

ABSTRACT

DUNN, DILLON MATTHEW. Productivity and Stem Quality of 9-Year-Old Loblolly Pine (*Pinus taeda*) as Influenced by Site, Management, Pest Control and Genetics (Under the direction of Dr. John S. King).

Demand for forest products and fiber will continue to increase as populations rise, while the land base for producing timber products is decreasing. I investigated the effect cultural treatment intensity, systemic insecticides, and pine genetics had on growth and stem quality of 9-year-old loblolly pine grown in two physiographic regions of North Carolina. In December 2008 and January 2009 improved genotypes of loblolly pine were planted in whole plot treatments of herbaceous weed control at an upper coastal plain site (UCP) and phosphorus fertilization at a lower coastal plain site (LCP), with split plot treatments of systemic insecticide (imidacloprid), and split-split plot treatments of improved genetics. I inventoried measures of productivity and stem form defects, and calculated yield after 9 years of growth. Results show that systemic insecticide treatments improved growth by 58.0% and 9.1% at UCP and LCP, respectively. Yield is improved at UCP by 40% over controls, while at LCP there is no difference (0.04%) in yield between imidacloprid treatments and controls. Imidacloprid treatment shortened rotation length at UCP, as treatment plots have reached or are approaching a first thinning (115 ft² BA/acre) where control trees do not yet fully occupy the site (80 ft²/acre) by year nine. At LCP there is no difference between imidacloprid treatments and controls in terms of basal area per acre (116-118 ft²/ acre respectively). Systemic imidacloprid treatments significantly improve growth, yield and value of medium quality sites experiencing heavy pest pressure. Systemic imidacloprid applied at planting does significantly improve growth rate but does not improve yield or value of pine plantations grown on high quality sites and are likely not economically advantageous.

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Productivity and Stem Quality of 9-Year-Old Loblolly Pine (*Pinus taeda*) as Influenced by Site,
Management, Pest Control and Genetics

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University in
partial fulfillment of the
requirements for the degree of
Master of Science

Forestry and Environmental Resources

Raleigh, North Carolina
2019

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BIOGRAPHY

Dillon Dunn was born on May 11th, 1993 in Orange County, North Carolina to Janet and Michael Dunn. He was accompanied on this journey by his triplet brothers Taylor and Tyler Dunn and was named by his older brother Adam. Dillon lived in Moore county, North Carolina for his first 18 years, after which he moved to Raleigh and then Bahama, North Carolina to work on his undergraduate and graduate education.

In 2012 Dillon enrolled in North Carolina State University in the Department of Forestry and Environmental Resources where he majored in Forest Management. During his junior and senior years, he worked for the Department of Forestry as a teaching assistant, forest technician and tutor. After earning his bachelors of forest management at NC State, he married his best friend, Morgan Scalici Dunn, on October 15, 2016. In August 2017, he accepted a graduate teaching assistantship that allowed him to pursue his graduate work in forestry. In 2018, Dillon moved to Logan Utah with his wife, where she is pursuing a M.S. in Ecology at Utah State University.

ACKNOWLEDGMENTS

I thank my committee chair, Dr. John King, for all the work he has done in helping me complete this project. Dr. King accepted me as a Master of Science candidate in August 2017 and provided me with an opportunity to finish graduate school. I am grateful for his help and this opportunity.

I acknowledge the help of Dr. Clyde Sorenson and Dr. David Dickey. Dr. Sorenson provided me with specific insights concerning entomology that greatly improved the impact of my research. He also taught me the fundamentals of arthropod management which improved my understanding of integrated pest management and how it applies to pine plantation management. Dr. Dickey provided his statistical expertise for the project. Thank you both for your advice and expertise.

I want to thank all the professors and staff in the Department of Forestry. I have learned much of what I know from you. I would not have been able to complete this program without the transportation and facilities this department provided me.

I want to also thank the staff at the Hofmann forest HQ and the RMS staff as well as Dominic Manz and Connor Nesbit for your time and support throughout this project. This project would not have been possible without all the hard work and hours spent in the pines. Finally, I want to give special thanks to my wife, Morgan Dunn, for her support and help with editing this thesis.

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CHAPTER 1: PRODUCTIVITY OF 9-YEAR-OLD *Pinus taeda* L. AS INFLUENCED BY SITE, SILVICULTURE, PEST MANAGEMENT AND GENETICS

ABSTRACT

Pine plantation silviculture is expected to increase in acreage and intensity to meet the growing demand for forest products on a decreasing land base. Short term studies on Nantucket pine tip moth herbivory have shown significant growth loss in intensively managed pine plantations. However, due to a lack of longer-term studies it is currently unclear if damage caused by Nantucket pine tip moth reduces productivity of loblolly pine in later stages of stand development. For this reason, I quantified measures of productivity (total height, diameter at breast height and individual stem volume) of four improved genotypes of 9-year-old loblolly pine growing in two physiographic regions (upper coastal plain and lower coastal plain) of North Carolina. Test trees were subject to two levels of cultural treatments (Phosphorus fertilization - LCP / Arsenal - UCP) with half of the trees from each treatment protected from Nantucket pine tip moth herbivory using systemic imidacloprid. I hypothesize measures of productivity will be enhanced by protection from Nantucket pine tip moth and that the greatest relative gains will occur at the upper coastal plain site where herbivory by Nantucket pine tip moth represents an additional obstacle for trees growing on a lower quality site. Results confirm that protection from Nantucket pine tip moth has a significant effect on measures of productivity of 9-year-old loblolly pine. However, results over time suggest that the imidacloprid treatment effect diminishes through time. Re-inventory of measures of productivity later in stand development is required to see if protection from tip moth herbivory improves productivity through a full 25-year rotation. I conclude that systemic protection from NPTM enhances productivity of 9-year-old loblolly pine grown in North Carolina.

INTRODUCTION

The population of the United States is projected to increase from 319 million to 417 million over the period 2014-2060 (Colby 2015). With this increase in population comes an increased demand for forest products, which must be met in an increasingly stressful global climate (Kirilenko and Sedjo 2007). Haynes et al. (2000) projected that forest product consumption in the United States will increase by 69 percent during the period 2000-2050. Furthermore, the rapid urbanization occurring in the US Southeast in response to the growing population will reduce available forestland by approximately 7,410,000 acres by 2050 (Nowak and Walton 2005). Additionally, this increasingly urban population will require much of the remaining natural forestlands, conserved or managed, for non-timber forest products and ecosystem services, thus further reducing the total land base for timber production (Prestemon and Abt 2002). Prestemon and Abt (2002) project a 2% loss in total forest cover in the South by 2040. However, they project a 67% gain in softwood plantation acres during this period. This increase in softwood plantation acreage will likely come from marginal agricultural lands and areas currently in natural forest management (Prestemon 2002). Wear et al. (2013) forecasted that 66% of domestic timber production will occur on softwood plantations, occupying 20% of the forested land area.

The expansion of pine plantation acreage in the South alone will not be enough to meet the future demand for forest products and fiber (Nowak and Walton 2005). Current growth rates achieved by loblolly pine plantations in the Southeast do not come close to the biological potential (Borders and Bailey 2001). In the southern hemisphere, loblolly pine plantations have achieved growth rates exceeding 500 cubic feet per acre per year. These incredible growth rates are in part due to climactic differences and an absence of natural enemies, but also to the

intensity by which these plantations are managed (Borders and Bailey 2001). Potential growth rates of loblolly pine in the Southeast are much higher than previously thought due to advancements in silviculture, with potential for further gains in productivity (Fox et al. 2007). Borders and Bailey (2001) report loblolly pine in high intensity culture near Waycross, Georgia grow in excess of 400 cubic feet per acre per year, demonstrating that southern forest plantations can rival plantations grown anywhere. For southern plantations to achieve growth rates that will satisfy the demands of a growing population on a decreasing land base, loblolly pine plantation management must adopt methods that will maximize wood production and yield. Management must become site specific and consider all factors, biotic and abiotic, that influence growth of crop trees and seek to manage those factors in an economically feasible way. Financial returns are greater for high intensity plantation management due to faster growth rates and shorter rotation lengths (Fox et al. 2007). This realization has marked a shift in the philosophy of plantation management away from minimizing cost per acre and towards minimizing cost per unit of wood (Fox et al. 2007). These increasingly intensive management regimes will require greater inputs and thus, increase the cost of management. Large investments will be put into the highest quality seedlings, intensive site preparation, multiple fertilizations as well as mechanical and chemical competition control. However, cultural treatments such as intensive site preparation, fertilization and competition control have been shown to increase pest abundance (Nowak and Berisford 2000). Increased pest abundance and damage levels have the potential to decrease economic returns of silvicultural investments to the point where managing pests at establishment becomes necessary (King et al. 2014).

Changes in land use, population demographics and associated changes in global climate will increase stress on forest resources (Southern Forest Futures Project 2011). Sun et al. (2008)

predict significant increases in air temperature (1-2°C) and a decrease in annual precipitation of 10 % in the South by 2020. Additionally, infestation of plantations by insect pests such as the Nantucket pine tip moth (NPTM), *Rhyacionia frustrana* Comstock, will likely become more frequent and intense with the expansion of high intensity silviculture (Asaro 2003, Asaro 2011, Fettig 2004, Kulhavy 2004, Nowak and Berisford 2000). Taken together, these biotic stresses represent a large obstacle for achieving the gains in productivity anticipated due to tree improvement and advanced silviculture (Berisford et al. 2013).

Nantucket pine tip moth, native to the eastern United States, occurs on members of the genus *Pinus* and is one of the most common pests of pine plantations in the Southeast (Asaro 2003, Bersiford 2000, Kelley and King 2014, King et al. 2014). Although NPTM damage is ubiquitous in southern pine plantations, many foresters and land managers simply tolerate the pest (Powers and Stone 1988). Tolerance of this pest is due in part to the high variability and poor understanding of pest pressure at the landscape scale and, until recently, a lack of efficacious chemical control methods that were cost effective. Finally, many managers simply believe that the growth losses suffered by young plantations due to NPTM will eventually disappear at 15-20 years of age (Powers and Stone 1988).

While many studies have reported significant reduction in growth of young pines damaged by tip moth, few studies have investigated long-term growth responses to tip moth damage, and those few that have sometimes produced equivocal results (Asaro 2003). Currently, it is unclear to what extent damage caused by tip moth at stand establishment influences productivity into the later stages of stand development. It is thought, however, that due to the nature of the damage, herbivory by NPTM has the potential to reduce or negate the gains anticipated by southern pine silviculture and tree improvement in the future (Bersiford et al.

2013). Furthermore, as plantation management intensifies and rotation lengths shorten, trees will have fewer years to outgrow the damage incurred during establishment (King et al. 2014).

Nantucket pine tip moth has a complex ecology with multiple overlapping generations occurring during the growing season synchronized with the phenology of the trees (Asaro 2003). As a result, pest density and damage levels vary across time and throughout its range (Figure 1). The variation in pest pressure combined with high variation in site quality and differences among management regimes for loblolly pine, makes the decision to invest in or forego pest control measures substantially difficult (Asaro 2006). However, if we are to realize the biological potential of loblolly plantations in the South, we must learn how to manage this pest in a way that is sustainable.

Early methods of NPTM control that relied on spray timing models and contact herbicides were not reliably efficacious and were not considered cost effective (Powers and Stone 1988). With the introduction of neonicotinoid pesticides, the most important of which is imidacloprid (Ford et al. 2011), forest managers now have an economically feasible chemical control option that is proven to protect expensive seedling investments against NPTM and pales weevil (*Hylobius pales* Herbst) (Asaro and Creighton 2011, King et al. 2014). In eastern North Carolina, protection from a single application of imidacloprid at planting lasts for approximately two years depending on stand productivity (King et al. 2014), and costs approximately \$82 per acre (2008 prices, John King, personal communication). The anticipated increase in pest abundance that comes with intensification of southern plantation management and the advent of efficacious systemic insecticides have provided the impetus for new research into controlling pests of establishment. Understanding the long-term effects of tip moth control on long-term productivity in plantations of loblolly pine is essential to the future sustainability of the United

States wood and fiber supply. For this reason, I revisited two experiments established in the winter of 2008-2009 to test how the systemic control of Nantucket pine tip moth would affect growth of individual stems and stands of 9-year-old loblolly pine grown in two physiographic regions of North Carolina.

Hypotheses and objectives

My objectives for the productivity experiments were to analyze differences in measures of productivity between intensities of cultural treatments: addition or lack of pest control, genotypes of improved loblolly pine, and any interactions of these effects. I want to compare my findings to previous research (Kelley and King 2014, King et al. 2014) and connect my work to the current understanding of southern pine management. Finally, I want to generate questions about the future of Nantucket pine tip moth control and recommend areas for future research.

My first hypothesis is that measures of productivity such as total height, diameter at breast height and stem volume of 9-year-old loblolly pine will be improved by pest control at stand establishment. Additionally, I hypothesize that relative gains in productivity will be greatest on the lower site index upper coastal plain site where tip moth herbivory represents an additional compounding obstacle for trees growing in an already stressful system.

METHODS AND MATERIALS

Field sites

In December 2008, and January 2009, two stand level experiments were established in the upper coastal plain (UCP) and lower coastal plain (LCP) of North Carolina, representing two physiographic regions common to intensive pine management in the South (King et al. 2014). Sites utilized by the study are a part of the landholdings of North Carolina State University (NCSU) and are managed for timber production. Experiments were set up as independent

randomized complete block designs with whole- and split-plot treatments replicated four times. The UCP site, also referred to as the Taylor Tract, is in Nash County, NC (36°07'44" N, 77°44'42" W; elevation 40 m) and was formerly an agricultural field in corn-soybean-winter wheat rotation for many decades prior to the establishment of the study (King et al. 2014). The mean annual temperature (1971-2000) is 60 °F with a mean annual low in January of 35.6 °F and a mean annual high of 82 °F in July (National Climatic Data Center, Asheville, NC). Mean annual precipitation is 46.5 inches with at least some rainfall every month. Soils are of the Goldsboro and Norfolk series, having a sand-loam texture and are moderately well-drained. Site preparation (e.g. sub-soiling) was not feasible at this site due a high-water table and saturation of the soils at the time of study establishment, as any intervention with machinery would have destroyed soil structure. The UCP site is of medium quality for plantation management and represents sites likely to transition to plantations in the future as predicted by Prestemon and Abt (2000).

The LCP site is in Jones and Onslow Counties, NC, on Hofmann Forest (34°49'37"N, 77°17'03" W; elevation 14 m), an 80,000-acre former pocosin ecosystem currently managed by Resource Management Systems (RMS) for timber production through contract with the College of Natural Resources Foundation at NCSU. Mean annual temperature is 63 °F with a mean annual low of 37.4 °F and a mean annual high of 82 °F (King et al. 2014). Mean annual precipitation is 56.5 inches with at least some rainfall occurring every month. Soils are of the Rains series having a fine sandy loam texture, a high organic matter content, and are poorly drained. Portions of this former pocosin currently in timber production have been ditched and drained in order to lower the water table. Standard silvicultural prescriptions call for planting seedlings on raised beds ~15 inches high to provide adequate aeration for young seedling root

systems (Allen and Campbell 1988). In contrast to the upper coastal plain site, the LCP field site is among the highest quality sites for loblolly pine plantation management (Fox and Allen 2011, King et al. 2014). This site was occupied by a 38-year-old loblolly pine plantation one year prior to the establishment of this installment of the tip moth exclusion study. After harvest, the site was V-sheared and bedded on 20-foot centers as is standard operating procedure on lower coastal plain sites (Allen and Campbell 1988).

Experimental design and treatments

In December 2008 and January 2009, independent randomized complete block design experiments of whole-and split-plot treatments replicated four times were established at each site. Whole plot factors were site specific and consisted of two levels of cultural treatment. Initial soil analysis at the UCP site showed high levels of nitrogen (N), calcium (Ca), and magnesium (Mg). Past land use history (e.g. agriculture) and high levels of soil nutrients meant that this plantation would have heavy competition from agricultural weeds. Thus, the whole plot factor at the UCP site was two application rates of herbicide (Arsenal®, BASF, Florham Park, NJ) treatment: the labeled rate of 0.062 gallons per acre and half of the labeled rate 0.031 gallons per acre (King et al. 2014).

Plantations that were previously pocosin systems, like those of the LCP site, have deep organic peat soils with high water tables. Phosphorus can be unavailable to these trees due to the high-water table and organic matter content of the soil (Allen and Campbell, 1988). Application of 12.4 pounds of elemental phosphorus at planting is standard operating procedure at the LCP site (King et al. 2014). Thus, whole plot factor at the LCP site was high- or low-level phosphorus fertilization, applied at 8.1 and 16.2 pounds, respectively. Phosphorous may be limiting in the low-level treatment while the high treatment would provide phosphorus in excess.

The split-plot factor nested within whole plot factor was the same at each site (Figure 1; Figure 2). The split-plot treatment was an application of a single dose of imidacloprid as a soil active tablet (CoreTect™, Bayer CropScience, RTP, NC) to half of all the trees in each whole plot (Figure 1; Figure 2). Previous research conducted at each site (King et al. 2014) determined that NPTM was present at damaging levels and the application of systemic imidacloprid was efficacious. Trees not treated with imidacloprid at planting had on average 70% and 69% of top whorls damaged by tip moth after two years of growth at the UCP and LCP sites, respectively (King et al. 2014). Imidacloprid reduced infestation levels to 8% and 39% of top whorls damaged at the UCP and LCP sites, respectively. Asaro et al. (2006) concluded that 30% of top whorl damage is the economic injury level (the level of injury where management of a pest become economically feasible) for tip moth damage in coastal plain plantations.

The split-split plot factor was pine genetics. The treatments installed were four genotypes of improved genetics loblolly pine (2 clonal varieties, 2 mass control pollinated families) planted in 50 tree blocks nested within split-plots (Figure 2; Figure 3). Seedlings were commercially available stock purchased from ArborGen Corporation (Summerville, SC). The full sib seedlings and the clones were more expensive than half sib or open pollinated seedlings, and therefore, better represent higher investment into planting stock likely to be seen in southern plantations in the future (McKeand et al. 2003). Trees on the LCP site were planted on a 20 x 5 ft spacing, resulting in 436 trees per acre and trees on the UPC were planted on a 10 x 10 ft spacing, also at 436 trees per acre. Both planting densities reflect standard operating procedures for plantations in each region. To buffer edge effects and separate treatments, split plots were surrounded by two rows of open pollinated bare root seedlings and whole plots were separated by five rows of bare root seedlings. Each block (replicate) contained 50 trees for each level of the split-split plot

treatment (genetics), 200 trees for each level of the split-plot treatment (imidacloprid) and 400 trees for each level of the whole plot treatment (herbicide-UPC; P fertilization- LCP). Blocks were replicated four times, making for 5088 trees at each site with 3200 test trees and 1888 trees acting as buffers (King et al. 2014). The interior 24 trees of the 50-tree split-split plot were used for measurements and statistical analysis.

Field measurements and calculations

Total height, defined as the vertical distance between ground level and the tallest leader of a stem, was measured using a Forestry Pro Laser Dendrometer (Nikon Corporation, Melville/NY; Figure 34) and were recorded to the nearest half foot. Height to live crown was defined as vertical distance from ground level to the point at which foliage begins to form the base of the crown and was recorded to the nearest half foot. Crown ratio was computed by taking the difference between total height and height to live crown, and then dividing that number (crown length) by total height and multiplying by 100.

Diameter at breast height (DBH) was defined as the diameter of a single stem measured at 4.5 feet above the ground level and was measured using calipers (Mantax 18"; Haglof, Sweden). To account for variation in cross sectional diameter, two measurements were taken, and the resulting average was the diameter used in calculations. Basal area was calculated using the forester's constant in the formula, $BA = 0.005454 * DBH^2$. Basal area per acre was calculated by multiplying mean basal area per stem by the number of trees surviving per acre. Volume of individual stems were calculated in cubic feet, utilizing volume equations from Burkhart (1977). The equation for cubic foot volume (outside bark) was used from this paper because trees measured to derive this equation closely matched the trees on my study sites.

The following equation estimates volume in cubic feet (outside bark) of plantation grown loblolly pine:

$$V = \beta_{01} + \beta_{11}D^2H$$

Where:

V = total stem cubic foot volume

D = tree DBH in inches

H = total tree height in feet

B_{ij} = coefficients to be estimated from sample data

Coefficients used for calculating volume outside bark (ft³) of plantation grown loblolly pine are:

$$B_{01} = 0.34864$$

$$B_{11} = 0.00232$$

The resulting equation:

$$\text{Volume} = 0.34864 + 0.00232(D^2H)$$

Volume per acre was calculated by taking the average volume per stem of a given treatment combination and multiplying the average volume by the surviving trees per acre. Mean annual increment (MAI) was calculated by dividing volume per acre by age (nine years).

