) trees were collected and evaluated for the effects of taproot form, split-plot treatment, or their interaction.

Sinuosity

Taproot deformation, resulting from poor planting or underground obstruction, is a suspected cause of poor stem form in loblolly pine. Stem sinuosity, an oscillating curvature of the stem, is an example of a stem defect. Sinuosity is a result of an overcorrection when the leading shoot wavers past its vertical position repeatedly. This creates a series of oscillating curves that continues up the stem until equilibrium is reached and normal growth resumes, usually remaining for the life of the tree (Timell, 1986). Sinuosity is an example of a severe stem deformity, rather than a sweep or bend. In some cases a tree can become commercially invaluable, such as with Toorour's syndrome. Toorour's syndrome occurs on some Australian plantations that have been established on former livestock pasture sites. These trees are very deformed and exhibit a variety of twisting and bending patterns. Like sinuosity, there is still not conclusive evidence as to what causes it (Downes and Turvey, 1990). It has been suggested that sinuosity is a result of fast growth due to the weight of the leading shoot and because there may be a possible lag between cambium formation and shoot elongation the weight of the tender shoot causes it to flop over (Spicer *et al*. 2000).

Compression Wood

Compression wood is present in all conifers as it forms beneath branches to provide support and helps the stem maintain its vertical orientation. When compression wood overcompensates to straighten the stem beyond a vertical position the sinuosity process is initiated as a series of overcorrections results in the process being repeated for the entire stem. Compression wood comprises 10 – 15% of wood volume in southern pines (Timell, 1986) and is generally undesirable for wood utilization purposes. Compression wood results in warping of lumber, which has less strength under tension, providing a product that may endanger life and property (Koch *et al.* 1990) and is also undesirable for pulpwood utilization because of reduced pulp yield, a consequence of its higher lignin content (Low, 1964). Debarking a stem to prepare for pulp production may also be limited by poor form (Hunter *et al*. 1990). Compression wood functions to correct a bent stem to its normal position by longitudinal expansion on the concave side of the stem. Although the exact mechanism is unknown, gravitational stimulus is commonly accepted as a cause of compression wood formation (Sinnott, 1952, Koch *et al*. 1990). However, data in a recent paper by M. Kwon *et al*. (2001) indicated compression wood formation in the microgravity environment of the space shuttle.

Biochemical factors

Growth hormones are known to be factors in the formation of compression wood. The plant hormone ethylene is often used to indicate plant stress and damage (Wilksch *et al*. 1998). Ethylene and Indole – 3 – acetic acid (IAA) are plant hormones thought to result in compression wood formation by regulating the production of longitudinal tracheids, the main component of compression wood (Little and Eklund, 1999). Auxins such as 2-4-D and IAA can induce compression wood formation when present in high enough concentrations (Koch *et al*. 1990).

Changes in ethylene production related to stress, have been illustrated in an experiment using simulated wind sway stress. Three-year-old loblolly pine seedlings were manipulated by mechanical perturbation (shaking and flexing). Ethylene production of the stem was then measured at the point of flexure using a specially designed, closed system trap. A positive correlation was found between ethylene production and wood density, and both ethylene production and wood density were higher in stressed seedlings (Telewski, 1990).

Silviculture

A mineral hardpan is an accumulation of nutrients that creates a layer below the soil that may be impenetrable to roots. Balneaves and Mare (1989) compared tree growth and root development in soils with a known mineral hardpan and found greater taproot penetration on ripped sites, where the hardpan is broken along planting row, when compared to unripped sites. In their comparison of ripping treatments they found taproot deformation and stem deflection to both be significantly correlated with the depth of taproot penetration.

Planting guidelines for bare root and containerized conifer seedlings typically specify that roots are planted with a vertical orientation causing the root tips to be predominately in the lower portion of the planting hole. Unlike a natural germinant, the lateral roots may not colonize the shallow, nutrient rich mineral-organic layer (Balisky *et al*. 1995). Natural regeneration generally results in greater taproot length and an array of lateral roots with sinker roots colonizing the shallow soil around the tree, providing advantageous growth conditions. In a comparison of eleven-year-old planted and naturally regenerated lodgepole pine (*Pinus contorta* var. *contorta* Dougl.), Halter *et al*. (1993) found significant differences for aboveground growth and root morphology. Naturally regenerated seedlings had increased height growth, leader growth, more lateral roots, and more sinker roots when compared to planted seedlings. Lateral roots for planted pines were found to be located deeper than naturally regenerated seedlings. Among the planted saplings, 15% showed basal sweep and/or toppling, defects not seen among naturally regenerated saplings.

On the other hand, several studies indicate that root deformation does not have negative effects on survival and growth, although the problems of compression wood and stem sinuosity were not addressed directly in these studies. In fact, some studies indicate greater early growth for trees with deformed root systems (Hay and Woods, 1974a, Hay and Woods, 1974b, Woods, 1980, Seiler *et al*. 1990). This may occur because deformed roots develop more lateral roots near the soil surface, which are more important than deep taproots for absorbing limited soil moisture during dry periods (Hay and Woods, 1974b). Deformed roots also have been found to improve wind resistance due to their increased upper lateral root growth (Hunter and Maki, 1980, Seiler *et al*., 1990). Deformed roots, however, can hinder later growth because as deformed roots grow in their twisted condition some break and die, making the tree more susceptible to windfall, insects, and disease (Hay and Woods, 1974a). Harrington *et al*. (1989) found a decrease in lateral roots when comparing planted and naturally regenerated loblolly and shortleaf pine (*Pinus echinata* Mill.). Lateral roots were found to be at greater depths for planted trees. This increase in depth may be a result of planting practices where the root collar is placed at a lower depth than that of naturally regenerated trees. An unexpected outcome of this study was the infrequent toppling of some planted but no naturally regenerated trees. Upon excavation these trees were either found to be J-rooted or lacking major lateral roots from one side of the tree. Similar variation in stability between naturally regenerated and planted trees was also reported for Scots pine (*Pinus sylvestris* L.) (Lindström, and Rune, 1999).

Although much of the literature supports the theory that root deformity has no negative affect on growth and survival, few researchers have addressed the problem of stem form in association with root deformity. Harrington and Gatch (1999) performed a retrospective study on machine planted loblolly pine to assess the relationship between stem sinuosity and root deformation. Trees identified as having sinuous characteristics were assigned an index based on the severity of sinuosity. Upon excavation, trees with bent taproots were found to have medium to high levels of sinuosity. Lindström and Rune (1999) determined that naturally regenerated Scots pine were straighter than planted trees in both young (age 7-9 years) and old (age 19-24 years) plantations.

Management practices such as thinning may lead to increased compression wood and stem deformities. In fact, the silvicultural activity most frequently associated with compression wood formation is thinning (Timell, 1986). Thinning results in less wind protection, increased radial growth, and phototrophic responses that may lead to compression wood formation. However, Reader and Kurmes (1996) found no statistically significant differences in compression wood development among different stocking levels for ponderosa pine (*Pinus ponderosa* Laws.), yet compression wood severity decreased with increased stocking level.

Nutrients

The abundance or limited availability of nutrients may be a cause of stem sinuosity. Several studies have been conducted relating copper deficiency and poor stem form in New Zealand Monterey pine (*Pinus radiata* D.Don). The pines in these studies were planted on formerly intensively farmed areas or wind-blown sands with low nutritive values. Soil pH, which copper solubility is dependent upon, may be a possible cause (Turvey, 1984). Conversely, severe twisting of Monterey Pine has been found to occur on sites with adequate copper values (Hunter *et al*. 1990).

Research has shown a relationship between copper deficiency and reduced lignification of wood. Lignin content has been found to be significantly lower for deformed items when compared to straight stems. A significant difference was also found in foliar copper concentrations between deformed and straight trees, with deformed trees being deficient in copper (Downes and Turvey, 1990).

Lignin content and copper availability is also associated with Toorour's syndrome. Carlyle *et al*. (1988) found trees with Toorour's syndrome on sites with adequate copper availability. It is suggested that this condition differs from deformities found in copper deficient trees and is a combination of genetic factors and high soil nitrification. Interestingly, no significant differences in lignin contents of straight and deformed trees were found in this study.

Physiology and Environment

Many environmental factors are known to have an effect on stem form. Lateral movement of the stem caused by wind has been shown to increase diameter growth (Telewski and Jaffe, 1986). Valinger *et al*. (1995), compared differences in diameter growth for five-year-old Scots pine (*Pinus sylvestris* L.) subjected to mechanical bending stress in both dormant and growing periods. Diameter growth was found to increase in both periods but was most pronounced during the growing period. Stokes and Berthier (2000) found eccentric growth to be the result of wind loading in coastal grown maritime pine (*Pinus pinaster* Ait.). In these trees, growth rings were enlarged on the leaning side and stem eccentricity was more pronounced along the bend. Finally, environmental factors such as ice or storm damage can lead to compression wood formation (and subsequent stem deformation) as does any element that bends the stem from its normal vertical position (Timell, 1986).

Genetics

Genetic variation is undoubtedly responsible for growth differences within a species, and there is some evidence supporting this. Sixteen provenances of 22-year-old Ocote pine (*Pinus oocarpa)* were evaluated for height, DBH, and basal area per hectare differences. Significant differences were found for all variables (Mugasha *et al*. 1997). It is worth noting that these provenances were selected by region rather than a known seed source.

There are many factors leading to the development of sinuosity and it is likely that many cases of sinuosity are a result of one or more of the factors mentioned in this review. In the following two studies, the objective was to examine the relationship between taproot form and stem shape, and identify whether these relationships changed with genetic differences (Whitehall study), nutrition, or competition control (older plantation study).

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CHAPTER 2

STEM SINUOSITY OF LOBLOLLY PINE (*Pinus taeda* L.) SEEDLINGS AS INFLUENCED BY TAPROOT SHAPE [1]

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ABSTRACT

Sinuous stem growth in loblolly pine (*Pinus taeda* L.) may result in a diminished potential for the utilization of wood products as these stems are difficult to mill and contain a higher percentage of compression wood. Ninety full-sibling loblolly pine seedlings (30 seedlings each from three families) were planted with five taproot configurations: 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 guy-wired to a 45 degree angle. Seedlings were irrigated and fertilized to maintain high growth rates, and insect control treatments were applied to minimize injury from the Nantucket pine shoot tip moth (*Rhyacionia frustrana* (Comstock)). Height, ground line diameter GLD, and diameter at breast height DBH were collected as well as stem form measurements of frequency (number of interwhorl curves) and amplitude (average depth of curves) for two growing seasons and post-harvest. Statistical analyses were conducted to determine if seedling growth rate and stem form varied significantly according to family, taproot treatment, or their interaction. Significant treatment differences were found in year one for the variables of diameter and frequency, while all variables were significantly different by family. For year two, there were no significant treatment effects, and the variables of DBH, height, and frequency remained significant for family. Amplitude was significant for the interaction effect in year two. Post-harvest measurements showed no treatment effects and only one significant difference among family for frequency. The sinuosity index measurement was significant for the interaction effect in the post-harvest measurement. No differences were found for treatment, family, or interaction among biomass dry-weight comparisons.

KEY WORDS: Stem form, Root form, J-root

INTRODUCTION

The objective of this study was to determine if there is a relationship between taproot form and stem form, particularly sinuosity, in full-sibling loblolly pine (*Pinus taeda* L.) The main hypothesis tested was that any modification in taproot form would result in sinuous stem growth. Sinuosity is an example of a severe stem deformity and is defined as a series of oscillating interwhorl curves that continues up a stem and usually remains for the life of the tree (Timell, 1986). Also, the heritability of stem form traits and their possible expression as a result of the taproot / family interaction was examined. Past studies have provided inconclusive results and have focused on growth variation rather than stem form. Stem form is an important consideration for plantation managers regardless of a stand's rotation length. Value is lost when young stands are harvested for pulp due to their high lignin content, and value is lost for sawtimber in the form of compression wood and stems that are too malformed to manufacture lumber, and because compression wood results in warping of lumber, that has less strength under tension, it results in a product that may endanger life and property (Koch *et al*. 1990) and is also undesirable for pulpwood utilization because of reduced pulp yield (Low 1964). Growth traits and stem form characteristics are influenced by genetic heritability as well (Hernandez *et al.*, 2002).