Statistical model and analysis

Data from UCP and LCP sites were analyzed independent of one another by analysis of variance using Proc Mixed for a randomized complete-block design (SAS version 9.4; SAS Institute, Inc., Cary, NC). Experimental block was treated as a random effect to minimize error due to variation in site attributes across the landscape. Inspection of residuals and quantile-quantile plots allowed for identification of outliers and revealed that data did not require transformation. Error Terms in F tests were determined according to the classic approach to the split-split plot design because we used blocks as replicates (Steel and Torrie 1980). Data are presented as means (SE) and treatment effects are considered significant at $p < 0.05$. In instances

where there are significant differences between treatments, a Tukey HSD test was performed, and the significant values bolded (see Table 2).

The overall statistical model utilized to analyze all variables was:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \delta_l + (\beta\delta)_{jl} + (\delta\gamma)_{lk} + (\beta\gamma\delta)_{jkl} + \varepsilon_{ijkl}$$

$$\varepsilon \sim N(0, \sigma^2)$$

$$i = 1-4, j = 1-2, k = 1-2, l = 1-4$$

Where:

Y_{ijkl} = observation of the i th block, j th cultural treatment, k th tip moth treatment and the l th genotype

α_i = Random effect due to block

β_j = Fixed effect due to cultural treatment (high- low P Fertilizer/LCP, high-low Arsenal/ UCP)

γ_k = Fixed effect due to imidacloprid

δ_l = Fixed effect due to genotype

$(\alpha\beta)_{ij}$, $(\beta\gamma)_{jk}$, $(\beta\delta)_{jl}$, $(\delta\gamma)_{lk}$, $(\alpha\beta\gamma)_{ijk}$, $(\beta\gamma\delta)_{jkl}$, are all interactions between random and fixed effects

ε_{ijkl} = Random error associated with model.

Results

Due to differences in experimental design, it would not be statistically valid to analyze the UCP and LCP sites together, but because the sites were planted at the same time and with the same genetics, it is informative to compare growth between sites. On average across all treatments, survival was 82 % and 92 % at the UCP and LCP sites, respectively. Upper coastal plain trees, on average, grew to 30.7 (4.88) feet tall, with a DBH of 7.06 (1.20) inches and contained 4.11 (1.52) cubic feet of wood per tree. Trees at the upper coastal plain site had on average 62 % of total height in live crown. At the lower coastal plain, trees grew to 37.2 (5.70) feet tall with a DBH of 7.19 (1.42) inches and contained 5.12 (2.20) cubic feet of wood per tree. Trees at the lower coastal plain had 66.7 % of total height in live crown. When adjusted for

survival and expanded to a per acre basis, trees at the UCP produced 1467.27 ft³ and trees at the LCP site produced 2053 ft³ of wood per acre over the nine-year experimental period. The UCP and LCP had mean annual increment (MAI) of 163.0 ft³ per acre per year and 228.0 ft³ per acre per year, respectively.

Upper coastal plain

Total height

The interaction between tip moth treatment and genotype, and the three-way interaction between herbicide, tip moth treatment, and genotype are both significant for mean total height of 9-year old loblolly pine grown at UCP (Figure 2). Across all treatments, genotype C2 was the tallest at 31.93 (0.53) ft tall, followed by V1 at 30.66 (0.51) feet, V2 at 29.73 (0.52) feet, and C1 was the shortest genotype at 29.26 (0.52) ft tall. Examples of significant 3-way interactions are genotype C2 given the high herbicide treatment was improved by 6.64 (1.29) feet or 23.7% by imidacloprid treatment. Genotype V1 with low herbicide was improved by 5.40 (1.22) feet or 19.1% with imidacloprid treatment. Genotype V1 with high herbicide was improved by 4.36 (1.23) feet or 15% by imidacloprid treatment at the upper coastal plain.

The interaction between tip moth treatment and genotype was highly significant ($p < 0.0001$) (Table 2). This two-way interaction produced numerous highly significant results ($p < 0.0001$). For instance, C2 genotype untreated grew to 29.06 (0.71) ft, but those treated grew to 34.8 (0.67) ft. In this case, tip moth treatment improved height of the C2 genotype by 5.75 feet (19.78%).

Diameter at breast height

Type three test of fixed effect showed highly significant effects for the tip moth treatment and between genotypes for diameter at breast height (Table 2). There were no significant interactions between treatments for diameter at breast height. On average, 9-year-old loblolly

pine grew to 7.34 (0.078) inches at breast height when treated with imidacloprid. Trees left unprotected grew to 6.73 (0.081) inches at breast height and this difference of 0.61 inches was highly significant (adjusted $p < 0.0001$). Genotype C1 attained the largest DBH with an average of 7.30 (0.092) inches followed by C2 at 7.04 (0.095) inches, V1 at 7.02 (0.089) inches, and finally, V2 at 6.78 (0.091) inches. The differences between least square means between genotypes were all significant except for the difference between C2 and V2 (adjusted $p = 0.9982$). The difference between genotype C1 and V2 was highly significant at adjusted $p < 0.0001$.

Stem volume

Type three fixed effects for tip moth treatment and genotype were highly significant for total stem volume at $p = 0 < .0001$ and $p = 0.0044$, respectively. There were no interactions of main effects regarding individual stem volume. On average, trees treated with imidacloprid accumulated 4.06 (0.129) ft^3 of stem wood volume by age nine. Trees not treated accumulated 3.52 (0.132) ft^3 of stem wood volume by age nine. This difference was highly significant after a Tukey test (adjusted $p < 0.0001$). Genotypes C2, C1, and V1 all produced approximately the same stem wood volume at age nine with 4.19 (0.138) ft^3 , 4.13 (0.135) ft^3 , and 4.11 (0.133) ft^3 of wood per stem respectively. Genotype V2 produced the least wood per stem with 3.82 (0.132) ft^3 of stem wood volume at age nine. Differences of least square means for genotype V2 compared to C2, C1 and V1 were determined to be significantly different after a Tukey test adjusted $p = 0.0072$, $p = 0.0271$, $p = 0.037$, respectively.

Results over time

Measurements reported for year two and year four of this research study were taken from King et al. (2014) and Kelley et al. (2014) and converted to the same units used in my study. Results from previous research were added to my data and plotted through time (see Figures 9

and 10). Results show that UCP trees treated with imidacloprid are taller and larger in diameter and contain more wood volume early in stand development and have maintained that advantage through year 9.

Total height

Loblolly pine treated with imidacloprid grew to 3.51 (0.07) ft tall at year 2, whereas control trees only grew to 1.94 (0.03) ft tall, a difference of 1.57 (0.05) feet. At year 4, imidacloprid treated trees grew to 11.02 (0.36) ft tall and control trees grew to 7.07 (0.39) feet tall, a difference of 3.95 (0.36) feet. At year 9, imidacloprid-treated trees grew to 32.47 (0.62) feet tall and control trees grew to 28.32 (0.62) feet tall, a difference of 4.15 (0.79) feet. Imidacloprid treated pines have maintained and slightly increased their height over control treatment trees at the upper coastal plain (Figure 10).

Average Diameter

Loblolly pine treated with imidacloprid grew to 0.94 (0.08) inches groundline diameter at year two, whereas, control trees only grew to 0.63 (0.04) inches groundline diameter, a difference of 0.31 (0.06) inches. At year four imidacloprid treated trees grew to 3.19 (0.12) inches groundline diameter, control trees grew to 2.15 (0.12) inches groundline diameter a difference of 1.04 (0.12) inches. At year nine imidacloprid trees grew to 7.35 (0.07) inches diameter at breast height and control trees grew to 6.34 (0.08) inches diameter at breast height, a difference of 1.01 (0.08) inches at breast height. Imidacloprid treated pines have maintained a larger diameter over the course of the study through year 9 (Figure 11).

Growth rate

Growth rate, presented as mean annual increment (MAI), was calculated by multiplying the average stem volume for a given treatment, by the number of trees surviving for that

treatment and then dividing by the number of years since planting (Figures 14 and 16). At the upper coastal plain, trees left unprotected from tip moth grew at a rate of 126.18 ft³/acre/year and trees protected from tip moth grew at a rate of 200.56 ft³/acre/year (Figure 14). This represents a 58 % increase in growth rate due to tip moth control. Across all treatments, genotype V1 grew the fastest at a rate of 178.36 ft³/acre/year. Genotypes V2 and C1 grew at approximately the same rate of 157.48 ft³/acre/year and 157.26 ft³/acre/year respectively. Genotype V2 was the slowest growing genotype at UCP growing at a rate of 151.87 ft³/acre/year (Figure 16). When V1 growth rate is compared to the average growth rate of the other three genotypes, this difference represents a 20.50% increase in growth rate due to genotype.

There was considerable variation in growth rate at the UCP site due to variation in survival, and differences in individual stem volume between genotypes protected and unprotected from tip moth. Across all genotypes, growth rate was improved by tip moth control (see Figure 14). The greatest improvement in growth rate due to tip moth protection was seen in genotype C2, which produced 107.87 ft³/acre/year when left unprotected and 205.25 ft³/acre/year when protected, an improvement of 90.3% with tip moth control. Genotype V2 was the second most improved, growing at a rate of 123.69 ft³/acre/year when unprotected and 196.69 ft³/acre/year when protected, an improvement of 59.01% due to tip moth protection. Genotype V1 was improved by 53.40 % with growth rates of 142.48 ft³/acre/year and 218.68 ft³/acre/year before and after protection. Growth rate of genotype C1 was improved by tip moth treatment by 41.5%, from 133.44 ft³/acre/year to 182.81 ft³/acre/year (see Figure 16).

Lower coastal plain

At the lower coastal plain, insecticide treatment and genotype were the experimental factors that resulted in significant results. There were very few interactions between

experimental factors (Figure 2). However, the three-way interaction between phosphorus fertilization, imidacloprid treatment and genetics was significant for total height (Table 2).

Total height

At LCP, trees protected from tip moth on average grew to 37.58 (0.48) ft while trees left unprotected grew to 36.79 (0.482) ft tall. This difference of 0.794 (0.53) ft was not significant ($p=0.1684$). Genotype C2 was the tallest on average with a mean total height of 40.65 (0.47) ft followed by V1 with a mean total height of 38.33 (0.462) ft. Genotype V2 grew to 35.07 (0.47) ft and C1 was the shortest genotype with a mean total height of 34.69 (0.47) ft. The three-way interaction between phosphorus fertilization, imidacloprid treatment and genotype was significant for height ($p=0.0085$). When a Tukey HSD test was applied, this three-way interaction produced numerous combinations of significant treatment effects. After analyzing the significant differences in three-way interactions, genetics played the major role in differences in height at the lower coastal plain. For example, genotype C2 with no imidacloprid and low phosphorus fertilization grew on average 6.81 (0.71) feet taller than C1 with high phosphorus fertilization and imidacloprid. These results demonstrate that genotype C2 was better suited for growing at the LCP site, and additional resources and protection from tip moth did not improve genotype C1 enough to make up for inferior genetics. Overall, the significant three-way interactions were dominated by genotype C2 over all other genotypes, and various combinations of treatments with genotype V1 also had significant height advantage over genotype C1 and V2.

Diameter at Breast Height

Tip moth treatment was the only significant main effect for diameter at breast height of 9-year-old loblolly pine grown in the LCP (Table 2). There were no treatment interactions between fixed effects on DBH. On average, trees protected from tip moth grew to 7.30 (0.087) inches,

and trees left unprotected grew to 7.08 (0.087) inches in diameter at breast height. This difference of 0.21 (0.085) inches is significant after a Tukey test was applied (adjusted $p=0.0428$). Diameter at breast height between genotypes was not significantly different ($p=0.845$), with genotype V2 having the largest diameter at 7.23 (0.101) inches and C1 having the smallest diameter at 7.15 (0.100) inches.

Cubic foot volume

Tip moth treatment and genotype were significant factors regarding the total stem volume of 9-year-old loblolly pine grown at LCP with p -values of 0.0428 and <0.0001 , respectively, and there were no significant interactions between fixed effects (Table 2). On average, trees protected from tip moth accumulated 5.35 (0.174) ft^3 of wood per stem while trees left unprotected from tip moth accumulated 4.90 (0.174) ft^3 of wood per stem (Table 5). This difference of least square means was significant after a Tukey HSD test (adjusted $p=0.028$). Genotype C2 was the largest genotype with 5.47 (0.184) ft^3 of wood per stem, followed by genotype V1 with 5.31 (0.182) ft^3 of wood per stem. Genotypes V2 and C1 were smaller, on average, with 5.04 (0.184) ft^3 and 4.67 (0.184) ft^3 , respectively. The differences between genotypes C2 and C1 of 0.79 (0.163) ft^3 was highly significant after a Tukey test was done (adjusted $p<0.0001$). The differences in stem volume between C2 and V2 as well as C1 and V1 were also significant after the Tukey test at adjusted $p=0.0413$ and adjusted $p=0.0005$, respectively.

Results over time

LCP trees treated with imidacloprid only gained a slight advantage in height and diameter early in stand development (King et al. 2014), and this advantage disappears by year 9. At year

9, imidacloprid treatment does not improve height or diameter of loblolly pine growing in the LCP of NC in any appreciable amount.

Total height

At year 2, LCP trees treated with imidacloprid grew to 7.18 (0.20) ft tall and control trees grew to 6.43 (0.16) ft tall, a difference of 0.75 (0.18) ft (Figure 12). At year 4, imidacloprid treated trees grew to 16.01 (0.60) ft and control trees grew to 15.4 (0.69) ft tall, a difference of 0.61 (0.63) ft. At year 9, imidacloprid treated trees grew to 37.58 (0.48) ft tall and control trees grew to 36.79 (0.48) ft, a difference of 0.79 (0.53) ft.

Average Diameter

At year 2, imidacloprid treated trees grew to 2.0 (0.09) inches in groundline diameter and untreated control trees grew to 1.81 (0.12) inches in groundline diameter a difference of 0.19 (0.10) inches in groundline diameter (Figure 13). At year 4 imidacloprid trees grew to 4.67 (0.22) inches in groundline diameter and control trees grew to 4.30 (0.24) inches in groundline diameter a difference of 0.23 (0.24) inches in groundline diameter. At year 9, imidacloprid treated trees grew to 7.30 (0.09) inches at breast height and untreated trees grew to 7.09(0.09) inches breast height, a difference of 0.21 (0.08) inches in breast height.

Growth rate

Growth rate, presented as mean annual increment (MAI), was calculated by multiplying the average stem volume for a given treatment by the number of trees surviving for that treatment and then dividing by nine (the number of years since planting; see Figures 15, 17). At the lower coastal plain, trees left unprotected from tip moth grew at a rate of 218.39 ft³/acre/year and trees protected from tip moth grew at a rate of 238.44 ft³/acre/year (Figure 15). This represents a 9.1% increase in growth rate due to tip moth control. This increase in growth rate is

driven by improved individual stem performance. Across all treatments, genotype V1 grew the fastest at a rate of 244.37 ft³/acre/year (Figure 17). Genotype C2 grew the second fastest with a MAI of 238.92 ft³/acre/year. V2 grew at a rate of 222.19 ft³/acre/year, and C1 grew at a rate of 205.87 ft³/acre/year. When the growth rate of V1 is compared to the average growth rate of the other three genotypes, the difference represents a 9.9% increase in growth rate due to genotype.

Due to variation in survival and individual stem volume between genotypes treated with imidacloprid or left unprotected, there was considerable variation in growth rates for most genotypes (Figure 17). Growth rate was improved by imidacloprid treatment in genotypes C2, V1 and V2. The greatest improvement in growth rate due to imidacloprid treatment at LCP was seen in genotype V2, which produced 202.35 ft³/acre/year when left unprotected and 241.04 ft³/acre/year when protected, an improvement of 19.1%. Genotype V1 was the second most improved, growing 230.28 ft³/acre/year when unprotected and 258.82 ft³/acre/year with protection, a 12.4% increase in growth rate with tip moth control. Genotype C2 saw a modest 3.3% improvement in growth rate with tip moth control, growing at 235.62 ft³/acre/year without treatment and 243.39 ft³/acre/year with protection.

Discussion

I sought to quantify the effect of systemic control of Nantucket pine tip moth on productivity of intensively managed 9-year old loblolly pine grown in two physiographic regions of North Carolina. I hypothesize that tip moth control will increase productivity of 9-year-old loblolly pine grown in both physiographic regions of North Carolina. Additionally, I hypothesize that the upper coastal plain site will experience relatively greater stimulation by tip moth control because tip moth represents an additional obstacle for trees to overcome on a site where resources are less available (King et al. 2014). My results show that systemic control of

Nantucket pine tip moth for the first two years following establishment in stands experiencing heavy pest pressure can greatly increase productivity at 9 years of age. However, interactions with site resource availability and competition were not always consistent with expectations.

It is understood that Nantucket pine tip moth populations and damage levels vary in relation to site and stand characteristics (Asaro 2003). Prior to the widespread deployment of pine plantations in the 1950's, Nantucket pine tip moth was generally regarded as a minor pest (Benedict and Baker 1963), however, it was hypothesized its pest status would increase with the expansion of southern pine plantation acreage and intensity (Benedict and Baker 1963). This hypothesis was confirmed by Warren (1964) in loblolly planted in Arkansas and later by Bersiford and Kulman (1967), whose research showed significantly higher infestation levels in planted pine compared to natural regeneration with similar stocking density. Additionally, research investigating the effect of site quality on tip moth populations have produced contradictory results, where relatively high site index was associated with relatively higher tip moth populations in east Texas, but relatively lower site index was associated with higher tip moth populations in the piedmont of Georgia and South Carolina (Asaro 2003). However, it is generally accepted that tip moth is of greater concern on lower quality sites where it represents an additional obstacle for trees which may not be able to respond effectively due to site limitations (King et al. 2014).

Silvicultural techniques influence tip moth damage levels

Reduction of Competing vegetation

Reduction of competing vegetation in young plantations either through intensive site preparation, mechanical removal (drum chopper or disking) or chemical means (herbicide) have been shown to exacerbate tip moth damage levels (Asaro 2003). Reduced competition increases

available space for growth, and focuses nutrients, water, and light on crop trees while also reducing habitat for natural enemies and removing physical barriers for oviposition (Asaro 2003). The increased palatability and availability of fast-growing shoots, the removal of habitat for natural enemies, and barriers to oviposition can lead to increased variability in tip moth populations (Asaro 2003). Highly variable tip moth populations that sometimes reach damaging levels have been used to explain inconclusive or contradictory results in competition control studies (Nowak and Berisford 2000). I observed a significant three-way interaction between herbicide application, imidacloprid treatment and genotype at the upper coastal plain site for total height. This suggests that high rates of herbicide application, when paired with tip moth treatment, increased site index for some of the genotypes at the upper coastal plain site in eastern North Carolina.

Fertilization

Increases in plant nutrient levels can increase palatability of plant parts for insect herbivores thus increasing survivorship and fecundity in pest populations (Asaro 2003). Sun et al. (2008) found increased infestation levels and greater pupal weights of tip moth in nitrogen fertilized seedlings. Following a greenhouse study involving fertilization and irrigation, Ross and Berisford (1990) concluded that forest management practices and techniques that increase availability of water and nutrients to seedlings will also increase tip moth infestation. However, other studies investigating the relationship between fertilization and tip moth damage have shown inconclusive or contradictory results (Asaro 2003). A study by Pritchett and Smith (1972) observed significantly lower tip moth damage in pines fertilized with phosphorus and potassium, and no significant difference between controls and trees fertilized with nitrogen. Previous research (King et al. 2014) did not observe significant differences in tip moth infestation or

mortality between levels of phosphorus fertilization at the LCP site of the current study. I did not observe significant differences in measures of productivity of individual stems between the high and low phosphorus applications. However, there was a three-way interaction between levels of phosphorus fertilization, imidacloprid treatment and genotype for total height at the LCP site at year nine. Additional measurements are required later in stand development to determine if phosphorus becomes limiting in the low application treatment before the high treatment and if the differences in height observed between interactions are maintained, enhanced or diminish.