As land increases in value and population growth pressures land use toward development into non-forested areas, land managers may have to efficiently maximize their stands to produce superior quality products on smaller areas. Any evidence supporting the relationship between a planting practice and stem form should promote improved planting practices to maximize future returns and utility.

METHODS

Study Site Description

The study was located at the University of Georgia's Whitehall Forest in Athens, Georgia. Growth of planted loblolly pine seedlings was studied both in raised beds and in an open field nursery. Both the beds and the field were tilled to a 30-cm depth prior to planting. The bare mineral soil was mulched with pine straw to decrease compaction and suppress development of competing vegetation. Both sites were planted in January 2002. Seedlings were irrigated throughout the growing season with soaker hoses and fertilized with macro and micro nutrients. Competing vegetation was removed as needed prior to and throughout the study using dry glyphosate in water (148ml Roundup Pro Dry ® in 3.8l water).

To minimize confounding effects, seedlings were sprayed with permethrin (29.6ml Bugstop® in 3.8l water) to control the Nantucket Pine Tip Moth (*Rhyacionia frustrana* Comstock). Three pesticide treatments were applied each season to coincide with flush growths and egg laying cycles according to the schedule in Fettig *et al.* (2000).

Study Design

The experimental design of the study was a randomized complete block with a factorial arrangement of treatments. Five taproot treatments were applied to 3 full-sibling families. The taproot treatments included a:

1. straight taproot/straight stem planting (control treatment)
2. a straight taproot with obstruction planting
3. a J-root planting
4. an angled taproot/angled stem planting
5. a straight taproot/angled stem planting.

An image of each of these treatments at planting can be seen in Figure 2.1.

The 3 full-sibling families were selected for their stem straightness characteristics. Each combination of the 5 taproot treatments and 3 families was replicated 6 times, resulting in a total of 90 seedlings being planted. Treatment replications were grouped in blocks, and three blocks each occurred in the raised beds and in the nursery field.

An effort was made to create identical soil disturbance conditions for each taproot treatment. The taproot obstruction required the use of a 45-cm x 45-cm clear acrylic sheet. A square area was excavated and the clear acrylic sheet was placed at a depth of 25-cm. This same large excavation was done for each planting. The angled planting was done by holding the entire tree at a 45 degree angle as soil was filled around it. The straight taproot/angled planting was done by planting the tree with a straight taproot, and then pulling it over to a 45 degree angle with a wire and maintaining it in that position by securing the wire to a stake.

Measurements

Dormant Season

Measurements of ground line diameter (GLD at 1 cm above ground), height, frequency, and amplitude was collected on October 8, 2002, one growing season after planting. 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, and these values were averaged for the entire stem of each tree. On November 18, 2003 after the second growing season, measurements were collected for ground line diameter GLD, diameter at breast height DBH, height, frequency, and amplitude of stem curvature.

Harvest

In February 2004, blocks I-III were harvested (the entire bed section). A hydraulic front-end loader and chain was used to pull the entire tree and root system free. The trees were stripped of needles and branches to leave an exposed stem and root system. The measurements of frequency, amplitude, total length, and wheel length were collected. Frequency and amplitude measurements were repeated as in previous measurements but with greater ease and accuracy without branches and having the tree in a horizontal position. Total length was a straight measurement taken from the stem base to the terminal bud. Wheel length was measured using a measurement wheel and rolling the wheel up one side of the stem. An index of sinuosity was calculated from the ratio of wheel length \ total length. The stem of each tree was sectioned, bagged, dried, and weighed for biomass comparison. Post – harvest images of each treatment root system can be seen in Figure 2.2.

Statistical Analysis

The variables of total length, wheel length, sinuosity index, frequency, amplitude, and stem biomass were subjected to analysis of variance to determine if tree size and stem curvature varied significantly ($P \leq 0.05$) among taproot treatments, families, or their interactions. Multiple comparisons of treatment means were conducted with Tukey's test. All analyses were performed using SAS (SAS Institute, Inc., 1989).

RESULTS

Whitehall Forest Seedling Study Year One

Treatment

Taproot treatment had a significant effect for the variables of diameter ($P \leq 0.0382$) and frequency ($P \leq 0.0122$) (Table 2.1). The J-root treatment resulted in the smallest values for GLD and differed significantly from the taproot obstruction treatment (Figure 2.3). The angled planting had the highest frequency and differed significantly from the J-root and control treatments which had the lowest (Figure 2.4).

Family

Family had a significant effect for all variables (Table 2.1). Family A outgrew the others for ground line diameter (Figure 2.5), and height (Figure 2.6), and it appears this growth affected frequency (Figure 2.7) and amplitude (Figure 2.8) as family A is also significantly different for these variables; however the relationship between growth and frequency is weak (r^2 =0.237) (Figure 2.9).

Interaction Effects

While significant differences existed among taproot treatments and families, there were no significant treatment interactions (Table 2.1).

Block

Amplitude was the only variable with a significant difference for block ($P \leq 0.0447$). This difference occurred between blocks I and III (Figure 2.10).

Whitehall Forest Seedling Study Year Two

Treatment

Unlike year one, there were no significant effects of treatment for any of the variables (Table 2.2). Although not a statistically significant effect, the J-root treatment resulted in smaller trees expressed through diameter and height, while the taproot obstruction treatment had the greatest growth (Figure 2.11).

Family

Three variables were significantly affected by family (Table 2.2). Family had a significant effect for DBH ($P \leq 0.0001$) (Figure 2.12), height ($P \leq 0.0001$) (Figure 2.13) and frequency ($P \leq 0.0029$) (Figure 2.14) due to the accelerated growth of family A. Regardless of the apparent relationship between the growth of family A and frequency the relationship between height and frequency was weaker than that in year one ($r^2=0.0893$) (Figure 2.15).

Interaction

The interaction effect for amplitude was significant in year two (Table 2.2). No obvious interaction effect trends were observed. The combination of taproot obstruction x family C and guy wired planting x family B proved to be the interactions with high significantly different amplitudes (Figure 2.16).

Block

There were no significant differences observed among the blocks for any variables (Table 2.2).

Harvest

Treatment

As in the year two measurements, no significant differences were found for any variable among treatment (Table 2.3).

Family

Frequency was the only significant variable for family (Table 2.3). As in the previous two measurements, family A had the highest frequency (Figure 2.17).

Interaction

The ratio of wheel length / total length was significant for the interaction of treatment and family ($P \leq 0.0236$) (Table 2.3). The combination of taproot obstruction and family C produced the highest value for the sinuosity index interaction and was significantly different from three other interactions (Figure 2.18).

Block

Amplitude had a significant block effect ($P \leq 0.0440$). As in year one this variation occurred between blocks I and III (Table 2.3).

Overall Means

The J-root treatment had reduced diameter and height growth for all three measurements. Other trends are not as evident in the table of means (Table 2.4).

DISCUSSION

Treatment

The significant treatment effects of diameter and frequency measurements made in the first year suggest a relationship between root and stem form, yet this relationship was not observed in the two subsequent measurements. In consideration of practical seedling establishment, care should still be taken in planting. Since results relating root form to sinuosity are variable and trends are difficult to observe, the focus should be on growth differences. For example, J-root growth was lowest for all three measurements (year one, year two, and harvest), while taproot obstruction growth was greatest. The J-root treatment causes the taproot to wind upon itself and turn into a ball, which many lateral roots graft into. This formation certainly leads to a diminished ability to seek out and take up nutrients and water. However, Seiler *et al.*, (1990) found that J-rooting does not significantly lower the water potential of loblolly or eastern white pines (*Pinus strobes* L.) seedlings. They concluded that reduced water potential is caused by the shallow planting of a J-root tree, but this effect does not continue as the root grows enough to compensate for the initial shallow placement. In their three year study, they also found greater height growth for J-root seedlings when compared to straight seedlings.

The taproot obstruction treatment allowed for vigorous taproot and lateral root formation and generally resulted in a broad, flattened root system. From visual observation, these root systems were often broader and had a large number of far reaching laterals near the surface. This lateral expansion likely increased the surface area available for nutrient and water uptake, hence the greater growth. Although the clear acrylic sheet used for the obstruction was put in at an angle to minimize water pooling, water and nutrients may have collected on its impermeable surface giving trees in this treatment an advantage. Balneaves and Mare (1989) did not find growth differences for Monterey Pine (*Pinus radiata* D. Don) grown in an area with a mineral hardpan that allowed root penetration to a maximum depth of 48cm. In their study, growth was compared between a control and a series of ripping depths where the soil was mechanically penetrated. Since 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 and guy wired plantings had greater diameter growth for all three measurements. Other studies have confirmed the role of bending stress and increased diameter growth. 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 through staking results in decreased diameter growth (Dean, 1991). Decreased height growth has been observed for Frasier fir (*Abies fraseri* Pursh) for trees that were subjected to wind stress or mechanical perturbation (Telewski and Jaffe, 1986). Because this effect did not occur at the Whitehall study, it may be an effect of the repetitive stress rather than an initial bend.

Family

The growth differences among family for year one and year two reveals the influence of genetics. One family (A) significantly outgrew the others during both seasons. Hernandez *et al.*, (2002) evaluated family heritability of growth traits for Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco) seedlings, and consistently found height to be under stronger genetic control than diameter, top weight or sinuosity. The same variation in height growth among families was found by Mugasha *et al.*, (1997) for *Pinus oocarpa* and *Pinus patula* var. *tecunamanii*. This research contradicts an observation that developed as results of the Whitehall study were interpreted in that sinuosity characteristics may be correlated with growth. This is the logic behind terms such as "speed wobble", which is sometimes applied to intensively managed trees with accelerated growth rates. Because of the weak correlations between family A growth and sinuosity characteristics, we can be fairly confident that "speed wobble " is not a confounding factor among the genetic comparisons, and that sinuosity is weakly correlated with growth. Bail and Pederick, (1989), also found a lack of correlation when comparing mean height and stem deformity characteristics among 44 full-sibling families of Monterey pine.

In the Whitehall study, full-sibling seedlings were chosen to reduce the possibility of confounding the effects of root treatments. If interaction differences would have existed between the family and root treatments, an interesting explanation could have been suggested. This would have been an indicator that the genetic expression of sinuosity is manifested when the tree is stressed in a certain way. Since previous data suggest that growth is more heritable than sinuosity, the significant treatment effect for frequency and amplitude in year one is an interesting occurrence.

CONCLUSION

The results of this study indicate that there is not a distinctive relationship between taproot shape and stem form, yet found supporting evidence that certain growth factors may be influenced by planting practices. The J-root treatment led to reduced growth compared to the other treatments for both years of the study. J-rooting is a practice that is already discouraged, but perhaps it should be examined more closely in future research. Because this study only includes measurements from the first two years of the seedlings' life, future possible changes are unknown. If there is an influence of taproot form, it is likely that it will increase over time as the root becomes more severely deformed with increasing growth. Because post harvest measurements were similar to those taken *in situ*, we can be confidant that the frequency and amplitude measurements taken in both years are accurate. It is interesting that while family growth differed significantly in both years there were no differences in biomass of the dry stem.

The role of family is more apparent as it had significant effects in both years for growth and form. The selection of genotype is already an important consideration when establishing a plantation; however stem form is often not taken into consideration. These results should hopefully lead to the encouragement of selection and breeding of specimens based on their stem form characteristics.

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(1) control planting

(2) taproot obstruction planting

(3) J-root planting

(4) angled planting

(5) guy-wired planting

Figure 2.1 Taproot treatment images at planting.

Figure 2.2 Post-harvest root images of each taproot treatment.

(1) control planting root

(2) taproot obstruction root

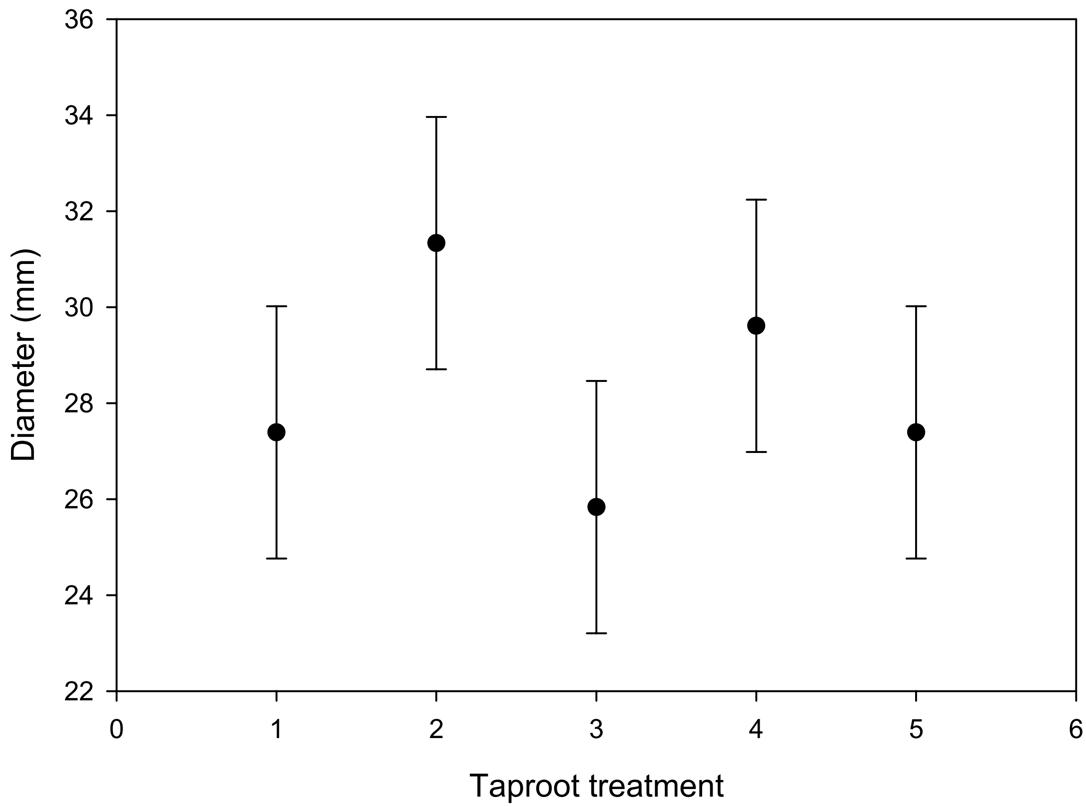
(3) J-root planting root

(4) angled planting root

(5) guy – wired planting root

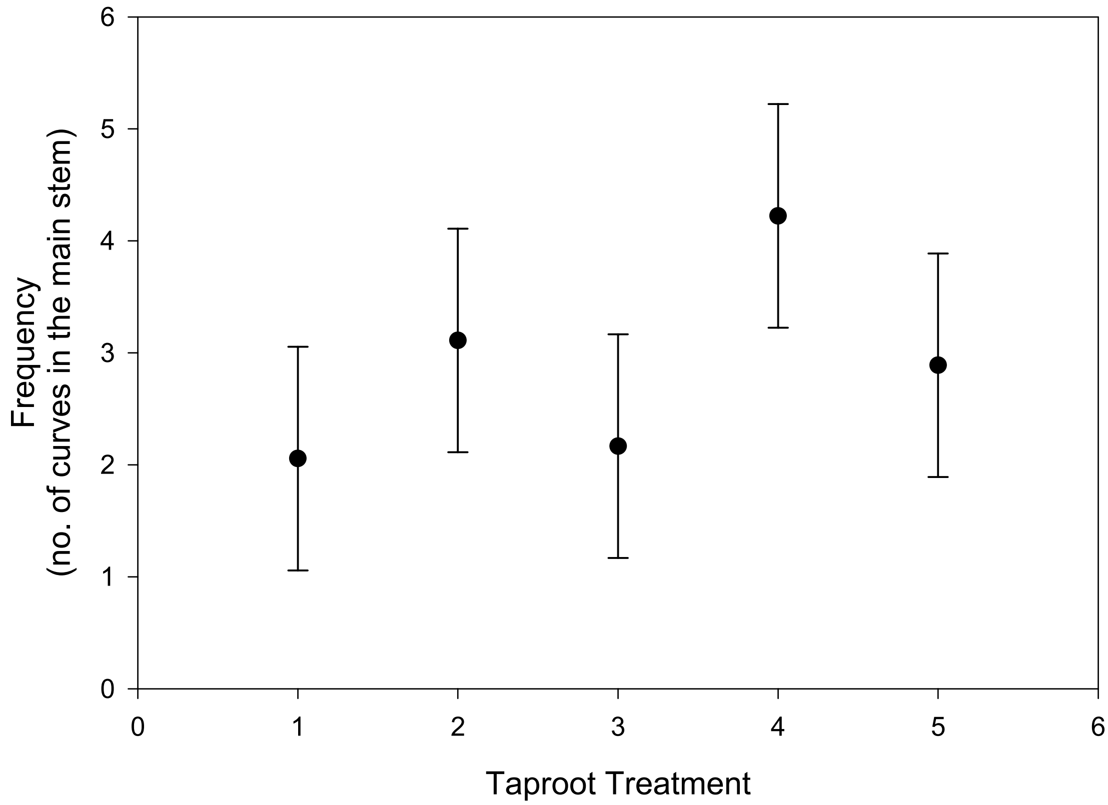
Table 2.1 Whitehall year one ANOVA p-values (effects were considered significant if $p \leq 0.05$).

Variable	Treatment	Family	Interaction	Block
Diameter	0.0382	0.0081	0.8548	0.8682
Height	0.5778	0.0003	0.9863	0.9608
Frequency	0.0122	0.0001	0.0977	0.1968
Amplitude	0.1121	0.0035	0.2352	0.0447



1 – control
2 – taproot obstruction
3 – J-root
4 – angled planting
5 – guy-wired planting

Figure 2.3 Year one taproot treatment diameter means with 95% confidence intervals.



1 – control
2 – taproot obstruction
3 – J-root
4 – angled planting
5 – guy-wired planting

Figure 2.4 Year one taproot treatment frequency means with 95% confidence intervals.

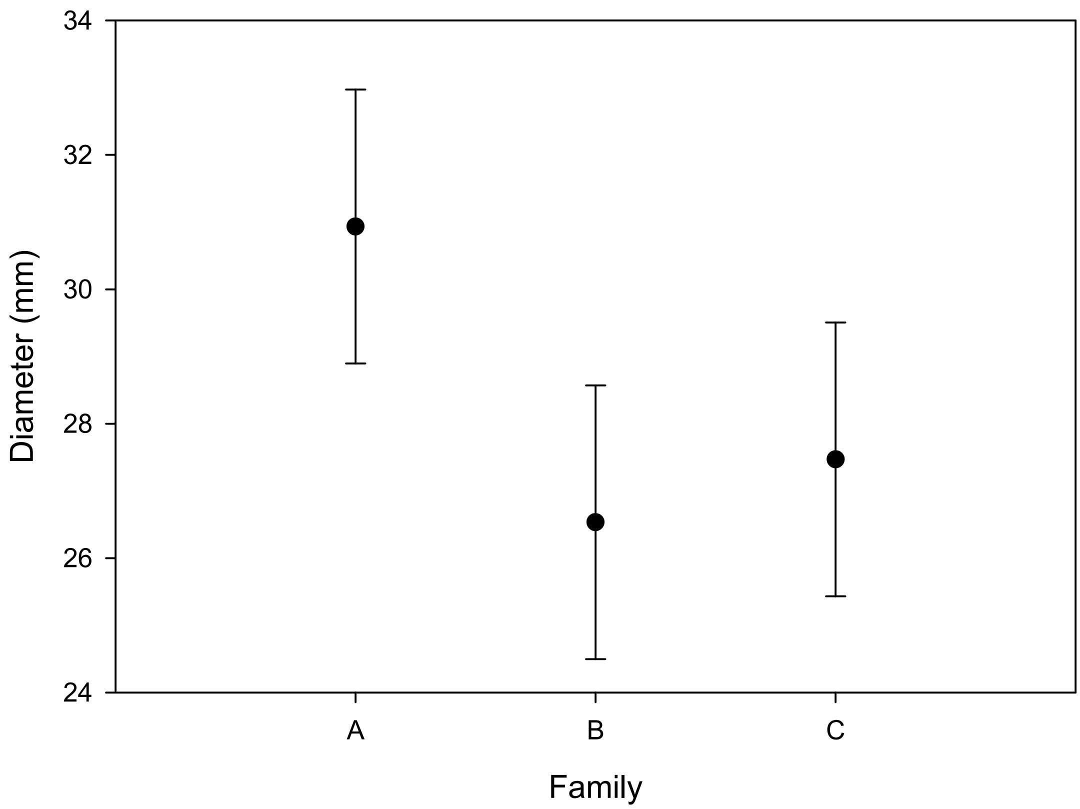


Figure 2.5 Year one family diameter means with 95% confidence intervals.

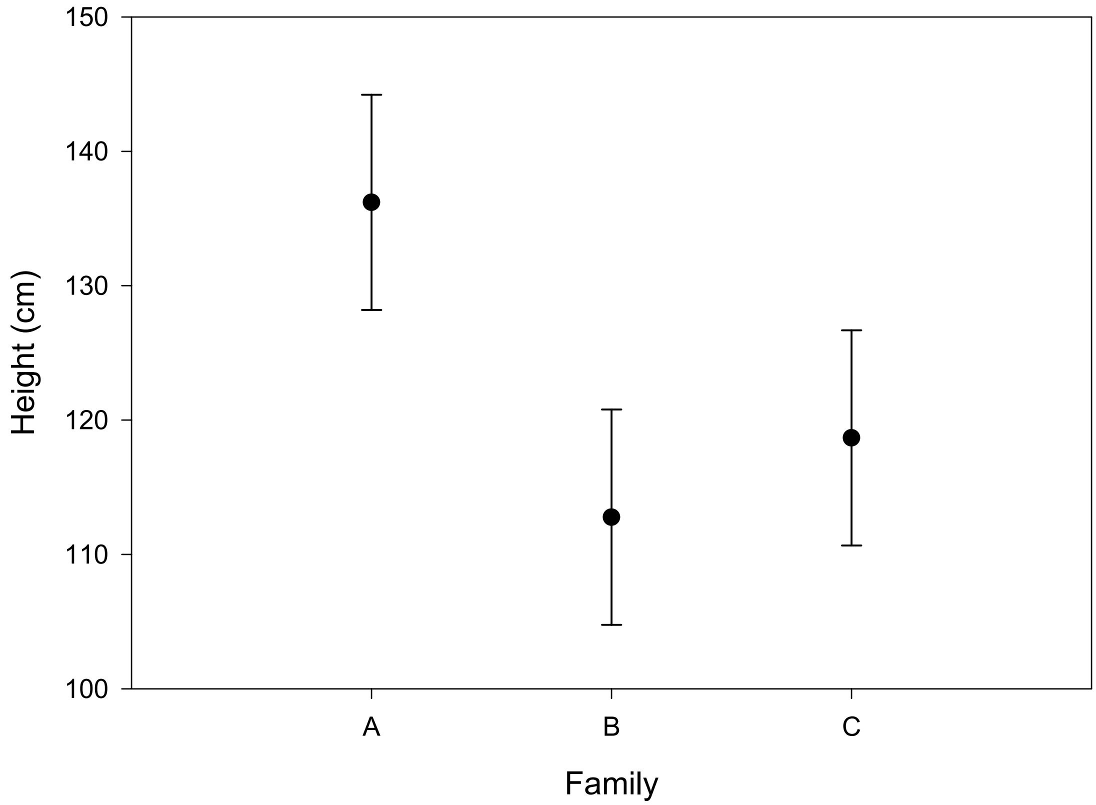


Figure 2.6 Year one family height means with 95% confidence intervals.