How my results compare to previous research

Research conducted at the UCP and LCP for the first two years following stand establishment (King et al. 2014) found that ground line diameter, total height and biomass production were all greater at the LCP, where biomass production was seven times that of the UCP site. This difference in production was attributed to more favorable climate at the LCP and droughty conditions occurring at the UCP following establishment. Differences in production between sites was driven by higher survival and greater individual tree growth (King et al. 2014). My results show the same relationship between sites but results over time suggest the difference between sites is diminishing. At year 9 the LCP produced 2054.23 ft³ of timber per acre across all treatments and the UCP produced 1474.78 ft³ of timber per acre across all treatments. This represents a 39% increase in production at the LCP 9 years following establishment, whereas the 2-year results showed a seven-fold difference in biomass production at between the UCP and LCP (King et al. 2014). The results of the two-year study found that tip moth control and genetics were the most significant factors affecting total height, ground line diameter and biomass production at both sites. My study reports similar results, where significant differences in diameter at breast height and volume are attributed to tip moth

treatment and genotype (Tables 2 and 3). However, unlike the previous study, I observed significant three-way interactions between fertilization, tip moth treatment, and genetics at the lower coastal plain site, affecting total height. Additionally, I found significant two-way interactions between tip moth treatment and genetics and three-way interactions between herbicide, tip moth treatment and genetics affecting total height at the upper coastal plain site. This suggests that tip moth control and cultural treatments have improved site index at both experimental locations, and those differences in site index have now become apparent at age nine. These findings are consistent with the large body of silvicultural research into competition control and nutrient amendments (Fox et al. 2007).

At the stand level, imidacloprid treatment improved growth rate by 9.1% and 58.9 % at the LCP and UCP sites, respectively, in support of my first hypothesis. While the LCP site grew at a faster average rate across all treatments than the UCP site ($228 \text{ ft}^3/\text{acre}/\text{year}$ vs. $163.37 \text{ ft}^3/\text{acre}/\text{year}$, respectively), the relative stimulation by imidacloprid was in fact greatest at the UCP, in support of my second hypothesis. One of the more important take away messages from this research comes from the UCP, where improved genotypes left unprotected from heavy tip moth herbivory experienced high mortality and accumulated less volume. On average, trees unprotected from herbivory grew at a rate of $126.18 \text{ ft}^3/\text{acre}/\text{year}$, and the least productive genotype C2 grew at a rate of $107.87 \text{ ft}^3/\text{acre}/\text{year}$, only 40% and 19.9% more than the unmanaged low-stocked natural stands producing $90 \text{ ft}^3/\text{acre}/\text{year}$ common in the 1950's before plantation management was widespread in the South (Fox et al. 2007). Genotype C2 experienced an improvement of 90.30% with tip moth control producing $205.25 \text{ ft}^3/\text{acre}/\text{year}$. These results are particularly important given that all trees are improved genotypes and did receive some level of competition control and were planted in a former agricultural field with high levels of residual

fertilizer. Results from my study at the UCP support the assertion of Berisford et al. (2013), that heavy damage by Nantucket pine tip moth has the potential to reduce or negate the gains of advanced pine silviculture and genetics, and therefore, the benefits of the control of pests of establishment persist into mid-rotation.

Other long-term tip moth research

The majority of Nantucket pine tip moth research has focused on the first few years following stand establishment, and there are few studies that have investigated the longer-term impacts of tip moth damage in relation to productivity. Beal (1967) established the first long-term study on growth impacts caused by *R. frustrana* infestations; that study established experiments in seven southern states and protected trees for the first 6 growing seasons. After 6 years of growth, Beal (1967) concluded that trees protected from tip moth significantly outgrew unprotected trees. Williston and Barras (1977) re-measured the same sites at year 16 and found that only 1 of the 4 sites with significant height differences at year 6 still showed a significant height difference corresponding to tip moth protection. And while they did observe significant differences in volume between controls and insecticide treatments, the insecticide treatments were determined to be unfeasible given the price of pulp wood at the time of the study. Thomas and Oprean (1984) re-measured three of the four sites that had significant differences at year 7 again at year 23 and found significant height differences at one of the sites. The authors concluded that: (1) early height gains from tip moth control might persist through a rotation, (2) pines on good quality sites showed less impact from tip moth infestation, and (3) pines grown on medium sites with high tip moth damage may benefit from control. My tip moth exclusion study suggests that the imidacloprid treatment effect is diminishing, which is in contrast with their first conclusion. However, my research supports their second and third conclusions. Berisford et al.

(1989) began a long-term study in 1985 in the upper coastal plain of Georgia examining the impact of tip moth control, competition control, and fertilization on loblolly pine growth. During the first three years of that study average damage level (percent top whorl shoots infested) was 62% in control plots, which is slightly less than damage levels reported in previous research conducted at the UCP and LCP (King et al. 2014). Bersiford (2003) reports that after 15 years of growth, trees with tip moth control averaged 1.5 ft³ more volume than unprotected trees. In my study, UCP trees protected from tip moth averaged 0.52 ft³ more wood per stem than unprotected trees after 9 years of growth. In Berisford's study (1989), differences in tree volume between the check and other treatments continued to diverge through year 18, as reported in Asaro (2003). Unlike Beresford's study (1989), our imidacloprid treatment seems to be diminishing through time as suggested by Powers and Stone (1988).

Conclusions

The age of intensive southern pine plantation management is upon us. If the southern United States is to remain the dominant timber market in the world there must be a shift away from minimizing cost per acre towards minimizing cost per unit of wood. Regimes are expected to intensify, and rotation lengths are expected to shorten in response to increased demand for wood and fiber. These changes in pine plantation management are proven to increase the pest status of Nantucket pine tip moth, which has the potential to reduce the gains of advanced pine silviculture.

I have shown that systemic imidacloprid treatments at establishment significantly improves volume production in 9-year-old loblolly pine grown in both the upper and lower coastal plain of North Carolina. Improvements in volume production were greatest at the lower quality UCP site, where imidacloprid treatment improved both survival and individual tree

performance. Survival was not a problem at the LCP site, but stand level volume was increased due to increased individual tree growth with protection from tip moth. Additionally, our results show that careful selection of genetic material and careful planning of silvicultural recommendations are key to maximizing growth on a given site.

Having said this, additional and continuing research is needed to evaluate the economic feasibility of systemic imidacloprid treatments on sites of varying quality under different regimes across the southern United States. Additional research into the high variation in pest pressure and damage on the landscape scale is essential to aid in the decision to apply or forego systemic protection from Nantucket pine tip moth. Additionally, tree improvement programs should incorporate tip moth damage screening into their selection process. Finally, re-measurement of the tip moth exclusion study needs to continue periodically through a full rotation (25 years) to see if the gains I observed at year nine are maintained, enhanced or diminish through time.

CHAPTER 2: STEM FORM AND DEFECTS OF 9-YEAR-OLD LOBLOLLY PINE AS INFLUENCED BY SITE, SILVICULTURE, PEST MANAGEMENT AND GENETICS

ABSTRACT

Studies have shown that Nantucket pine tip moth damage increases with intensity of management in young loblolly pine (*Pinus taeda* L.) stands (Nowak and Berisford 2000). There is limited data suggesting that damage from Nantucket pine tip moth increases the incidence of fusiform rust (*Conartium quercuum* f. sp. *fusiforme*.) in young plantations (Powers and Stone 1988). Additionally, intensifying management regimes to increase growth rate may induce nutrient deficiencies (Fox et al. 2007) that can cause sweep defect in southeastern plantations (Espinoza et al. 2012). Additionally, stem form defects including fork, crook, ramicorn branching, and excessive sweep pose problems for processing machinery (Nyland 2001) and increase compression wood content of stems, thus, reducing yield and subsequent value (Xiong et al. 2014). Moreover, previous work at our study sites suggest that protection from tip moth damage may reduce plantation damage following extreme weather events (Kelley and King 2014). For these reasons, I inventoried stem form defects including fork, crook, ramicorn branch, broken top, fusiform rust and the degree of sweep of four improved genotypes of 9-year-old loblolly pine growing in two physiographic regions of North Carolina subject to two of levels of cultural treatments. I hypothesized that trees protected from herbivory at stand establishment will have fewer stem form defects than those left unprotected after nine years of growth. Results suggest that imidacloprid treatment greatly improves quality and future potential of unthinned 9-year-old loblolly pine stands grown at the UCP but generally did not improve quality or future potential of unthinned stands grown at LCP.

INTRODUCTION

Successful production of solid wood products requires plantation management that encourages both financially viable, volumetric production and adequate tree quality (Green 2018). Quality in the context of timber production is a measure of how well the physical and chemical characteristics of a piece of wood meet the physical requirements of a product (Nyland 2001). Trees of high quality generally have large diameters, straight boles, and contain wood absent of physical defect (Nyland 2001). High quality trees are the most valuable because they yield the greatest number of high-quality end-use products, and they have superior wood anatomy for lumber and pulping applications (Nyland 2001). Additionally, plantation yield and subsequent value are greatest in stands that have high uniformity and minimal defect.

Increases in management intensity anticipated in southeastern pine plantations have the potential to increase volumetric growth to rates that can rival plantations around the world (Moorhead et al. 1998). However, these regime changes can alter ecological processes within the plantation, which may result in reduced stem quality (Nyland 2001). For example, rapidly growing stems may be more susceptible to damage from high winds and extreme weather events (Kelley and King 2014). Additionally, deficiencies of micronutrients are expected to increase as fertilization regimes intensify and growth rates demand greater amounts of all limited nutrients (Fox et al. 2007). For example, *Pinus* spp. deficient of copper or calcium may display Tooruors syndrome, characterized by corkscrew growth of the stem and branches (Espinoza et al. 2012). Furthermore, damage from insect pests such as Nantucket pine tip moth (*Rhyacionia frustrana* Comstock), Pales weevil (*Hylobius pales* Herbst) and pine cone worms (*Dioryctria* spp.) is positively correlated to management intensity (Nowak and Berisford 2000). It has been suggested that due to the nature of the damage, Nantucket pine tip moth has the potential to

reduce or negate the gains anticipated by silviculturalists and tree breeders in the South (Bersiford et al. 2013). As well, some defects such as forking, ramicorn branching, and possibly sweep, are under genetic control and may be stimulated by nitrogen fertilization (Espinoza et al. 2012). Studies show that genes regulating these defects also contribute to growth rate and that breeding for faster growth may have delirious effects on stem quality (Xiong et al. 2014). Recently, Green et al. (2018) report lower solid wood potential for improved genetics loblolly pine grown in high intensity culture when compared to trees grown in lower intensity culture.

High quality loblolly pine grown in plantations offer southern landowners some of the highest value forest investments attainable. Many factors including site selection, site preparation, genetic selection, and various cultural treatments must be considered in a management regime to achieve plantations of high quality. Moreover, the increased investment in genetic material and cultural treatments may lower action thresholds, making chemical control necessary (Nowak and Berisford 2000).

Hypotheses and objectives

My objective for this stem quality experiment was to analyze differences in the number and types of defects occurring in four genotypes of improved 9-year-old loblolly pine subject to two levels of cultural treatments and pest control. I also investigated the link between Nantucket pine tip moth infestation and occurrence of fusiform rust. Finally, I will incorporate stem quality data with productivity data (Chapter 1) to understand how protection from tip moth affects wood yield and the grade of lumber produced, both of which determine overall economic value of plantation forests.

Research suggests that pest pressure from NPTM is positively correlated to intensity of management (Nowak and Berisford 2000). Additionally, Green and Bullock (2018) report lower

solid wood potential in high intensity plantations versus lower intensity management. For these reasons, I hypothesize that trees receiving the lowest level of cultural treatments (low fertilization at LCP, low herbicide at UCP) and protection from pests of establishment will be of the highest quality. I expect to see the greatest improvement to the quality of trees at the upper coastal plain site, where pest pressure is only one of many environmental stressors to which these trees are exposed. Damage from Nantucket pine tip moth represents a relatively small obstacle for trees growing on the high quality lower coastal plain site, where long growing seasons and high availability of water and nutrients promote rapid growth (King et al. 2014). For this reason, I hypothesize that the quality of trees growing on the lower coastal plain site will be uniform regardless of pest control.

METHODS AND MATERIALS

Field sites

In December 2008 and January 2009, two stand level experiments were established in the upper coastal plain (UCP) and lower coastal plain (LCP) of North Carolina, representing two physiographic regions common to intensive pine management in the South (King et al. 2014). Sites utilized by the study are part of the landholdings of North Carolina State University (NCSU) and are managed for timber production. Experiments were set up as independent randomized complete block designs with whole- and split-plot treatments replicated four times. The UCP site, also named the Taylor Tract (36°07'44" N, 77°44'42" W; elevation 40 m), was formerly an agricultural field in a corn-soybean-winter wheat rotation for many decades prior to the establishment of the study (King et al. 2014). The mean annual temperature (1971-2000) is 60.0 °F with a mean annual low in January of 35.6 °F and a mean annual high of 82.0 °F occurring in July (National Climatic Data Center, Asheville, NC). Mean annual precipitation is

46.5 inches with at least some rainfall every month. Soils are of the Goldsboro and Norfolk series having a sand-loam texture that are moderately well-drained. Site preparation was not feasible at this site due a high-water table and saturation of the soils, as any intervention with machinery would have destroyed soil structure. The UCP site is not the highest quality for plantation management but does represent sites likely to transition to plantations in the future, as predicted by Prestemon and Abt (2000).

The LCP site is located on Hofmann Forest (34°49'37"N, 77°17'03" W; elevation 14 m), an 80,000-acre former pocosin ecosystem currently managed by Resource Management Systems (RMS) for timber production through contract with the College of Natural Resources Foundation at NCSU. The mean annual temperature is 63.0 °F with a mean annual low of 37.4 °F and a mean annual high of 82.0 °F (King et al. 2014). Mean annual precipitation is 56.5 inches with at least some rainfall occurring every month. Soils are of the Rains series having a fine sandy loam texture, a high organic matter content and are poorly drained. Portions of this former pocosin currently in timber production have been ditched and drained to lower the water table. Standard silvicultural prescriptions call for planting seedlings on raised beds 15 inches high to provide adequate aeration for young seedlings (Allen and Campbell 1988). In contrast to the upper coastal plain site, this field site is among the highest quality sites for loblolly pine plantation management (King et al. 2014). This site was occupied by a 38-year-old loblolly pine plantation one year prior to the establishment of this installment of the tip moth exclusion study. After harvest, the site was V-sheared and bedded on 20-foot centers as is standard operating procedure on lower coastal plain sites (Allen and Campbell 1988).

Experimental design and treatments

Independent randomized complete block design experiments of whole-and split-plot treatments replicated four times were established at each site. Whole plot factors are site specific and consisted of two levels of cultural treatment. Initial soil analysis at the UCP site showed high levels of nitrogen (N), calcium (Ca), and magnesium (Mg). Past land use history and high levels of soil nutrients suggested this plantation would experience heavy competition from agricultural weeds. Thus, the whole plot factor at the UCP site was two application rates of herbicide (Arsenal®, BASF, Florham Park, NJ) treatment: the labeled rate of 0.062 gallons per acre, and half of the labeled rate at 0.031 gallons per acre (King et al. 2014). Plantations that were previously pocosin systems, like that of the LCP site, have deep organic peat soils with high water tables. These sites require drainage, and so, bedding approximately 15 inches above ground level is generally recommended (Allen and Campbell 1988). Phosphorus can be unavailable to these trees due to the high-water table and organic matter content of the soil. Application of 12.4 pounds per acre of elemental phosphorus at planting is standard operating procedure at the LCP site. Thus, whole plot factor at the LCP site was high- and low- level phosphorus fertilization, applied at 8.1 and 16.2 pounds per acre, respectively (King et al. 2014). Phosphorous may be limiting in the low-level treatment, while the high treatment would provide phosphorus in excess.

A split-plot factor nested within whole-plot factor was the same at each site (Figures 2 and 3). The split-plot treatment was an application of a single dose of imidacloprid (as a soil active tablet, CoreTect™ Bayer CropScience Corporation, RTP, NC) to half of all the trees in each whole plot (Figures 2 and 3). Previous research conducted at each site determined that tip moth was present at damaging levels and the application of systemic imidacloprid was

efficacious (King et al. 2014). Trees not given imidacloprid at planting had on average 70 and 69 percent of top whorls damaged by tip moth at the UCP and LCP sites, respectively (King et al. 2014). Imidacloprid reduced infestation to 8 and 39 percent of top whorls damaged at the UCP and LCP sites, respectively. Asaro et al. (2006) concluded that 30% of top whorl damage is the economic injury level (the level of damage done to a commodity at which management of a pest becomes economically feasible) for tip moth damage in coastal plain plantations. The lower efficacy experienced at the lower coastal plain site is likely due to the accelerated growth of the trees diluting the active ingredient (imidacloprid) below levels that are lethal to tip moth larvae (King et al. 2014).

The split-split plot factor was pine genetics. The treatments installed were four genotypes of improved genetics loblolly pine (2 clonal varieties, 2 mass control pollinated families) planted in 50 tree blocks nested within split-plots (Figures 2 and 3). Seedlings were commercially available stock purchased from ArborGen Corporation (Summerville, SC). The full sib seedlings and the clones were more expensive than half sib or open pollinated seedlings, and therefore, better represent the investment into planting stock we will see in southern plantations in the future (Fox et. al. 2007). Trees on the LCP site were planted on a 20 x 5 ft spacing, resulting in 436 trees per acre and trees on the UPC were planted on a 10 x 10 ft spacing, also at 436 trees per acre. Both planting densities reflect standard operating procedures for plantations in each region (Allen and Campbell 1988). To buffer edge effects and separate treatments, split plots were surrounded by two rows of open pollinated bare root seedlings and whole plots were separated by five rows of bare root seedlings. Each block (replicate) contained 50 trees for each level of the split-split plot treatment (genetics), 200 trees for each level of the split-plot treatment (imidacloprid) and 400 trees for each level of the whole-plot treatment (herbicide-UPC; P

fertilization-LCP). The blocks were replicated four times to contain 5088 trees at each site, with 3200 test trees and 1888 trees acting as buffers between cultural treatments (King et al. 2014). Split-split plots contain 50 trees (Figure 2, 3) however, only the 24 interior trees of each split-split plot were used for measurements and analysis in the current study. The exterior 26 trees of each split-split plot were excluded from analysis to buffer any interactions between genotypes on the edge of split-split plots.

Field Measurements

In winter 2017-2018, after 9 years of growth, I inventoried stem form defects on all surviving test trees. Specifically, I inventoried major stem defects including crook, fork, ramicorn branching, fusiform rust, broken top and sweep occurring in the first 17 feet above a 1-foot stump. Crook, fork, ramicorn branch, broken top, and fusiform rust were all inventoried as a binomial variable with presence (1) and absence (0) of defect. Sweep was inventoried along an index 0-3 and will be explained in full. Crooks are stem defects that result in an abrupt change in direction of a stem (Bronson Bullock, personal communication, 2015). A ramicorn branch is a branch (Figure 21) with twice the diameter and a steeper angle than other branches in the same whorl (Xiong et al. 2014). Forking (Figure 24) is defined as a tree having multiple stems of similar size competing for dominance (Birk 1989). Fusiform rust was inventoried by the presence or absence of galls on the stem or branches (Figure 20). Broken top (Figure 22) was inventoried if any part of the main stem was snapped or severed resulting in the loss of some or all the crown. Sinuosity, sometimes called sweep, is defined as any stem crookedness that occurs in the segment between two whorls resulting in slight or severe curvature affecting stem quality (Espinoza et al. 2012). Sinuosity was judged based on an index of 0-3, where perfectly straight

trees were scored as zero, trees with slight sweep scored one, moderately swept trees scored two, and extremely swept trees scored three (Figure 25).

TPA Calculations

Trees per acre absent of each defect type, was calculated for each treatment by adjusting the proportion of trees absent of defect for mortality and then expanding that to a per acre basis.

Harvest volume calculation

Due to the constraints of processing equipment, severely swept trees and trees with multiple stem defects on the lower bole are lost as cull. To calculate cull, I dropped all the trees with a sinuosity index score of 3 and trees with more than 2 defects on the lower bole. I then re-ran the volume models from Chapter 1 using the reduced datasets. I took average volume in cubic feet per stem and multiplied by 436, and then multiplied that by the percentage of trees remaining of the original (after mortality and cull removal). I graphed the new values along with the original total volume values from Chapter 1 as well as the difference (loss to defect).

Statistical model and analysis

Binomial defect data from UCP and LCP sites were analyzed independent of one another by regression statistics using proc GLIMIX or proc LOGISTIC for a randomized complete-block design (SAS version 9.4; SAS Institute, Inc., Cary, NC). Proc CATMOD was used to analyze the sweep data. Experimental block was treated as a random effect to minimize error due to variation in site attributes across the landscape. However, some models using proc GLIMIX would not converge with random statements, specifically models for fork, ramicorn branch and fusiform rust at LCP, and ramicorn branch, broken top and fusiform rust at UCP. In instances where the model would not converge in GLIMIX unless the random statement was removed, those variables were instead analyzed using proc LOGISTIC. Data are presented as odds ratios and

treatment effects are considered significant at $p \leq 0.05$. In instances where there are significant differences between treatments, a Tukey HSD test was performed, and the significant values bolded (Tables 6,7).

The overall statistical model utilized to analyze all variables was:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \gamma_k + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \delta_l + (\beta\delta)_{jl} + (\delta\gamma)_{lk} + (\beta\gamma\delta)_{jkl} + \varepsilon_{ijkl}$$

$$\varepsilon \sim N(0, \sigma^2)$$

$$i \ 1-4, j \ 1-2, k \ 1-2, l \ 1-4$$

Where:

Y_{ijkl} = observation of the i th block, j th cultural treatment, k th imidacloprid treatment and the l th genotype

α_i = Random effect due to block

β_j = Fixed effect due to cultural treatment (high-low P fertilizer/LCP, high-low Arsenal/ UCP)

γ_k = Fixed effect due to imidacloprid

δ_l = Fixed effect due to genotype

$(\alpha\beta)_{ij}$, $(\beta\gamma)_{jk}$, $(\beta\delta)_{jl}$, $(\delta\gamma)_{lk}$, $(\alpha\beta\gamma)_{ijk}$, $(\beta\gamma\delta)_{jkl}$, are all interactions between random and fixed effects

ε_{ijkl} = Random error associated with model.

RESULTS

Upper coastal plain

Arsenal Application Rate

Broken top

There is no evidence to suggest that the main effect, arsenal application rate, influenced frequency of broken top defects occurring on 9-year-old loblolly pine grown in the upper coastal plain of North Carolina ($p = 0.316$, Table 7).

Crook

There is no evidence to suggest that the main effect, arsenal application rate, influenced frequency of crook defects occurring on 9-year-old loblolly pine grown in the upper coastal plain of North Carolina (P=0.971, Table 7).

Fork

There is no evidence to suggest that the main effect, arsenal application rate, influenced the presence of fork defects occurring on 9-year-old loblolly pine grown in the upper coastal plain of North Carolina (P= 0.316, Table 7).

Fusiform rust

Arsenal application rate was significant for the presence of fusiform rust occurring on 9-year old loblolly pine growing in the upper coastal plain of North Carolina (p= 0.001, Table 7). Thus, 77(1.7)% of trees given the label rate of arsenal (0.062 gal/acre) were free of fusiform rust, whereas 82(1.4)% of trees given half the label rate (0.031 gal/acre) were free of fusiform rust. When adjusted for survival, stands receiving the label rate of arsenal possessed 263(6) trees per acre free of fusiform rust and stands treated with half the label rate possessed 307(5) trees per acre (Figure 26).

Ramicorn branch

There is no evidence to suggest that the main effect, arsenal application rate, influenced frequency of fork defects occurring on 9-year-old loblolly pine grown in the upper coastal plain of North Carolina (P= 0.217, Table 7).

Sinuosity

Arsenal application rate was involved in a significant interaction with imidacloprid and genotype for sinuosity in 9-year-old loblolly pine growing in the upper coastal plain. The results of the three-way interaction are reported below.

Imidacloprid treatment

Broken top

Imidacloprid treatment was found to influence the presence of broken top in 9-year-old loblolly pine growing in the upper coastal plain of North Carolina ($P= 0.011$, Table 7). Thus, 95(0.9)% of trees in the control group were free of broken top, and 92(1.0)% of trees in the imidacloprid group were free of broken top. When adjusted for survival, control stands possessed 307(35) trees per acre without broken top and imidacloprid stands possessed 362(30) trees per acre (Figure 27).

Crook

I found no evidence that imidacloprid treatment influenced the presence of crook defects occurring on 9-year-old loblolly pine growing in the upper coastal plain of North Carolina ($P= 0.276$, Table 7).

Fork

I found no evidence to suggest that imidacloprid treatment influenced the presence of fork defects occurring on 9-year-old loblolly pine growing in the upper coastal plain of North Carolina ($P= 0.161$, Table 7).

Fusiform rust

I found no evidence to suggest that imidacloprid treatment influenced the presence of fusiform rust occurring on 9-year-old loblolly pine growing in the upper coastal plain of North Carolina (P= 0.282, Table 7).

Ramicorn branch

The main effect imidacloprid was involved in a significant two-way interaction with genotype, the results are reported in “imidacloprid*genotype” heading.

Sinuosity

Imidacloprid treatment was involved in a significant three-way interaction with arsenal application and genotype that influenced sweep category in 9-year-old loblolly pine growing in the upper coastal plain of North Carolina.

Genotype

Broken top

The main effect genotype significantly influenced the presence of broken top defects occurring on 9-year-old loblolly pine growing in the upper coastal plain of North Carolina. (P=0.000, Table 7). Broken top was absent on 96 (1.2) percent of trees in genotype C1, 87(2.0) percent of trees in genotype C2, 93(1.4) percent of genotype V1 and 98(0.74) percent of genotype V2. When adjusted for survival, stands of genotype C1 possessed 328(37) trees per acre without broken top. Stands planted with genotype C2 possessed 283(52) trees per acre without broken tops. Stands planted with genotype V1 had 364(21) without broken top and stands planted with genotype V2 also contained 364(22) trees per acre without broken tops (Figure 28).

Crook

The main effect genotype significantly influenced the presence of crook defects occurring on 9- year-old loblolly pine growing in the upper coastal plain of North Carolina ($P < 0.0001$, Table 7). Thus, 89(1.75)% of trees of genotype C1 were free from crook and when adjusted for survival possessed 307(37) trees per acre free of crook. Similarly, 80(2.33) percent of genotype C2 were free from fork, and when adjusted for survival produced 260(49) trees per acre free of crook. Likewise, 74(2.33) percent of trees of genotype V1 were free of fork, and when adjusted for survival possessed 292(22) trees per acre free from crook. Finally, 88(1.75) percent of trees of genotype V2 were free of crook defects, and when adjusted for survival produced 330(23) trees per acre free of crook.

Fork

The main effect genotype significantly influenced the presence of fork defects occurring on 9- year-old loblolly pine growing in the upper coastal plain of North Carolina ($P < 0.0001$, Table 7). Fork defects were absent on 73(2.55) percent of trees of genotype C1, and when adjusted for survival it possessed 250(34) trees per acre free from fork. Fork defects were absent on 79(2.38) percent of trees of genotype C2, and when adjusted for survival it possessed 258(49) trees per acre free from fork. Fork defects were absent on 86(1.86) percent of trees of genotype V1, and when adjusted for survival it possessed 339(22) trees per acre free from fork. Fork was absent on 90(1.62) percent of trees of genotype C1, and when adjusted for survival it possessed 336(23) trees per acre free from fork (see Figure 30).

Fusiform Rust

Genotype was involved in a significant interaction with imidacloprid treatment that influenced the presence of fusiform rust on 9-year-old loblolly pine growing in the upper coastal

plain of North Carolina (see Imidacloprid*Genotype interaction). The results of the two-way interaction are reported below.

Ramicorn Branch

Genotype was involved in a significant interaction with imidacloprid treatment that influenced the presence of ramicorn branch on 9-year-old loblolly pine growing in the upper coastal plain of North Carolina. The results of the two-way interaction are reported below.

Sinuosity

Genotype was involved in a significant interaction with arsenal application rate and imidacloprid treatment that influenced sweep category in 9-year-old loblolly pine growing in the upper coastal plain of North Carolina (Figure 33).

*Arsenal * Imidacloprid interaction*

The arsenal*imidacloprid interaction was not significant for the presence of broken top, crook, fork, fusiform rust, ramicorn branch, or degree of sinuosity in 9-year-old loblolly pine grown in the upper coastal plain of North Carolina (P= 0.568, 0.289, 0.833, 0.868, 0.175, and 0.658, respectively; Table 7).

*Arsenal * Genotype interaction*

The arsenal*genotype interaction was not significant for the presence of broken top crook, fork, fusiform rust, ramicorn branch, or degree of sinuosity in 9-year-old loblolly pine grown in the upper coastal plain of North Carolina (P= 0.148, 0.947, 0.119, 0.068, 0.401, and 0.269, respectively; Table 7).

*Imidacloprid*Genotype interaction*

Broken top

The imidacloprid*genotype interaction was not significant for presence of broken top defect in 9-year-old loblolly pine growing in the upper coastal plain of North Carolina (P=0.467, Table 7).

Crook

The imidacloprid*genotype interaction was not significant for presence of crook defect in 9-year-old loblolly pine growing in the upper coastal plain of North Carolina (P=0.433, Table 7).

Fork

The imidacloprid*genotype interaction was not significant for presence of fork in 9-year-old loblolly pine growing in the upper coastal plain of North Carolina (P=0.177, Table 7).

Fusiform rust

There were 42(4.12) percent of trees in the C1 control group that were free of fusiform rust, and C1 trees treated with imidacloprid only managed 29(3.64) percent of trees without rust. A total of 88(3) percent of C2 control trees were without fusiform rust, and when treated with imidacloprid, 94(1.79) percent of C2 trees were free of fusiform rust. Similarly, 96(1.42) percent of V1 control trees did not have fusiform rust, and V1 imidacloprid trees were 97(1.22) percent free of the disease. Genotype V2 control trees were 88(2.62) percent free from fusiform rust, while imidacloprid treated trees were 97(1.23) percent free from disease. When adjusted for survival, genotype C1 produced 138(24) trees per acre and 106(26) trees per acre in the control and imidacloprid treatments, respectively. Genotype C2 produced 233(61) trees per acre and 365(48) trees per acre in the control and imidacloprid treatments, respectively. Stands planted with genotype V1 possessed 358(21) trees per acre without rust in the control group and 399(22)

trees per acre without rust in the imidacloprid group. Stands planted with genotype V2 had 297(35) trees per acre in the control group and 395(13) trees per acre free of fusiform rust in the imidacloprid treated plots (Figure 31).

Ramicorn branch

A total of 47(3.99) percent of trees in the C1 control group were free of ramicorn branch, and when treated with imidacloprid it only managed 55(4.16) percent of trees without ramicorn branch. Likewise, 44(4.65) percent of C2 control trees were without ramicorn branch, and when treated with imidacloprid 56(3.8) percent were free of ramicorn branch. Similarly, 57(3.89) percent of V1 control trees did not have ramicorn branch, and imidacloprid trees were 61(3.89) percent free of the ramicorn branch. Genotype V2 control trees were 42(4.06) percent free from ramicorn branch and imidacloprid treated trees were 58(3.69) percent free from disease. When adjusted for survival, genotype C1 produced 156(25) trees per acre and 198(39) trees per acre in the control and imidacloprid treatments, respectively. Genotype C2 produced 111(37) trees per acre and 219(39) trees per acre in the control and imidacloprid treatments, respectively. Stands planted with genotype V1 possessed 211(24) trees per acre without ramicorn branch in the control group, and 256(25) trees per acre without ramicorn branch in the imidacloprid group. Stands planted with genotype V2 had 143(26) trees per acre in the control group, and 239(20) trees per acre free of ramicorn branch in the imidacloprid treated plots (see Figure 32).

Arsenal Imidacloprid* Genotype Interaction*

The arsenal* imidacloprid*genotype interaction resulted in significant differences in the severity of sweep in 9-year old loblolly pine growing in the upper coastal plain of North Carolina (p=0.002, Table 7).

Low arsenal rate, control

Of trees receiving low arsenal treatment and not given imidacloprid, genotype C2 was the highest quality in terms of sinuosity with 250 good quality stems (sinuosity “0” or “1”) per acre. Genotype C1 had 14 trees per acre of sinuosity class 0, and 173 TPA of form class 1, 141 TPA of form class 2, and 9 TPA of form class 3. Genotype C2 had 59 TPA of sinuosity class 0, and 191 TPA of form class 1, 55 TPA of form class 2, and 14 TPA of form class 3. Genotype V1 had 23 trees per acre of sinuosity class 0, 118 TPA of form class 1, 173 TPA of form class 2, and 77 TPA of form class 3. Genotype V2 had 14 trees per acre of sinuosity class 0, 204 TPA in form class 1, 95 TPA of form class 2, and 36 TPA of form class 3 (Figure 33).

Low arsenal rate, imidacloprid

Of trees receiving 0.031 gal/acre arsenal treatment and imidacloprid, genotype V2 was slightly better quality than genotype C1 producing 286 and 282 good quality trees per acre in terms of sinuosity index. Genotype C1 had 50 trees per acre of sinuosity class 0, and 232 TPA of form class 1, 95 TPA of form class 2, and 14 TPA of form class 3. Genotype C2 had 27 TPA of sinuosity class 0, and 209 TPA of form class 1, 132 TPA of form class 2, and 18 TPA of form class 3. Genotype V1 had 18 trees per acre of sinuosity class 0, and 141 TPA of form class 1, 191 TPA of form class 2, and 77 TPA of form class 3. Genotype V2 had 45 trees per acre of sinuosity class 0, and 241 TPA of form class 1, 91 TPA of form class 2, and 23 TPA of form class 3 (Figure 34).

High arsenal rate, control

Of trees receiving High arsenal treatment and no imidacloprid, genotype C1 was the highest quality in terms of stem form with 204 good quality trees per acre in terms of sinuosity index. Genotype C1 had 27 trees per acre of sinuosity class 0, and 177 TPA of form class 1, 109

TPA of form class 2, and 5 TPA of form class 3. Genotype C2 had 18 TPA of sinuosity class 0, and 109 TPA in form class 1, 68 TPA in form class 2, and 18 TPA in form class 3. Genotype V1 had 0 trees per acre of sinuosity class 0, and 36 TPA of form class 1, 204 TPA of form class 2, and 104 TPA of form class 3. Genotype V2 had 14 trees per acre of sinuosity class 0, and 145 TPA in form class 1, 132 TPA in form class 2, and 32 TPA in form class 3. Only stands of genotype C1 in the high arsenal rate/control group have close to enough good quality TPA (approximately 200 TPA required) to move to the next stage of stand development. After removals of trees with broken top, large ramicorn branches and crooks, it is unlikely these stands would have enough trees per acre to justify managing these stands for saw timber. This supports my hypothesis that trees given the highest levels of cultural treatment and no imidacloprid would be of the lowest quality (Figure 35).

High arsenal rate, imidacloprid

Of trees receiving high-arsenal treatment and imidacloprid, genotype C2 was the highest quality in terms of stem form with 241 good quality trees per acre. Genotype C1 had 5 trees per acre of sinuosity class 0, and 195 TPA of form class 1, 109 TPA of form class 2, and 18 TPA of form class 3. Genotype C2 had 18 TPA of sinuosity class 0, and 223 TPA of form class 1, 132 TPA of form class 2, and 18 TPA of form class 3. Genotype V1 had 5 trees per acre of sinuosity class 0, 104 TPA of form class 1, 236 TPA of form class 2, and 59 TPA of form class 3. Genotype V2 had 23 trees per acre of sinuosity class 0, and 182 TPA of form class 1, 209 TPA of form class 2, and 0 TPA of form class 3. Genotype V1 does not come close to having enough stem quality to justify moving on with a sawtimber rotation thus limiting its value. Genotypes C1 and V2 only just meet the requirement of approximately 200 good quality TPA and will likely not meet that guideline after cull for other defects (Figure 36).

Lower coastal plain

Phosphorus application rate

The main effect phosphorus application rate was not involved in significant differences in defects occurring on 9-year old loblolly pine growing in the lower coastal plain of North Carolina. However, phosphorus application rate was involved in a significant three-way interaction with imidacloprid treatment and genotype for the level of sinuosity of lower coastal plain pines. Results of the three-way interaction are reported below.

Imidacloprid treatment

The main effect imidacloprid was not significant for the presence of broken top, crook, fork or fusiform rust present on 9-year old loblolly pine growing in the lower coastal plain of North Carolina. However, the presence of ramicorn branches on LCP pines was found to be significantly different between control and imidacloprid treatments ($p=0.029$, Table 8). Trees planted in the control treatment were 99(0.3) percent free from ramicorn branch and imidacloprid trees were 96(0.7) percent free from ramicorn branch at the lower coastal plain. When adjusted for survival and expanded to a per-acre basis, control plots contained 396(23) trees per acre without ramicorn branches and imidacloprid trees contained 384(25) trees per acre without ramicorn branches. While the proportions of ramicorn branch present are technically significant, there is no practical difference between the number of trees per acre existing without ramicorn branches between control and imidacloprid treatments at the lower coastal plain.

Genotype

Broken top

The main effect genotype was significant for the presence of broken top on 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p<0.0001$, Table 8). Genotype C1

was 70(2.45) percent free from defect and produced 274(32) trees per acre without broken top at the lower coastal plain. Genotype C2 was 78(2.2) percent free from broken top and C2 stands contained 310(22) trees per acre without broken tops. Genotype V1 was 64(2.5) percent free from broken top and, when adjusted for survival, produced 265(24) trees per acre without broken top. Genotype V2 was 82(2.05) percent free from broken top and stands planted with V2 contained 324(34) trees per acre without broken top (Figure 38).

Crook

The main effect genotype was significant for the presence of crook on 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p < 0.0001$, Table 8). Genotype C1 was 92(1.4) percent free from crook and stands planted with C1 contained 370(25) trees per acre without crook defects. Genotype C2 was 90(0.6) percent free from crook defect and stand planted with C2 contained 356(31) trees per acre without crook defect. Genotype V1 was 72(2.34) percent free from defect and stands planted with V1 contained 299(22) trees per acre without crook defects. Genotype V2 was 93(1.3) percent free from defect and stands planted with V2 contained 368(25) trees per acre without crook defects (Figure 39).

Fork

The main effect genotype was not significant for the presence of fork defect occurring in 9-year-old loblolly pine growing at the lower coastal plain of North Carolina ($p = 0.279$, Table 8).

Fusiform rust

The main effect genotype was not significant for the presence of fusiform rust defect occurring in 9-year-old loblolly pine growing at the lower coastal plain of North Carolina ($p = 0.221$, Table 8).

Ramicorn branch

The main effect genotype was not significant for the presence of fork defect occurring in 9-year-old loblolly pine growing at the lower coastal plain of North Carolina ($p=0.185$, Table 8).

Phosphorus Imidacloprid interaction*

Broken top

The phosphorus*imidacloprid interaction was not significant for the presence of broken top in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.790$, Table 8).

Crook

The phosphorus*imidacloprid interaction was not significant for the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.178$, Table 8).

Fork

The phosphorus*imidacloprid interaction was marginally significant for the presence of fork defects on 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p=0.054$, Table 8). Trees planted in the low phosphorus, control plots were 94(1.21) percent free of fork defects and, when adjusted for survival, produced 375(33) trees per acre without fork defects. Trees in the low phosphorus, imidacloprid treated plots were 94(1.20) percent free of fork defects and contained 380(21) trees per acre without fork defects. High phosphorus, control plots were 94(1.19) percent free from fork defects at the LCP and contained 382(29) trees per acre without forks. The high phosphorus, imidacloprid plots were 90(1.58) percent free from fork and contained 358(18) trees per acre without fork defects (Figure 40). While these differences may be marginally statistically significant, they do not represent practical differences that influence stand development and future management.

Fusiform rust

The phosphorus*imidacloprid interaction was not significant for the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.253$, Table 8).

Ramicorn branch

The phosphorus* imidacloprid interaction was not significant for the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.178$, Table 8).

Phosphorus Genotype interaction*

Broken top

The phosphorus*genotype interaction was significant for the presence of broken top defects on 9-year-old loblolly pine grown in the lower coastal plain of North Carolina ($p=0.031$, Table 8). A total of 75(3.23) percent of genotype C1 trees given low phosphorus did not have broken tops, and when adjusted for survival had 304(32) trees per acre without broken top. Similarly, 81(2.95) percent of genotype C1 given high phosphorus did not have broken top, and when adjusted for survival produced 320(22) trees per acre without broken top. Genotype C2 given low phosphorus was 71(3.46) percent free of broken top, and when adjusted for survival produced 277(38) trees per acre without broken tops. Genotype C2 given high phosphorus was 69(3.47) percent free of broken top and produced 277(32) trees per acre without broken top. Genotype V1 given low phosphorus was 68(3.43) percent free of broken top and produced 277(22) trees per acre without broken top. Genotype V1 given high phosphorus was 60(3.59) percent free from broken top and produced 254(25) trees per acre without broken top. Genotype V2 given low phosphorus was 86(2.56) percent free from broken top and produced 345(32) trees per acre without broken top. Genotype V2 given high phosphorus was 78(3.16) percent free of broken top and produced 304(22) trees per acre without broken top (Figure 41).