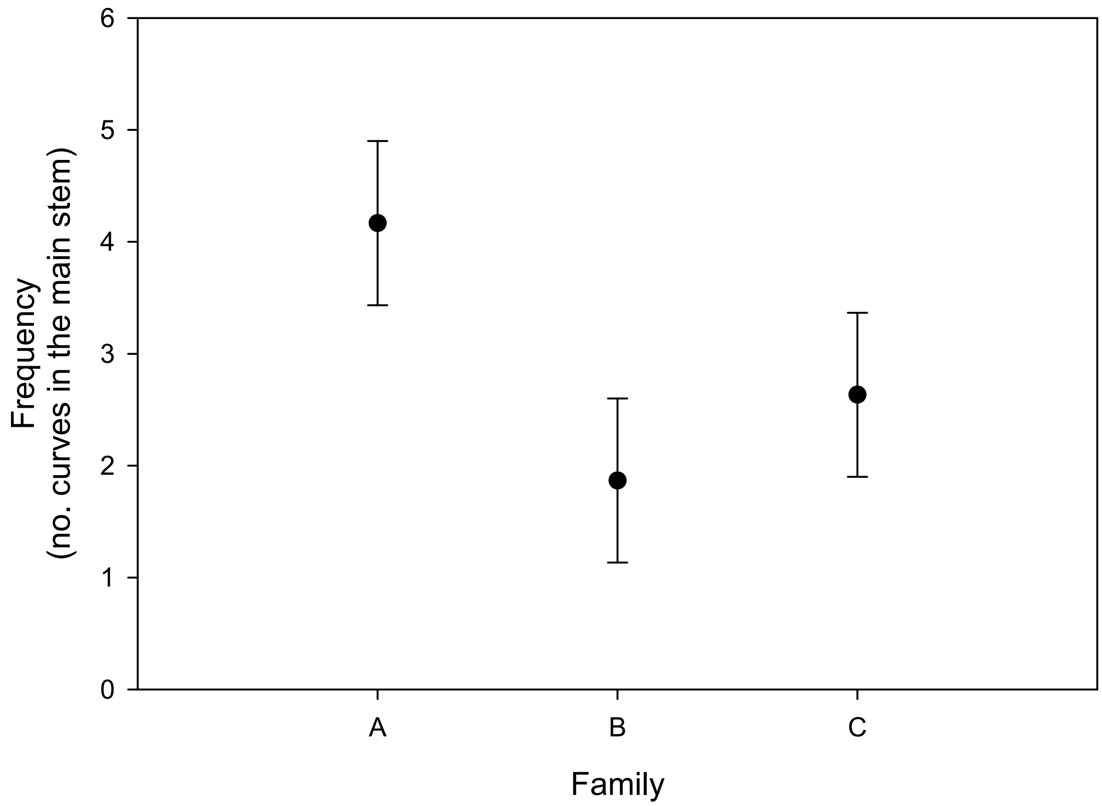


Figure 2.7 Year one family frequency means with 95% confidence intervals.

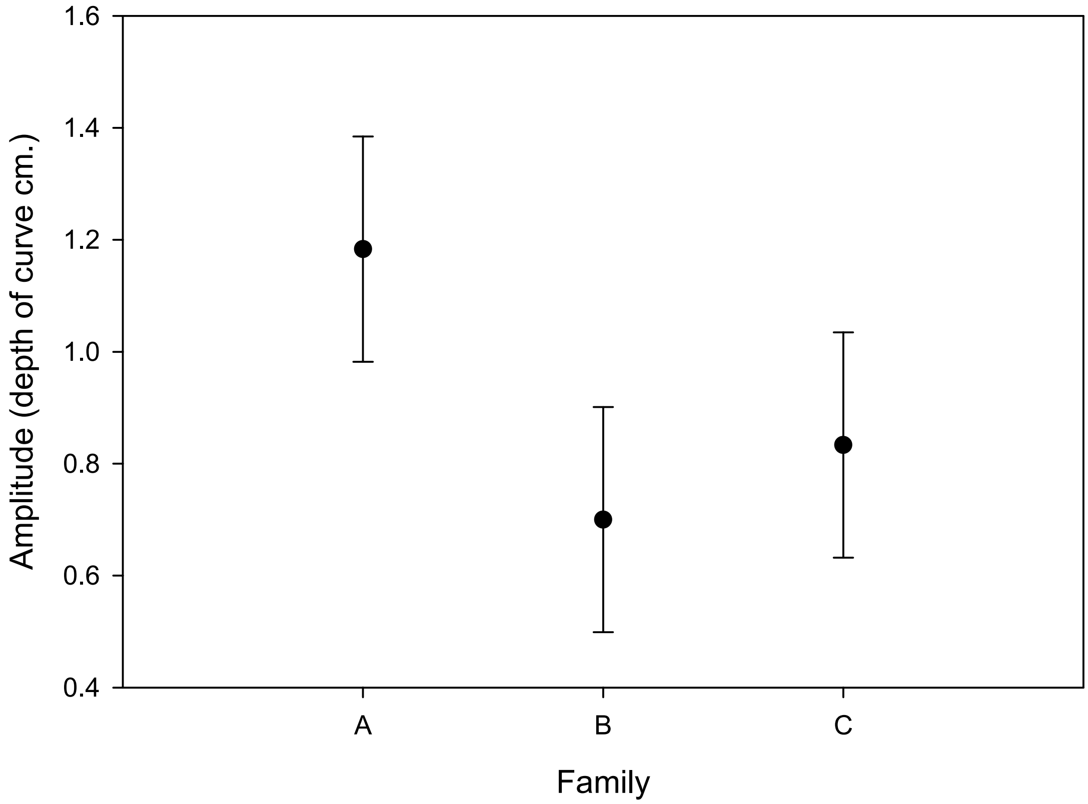


Figure 2.8 Year one family amplitude means with 95% confidence intervals.

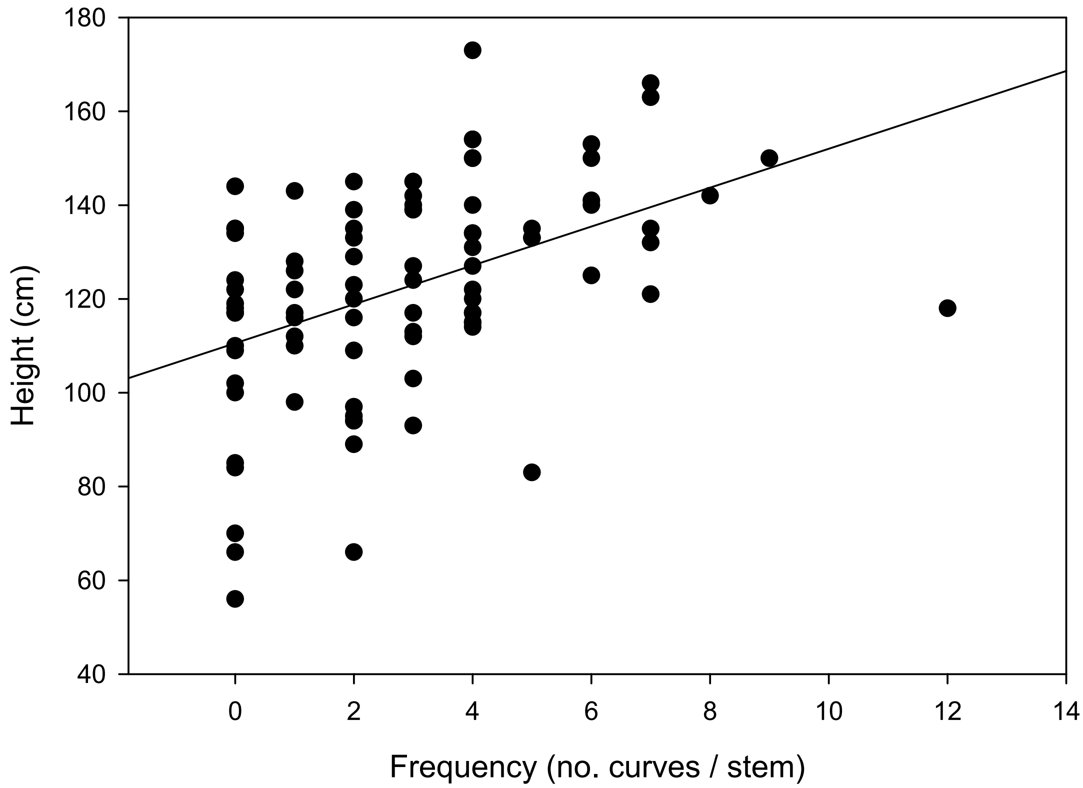


Figure 2.9 Year one height / frequency regression (r^2=0.237, n=90).

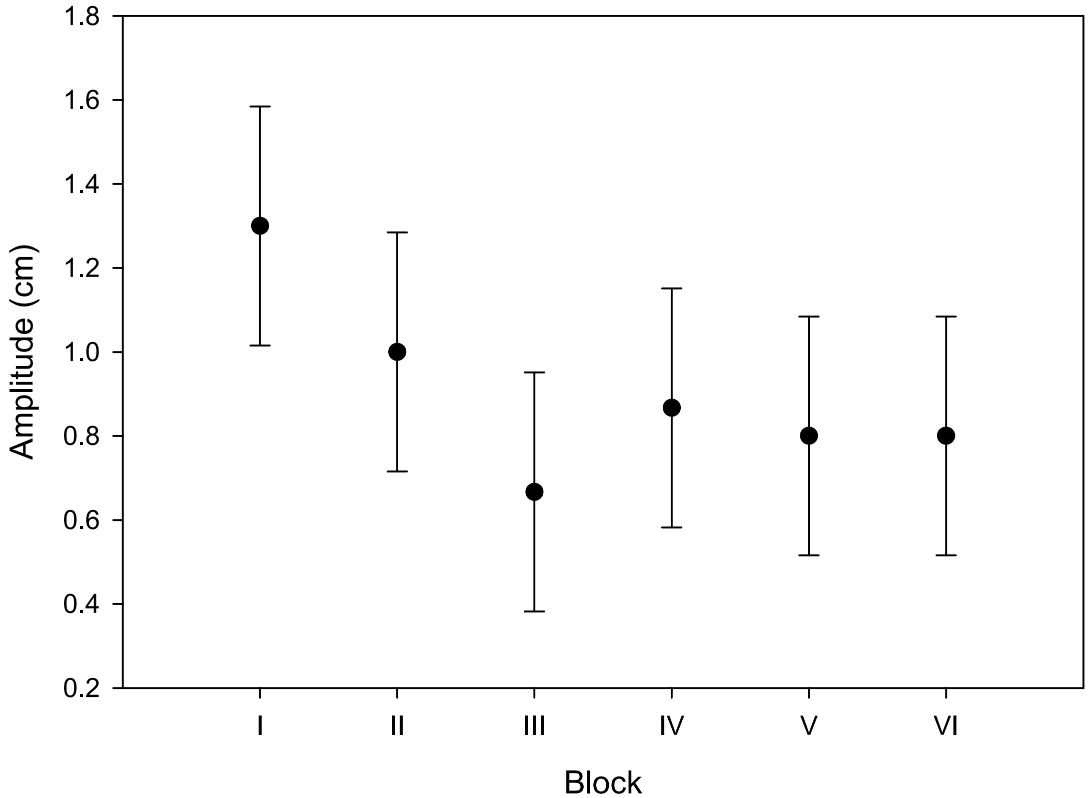
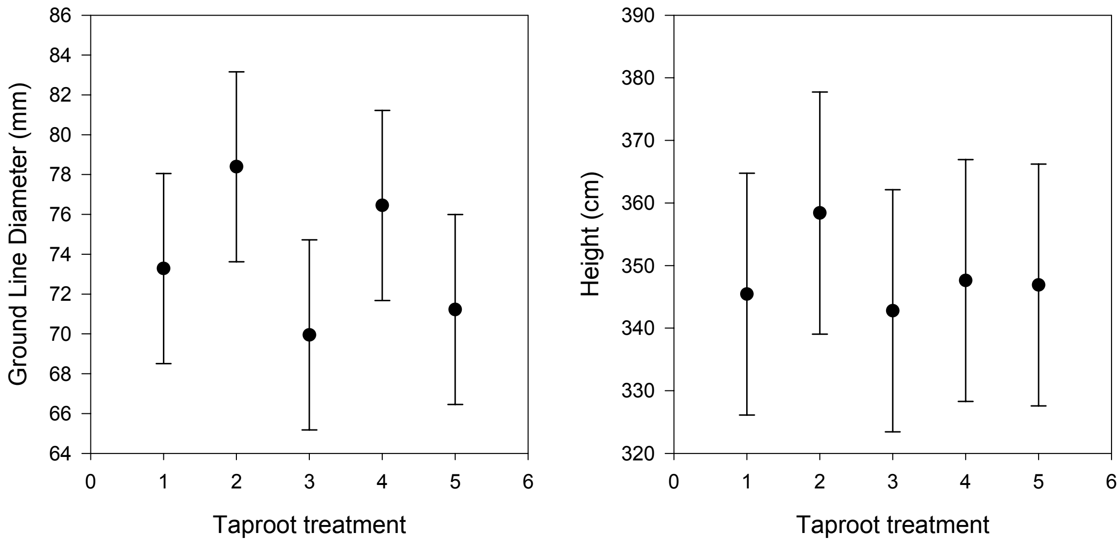


Figure 2.10 Year one block amplitude means with 95% confidence intervals.