Crook

The phosphorus*genotype interaction was not significant for the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina (p= 0.340, Table 8).

Fork

The phosphorus*genotype interaction was not significant for the presence of fork in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina (p= 0.264, Table 8).

Fusiform rust

The phosphorus*genotype interaction was not significant for the presence of fusiform rust in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina (p= 0.967, Table 8).

Ramicorn branch

The phosphorus*genotype interaction was not significant for the presence of ramicorn branch in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina (p= 0.430, Table 8).

*Imidacloprid*Genotype interaction*

Broken top

The imidacloprid*genotype interaction was significant in influencing the presence of broken top in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina (p= 0.001, Table 8).

Crook

The imidacloprid*genotype interaction was not significant in influencing the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina (p= 0.367, Table 8).

Fork

The imidacloprid*genotype interaction was not significant in influencing the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.342$, Table 8).

Fusiform rust

The imidacloprid*genotype interaction was not significant in influencing the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.982$, Table 8).

Ramicorn branch

The imidacloprid*genotype interaction was not significant in influencing the presence of crook in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.715$, Table 8).

Sinuosity

The imidacloprid*genotype interaction was not significant in influencing the presence of sinuosity in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p= 0.490$, Table 8).

*Phosphorus*imidacloprid*genotype interaction*

The phosphorus* imidacloprid*genotype interaction resulted in significant differences in the severity of sweep in 9-year-old loblolly pine growing in the upper coastal plain of North Carolina ($p=0.002$, Table 8).

Low phosphorus rate, control

Of loblolly pine receiving 8.1lbs of elemental phosphorus per acre at planting and no imidacloprid, genotype C1 was the highest quality in terms of sinuosity, with 309 good quality

trees per acre (note: genotype V2 also has 309 TPA of good quality stems; however, a larger proportion (209 of 309) are in sinuosity class 1. Genotype C1 had 100 trees per acre of sinuosity class 0, 209 TPA of form class 1, 100 TPA of form class 2, and 14 TPA of form class 3. Genotype C2 had 64 TPA of sinuosity class 0, 177 TPA of form class 1, 136 TPA of form class 2, and 14 TPA of form class 3. Genotype V1 had 41 trees per acre of sinuosity class 0, and 104 TPA of form class 1, 182 TPA of form class 2, and 73 TPA of form class 3. Genotype V2 had 100 trees per acre of sinuosity class 0, 209 TPA of form class 1, 100 TPA of form class 2 and 14 TPA of form class 3 (Figure 43).

Low phosphorus rate, imidacloprid

Of trees receiving 8.1lbs of elemental phosphorus per acre at planting and imidacloprid, genotype C2 was the highest quality in terms of stem form. Genotype C1 had 123 trees per acre of sinuosity class 0, and 168 TPA of form class 1, 77 TPA of form class 2, and 18 TPA of form class 3. Genotype C2 had 141 TPA of sinuosity class 0, 141 TPA of form class 1, 68 TPA of form class 2, and 36 TPA of form class 3. Genotype V1 had 32 trees per acre of sinuosity class 0, 104 TPA of form class 1, 145 TPA of form class 2, and 132 TPA of form class 3. Genotype V2 had 59 trees per acre of sinuosity class 0, 245 TPA of form class 1, 114 TPA of form class 2, and 5 TPA of form class 3 (Figure 44).

High phosphorus rate, control

Trees receiving 16.2 lbs./acre of elemental phosphorus at planting and no imidacloprid, genotype C2 was the highest quality in terms of sinuosity. Genotype C1 had 154 trees per acre of sinuosity class 0, 191 TPA of form class 1, 45 TPA of form class 2, and 5 TPA of form class 3. Genotype C2 had 204 TPA of sinuosity class 0, and 145 TPA in form class 1, 45 TPA in form class 2, and 5 TPA in form class 3. Genotype V1 had 27 trees per acre of sinuosity class 0, 132

TPA in form class 1, 132 TPA in form class 2, and 132 TPA in form class 3. Genotype V2 had 86 trees per acre of sinuosity class 0, 191 TPA in form class 1, 109 TPA in form class 2, and 14 TPA in form class 3 (Figure 45).

High phosphorus rate, imidacloprid

Of trees receiving 16.2 lbs. of elemental phosphorus per acre at planting and imidacloprid, genotype C2 was the highest quality in terms of sinuosity with 304 TPA good quality stems. Genotype C1 had 104 trees per acre of sinuosity class 0, 159 TPA of form class 1, 91 TPA of form class 2, and 41 TPA of form class 3. Genotype C2 had 114 TPA of sinuosity class 0, 195 TPA in form class 1, 59 TPA in form class 2, and 23 TPA in form class 3. Genotype V1 had 36 trees per acre of sinuosity class 0, 100 TPA in form class 1, 141 TPA in form class 2, and 145 TPA in form class 3. Genotype V2 had 104 trees per acre of sinuosity class 0, 150 TPA in form class 1, 109 TPA in form class 2, and 18 TPA in form class 3 (Figure 46).

Loss to defect

Loss to defect varied according to genotype, cultural treatment and imidacloprid status. Cull was substantial at both sites, however, loss to defect expressed as a percentage of the total volume was worse at UCP, where trees not given imidacloprid lost 19.37% of volume as cull and trees protected from Nantucket pine tip moth lost 14.18% of volume as cull. Therefore, imidacloprid treatment reduced the loss to cull at UCP by approximately 5% across all genotypes, suggesting that imidacloprid treatment increases quality of timber growing on medium quality sites. At the LCP, trees not given imidacloprid lost 8.89% of volume as cull and trees protected from tip moth lost 13.92% of volume as cull. Loss to defect expressed as a percentage of total volume was less than the loss experienced at the UCP. However, results

suggest that stands treated with imidacloprid were lower quality than control stand and lost approximately 5% more volume than trees in the control group (calculations not shown).

DISCUSSION

I sought to quantify the effect systemic control of Nantucket pine tip moth had on stem quality of intensively managed 9-year old loblolly pine grown in two physiographic regions of North Carolina. I hypothesized that tip moth control would decrease the number of defects occurring on 9-year-old loblolly pine grown in both physiographic regions of North Carolina. Additionally, I expected to see the greatest improvement to the quality of trees at the upper coastal plain site, where pest pressure is only one of many environmental stressors to which these trees are exposed. Damage from Nantucket pine tip moth represents a relatively small obstacle for trees growing on the high quality lower coastal plain site, where long growing seasons and high availability of water and nutrients promote rapid growth (King et al. 2014). I hypothesized that the quality of trees growing on the lower coastal plain site will be uniform regardless of pest control.

After nine years of growth, many UCP and LCP pine stands have reached, or are approaching canopy closure. A first commercial thinning is near; thus, my discussion will relate the stand quality metrics to real world forestry considerations. Given the high prevalence of defect at each site, I would suggest a selective low thinning retaining approximately 220 crop trees or approximately 70 square feet of basal area per acre. Trees with stem form defects are removed first, trees with smaller diameters and suppressed canopy positions are removed next. This approach to thinning does take considerably more work marking individual trees for removal but will leave the largest best quality stems to grow through the rotation. Results show that systemic control of Nantucket pine tip moth for the first two years following establishment

in medium quality stands experiencing heavy pest pressure can greatly increase quality of 9-year-old loblolly pine stands. However, like previous research on these sites have shown, interactions between sites resources, cultural treatments, insecticides and genotype are not always consistent with expectations (King et al. 2014).

Cultural treatments

Arsenal application rate

Stands given the low arsenal rate were estimated to possess 307 crop trees per acre without fusiform rust as compared 263 trees per acre without fusiform rust estimated for stands given the label rate. Increased woody vegetation and foliage surrounding growing pines associated with the lower herbicide rate may act as a physical barrier for fusiform rust basidiospores. Eaton et al. 2006 found significantly higher fusiform rust infection in 7-year-old loblolly pine stands where compete competition control was done when compared to stands without competition control. They concluded that differences in stand attributes that change air movement through the plantation (height to live crown and understory component height) may influence fusiform rust infection. Having 30-40 more trees per acre to choose from to move to the next stage in a sawtimber rotation is a practical advantage at a lower cost.

The three-way interaction between arsenal application rate, imidacloprid treatment and genotype had a profound impact on stand quality in terms of sinuosity. Increasing arsenal application rate led to increased sinuosity and a reduction in sawtimber potential in future stands across all genotypes. When given 0.031gal/acre arsenal, genotype C1 produced 234 TPA of good quality (sinuosity “0” or “1”) stems, and only 202 TPA good quality stems when given the label rate (0.062gal/acre arsenal), for a considerable 34 TPA difference. Stands of genotype C2 treated with 0.031gal/acre arsenal produced 243 good quality stems per acre; when given the label rate

0.062 gal/acre arsenal, the same genotype only produced 184 good quality stems, a 59 TPA difference. Genotype V1 treated with half the label rate arsenal produced 150 good quality stems per acre and only 72 good quality stems in the label rate treatment, for a 77 TPA difference. Finally, stands of genotype V2 treated with 0.031gal/acre arsenal produced 252 TPA considered good quality, but only 182 TPA were considered good quality in the label rate of arsenal, a 70 TPA difference. Averaged across all genotypes, the low arsenal treatment produced 219 TPA scoring “0” or “1” on the sinuosity index while the high arsenal application rate only produced 160 TPA, for a difference of 59 TPA . These additional 59 TPA are essential to fully occupy the site with straight stems after the first thinning. On average, an individual codominant stem covers 0.30 ft² of basal area at the UCP, meaning the low arsenal rate treatment could be thinned to approximately 70 ft² of basal area per acre at year nine maintaining only straight stems. The high arsenal treatment would only possess 48 ft² of basal area in straight stems, which is not enough to fully occupy the site after a thinning. The other residual trees making up the future stand in this treatment would come from sinuosity class “2” or “3” and thus severely degrade the quality and potential and limit future value. A likely explanation to the increased stem quality in the lower herbicide treatment is that increased woody vegetation (*Liquidambar styraciflua*, *Baccharis halimifolia*, *Quercus spp.* *Rubus sp.*) surrounding crop pine trees in the lower arsenal applications act as “trainer” trees through the first stage of the rotation keeping pine stems growing straight. Also, increased woody vegetation associated with the half label rate arsenal treatment increases habitat for natural enemies (Nowak and Berisford 2000) and may act as a physical barrier to tip moth oviposition(Asaro 2003) and likely contributed to increased stem straightness at the UCP.

Phosphorus application rate

At the LCP, phosphorus application rate interacted with genotype to influence the number of trees per acre without broken top, however, this was not consistent across genotypes. Stands planted with genotype C1 given 8.1 lbs. of elemental phosphorus at planting contained 304(32) trees per acre without broken top, and C1 stands given 16.2 lbs./acre elemental phosphorus at planting contained 320(22) trees per acre without broken top. While C1, low phosphorus treatment, on average, produced fewer TPA without broken top and was more variable than the high phosphorus treatment, these differences are likely not significant or practically different from a stand management perspective. Stands planted with genotype C2 given the 8.1 lbs. phosphorus per acre contained 277(38) trees per acre free of broken top and when treated with 16.2 lbs. elemental phosphorus produced 277(32) trees per acre without broken top. While phosphorus application rate did not change the number of trees free from broken top in stands planted with genotype C2, stands planted with C2 did contain fewer trees free from broken top than genotype C1 given the high phosphorus fertilization. Stands planted with genotype V1 given 8.1 lbs. elemental phosphorus per acre contained 277(22) trees per acre without broken top and 254(25) trees per acre without broken top when fertilized with 16.2 lbs. elemental phosphorus per acre. In genotype V1, it seems that increased phosphorus fertilization increased the number of broken tops in V1. While the numbers of trees present per acre without broken top in V1, is not practically different than genotype C2. There is a practical difference between genotype V1 and genotype C1 with high phosphorus. Finally, genotype V2 produced 345(32) trees per acre without broken top in the low phosphorus fertilization rate and 304(22) trees per acre without broken top in the high phosphorus application rate. Like Genotype V1, the number of trees free from broken top decreased in genotype V2 with an increase in phosphorus

fertilization rate. Stands planted with genotype V2 treated with the low phosphorus rate contained more trees per acre 345(32) without broken top than any other genotype fertilization combination excluding (genotype C1, high phosphorus rate) which is a practical management advantage at a lower cost of fertilizer (see Figure 41). The differences in interactions between genotype and fertilization rate influencing broken top highlight the need to craft site specific management recommendations that integrate genetic qualities with cultural treatments and site characteristics.

Additionally, the three-way interaction between phosphorus fertilization, imidacloprid and genotype resulted in practical differences in severity of sweep of 9-year-old loblolly pine grown at the lower coastal plain. In genotype V2, increased phosphorus fertilization increased sinuosity. Stands planted with V2 given 8.1 lbs elemental phosphorus/acre at planting produced 306 good quality stems (sinuosity “0” or “1”) per acre. Stands planted with V2 given 16.2 lbs per acre elemental phosphorus at planting only contained 265 good quality stems. In genotypes C1 and V1, increasing phosphorus fertilization did not markedly influence the sinuosity of the stand. Genotype C1 produced 300 TPA good quality stems in the low phosphorus rate and 304 TPA good quality stems in the high phosphorus rate treatment. Likewise, V1 produced 140 TPA good quality stems per acre in the low phosphorus treatment and 147 TPA good quality stems in the high phosphorus treatment. Genotype C2 was improved substantially with an increase in phosphorus fertilization, having 261 TPA good quality stems in the low phosphorus treatment and 327 good quality stems in the high phosphorus treatment. The differences in level of sinuosity in 9-year-old loblolly pine following interactions between genotype and fertilization rates at the lower coastal plain highlight the complexity of plantation management.

Problems with broken top and increased sinuosity in pine plantations attributed to fertilization are sometimes explained by reasoning that the accelerated growth rate can reduce lignification, making stems weak or limber (Birk Et al. 1989). Additionally, Albaugh Et al. 2004 found fertilization was linked to a reduction in wood strength. Aubrey Et. al 2007 observed greater damage from ice on fertilized loblolly pine compared to unfertilized pines, however they concluded this was due to the fertilized trees growing into a size class more susceptible to top breakage during the storm. I observed fewer trees per acre without broken top in the lower phosphorus fertilization treatment in genotypes V1 and V2. Also, I observed a significant increase in quality regarding sinuosity in genotype V2 with an increase in phosphorus fertilization. While reduced lignification due to accelerated growth may explain broken top and sinuosity in some pine plantations in some genotypes, the relationship is not constant across all situations or genotypes.

Imidacloprid treatment

Upper coastal plain

Control group

After nine years of growth at the upper coastal plain, loblolly pine trees not given imidacloprid (control group) on average grew to 28.32(0.62) feet tall, 6.34(0.08) inches in diameter at breast height and contained 3.52 cubic feet of wood volume per stem. Control stands had 328(24) trees per acre surviving and contained approximately 80(21) ft²/acre basal area. Stands not given imidacloprid contained 307(35) trees per acre without broken tops, 265(42) trees per acre without crook, 272(36) trees per acre without fork, 256(35) trees per acre free of fusiform rust, and 155(28) trees per acre without ramicorn branches. Control group stands at UCP contain approximately 165 trees per acre considered good quality in terms of sinuosity.

Stands not treated with imidacloprid at the upper coastal plain contained 1135(360) cubic feet of woody biomass per acre, of which, 184(45) cubic feet per acre was lost to cull, leaving 951(338) cubic feet of merchantable timber volume.

Treatment group

After nine years of growth at the upper coastal plain, loblolly pine trees treated with systemic imidacloprid (treatment group), on average, grew to 32.47(.62) feet tall, 7.35(0.08) inches in diameter at breast height, and contained 4.61 cubic feet of wood volume per stem. Treatment stands had 391(17) trees per acre surviving and contained approximately 115(12) ft²/acre basal area. Stands given imidacloprid contained 362(30) trees per acre without broken tops 328(34) trees per acre without crooks, 316(31) trees per acre without fork, 316(27) trees per acre without fusiform rust and 243(31) trees per acre without ramicorn branch. Imidacloprid treated stands contain approximately 214 trees per acre considered good quality in terms of sinuosity. Stands treated with imidacloprid at the upper coastal plain contained 1805(310) cubic feet of woody biomass per acre, of which, 224(22) cubic feet per acre were lost to cull, leaving 1580(332) cubic feet of merchantable timber volume.

Results from the UCP show systemic imidacloprid treatment offers many benefits to medium quality pine plantations where pests of establishment are likely present and could pose a risk to plantation success which falls in line with the third conclusion of Thomas and Oprean 1984. The 82 dollar/acre investment in imidacloprid, applied in 2009 produced plantations that have approximately 70 more trees per acre surviving than control treatments at year nine. On average imidacloprid treated pines were 4.15(0.78) feet taller than control trees and 0.61(0.06) inches larger in diameter at breast height. Imidacloprid treated trees have accumulated 1.09(0.12) ft³ more wood volume per stem than untreated controls. Imidacloprid treated stands grew at

approximately 58% faster rate over the last 9 years, which has driven forward the rotational timeline. Imidacloprid treated stands have moved out of the period of stand establishment and into the period of stem exclusion and canopy closure, control stands are still trying to capture the site. Per acre, imidacloprid stands have approximately 35ft² more basal area per acre than control plots; the additional basal area held in imidacloprid stands can be thinned for a small economic return now, control plots cannot yet be thinned for profit, and in some extreme cases will never be thinned due to low survival and quality. Stands treated with imidacloprid have more potential to leave higher quality residual trees after a thinning when compared to control stands. A commercial thinning will leave approximately 225 crop trees per acre, control stands do not meet this TPA requirement for trees free from ramicorn branch (155), or in numbers of good quality straight stems per acre (165). Imidacloprid treated stands hold a wide margin in numbers of trees without defect in every category. Although the imidacloprid treatment falls short on TPA of good straightness with 214, that is approximately 30% more straight trees per acre than control plots. Imidacloprid treatments did lose more volume to cull than control plots, however the overall growth stimulation over control plots by imidacloprid was greater than the additional loss in cull over controls. Treatment stands possess approximately 629 ft³, or 66% more harvestable wood volume per acre than control plots at year 9.

Lower coastal plain

Control group

After nine years of growth at the lower coastal plain, loblolly pine trees not given imidacloprid (control group) on average grew to 36.79(0.48) feet tall, 7.09(0.09) inches in diameter at breast height, and contained 4.90 cubic feet of wood volume per stem. Control stands had 324(58) trees surviving per acre and covered approximately 118(12) ft²/acre basal area.

Control stands contained 298(28) trees per acre without broken tops, 285(46) trees per acre without crook, 378(31) trees per acre without fork, 323(21) trees per acre without fusiform rust and 396(22) trees per acre without ramicorn branches. Control treatment stands at LCP contained approximately 266 trees per acre considered good quality in terms of sinuosity. Stands not treated with imidacloprid at the lower coastal plain contained 1965(101) cubic feet of woody biomass per acre, of which, 160(40) cubic feet per acre was lost to cull, leaving 1804(36) cubic feet of merchantable timber volume.

Treatment group

After nine years of growth at the lower coastal plain, loblolly pine trees not given imidacloprid (treatment group) on average grew to 37.58 (0.48) feet tall, 7.30(0.09) inches in diameter at breast height, and contained 5.35 cubic feet of wood volume per stem. Control stands had 392(40) trees per acre surviving and contained approximately 116(10) ft²/acre of basal area. LCP stands given imidacloprid contained 290(23) trees per acre without broken tops, 337(19) trees per acre without crook, 369(19) trees per acre without fork, 390(24) trees per acre without fusiform rust, and 384(25) trees per acre without ramicorn branches. Treatment group stands at LCP contained approximately 246 trees per acre considered good quality in terms of sinuosity. Stands treated with imidacloprid at the lower coastal plain contained 2145(174) cubic feet of woody biomass per acre, of which, 262(73) cubic feet per acre was lost to cull, leaving 1883(31) cubic feet of merchantable timber volume.