Table 2.2 Whitehall year two ANOVA p-values (effects were considered significant if $p \leq 0.05$).

Variable	Treatment	Family	Interaction	Block
GLD	0.0804	0.0738	0.9295	0.2281
DBH	0.5808	<0.0001	0.9722	0.7398
Height	0.8220	<0.0001	0.8380	0.9653
Frequency	0.0823	0.0029	0.2240	0.3986
Amplitude	0.3714	0.0951	0.0368	0.2883



1 – control
2 – taproot obstruction
3 – J-root
4 – angled planting
5 – guy-wired planting

Figure 2.11 Year two taproot treatment GLD and height means with 95% confidence intervals.

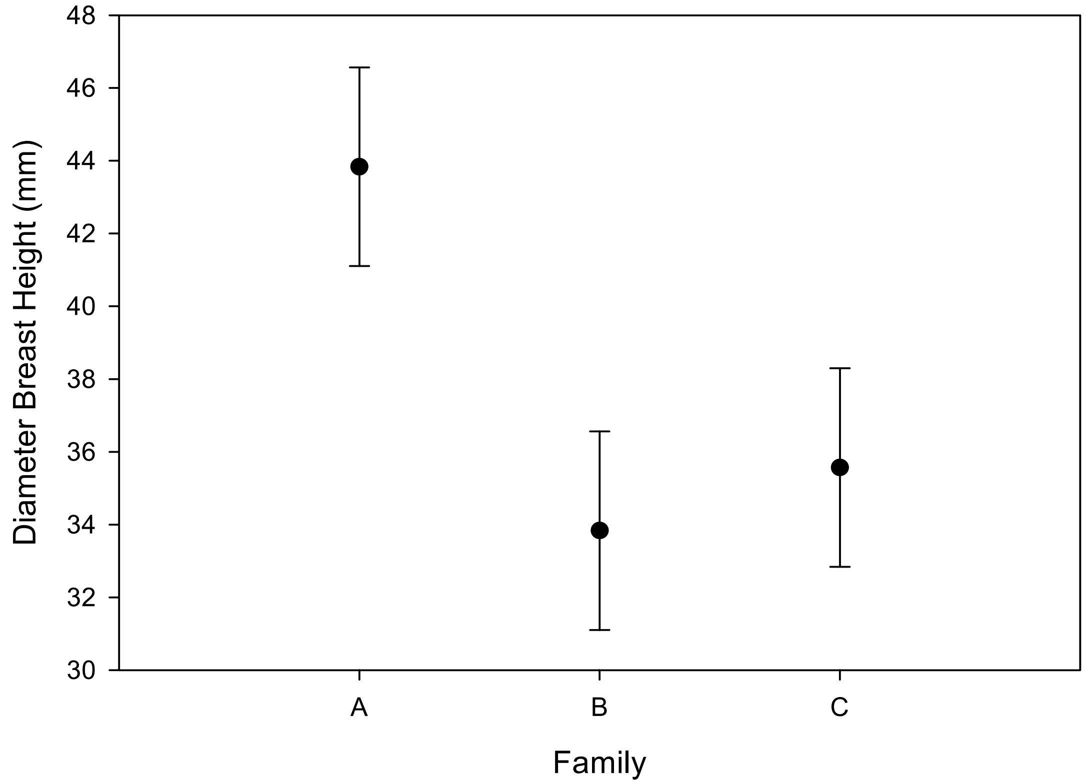


Figure 2.12 Year two family DBH means with 95% confidence intervals.

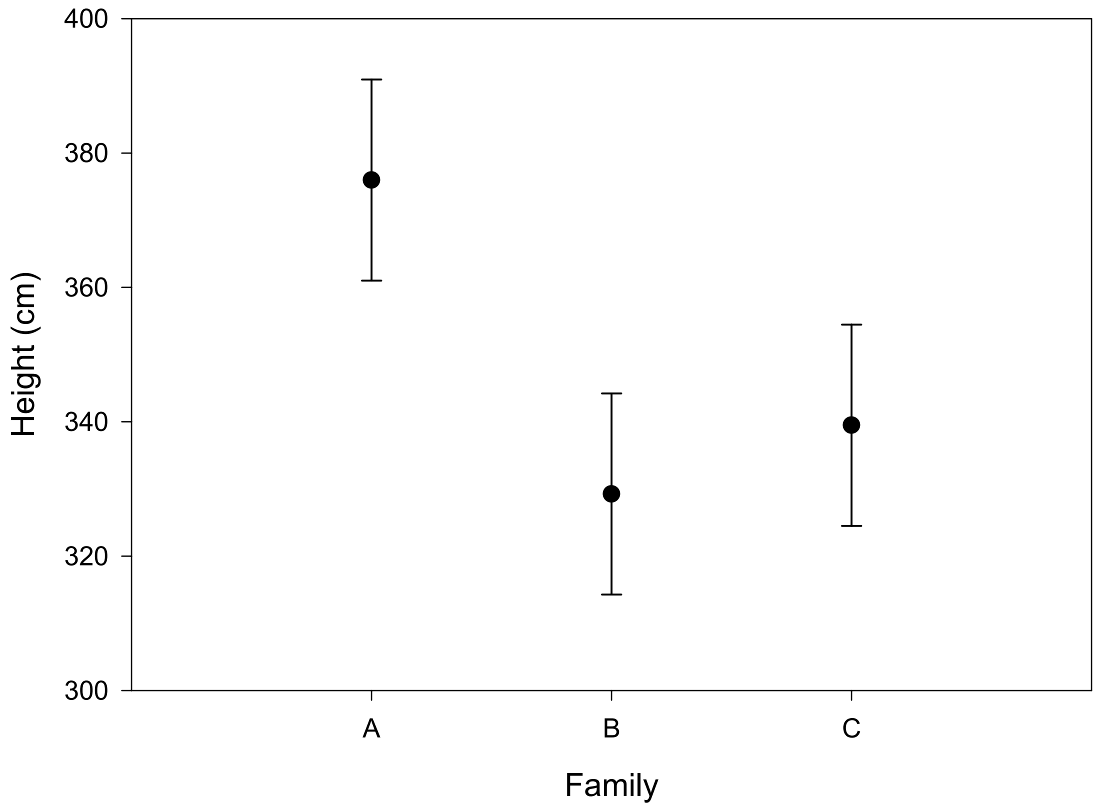


Figure 2.13 Year two family height means with 95% confidence intervals.

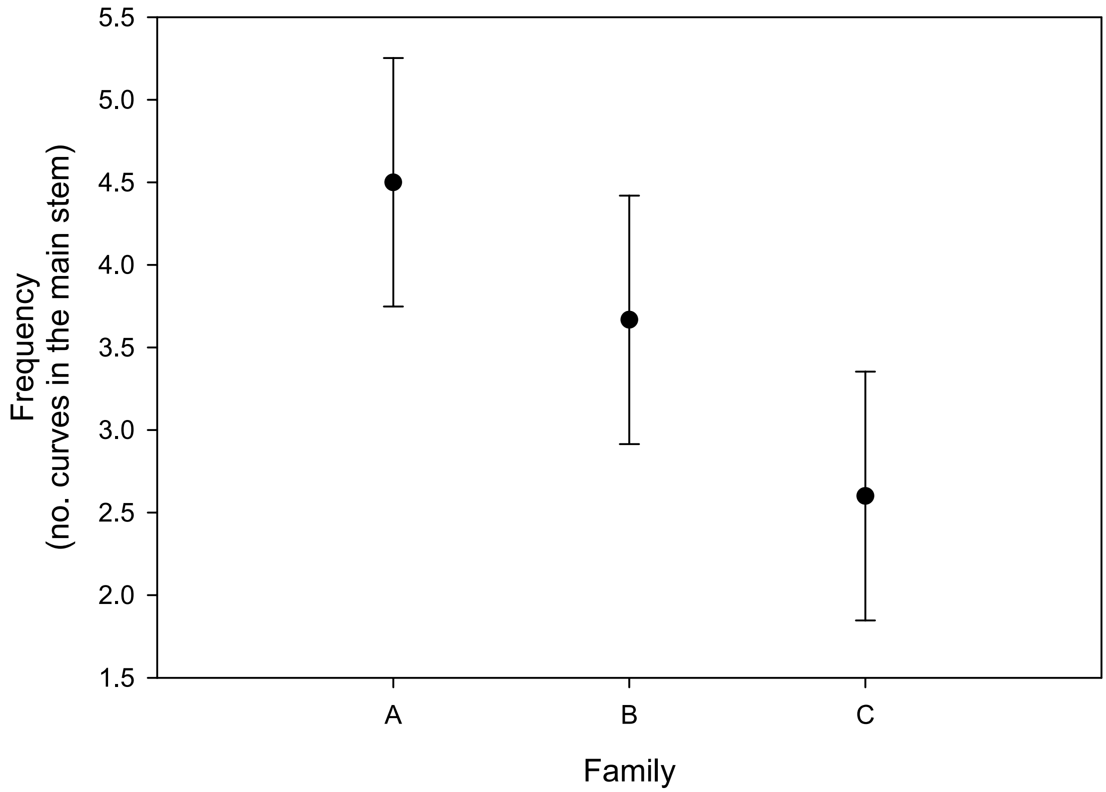


Figure 2.14 Year two family frequency means with 95% confidence intervals.

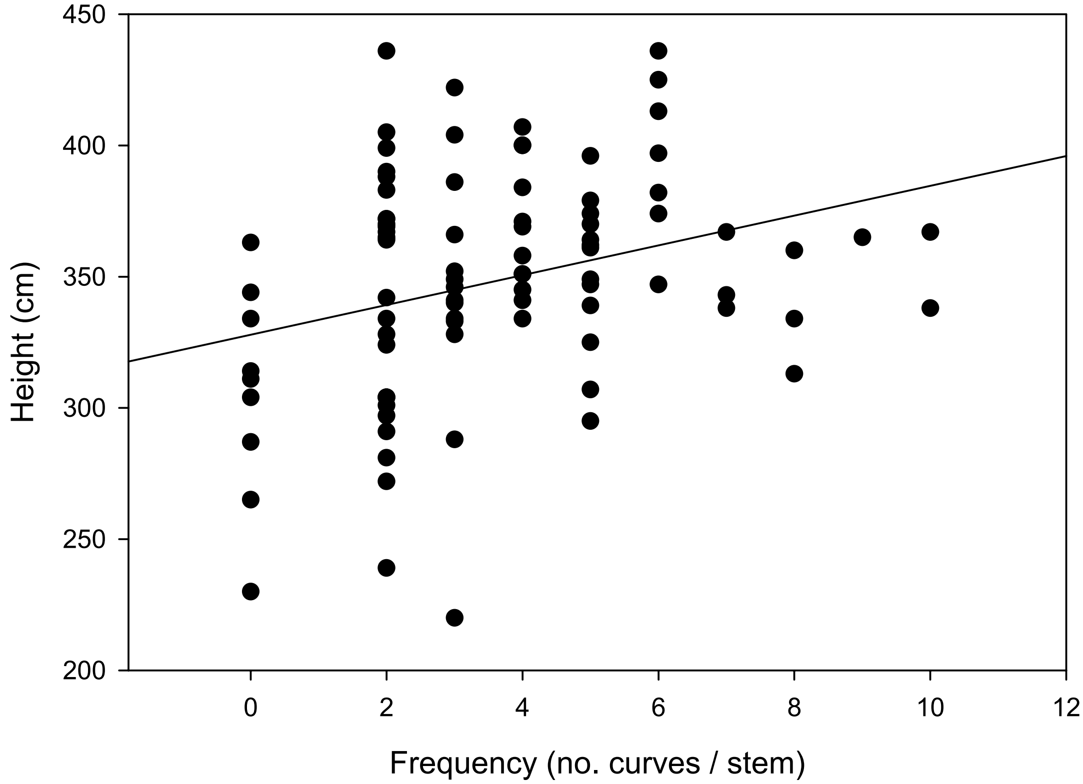


Figure 2.15 Year two height frequency regression (r^2=0.089, n=90).

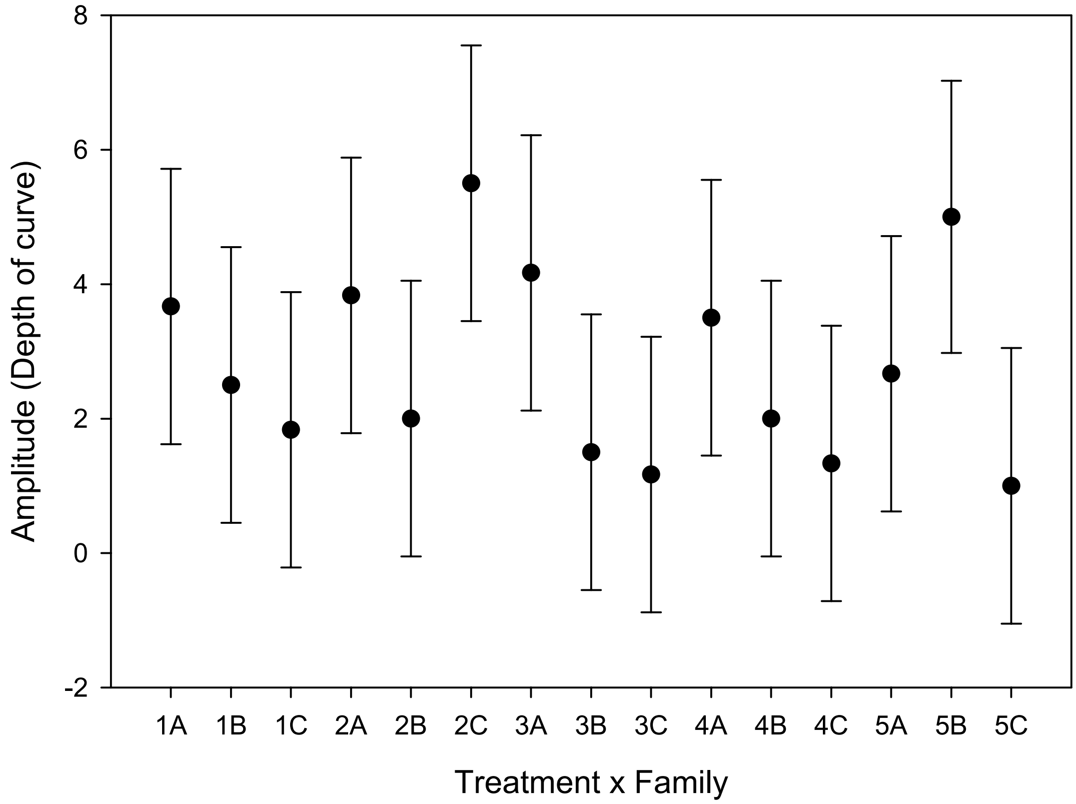


Figure 2.16 Year two amplitude interaction with 95% confidence intervals.

Table 2.3 Whitehall harvest ANOVA p-values (effects were considered significant if $p \leq 0.05$).

Variable	Treatment	Family	Interaction	Block
Frequency	0.7962	0.0007	0.1062	0.3753
Amplitude	0.2624	0.2317	0.3530	0.0440
Total Length	0.7803	0.1818	0.9225	0.4893
Wheel Length	0.7743	0.1704	0.9346	0.4906
Index	0.7182	0.8014	0.0236	0.7846
Biomass	0.8484	0.1609	0.3819	0.4654

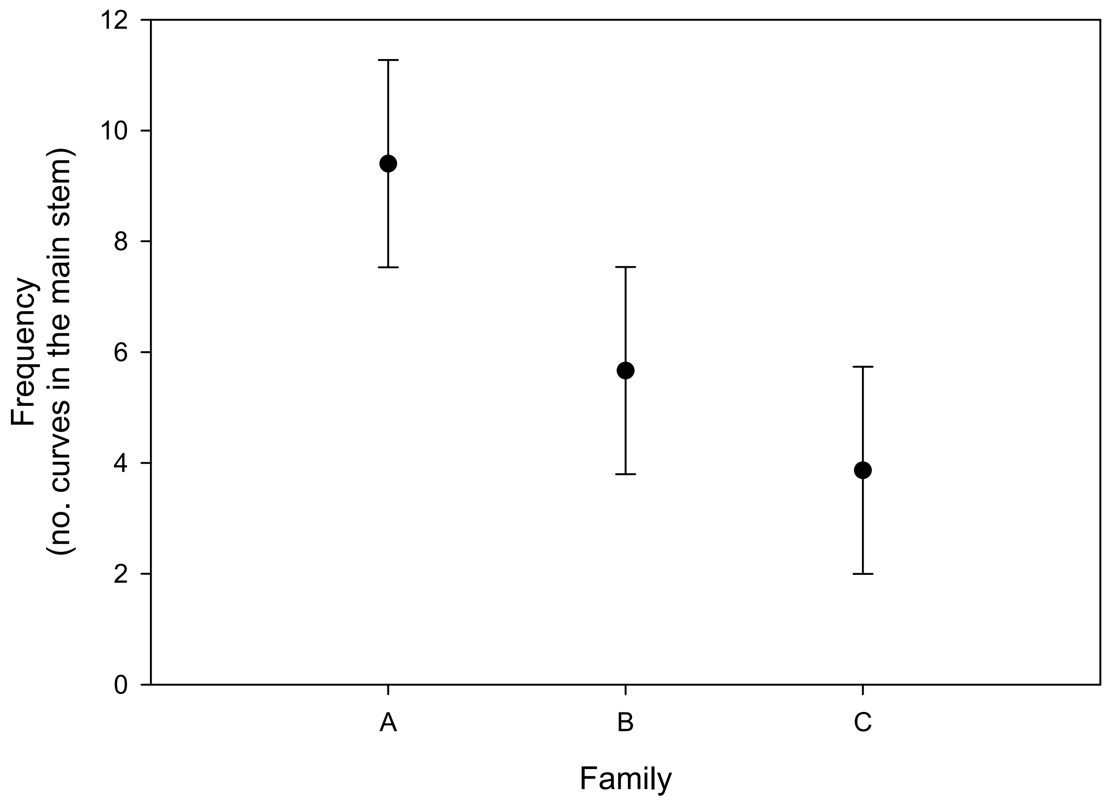


Figure 2.17 Harvest family frequency means with 95% confidence intervals.

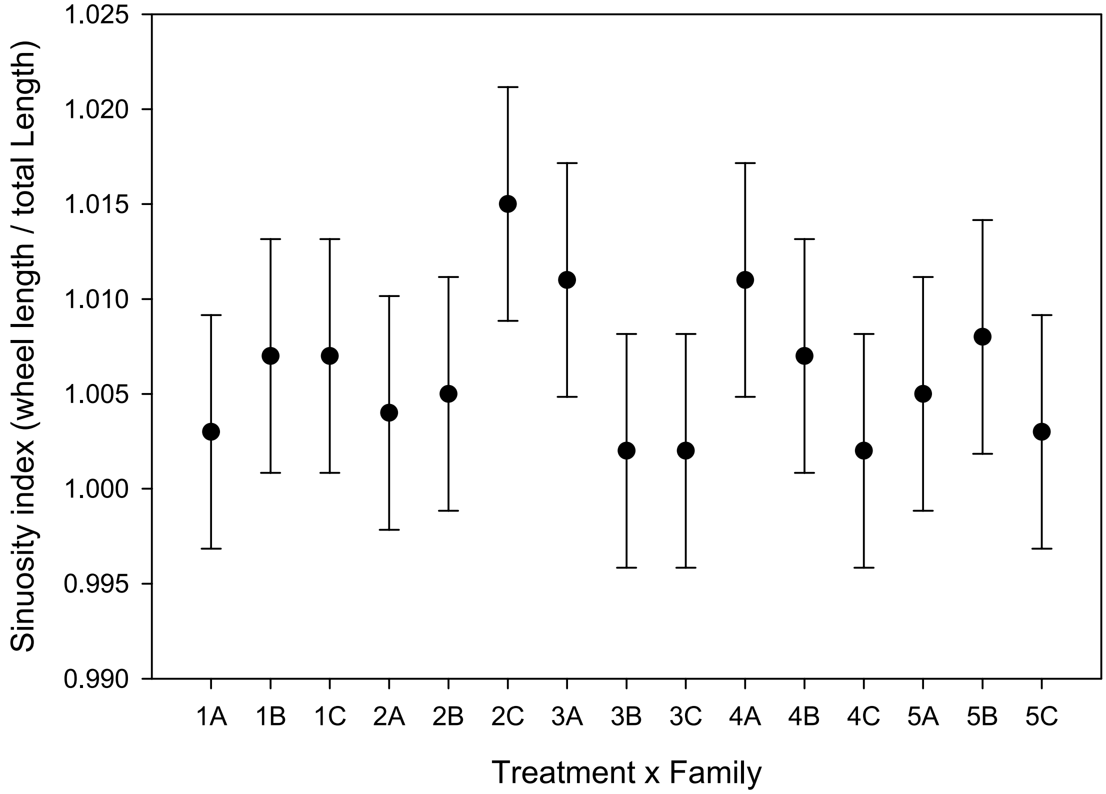


Figure 2.18 Harvest interaction sinuosity index means with 95% confidence intervals.

Table 2.4 Root treatment means for year one, year two, and harvest.

Measurement	*Variable*	*Root Treatment*				
		1	*2*	*3*	*4*	*5*
Year One	*GLD (mm)	27.4	31.3	25.8	29.6	27.4
	Height (cm)	118.9	127.2	116.9	125.8	123.4
	*Frequency	2.8	3.7	2.4	4.7	2.9
	Amplitude	1.0	0.9	0.7	1.1	0.7
Year Two	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
	Amplitude	2.7	3.8	2.3	2.3	2.9
Harvest	Frequency	5.2	7.3	6.4	6.4	6.1
	Amplitude	1.7	3.0	1.7	1.9	1.8
	Length (cm)	347.2	352.8	341.0	332.3	357.7
	Wheel (cm)	349.1	355.6	342.8	334.4	359.4
	Biomass (g)	1786.5	1927.9	1767.8	1792.7	1993.8

* - indicates a significant difference at $p \leq 0.05$

1 - control
2 - taproot obstruction
3 – J-root planting
4 – angled planting
5 – guy-wired planting

CHAPTER 3

STEM SINUOSITY IN SLASH (*Pinus elliotti* Engelm.) AND LOBLOLLY PINE (*Pinus taeda* L.) WITH THREE ROOT TREATMENTS [1]

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[1] Murphy, M.S. and T.B. Harrington. 2004. To be submitted to *Southern Journal of Applied forestry*.

ABSTRACT

Six loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliotti* Engelm.) plantations were established in the Piedmont, Upper Coastal Plain, and Lower Coastal Plain of Georgia in 1997 or 1999. At each location, seedlings were planted with three different taproot configurations (J, L, or straight-rooted) as the main treatment. Split-plot treatments were weed control/fertilization *versus*. no treatment. During the winter of 2003-2004, measurements were collected for ground line diameter, diameter at breast height, height, frequency (number interwhorl curves), and amplitude (severity of curve) to assess growth differences and sinuosity symptoms. Significant main treatment differences existed for DBH, height, and frequency at one location (Upper Coastal Plain) and amplitude at another (Piedmont). No significant differences were found between split treatments or their interaction with the main treatments. While not significant, growth varied among the main treatments at each location.

Key words: taproot, stem form, fertilization, J-root, L-root

INTRODUCTION

In this study we tested the hypotheses that there would be stem form and growth variation among three taproot treatments, there would be stem form and growth variation among plots split on the basis of whether they had received weed control and fertilization or not, and there would be stem form and growth variation among the taproot treatment and split plot interaction. Measurements were collected on three to six year-old loblolly (*Pinus taeda* L.) and slash pine (*Pinus elliotti* Engelm.) that were grown with three different taproot manipulations (J, L, straight root) and with or without weed control / fertilizer regimes.

Artificial regeneration of loblolly and slash pine is accomplished through hand planting or machine planting. Large scale plantings must be established with swiftness and efficiency, leaving the possibility of poorly planted trees. Historically, speculation has existed regarding the effects of root deformity on stem growth. Harrington and Gatch (1999) excavated 3 to 10 year-old loblolly pine to determine if taproots were bent or straight and if these responses were related to stem form. It was found that trees with bent taproots had medium to high levels of sinuosity, while those with straight taproots had low levels. Research related to taproot form and sinuosity is scarce, and most research associated with negative aspects of root deformity deal with growth variations and survival. Many consider trees planted with a J-root or other poor form will result in decreased wind resistance. (Hunter and Maki, 1980, Harrington *et al*. 1989, Lindström and Rune, 1999). Greater diameter growth has been reported for trees with deformed roots (Hunter and Maki, 1980) (Harrington *et al.*, 1989) (Seiler *et al.*, 1990), while others have found greater growth among straight rooted trees (Harrington and Gatch, 1999).