Results from the LCP show systemic imidacloprid treatment at establishment is likely not feasible for plantations established on high quality sites even when pests of establishment are likely present in damaging densities. The 82 dollar/acre investment in imidacloprid, applied in 2009 produced plantations that have approximately 70 more trees per acre surviving than control

treatments. On average imidacloprid treated pines were 0.79(0.52) feet taller than control trees and 0.22(0.08) inches larger in diameter at breast height. Imidacloprid treated trees have accumulated 0.45(0.16) ft³ more wood volume per stem than untreated controls. Imidacloprid treated stands grew at approximately 9% faster rate over the last 9 years, however, this increased growth rate has not given imidacloprid plots a distinct advantage in stand development like observed at UCP. At LCP, both control and imidacloprid treatments are leaving the stand initiation stage and are moving into the period of canopy closure/stem exclusion. Per acre, imidacloprid stands have approximately 2 ft² less basal area per acre than control plots, which is within error terms (no difference). Both control and imidacloprid treated stands at the LCP are approaching a first commercial thinning. Commercial thinning will leave approximately 225 crop trees per acre, having a wide margin over 225 in each defect is essential to minimizing defect in later stages of stand management. Imidacloprid improved quality of stands over control treatment in number of trees per acre without crook from a stand management perspective, having 337(19) TPA without crook is better than 285(46). Control stands are more variable and, in the worst stands it may not be possible to thin out all the crooks in the control treatment. Imidacloprid stands have approximately 70 more trees per acre without fusiform rust, however, control plots likely have enough TPA to minimize fusiform rust in the next rotation, making this difference relatively less of a practical advantage. Control plots held a slight advantage over imidacloprid plots with 22 more TPA of straight stems per acre. With 246 straight stems per acre, imidacloprid treatments may retain higher sinuosity stems in the next stage of stand development thus reducing the value of the rotation. There was no practical difference in number of TPA without broken top, fork or ramicorn branch between control and imidacloprid treatments, each treatment possessed enough numbers of trees per acre without defect to

minimize the defects in the stand following thinning. Imidacloprid treatments did lose more volume to cull than control plots, with 262 ft³/acre lost to cull (Control: 161ft³/acre), however the overall stimulation by imidacloprid was enough to offset the difference between treatments lost to cull. Imidacloprid treatment stands possess approximately 80 ft³ or .04% more harvestable wood volume per acre than control plots at year 9. My results from the LCP are compatible with the second conclusion of Thomas and Oprean 1984, which states pines grown on good quality sites show less impact from tip moth infestation. At year nine, results from the LCP suggest imidacloprid treatment to manage Nantucket pine tip moth may not be feasible on high quality sites.

Genetic influence

Improved genetics are the building blocks of a forest plantation (Mckeand et al. 2003), and while cultural treatments like herbicide applications and fertilizers can influence how these genetics perform, the genotypes planted will set the stage for future plantation success or failure. This study demonstrates that it is paramount that careful attention is given selecting appropriate genotypes for planting sites(Fox Et al. 2007, King Et. al 2014). My results show a strong connection between genetics and the presence of stem defects (Tables 6 and 7). The main effect genotype was significant or was involved in significant interactions in all defects surveyed at UCP, and 3 of 6 defects at LCP (Tables 6 and 7).

Upper coastal plain

After nine years of growth at the UCP site, genotype C1 grew to 29.2(0.52) feet tall, 7.30(0.009) inches in diameter at breast height, and contained 4.13(0.14) ft³ of wood volume per individual stem. Stands planted with this genotype had 342(20) trees surviving per acre, covering 100(13) ft²/acre of basal area, and grew at 157 ft³/acre/year over the last 9 years. UCP stands

planted with genotype C1 contained 328(37) trees per acre without broken top, 307(37) trees per acre without crook, 250(34) trees per acre without fork, 122(25) trees per acre without fusiform rust and 177(32) trees per acre without ramicorn branches. Stands planted with C1 at UCP had approximately 218(13) trees per acre considered good quality in terms of sinuosity. C1 stands accumulated 1349(141) ft³/acre of woody biomass of which 231(36) ft³/acre was lost to cull, leaving 1118(136) ft³/acre of merchantable timber volume at year nine.

After nine years of growth at UCP, genotype C2 grew to 31.9(0.52) feet tall, 7.04(0.09) inches in diameter at breast height, and contained 4.19(0.14) ft³ of wood volume per individual stem. Stands planted with this genotype had 329(20) trees surviving per acre, covering 89(23) ft²/acre of basal area, and grew at 152 ft³/acre/year over the last 9 years. UCP stands planted with genotype C2 contained 283(52) trees per acre without broken top, 260(49) trees per acre without crook, 258(49) trees per acre without fork, 165(38) trees per acre without ramicorn branch and 299(54) trees per acre without fusiform rust. Stands planted with C2 at UCP had approximately 213(13) trees per acre considered good quality in terms of sinuosity. C2 stands accumulated 1408(150) ft³/acre of woody biomass of which 147(42) ft³/acre was lost to cull, leaving 1261(147) ft³/acre of merchantable timber volume at year nine.

After nine years of growth at the UCP site, genotype V1 grew to 30.60(0.51) feet tall, 7.02(0.09) inches in diameter at breast height, and contained 4.11(0.13) ft³ of wood volume per individual stem. Stands planted with this genotype had 390(20) trees surviving per acre, covering 106(17) ft²/acre of basal area, and grew at 178 ft³/acre/year over the last 9 years. UCP stands planted with genotype C1 contained 364(21) trees per acre without broken top, 292(22) trees per acre without crook, 339(22) trees per acre without fork, 378(21) trees per acre without fusiform rust and 233(24) trees per acre without ramicorn branches. Stands planted with V1 at UCP had

approximately 111(6) trees per acre considered good quality in terms of sinuosity. V1 stands accumulated 1634(153) ft³/acre of woody biomass of which 330(47) ft³/acre was lost to cull, leaving 1004(139) ft³/acre of merchantable timber volume at year nine.

After nine years of growth at the UCP site, genotype V2 grew to 29.7(0.51) feet tall, 6.78(0.09) inches in diameter at breast height, and contained 3.82(0.13) ft³ of wood volume per individual stem. Stands planted with genotype had 370(15) trees surviving per acre, covering 94(18) ft²/acre of basal area, and grew at 157 ft³/acre/year over the last 9 years. UCP stands planted with genotype V2 contained 364(22) trees per acre without broken top, 330(23) trees per acre without crook, 336(73) trees per acre without fork, 346(24) trees per acre without fusiform rust and 191(23) trees per acre without ramicorn branches. Stands planted with V2 at UCP had approximately 217(11) trees per acre considered good quality in terms of sinuosity. V2 stands accumulated 1441(159) ft³/acre of woody biomass of which 120(29) ft³/acre was lost to cull, leaving 1321(149) ft³/acre of merchantable timber volume at year nine.

Lower coastal plain

After nine years of growth at the LCP site, genotype C1 grew to 34.67(.40) feet tall, 7.15(0.10) inches in diameter at breast height, and contained 4.67(0.18) ft³ of wood volume per individual stem. Stands planted with genotype C1 had 398(22) trees surviving per acre, covering 111.0(8.0) ft²/acre of basal area, and grew at 206 ft³/acre/year over the last 9 years. LCP stands planted with genotype C1 contained 275(33) trees per acre without broken top, 370(26) trees per acre without crook, 372(21) trees per acre without fork, 388(24) trees per acre without fusiform rust and 381(22) trees per acre without ramicorn branches. Stands planted with C1 at LCP had approximately 302(17) trees per acre considered good quality in terms of sinuosity. C1 stands

accumulated 1865(61) ft³/acre of woody biomass of which 71(65) ft³/acre was lost to cull, leaving 1794(58) ft³/acre of merchantable timber volume at year nine.

After nine years of growth at the LCP site, genotype C2 grew to 40.65(0.47) feet tall, 7.17(0.10) inches in diameter at breast height, and contained 5.47(0.18) ft³ of wood volume per individual stem. Stands planted with this genotype had 394(31) trees surviving per acre, covering 110(12) ft²/acre of basal area, and grew at 238(10) ft³/acre/year over the last 9 years. UCP stands planted with genotype C2 contained 310(22) trees per acre without broken top, 356(32) trees per acre without crook, 216(9) trees per acre without fork, 392(33) trees per acre without fusiform rust and 229(10) trees per acre without ramicorn branches. Stands planted with C2 at LCP had approximately 294(23) trees per acre considered good quality in terms of sinuosity. C2 stands accumulated 2155(64) ft³/acre of woody biomass of which 121(96) ft³/acre was lost to cull, leaving 2034(68) ft³/acre of merchantable timber volume at year nine.

After nine years of growth at the LCP site, genotype V1 grew to 38.3(0.46) feet tall, 7.22(0.09) inches in diameter at breast height, and contained 5.31(0.18) ft³ of wood volume per individual stem. Stands planted with this genotype had 412(17) trees surviving per acre, covering 118(7) ft²/acre of basal area, and grew at 244 ft³/acre/year over the last 9 years. LCP stands planted with genotype V1 contained 265(25) trees per acre without broken top, 356(32) trees per acre without crook, 389(16) trees per acre without fork, 412(9) trees per acre without fusiform rust and 410(17) trees per acre without ramicorn branches. Stands planted with V1 at LCP had approximately 144(6) trees per acre considered good quality in terms of sinuosity. V1 stands accumulated 2200(98) ft³/acre of woody biomass of which 571(101) ft³/acre was lost to cull, leaving 1629(91) ft³/acre of merchantable timber volume at year nine.

After nine years of growth at the LCP site, genotype V2 grew to 35.07(0.46) feet tall, 7.23(0.10) inches in diameter at breast height, and contained 5.04(0.18) ft³ of wood volume per individual stem. Stands planted with this genotype had 394(24) trees surviving per acre, covering 110(9) ft²/acre of basal area, and grew at 238 ft³/acre/year over the last 9 years. LCP stands planted with genotype V2 contained 324(34) trees per acre without broken top, 368(25) trees per acre without crook, 371(22) trees per acre without fork, 395(22) trees per acre without fusiform rust and 388(23) trees per acre without ramicorn branches. Stands planted with V2 at LCP had approximately 285(17) trees per acre considered good quality in terms of sinuosity. V2 stands accumulated 1958(73) ft³/acre of woody biomass of which 74(81) ft³/acre was lost to cull, leaving 1884(76) ft³/acre of merchantable timber volume at year nine.

Genotype was a major influence on growth and yield of 9-year-old loblolly pine at grown at the upper and lower coastal plain sites. Fusiform rust was a major damaging factor for genotype C1 stem quality at UCP , with only 122(25) trees per acre without rust, the residual stand left after thinning genotype C1 will retain trees with fusiform galls, which in turn reduces stand resilience to extreme weather (Belanger Et al. 1996) and reduces value substantially (Cubbage Et al. 2000). Fusiform was present and did cause damage on other genotypes but none to the degree and severity of genotype C1. Fusiform rust was present at the LCP site and did infect genotype C1, but the galls were reduced in size and the disease was much less frequent at LCP, suggesting that edaphic and climactic factors interact with genotype to influence the severity of rust infection (Kelley and King 2014).

All genotypes at UCP were significantly damaged by presence of ramicorn branches, however imidacloprid treatment improved the number of trees free of ramicorn branch to

acceptable levels in each genotype, excluding C1, again suggesting genotype C1 is not a good genetic match for UCP.

Sinuosity was another trait that was distinctly influenced by genetics. Genotype V1 is the most sinuous genotype both at UCP and LCP, with 94% less straight trees per acre (111) than the average of the other three genotypes (216) at UCP, and 88% less straight trees per acre (144) than the average of the three other genotypes (271). This study also showed that cultural treatments can influence sinuosity. At UCP, the low Arsenal treatment generally improved sinuosity. At LCP, the high level of phosphorus fertilization increased sinuosity in V1 and V2 but improved it in C2. However, genotype V1 is genetically more sinuous than other genotypes overall, and this is a disadvantage for plantation management.

Research sites UCP and LCP were planted with four genotypes, of which two are mass control pollinated varieties and two clonal varieties. The genetic diversity of these plantations is adequate but could be considered minimal. On the landscape, plantations are likely more genetically diverse planted with open pollinated and mass control pollinated varieties and few clones on an industrial scale. Many of the defects and traits measured in my study have a genetic connection and thus real-world plantations could display higher variation in the traits I measured compared to my results.

Growth rate drives rotation timeline and financial return

Results from Chapter 1 show systemic imidacloprid treatments increased total height, diameter at breast height, individual stem volume, survival and annual growth rate growth rate (>30%) across all genotypes of 9-year-old loblolly pine on the medium quality UCP site. Increased survival, total height, average diameter, stem volume and growth rate of imidacloprid stands allows the crop pine trees to capture and occupy the site fully, faster than their untreated

counterparts (Figure 25). Rapid and full occupation of the site reduces the potential for volunteer vegetation to establish and compete for resources (Fox Et al. 2007). As well, stands that fully occupy the site faster can be thinned sooner, providing for some economic benefit earlier in the rotation and reducing the total rotation length. Reduced rotation length provides total economic benefits to landowners sooner and allows for a subsequent pine rotation to begin sooner, thus increasing the net present value (NPV) of the rotation. While many of the imidacloprid treatments at UCP are only beginning to break even by year nine (numbers not reported), the reduced rotation timeline and accelerated growth rate could potentially provide considerable financial return by the end of a sawtimber rotation (Borders and Bailey 2001, Fox Et al. 2007).

At the high-quality LCP site, there is no evidence that imidacloprid treatment increased total height. However, there are significant differences in average diameter and individual stem volume between the control and imidacloprid treatments. Mean annual increment was increased substantially in some genotypes. However, as hypothesized, the increases in measures of productivity were relatively smaller at the high-quality site. While some of these differences are statistically significant, most differences in productivity are not large enough to make a practical difference in management decisions. Unlike the upper coastal plain, the treated and untreated stands have not diverged in stand development, regardless of treatment status were able to occupy the site and enter the stage of canopy closure after nine years of growth. At the LCP, there is no evidence to support that imidacloprid treatment has reduced the rotation length. After nine years of growth at the LCP, results suggest that systemic insecticides do not increase growth rate enough to justify their use on high quality sites where insect damage is less of an obstacle for plantation success, which falls in line with the conclusions Willison and Barras, Thomas and Oprean, Powers and Stone.

CONCLUSIONS

As populations continue to increase, wood and fiber consumption will also increase while simultaneously reducing the land base for producing wood products. Loblolly pine plantation management in the United States South is projected to contribute 60% of our nation's total roundwood harvest in 2050 (Haynes et al. 2000). Plantation management is projected to expand throughout the region and management regimes will likely intensify to meet the increased demand for wood and fiber required of a growing population. Much of the expansion in southern pine plantation acres is projected to occur on marginal agricultural lands in the coastal plain and piedmont physiographic regions (Prestemon and Abt 2002).

The U.S. Southeast is a major wood producing region on a global scale, but in order to remain competitive, southeastern land managers must move away from minimizing cost per acre and maximize wood production per dollar invested (Borders and Bailey 2001). This will require significant effort on the silviculturalists part to write site specific management recommendations that match sites with superior genetics and develop management regimes that ameliorate site limitations and address any obstacles to plantation success while also maintaining cost efficiency.

Marginal agricultural lands, like those projected to transition into loblolly pine plantation, are represented by the UCP site and present future foresters with an opportunity. However, this opportunity comes with special considerations. Marginal agricultural lands are generally not high-quality plantation sites but can usually be considered of medium quality for growing loblolly pine.

My research shows that efforts to establish loblolly plantations on marginal agricultural land can be hindered, and even ruined, if pests of establishment are present at damaging levels.

Results from my research show that systemic imidacloprid applied at planting was effective in increasing growth by 58% and yield by 40% of 9-year-old loblolly pine grown in the upper coastal plain of North Carolina. Moreover, the stimulation in growth rate has driven treatment stands through the period of stand establishment and into the period of canopy closure, shortening the time to an initial financial incentive (commercial thinning) and shortening the rotation length. Additionally, defects like crook and ramicorn branch were reduced enough in treatment stands to make a practical difference in terms of residual quality after a thinning. Likewise, systemic imidacloprid did improved growth by 9% at the high quality lower coastal plain site but because of greater loss to cull, there was no real difference in yield (.04% or 80ft³/acre) between control and imidacloprid treated stands at LCP. I conclude that in situations where pine tip moths are present in damaging numbers, investments in systemic imidacloprid at planting can mean the difference between plantation success and failure on medium quality sites but are likely not economically feasible on high quality sites.

Finally, results have been influenced by and can be attributed in part to the climactic factors associated with the upper and lower coastal plains of North Carolina over the last decade. Research and projections suggest that global climate is going to become more variable, and therefore, different than the climate of the past decade(Seager et al. 2009, Li et al. 2011). Changes in environmental factors within projected future limits could have a profound impact on many other factors that influence variables measured in my study. Therefore, my work must be evaluated in this context and my results recognized to reflect the climate of today. As well, future inventories of the Nantucket pine tip moth exclusion study and additional tip moth research studies must take differences in climate into consideration when evaluating results and drawing conclusions and making management decisions.

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TABLES

Table 1. Site attributes for Nantucket Pine Tip Moth Exclusion Study Established in the Upper and Lower coastal plain of North Carolina in December 2008 and January 2009.

Site name	UCP(Taylor Tract)	LCP (Hofmann Forest)
County, State	Nash County, NC	Onslow/Jones County, NC
Latitude	36°07'44" N	34°49'37" N
Longitude	77°17'44' 'W	77°17'03"W
Elevation (ft)	131.2	45.93
Soil series	Goldsboro/Norfolk	Rains
Planting spacing (ft)	10 x 10	5 x 20
Whole plot treatment	High-Low Arsenal	High-Low Phosphorus
Split plot Treatment	Imidacloprid	Imidacloprid
Split-Split plot treatment	Pine genetics	Pine genetics

Table 2. Statistical results (p values) of the effects of whole-plot (fertilizer or herbicide) split-plot (imidacloprid treatment) and split-split plot (genetics) factors on individual tree height, diameter at breast height and individual stem volume in improved genotypes of loblolly pine after nine years of growth along the UCP and LCP of North Carolina significant values are bolded.

P Values of Main Effects and Interactions							
Source ^a	LCP(Hofmann)			Source ^b	UCP(Taylor Tract)		
	Total Height	Diameter	Volume		Total Height	Diameter	Volume
F	0.3316	0.9708	0.9886	H	0.3432	0.9070	0.5487
I	0.1683	0.0444	0.0293	I	0.0019	<0.0001	<0.0001
FxI	0.4899	0.6027	0.6013	HxI	0.7369	0.7063	0.6702
G	<0.0001	0.8510	<0.0001	G	<0.0001	<0.0001	<0.0001
FxG	0.6157	0.7902	0.5949	HxG	0.8953	0.6061	0.5383
IxG	0.1340	0.8321	0.4654	IxG	<0.0001	0.6205	0.4862
FxIxG	0.0084	0.8095	0.5775	HxIxG	0.0167	0.2684	0.2562

Sources of variation at the LCP are Phosphorus fertilization (F) tip moth control (I) and pine genetics (G). Sources of variation at the UCP are Herbicide (H) tip moth control (I) and pine genetics (G).

Table 3. Least Square Mean (Standard Error) of total height, diameter at breast height, and individual stem volume averaged by tip moth treatment and genetics after the 9th growing season in the upper coastal plain.

UCP				
Tip Moth Treatment	Genotype	Total Height (ft)	DBH (in)	Stem volume(ft ³)
Control	V1	28.33 (4.00)	6.69 (1.22)	3.49 (1.36)
Control	V2	28.07 (4.37)	6.47 (1.32)	3.31 (1.40)
Control	C1	28.17 (4.17)	6.99 (0.98)	3.67 (1.16)
Control	C2	29.29 (4.34)	6.82 (1.11)	3.65 (1.22)
Imidacloprid	V1	33.06 (4.54)	7.37 (1.17)	4.73 (1.59)
Imidacloprid	V2	31.55 (4.83)	7.12 (1.38)	4.35 (1.77)
Imidacloprid	C1	30.47 (3.75)	7.61 (1.06)	4.58 (1.35)
Imidacloprid	C2	34.87 (3.92)	7.28 (0.88)	4.75 (1.24)

Table 4. Least Square Mean (Standard Error) of total height, diameter at breast height, and individual stem volume averaged by tip moth treatment and genetics after the 9th growing season in the lower coastal plain.

LCP				
Tip Moth Treatment	Genotype	Total Height (ft)	DBH (in)	Stem volume(ft ³)
Control	V1	37.96 (4.48)	7.09 (1.33)	5.04 (2.09)
Control	V2	34.20 (6.01)	7.08 (1.65)	4.68 (2.26)
Control	C1	34.35 (3.61)	7.07 (1.25)	4.54 (1.62)
Control	C2	40.64 (3.93)	7.10 (1.26)	5.33 (1.87)
Imidacloprid	V1	38.66 (5.51)	7.36 (1.47)	5.57 (2.51)
Imidacloprid	V2	35.98 (6.43)	7.38 (1.75)	5.39 (2.71)
Imidacloprid	C1	35.07 (4.76)	7.22 (1.29)	4.82 (1.86)
Imidacloprid	C2	40.60 (5.73)	7.24 (1.29)	5.60 (2.16)

Table 5. Least Square Mean (Standard Error) of total height, diameter at breast height, and individual stem volume averaged by tip moth treatment after the 9th growing season in the Upper and Lower coastal plain of North Carolina. When significant differences were found a Tukey HSD test was performed, and the adjusted p values are reported.

LCP			
	Total Height (std err)	Average DBH (std err)	Stem Volume (std err)
Imidacloprid	37.58 (0.48)	7.30 (0.09)	5.35 (0.17)
Control	36.79 (0.48)	7.09 (0.09)	4.90 (0.17)
▲	0.79 (0.53)	0.22 (0.08)	0.45 (0.16)
adj p value	0.1684	0.0428	0.0288
UCP			
	Total Height (std err)	Average DBH (std err)	Stem Volume (std err)
Imidacloprid	32.47 (0.62)	7.35 (0.07)	4.61 (0.13)
Control	28.32 (0.62)	6.73 (0.08)	3.52 (0.13)
▲	4.14 (0.79)	0.61 (0.08)	1.09 (0.12)
adj p value	0.0019	<.0001	<.0001

Table 6. Statistical results (p values)of the effects of whole-plot (fertilizer or Herbicide) split-plot (imidacloprid treatment) and split-split plot (genetics) factors on individual Stem form defects in improved genotypes of loblolly pine after nine years of growth along the LCP of North Carolina.

LCP						
Source	Crook	Broken Top	Fusiform rust	Ramicorn Branch	Fork	Sweep
F	0.208	0.285	0.827	0.854	0.070	0.049
I	0.223	0.885	0.828	0.029	0.709	0.078
G	<.0001	<.0001	0.221	0.185	0.279	<.0001
FxI	0.178	0.790	0.253	0.398	0.054	0.005
FxG	0.340	0.031	0.967	0.430	0.264	0.088
IxG	0.367	0.001	0.982	0.715	0.342	0.490
FxIxG	0.139	0.130	0.695	0.342	0.315	0.002

Sources of variation at the LCP are Phosphorus fertilization (F) tip moth control (I) and pine genetics (G).

Table 7. Statistical results (p values)of the effects of whole-plot (fertilizer or Herbicide) split-plot (imidacloprid treatment) and split-split plot (genetics) factors on individual Stem form defects in in improved genotypes of loblolly pine after nine years of growth along the UCP of North Carolina.

UCP						
Source	Fork	Crook	Broken Top	Fusiform Rust	Ramicorn Branch	Sweep
H	0.316	0.971	0.316	0.001	0.217	<.0001
I	0.161	0.276	0.038	0.282	0.011	0.114
G	<.0001	<.0001	0.000	<.0001	0.028	<.0001
HxI	0.833	0.289	0.568	0.868	0.175	0.658
HxG	0.119	0.947	0.148	0.068	0.401	0.269
IxG	0.177	0.433	0.467	0.003	0.013	0.031
HxIxG	0.070	0.893	0.635	0.236	0.465	0.002

Sources of variation at the UCP are Herbicide (H) tip moth control (I) and pine genetics (G).

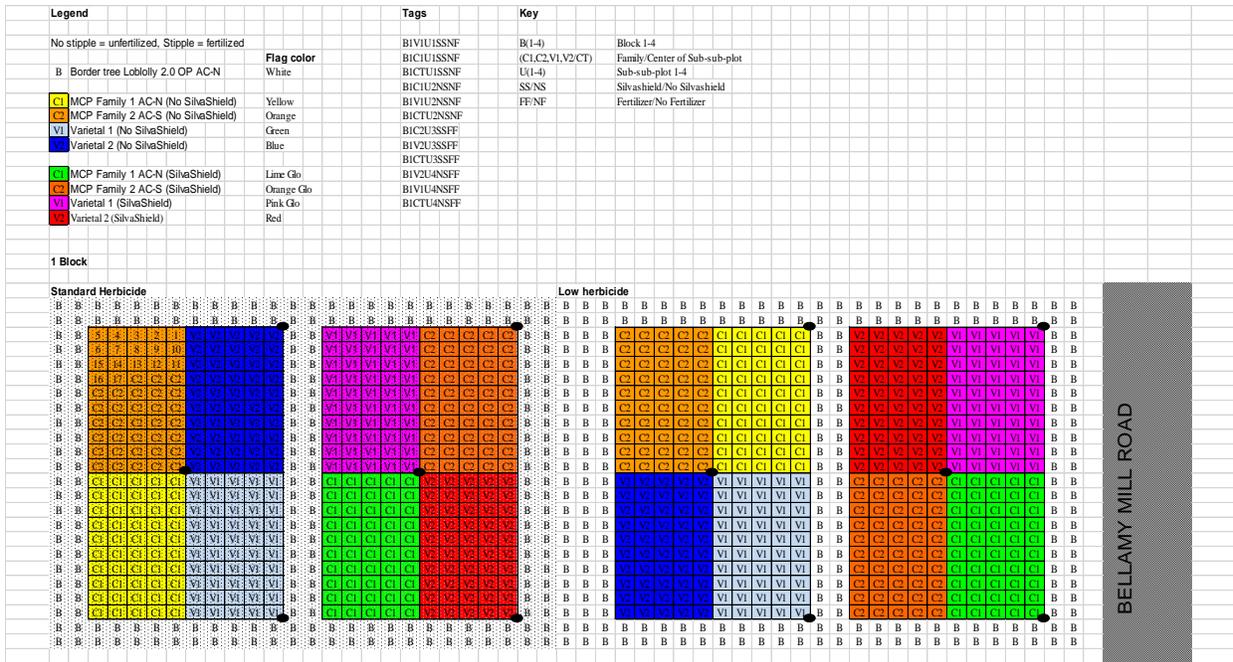


Figure 3. Diagram of study design established for the Nantucket pine tip moth exclusion study at the UCP. This Diagram represents one block, these blocks were part of a complete randomized design and were replicated four times.



Figure 4. Adult female Nantucket pine tip moth (*Rhyacionia frustrana* Comstock). This species is approximately 10-15 mm long and has characteristic rust/russet colored banding on the forewings. Damage occurs when feeding larvae tunnel into young pine meristems causing shoot death and loss of apical dominance. Larval feeding is rarely fatal but can reduce growth and lower stem quality in young plantations. (USDA Forest Service, USDA Forest Service, Bugwood.org)



Figure 5. Measuring DBH with Haglof Mantax 18-inch calipers. Calipers were used to measure diameter at breast height (4.5 ft or 1.3 m above groundline). Two measurements were taken perpendicular to one another and an average diameter was calculated.



Figure 6. Data collection at LCP, here I am collecting DBH measurements on genotype V2 protected from tip moth.



Figure 7. Total height data collection with Nikon Forestry pro laser dendrometer at UCP. In my left hand are the Haglof Mantax 18" calipers. The Nikon Forestry Pro dendrometer measures to a half-foot margin and the Haglof calipers are precise to within one tenth of an inch.

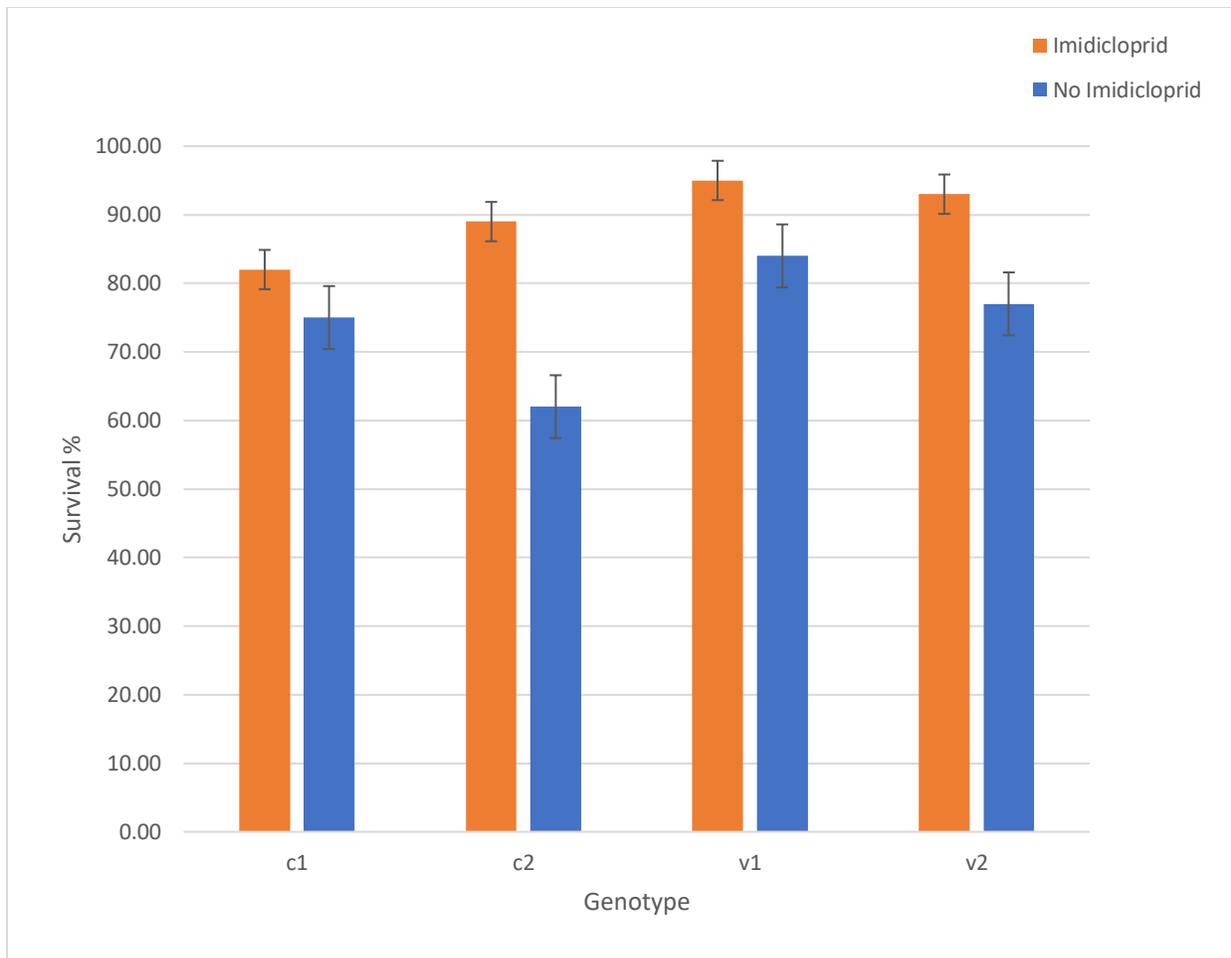


Figure 8. Survival (standard error) of 9-year-old loblolly pine planted at UCP by imidacloprid treatment and genotype. Systemic insecticide improved survival across all genotypes, and increased C2 survival by 27 %. Unlike the LCP site, survival at the UCP was influenced by insecticide treatment. Many plots not treated with imidacloprid suffered > 20% mortality.

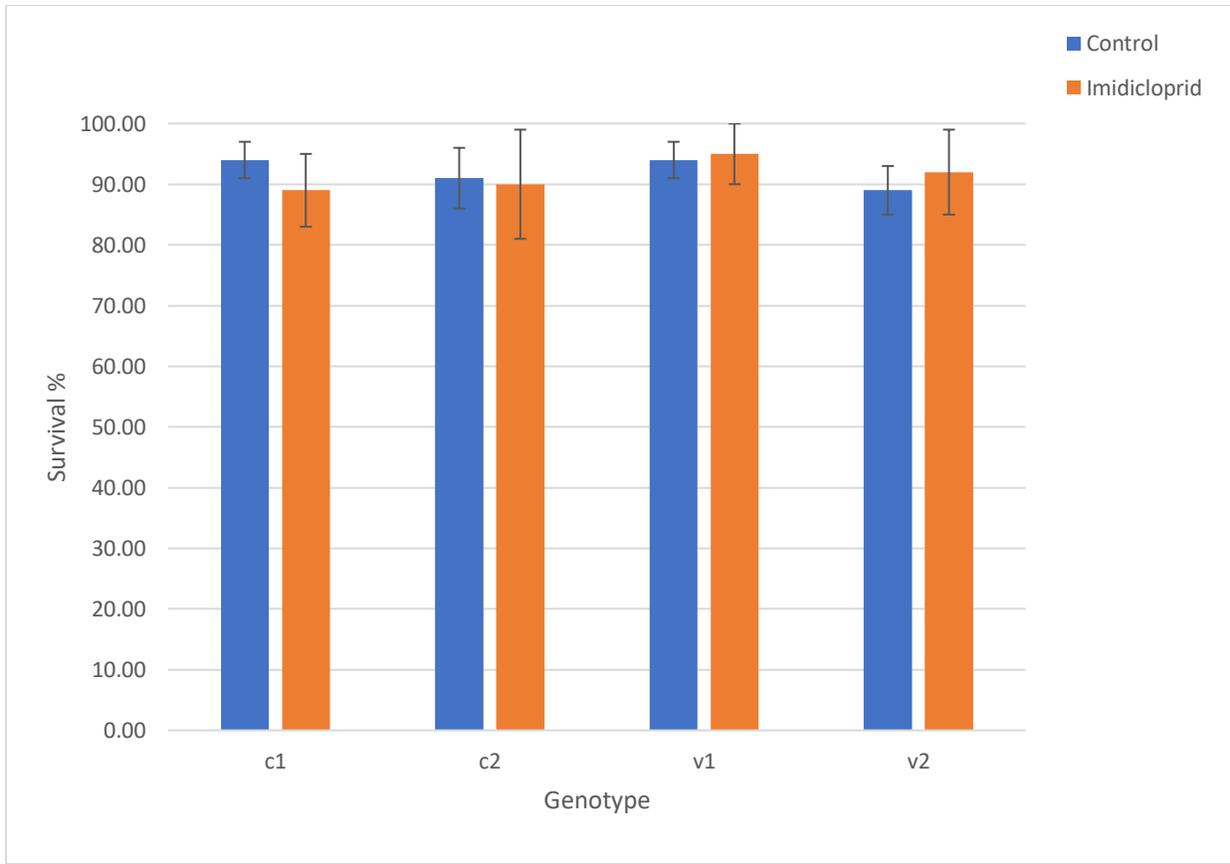


Figure 9. Survival (SE) of 9-year-old loblolly pine planted at Hofmann Forest (LCP). Survival was not a problem at Hofmann forest with many of the genotypes achieving 90 percent or greater survival. Survival was consistent and uniform across the LCP site.

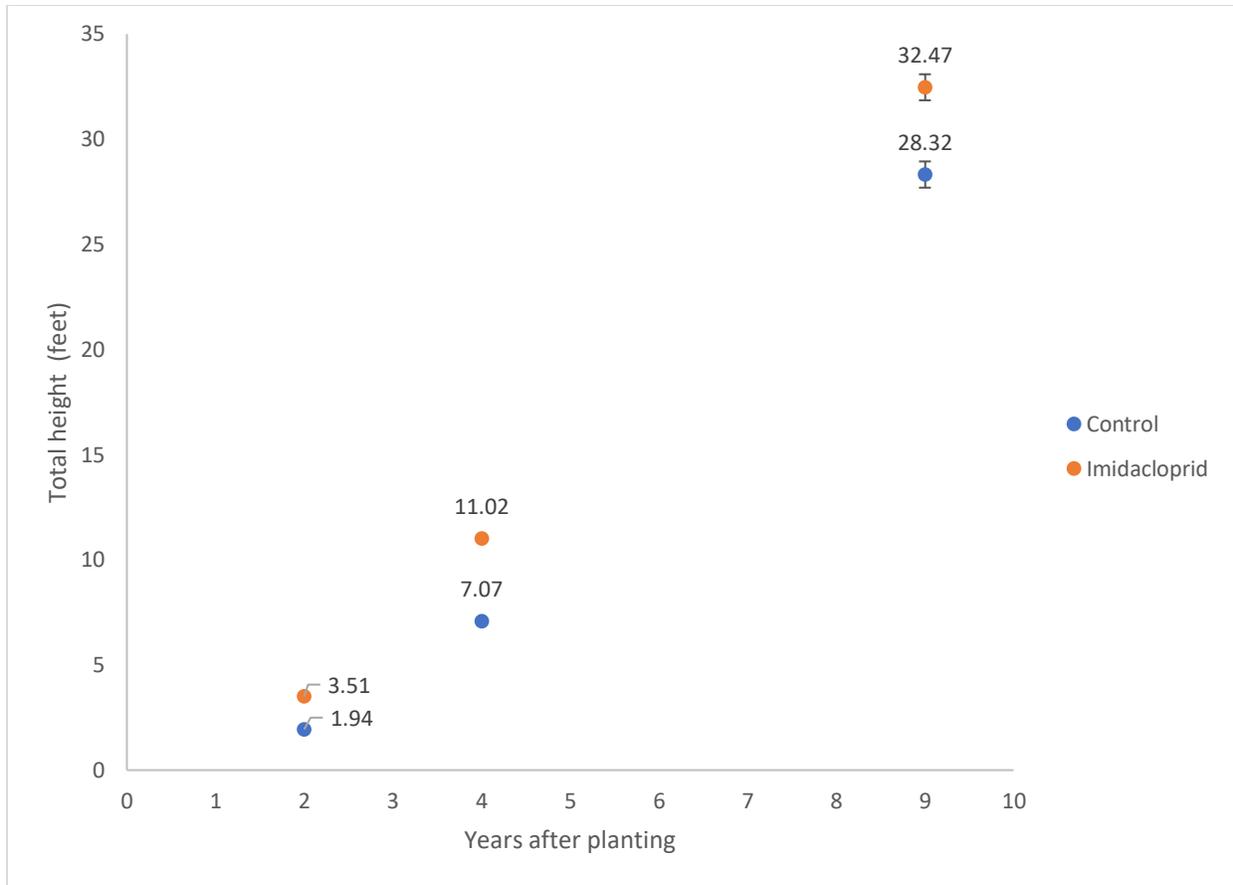


Figure 10. Total height of loblolly pine growing at UCP at year 2, 4 and 9 by imidacloprid treatment. Data from year 2 inventory and year 4 inventory was adapted from King et. al. (2014) and Kelley et. al. (2014). Loblolly pine treated with imidacloprid grew to 3.51(.07) ft tall at year 2, control trees grew to 1.94(.03) ft, a difference of 1.57 feet. At year 4, imidacloprid treated trees grew to 11.02(.36) ft tall, control trees grew to 7.07(.39) ft tall, a difference of 3.95(.37) ft. At year 9, imidacloprid trees grew to 32.47(.62) ft tall and control trees grew to 28.32(.62) ft, a difference of 4.15(.62) ft. Imidacloprid treated pines have maintained and slightly increased their height over control treatment trees at UCP.