METHODS

Study Sites

Six sites were established in the Piedmont, Upper Coastal Plain, and Lower Coastal Plain of Georgia to test three root treatments for loblolly and slash pine. These sites varied by location, species, establishment date, and follow-up maintenance (Table 3.1).

Experimental Design

The experimental design of this study was a split plot (weed control/fertilization *versus* no treatment) with main plots (J-, L-, or straight-rooted) assigned to a completely randomized design for a total of three replications per site. A total of six sites were established: three loblolly pine and three slash pine. Each location was divided into nine main plots, sub- divided into 18 split plots. Each split plot contained 25 trees. Sites were replanted or interplanted to replace mortality as necessary (Table 3.1). Three of each main treatments (J-, L-, or straight-root) were randomly assigned to the nine plots at each location. J-root trees were planted with the taproot bent into a J shape, with the root tip pointing upward and parallel to the planting row. L-root trees were planted with the taproot bent midway and the root tip pointing perpendicular to the stem and parallel to the planting row. Straight root trees were planted with the taproot vertically aligned with the tree.

Measurements

Data were collected during the winter of 2002-2003 at all six locations for ground line diameter GLD, diameter at breast height DBH, height, frequency, and amplitude. Calipers were used for diameter measurements. For the stands with smaller trees, a telescoping fiberglass height pole was used to measure height. For stands with larger trees, height was collected with a Vertex III hypsometer manufactured by Haglof of Sweden. Frequency was determined by counting all prominent interwhorl curves that occurred along the main stem. Average amplitude was estimated as the cumulative depth of the curve(s) in centimeters divided by the total frequency.

RESULTS

Mortality

There was no discernable pattern for tree mortality among treatment (Figure 3.1). At two sites, Milledgeville and Cordele, the plantations followed the anticipated pattern of highest mortality among J-root trees and lowest mortality for straight root trees. The other sites showed much variation, with the exception of Fort Valley slash pine, which had the greatest mortality for the L-root treatment. The high mortality of the straight root treatment for the Waycross site cannot be interpreted as most of this treatment was destroyed by fire in 2003.

Growth and Sinuosity

Significant differences existed for DBH, height, and frequency at Milledgeville (Table 3.2). The straight root treatment lagged behind in diameter and height growth (Figure 3.2), while J and straight root treatments differed significantly for frequency, with the J-root treatment being higher (Figure 3.3).

One significant difference occurred at Juliette for amplitude (Table 3.2). The L-root treatment differed significantly from the straight treatment with a higher amplitude, while the J-root treatment was intermediate (Figure 3.4). While not significant, trees receiving the J-root treatment had the lowest mean DBH and height (Table 3.3).

There were no significant effects for the Fort Valley loblolly pine (Table3.2). Mean DBH and height values were lowest for the L-root treatment (Table3.3).

There were no significant effects for the Fort Valley slash pine (Table 3.2). Straight-rooted trees grew slightly less than (J) or (L) treatments with the (L) rooted trees having the overall greatest growth (Table 3.3).

There were no significant effects for any variables at Cordele (Table 3.2). Mean GLD, DBH, and height values were greatest for trees with the straight root treatment (Table 3.3).

There were no significant effects for any variables at Waycross (Table 3.2). Mean GLD, DBH, and height were greatest for trees with the J-root treatment (Table 3.3).

DISCUSSION

Trees with malformed roots may be at a disadvantage for growth and survival. Trees planted with a J or L shape may have more limited access to water and nutrients than those with straight roots because of diminished lateral root growth. Lateral roots are required to capture water received from light showers that do not penetrate soil layers surrounding deeper roots. In a study comparing planted and naturally regenerated loblolly and shortleaf pine (*Pinus echinata* Mill.) root characteristics, fewer first-order lateral roots were found among planted trees. In this same study, trees with malformed roots were found to be more susceptible to wind damage until their lateral roots developed, as infrequent toppling of some planted trees but none of the seeded trees was noted. Upon excavation of these trees it was found that either the taproot had been J-rooted at planting or major lateral roots were largely absent from one side of the tree (Harrington *et al.*, 1989). Lindström and Rune, (1999) found decreased stability among planted Scots pine when compared to naturally regenerated trees. These effects may be responsible for the higher mortality among the J-root treatments for the Milledgeville and Cordele sites and the L root treatment at the Fort Valley loblolly pine site (Figure 3.1).

It has been proposed that J-root trees are not at a disadvantage nor are they more susceptible to drought. Seiler *et al.* (1990) found no differences in water potential for J-root versus straight root trees; however J-root trees may be at a disadvantage early in life because of their shallow roots.

The significant growth differences that occurred at the Milledgeville site support the hypothesis that taproot form is related to stem form, yet these differences are not clear for the other sites. The Milledgeville site results are unexpected given the outcome of the Whitehall seedling study. Straight-root trees lagged behind in DBH, and height, whereas in the Whitehall study J-root trees grew the least. Straight root trees also had decreased growth for the Fort Valley slash pine and Waycross sites. The anticipated trend of decreased growth for the J-root treatments was apparent at the Juliette and Cordele sites.

Woods (1980) found the greatest mean diameter growth for trees planted with an (L) root, when compared with other root treatments. This may be explained by swelling at the root collar area that can occur when a tree's roots are deformed. Hunter and Maki (1980) found that curl-rooted trees had a more pronounced swelling at the root collar than straight-rooted trees. Significantly greater diameter growth was found at the 12 cm level for planted loblolly pine when compared to seeded trees (Harrington *et al.*, 1989). Significantly greater height growth and biomass was found for loblolly and white pine J-rooted trees after three years of growth (Seiler *et al.* 1990). Conversely, significantly greater DBH and height growth was found for trees with straight versus bent taproots. These trees also exhibited lesser symptoms of sinuosity (Harrington and Gatch, 1999).

Interestingly, there were no split plot variations. The data collected only represents the growing season of 2003. Fertilization occurred at plantation establishment and weed control was practiced 2-3 times after establishment. It is likely that the initial differences that may have occurred stabilized over this time period as density and crown closure were reached. Jokela *et al.*, (2004), found increased growth for loblolly pine with fertilization and weed control treatments over a wide range of southern US sites. On several sites this growth was found to decline sharply as soon as treatments ceased. The lack of variation among split treatments in our study may be a result of early decreased growth caused by the Arsenal® application. Additionally, Jokela *et al.*, (2004) found stand density to be the biggest factor affecting diameter growth. Crown closure has been reached at both Juliette and the Fort Valley loblolly pine sites.

CONCLUSION

While significant differences were only found on only two sites, the variation in growth supports past findings of both increased and decreased growth for trees with deformed roots. From visual observation, many individual trees at each site had moderate to severe symptoms of sinuosity, and these trees likely had high frequency and/or amplitude sinuosity measurements. Because these trees did not heavily influence the means, they may be exceptional in their response. These findings reinforce the difficulty in classifying sinuosity and suggest a need for future research into its causes.

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Table 3.1 Site location, history, and follow-up

Location	*Species*	*Date Planted*	*Date Replanted*	*Herbaceous Veg. Control*	*Fertilize*	*Other herbicide treatments*
Milledgeville	loblolly	1997	2000	1997[b]/1998[c]	1997[f]	2000[i]
Juliette	loblolly	1997	-	1997[b]	1997[f]	1999[j]
Fort Valley	loblolly	1997	-	1997[b]	1997[f]	-
Fort Valley	slash	1999	2000	1999[d]/1999[e]	1999[h]	2000[i]/2001[k]
Cordele	slash	1999	2000[a]	1999[d]	1999[h]	1998[g]/2000[i]/2001[k]
Waycross	slash	1999	2000[a]	1999[d]	1999[h]	2000[i]/2001[k]

[a] replaced dead seedlings only

[b] banded (1.22 m width over seedlings) application to split plots in March (170 g Oust® herbicide in 374.2 l of water per treated hectare)

[c] broadcast site preparation spray in June to all plots (710.4 ml Arsenal® AC plus 5.7 l Accord® herbicides in 187.1 l of water plus 1% surfactant per hectare)

[d] banded (1.22 m width over seedlings) application to split plots in March (177.6 ml Arsenal® herbicide in 140.3 l of water with no surfactant per treated hectare)

[e] broadcast site preparation spray in October to all plots (1.89 liters Accord® plus 236.8 ml Arsenal® herbicides applied in 140.3 l of water with ½ % surfactant per hectare)

[f] fertilization to split plots in June with urea and triple super phosphate (TSP) (56.0 kg/ha elemental N and P)

[g] broadcast application in September to all plots to control nutsedge (3.8 l Accord® herbicide in 765.7 l of water per hectare with 1% surfactant).

[h] fertilization to split plots in April with TSP only (56.04 kg/ha elemental P)

[i] broadcast competition release spray in March to all plots (710.4 ml Velpar® and 56.7 g Oust® herbicides in 140.31 l of water per hectare)

[j] broadcast competition release spray in October to all plots (473.6 ml Arsenal® plus 28.3 g Escort® herbicides and ¼ % surfactant in 233.9 l of water per hectare)

[k] broadcast competition release spray in March to all plots (947.2 ml Velpar® and 56.7 g Oust® herbicides in 140.31 l of water per hectare)

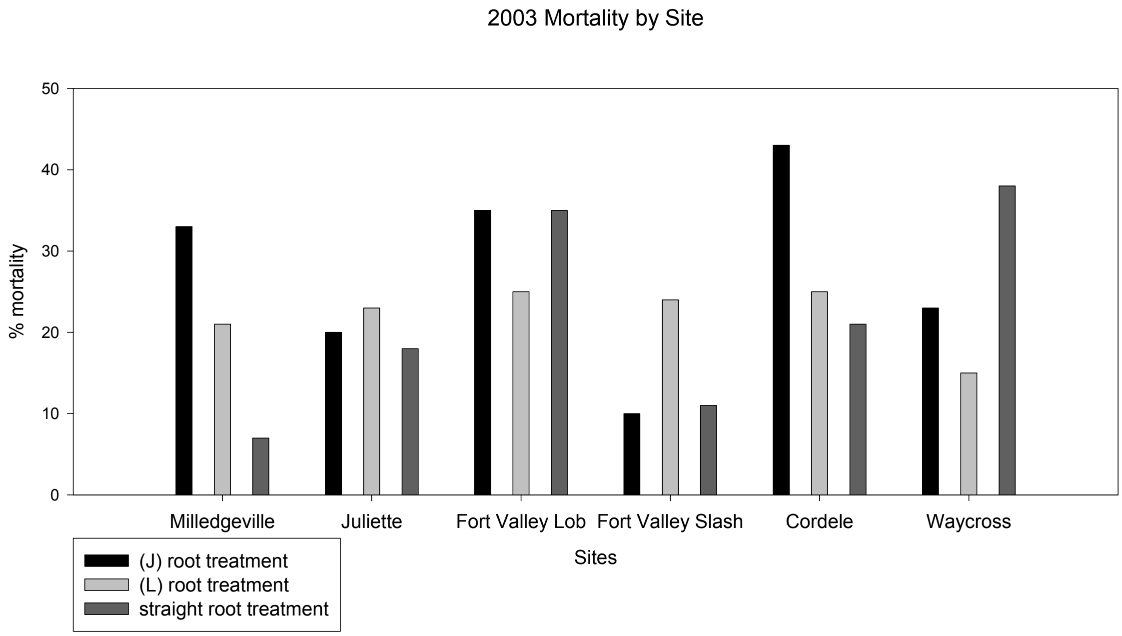

Figure 3.1 Site mortality by treatment

Table 3.2 Analysis of variance p-values by site (effects were considered significant if p≤0.05)

Location	*Variable*	*Main Treatment*	*Split Treatment*	*Mtrmt x Strmt*
Milledgeville	GLD	0.1688	0.7450	0.1361
	DBH	0.0067*	0.4251	0.0953
	Height	0.0061*	0.5500	0.0707
	Frequency	0.0287*	0.1745	0.2416
	Amplitude	0.6419	0.0811	0.2967
Juliette	GLD	--	--	--
	DBH	0.1204	0.6765	0.3977
	Height	0.0639*	0.8025	0.5343
	Frequency	0.1432	0.6796	0.1112
	Amplitude	0.0437	0.8080	0.1348
Fort Valley[a]	GLD	--	--	--
	DBH	0.7820	0.2917	0.9915
	Height	0.5384	0.4900	0.4247
	Frequency	0.5287	0.9607	0.2842
	Amplitude	0.5286	0.8498	0.6541
Fort Valley[b]	GLD	0.9737	0.1802	0.7126
	DBH	0.6819	0.1198	0.5241
	Height	0.8894	0.1337	0.4456
	Frequency	0.5135	0.2124	0.8886
	Amplitude	0.4730	0.4828	0.9983
Cordele	GLD	0.1801	0.8667	0.1682
	DBH	0.1601	0.6226	0.1966
	Height	0.0713	0.8386	0.1956
	Frequency	0.3386	0.3986	0.4916
	Amplitude	0.9680	0.1515	0.6872
Waycross	GLD	0.5992	0.6037	0.7456
	DBH	0.2416	0.9241	0.7463
	Height	0.4485	0.5527	0.7418
	Frequency	0.6788	0.9249	0.5900
	Amplitude	0.5522	0.5427	0.3407

[a] loblolly planting
[b] slash planting

* - indicates significance at p ≤ 0.05

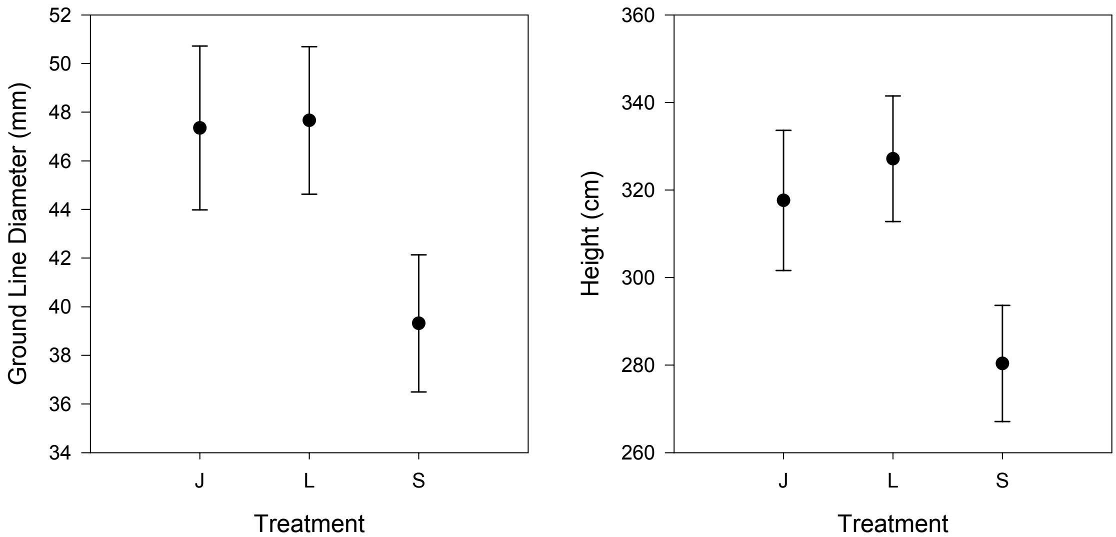

Figure 3.2. Milledgeville main treatment DBH and height means with 95% confidence intervals.

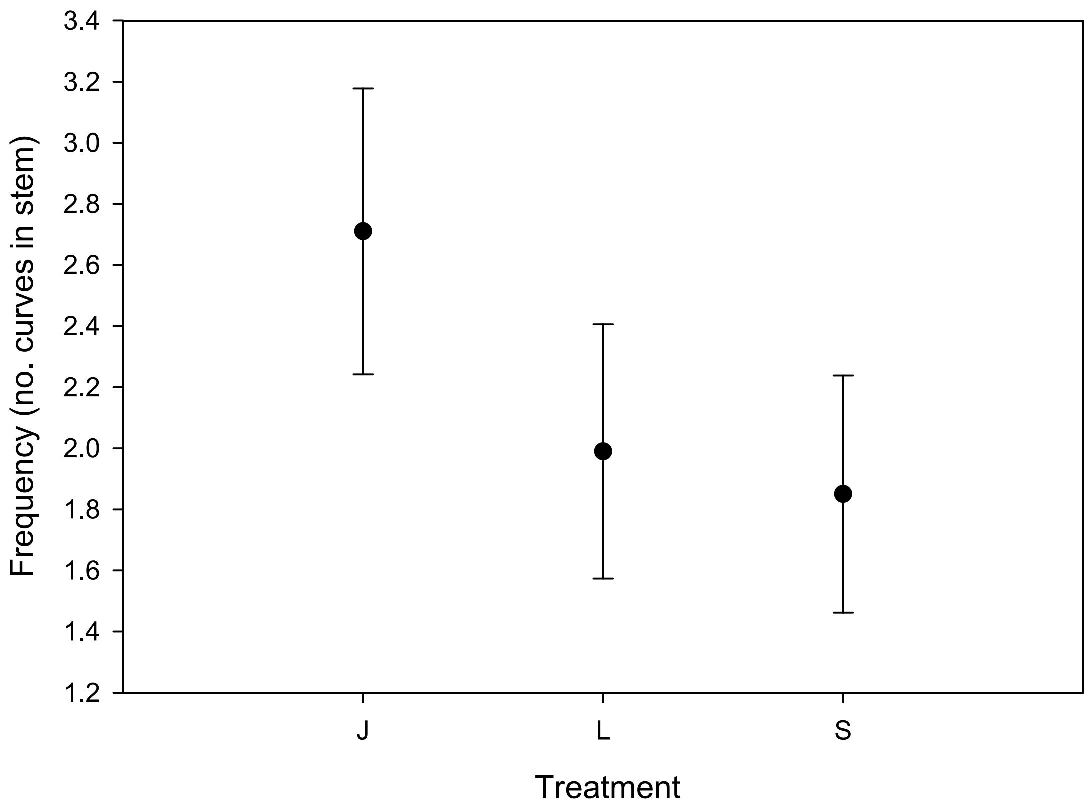

Figure 3.3 . Milledgeville main treatment frequency means with 95% confidence intervals.

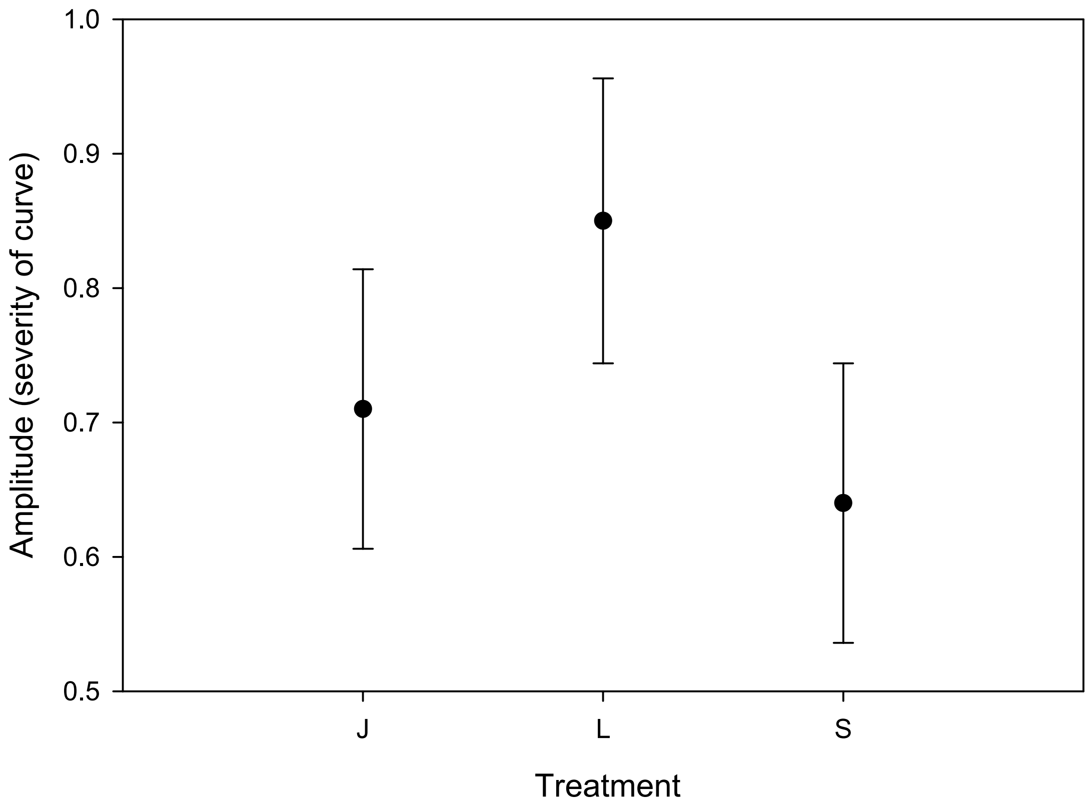

Figure 3.4. Juliette main treatment amplitude means with 95% confidence intervals.

Table 3.3. Root treatment means by site for all variables.

Tree Species	*Location*	*Variable*	*Root Treatment*		
			J	*L*	*S*
Loblolly Pine	Milledgeville	GLD (mm)	83.76	83.93	77..06
		*DBH (mm)	47.35	47.66	39.31
		*Height (cm)	317.60	327.12	280.36
		*Frequency	2.71	1.99	1.85
		Amplitude	0.77	0.70	0.69
	Juliette	DBH (mm)	48.78	54.84	54.86
		Height (cm)	371.62	419.09	409.45
		Frequency	2.05	2.46	1.84
		*Amplitude	0.71	0.85	0.64
	Fort Valley	DBH (mm)	110.72	107.45	111.28
		Height (cm)	643.65	633.94	674.67
		Frequency	2.25	2.74	2.98
		Amplitude	1.45	1.29	1.16
Slash Pine	Fort Valley	GLD (mm)	66.24	65.74	65.51
		DBH (mm)	37.86	40.51	37.85
		Height (cm)	269.46	275.66	266.19
		Frequency	2.14	2.35	1.87
		Amplitude	1.47	1.40	1.13
	Cordele	GLD (mm)	66.90	67.25	74.56
		DBH (mm)	35.80	37.46	41.55
		Height (cm)	257.08	277.78	296.55
		Frequency	1.85	1.51	1.32
		Amplitude	1.20	1.14	1.16
	Waycross	GLD (mm)	79.99	74.83	69.30
		DBH (mm)	48.29	40.75	37.68
		Height (cm)	301.54	269.01	260.88
		Frequency	0.86	0.69	0.20
		Amplitude	0.82	0.35	0.30

* - indicates significant difference at $p \leq 0.05$

CHAPTER 4

CONCLUSIONS AND SILVICULTURAL IMPLICATIONS

The demand to produce quality wood and diminish waste in intensively managed southern pin plantations is likely to increase in the future. The results of these studies lack conclusive evidence linking taproot form to stem form, but both studies showed the variation in growth caused by taproot form that should be considered when establishing plantations. In the Whitehall study, evidence was found supporting the role of genetics on growth and stem form characteristics enforcing the need for careful seedling selection.

In the Whitehall study reduced growth of the J-root treatment occurred in both years of the study. This influence of taproot form will likely increase over time as the root becomes more severely deformed with increasing growth; however because this study only includes measurements from the first two years of the seedlings' life, future possible changes are unknown. The role of family is more apparent as it had significant effects in both years for growth and form. The selection of family is already an important consideration when establishing a plantation. These results should hopefully lead to the encouragement of selection and breeding of loblolly and slash pine based on stem form characteristics.

For the older plantation study, significant growth differences among the taproot treatments were found on only two sites, while mean growth differences varied for all locations. The variation in growth supports past findings of both increased and decreased growth for trees with deformed roots. Only one significant difference existed for a stem form characteristic (frequency) at one location (Juliettte). Individual trees with extreme amplitude and frequency measurements were detected both visually and within the raw data, however were not expressed within the means. This should lead to future research that seeks to find other factors causing these symptoms and innovative approaches in quantifying them.