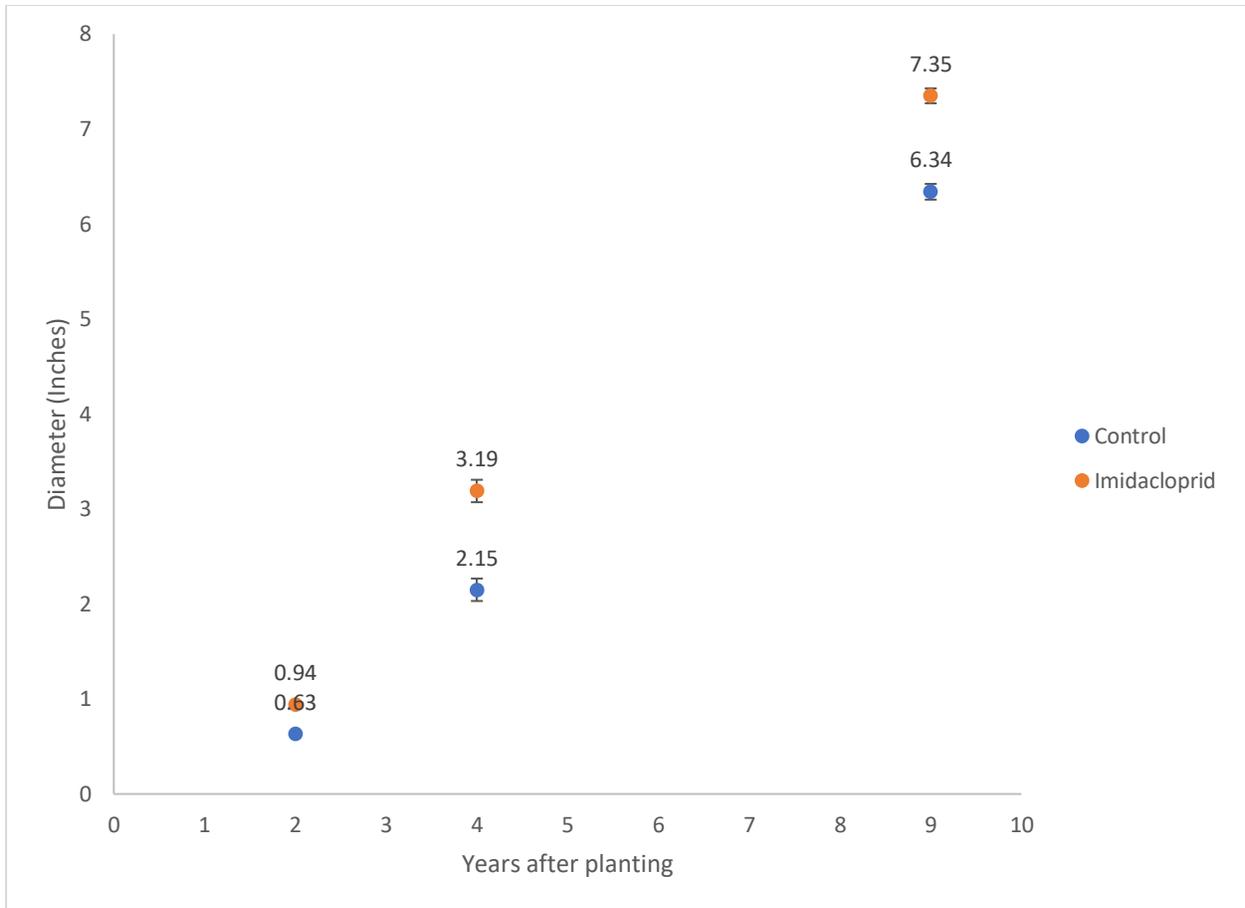


Figure 11. Average diameter of loblolly pine growing at UCP at year two, four and nine by imidacloprid treatment. UCP trees treated with imidacloprid have maintained a larger average diameter for the first 9 years of the study. At year two control trees on average grew to 0.63(0.08) inches and imidacloprid treated trees grew to 0.94(0.15) inches, a difference of 0.31(.12) inches. At year 4 control trees grew to 2.15(0.12) inches and imidacloprid treated trees grew to 3.19(1.2) inches in groundline diameter, a difference of 1.04(0.12) inches. By year nine control trees grew to 6.34(.08) inches in diameter at breast height and imidacloprid trees grew to 7.35(.08) inches in diameter at breast height, a difference of 1.01(0.07) inches.

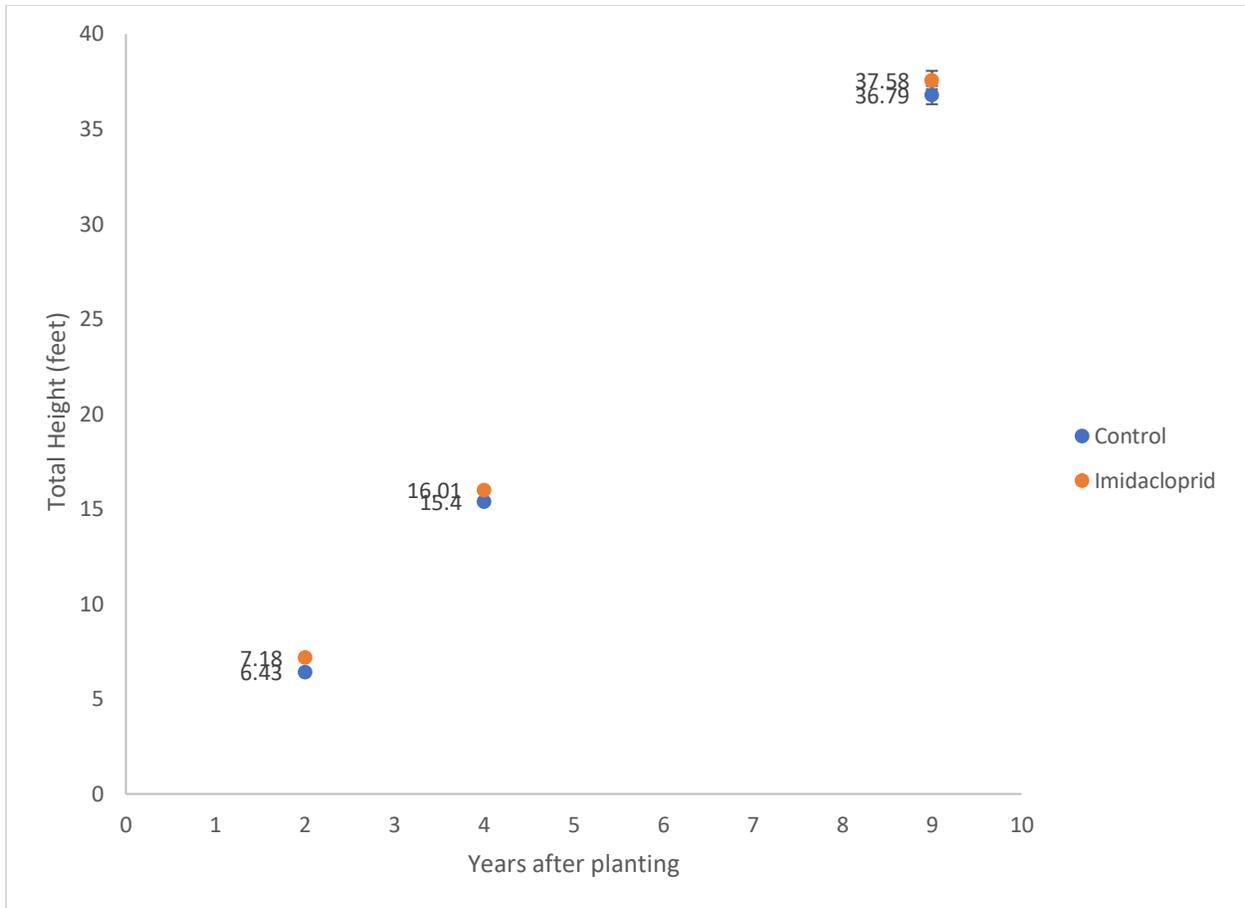


Figure 12. Total height of loblolly pine growing at LCP at year 2, 4 and 9 by imidacloprid treatment. At year 2, LCP trees treated with imidacloprid grew to 7.18(0.20) ft tall and control trees grew to 6.43(0.16) ft tall, a difference of 0.75(0.18) ft. At year 4, imidacloprid treated trees grew to 16.01(0.60) ft and control trees grew to 15.4(0.69) ft tall, a difference of 0.61(0.51) ft. At year 9, imidacloprid treated trees grew to 37.58(0.48) ft tall and control trees grew to 36.79(0.48) ft, a difference of 0.79(0.48) ft.

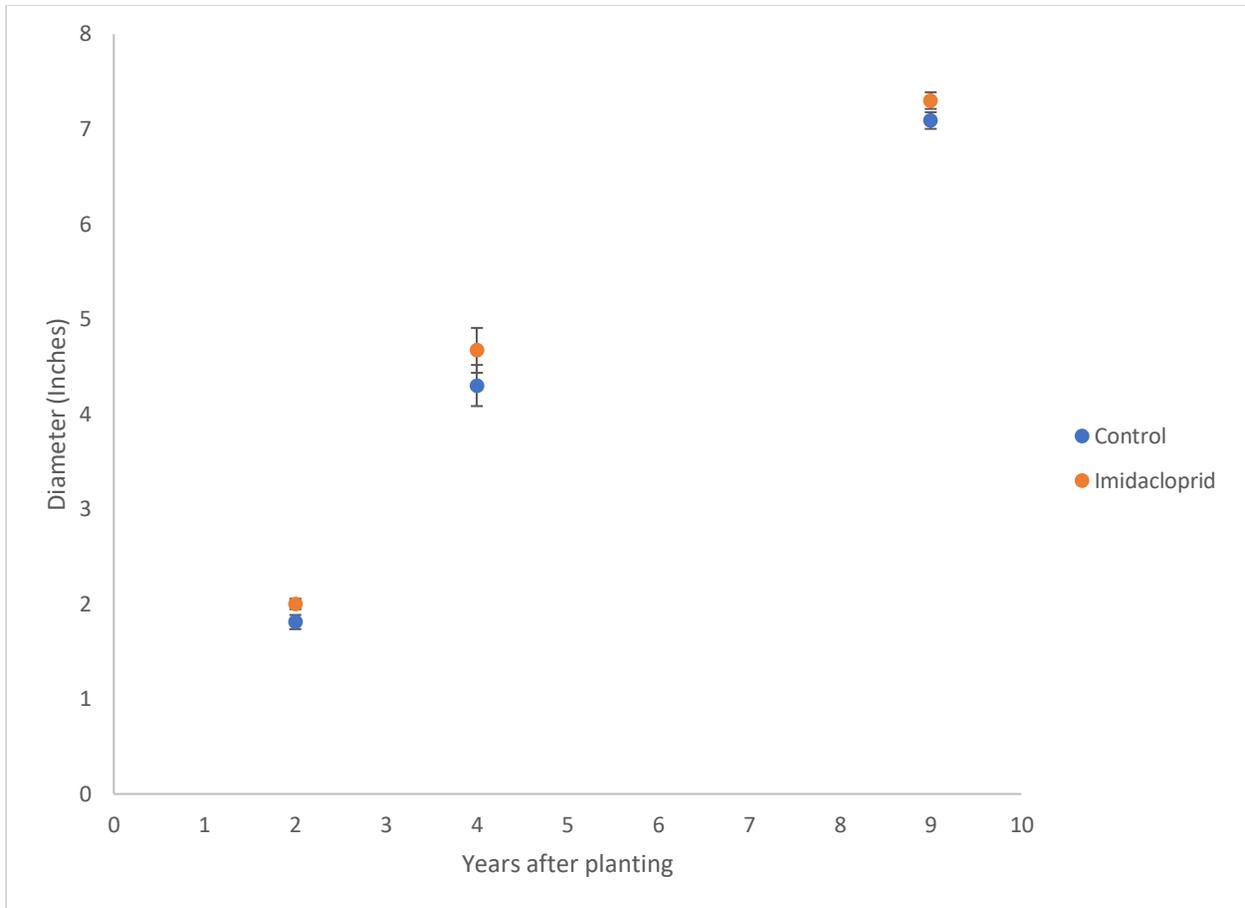


Figure 13. Average diameter of loblolly pine growing at LCP at year 2, 4 and 9 by imidacloprid treatment. At year 2, imidacloprid treated trees grew to 2.0(0.13) inches groundline diameter and untreated control trees grew to 1.81(0.09)inches in groundline diameter, a difference of 0.19(0.11) inches in groundline diameter. At year 4, imidacloprid trees grew to 4.67(0.22) inches in groundline diameter and control trees grew to 4.30(0.24)inches in groundline diameter, a difference of 0.23(0.24)inches in groundline diameter. At year 9, imidacloprid treated trees grew to 7.30(0.09) inches at breast height and untreated trees grew to 7.09(0.09) inches breast height, a difference of 0.21(0.08) inches in diameter at breast height.

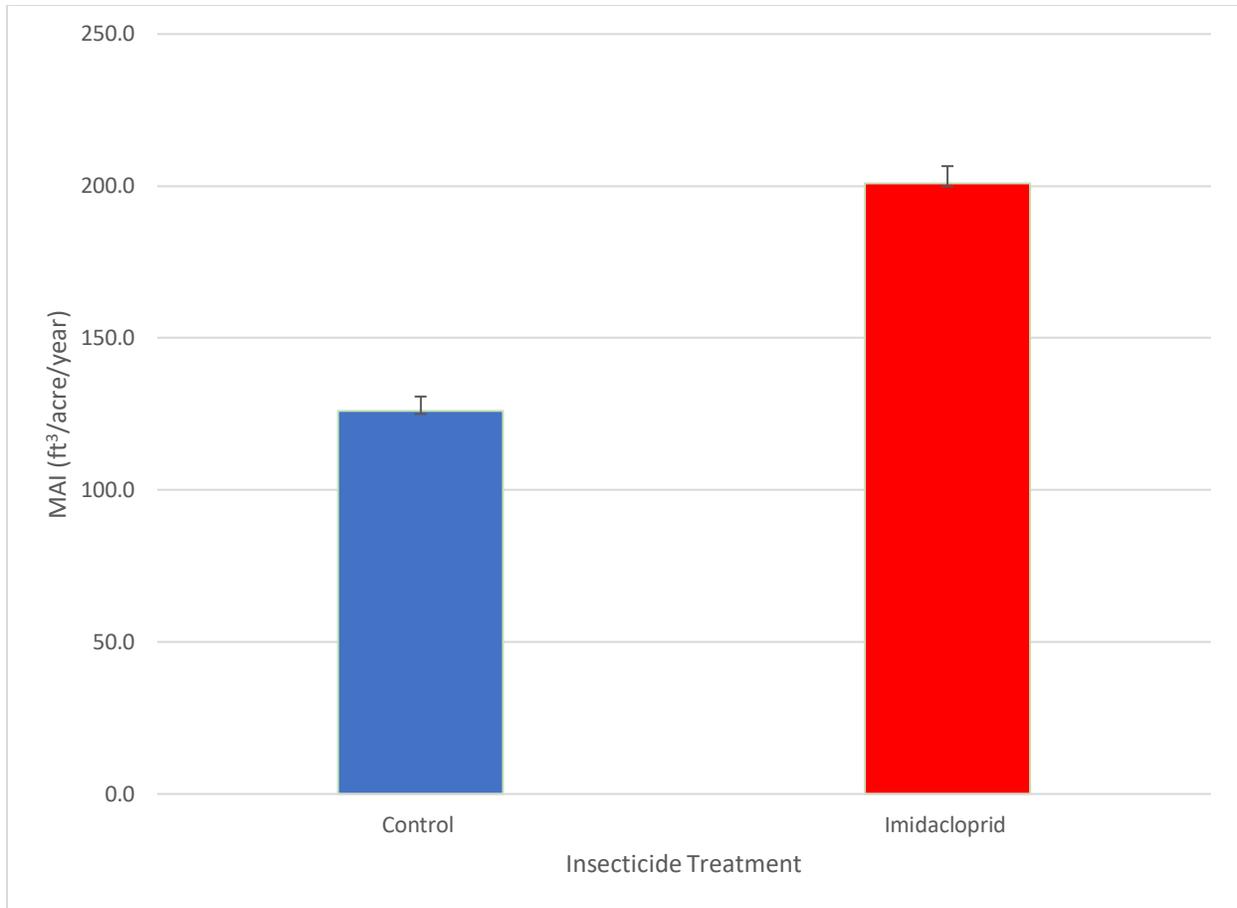


Figure 14. Mean annual increment (ft³/acre/year), plus one standard error, of 9-year old loblolly pine grown at UCP by tip moth treatment. Mean annual increment was calculated by multiplying LS Mean estimates for individual stem volume by the number of trees surviving per acre, producing yield per acre. Yield per acre was divided by 9, growth rate is in cubic feet per acre per year. Individual stem volumes between the control and the imidacloprid tip moth treatments were found to be significantly different ($p < 0.0001$). Likewise, survival was greatly improved by the imidacloprid treatment at UCP (averages for each). Pine trees in the control group grew at 126(5.43) cubic feet per acre per year, and imidacloprid treated trees grew at 200.89(6.53) cubic feet per acre per year. The difference of 74.88 cubic feet per acre per year is worth approximately \$20.00 per acre per year in pulp produced. Also, because imidacloprid treated pines grew 58% faster than the untreated controls, imidacloprid treated stands have progressed closer to a first thinning. Imidacloprid has sped up the timeline for an UCP pine first thinning by approximately two years.

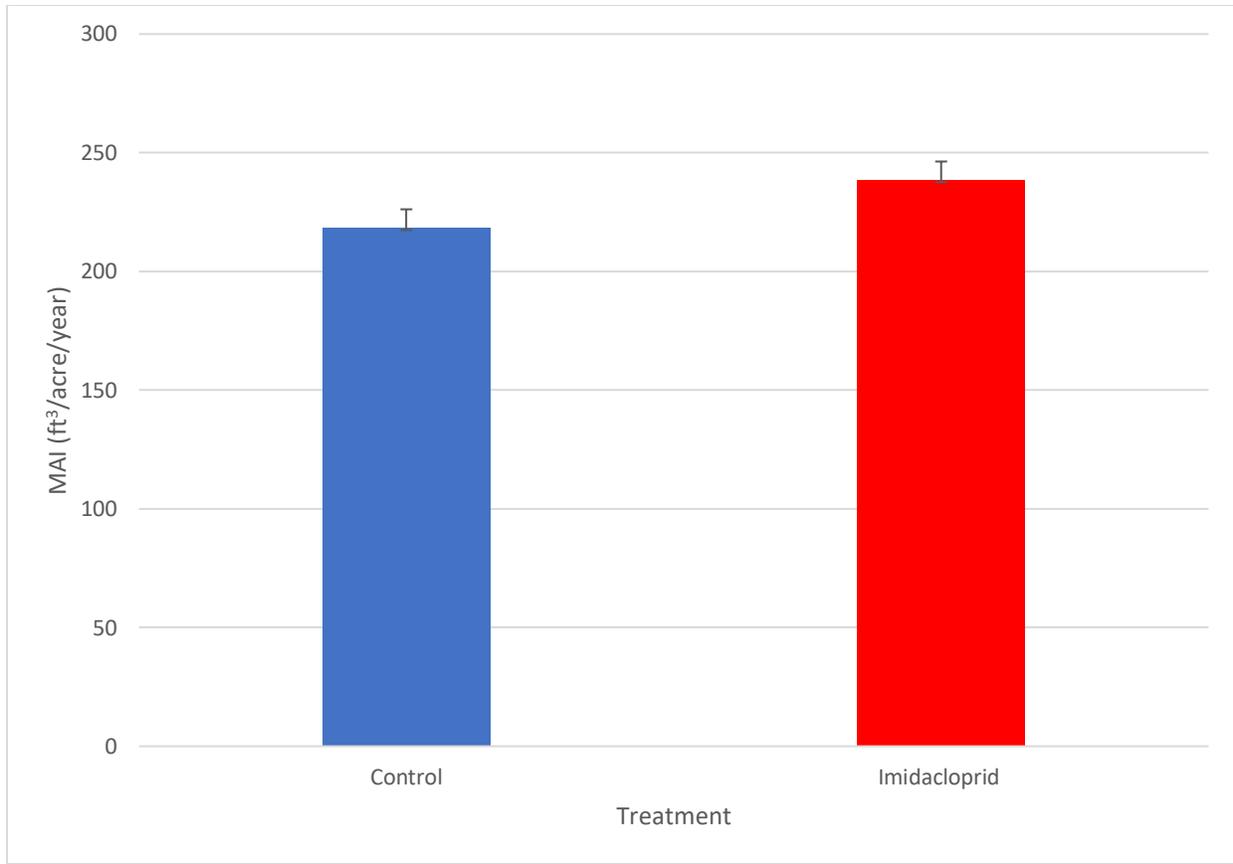


Figure 15. Mean annual increment (SE)(ft³/acre/year) of 9-year-old loblolly pine grown at LCP. Mean annual increment was calculated by multiplying the average volume per stem of a treatment by the average number of stems surviving per acre for that treatment. That product was divided by 9 (number of years since planting). Control trees grew at a rate of 218.44(7.45) cubic feet per acre per year and imidacloprid treated trees grew to 238.58(9.41) cubic feet per acre per year. While imidacloprid treatment improved growth rate by 9% across all genotypes and cultural intensities, there was significant variation within the treatments and the treatments are likely not statistically significantly different. Practically the difference in growth rate of 20 cubic feet per acre per year is worth approximately \$5.40 per acre if pine pulp sells for \$10.00 per ton. This difference in growth rate does not support imidacloprid as an economically feasible method to increase growth at the lower coastal plain site.

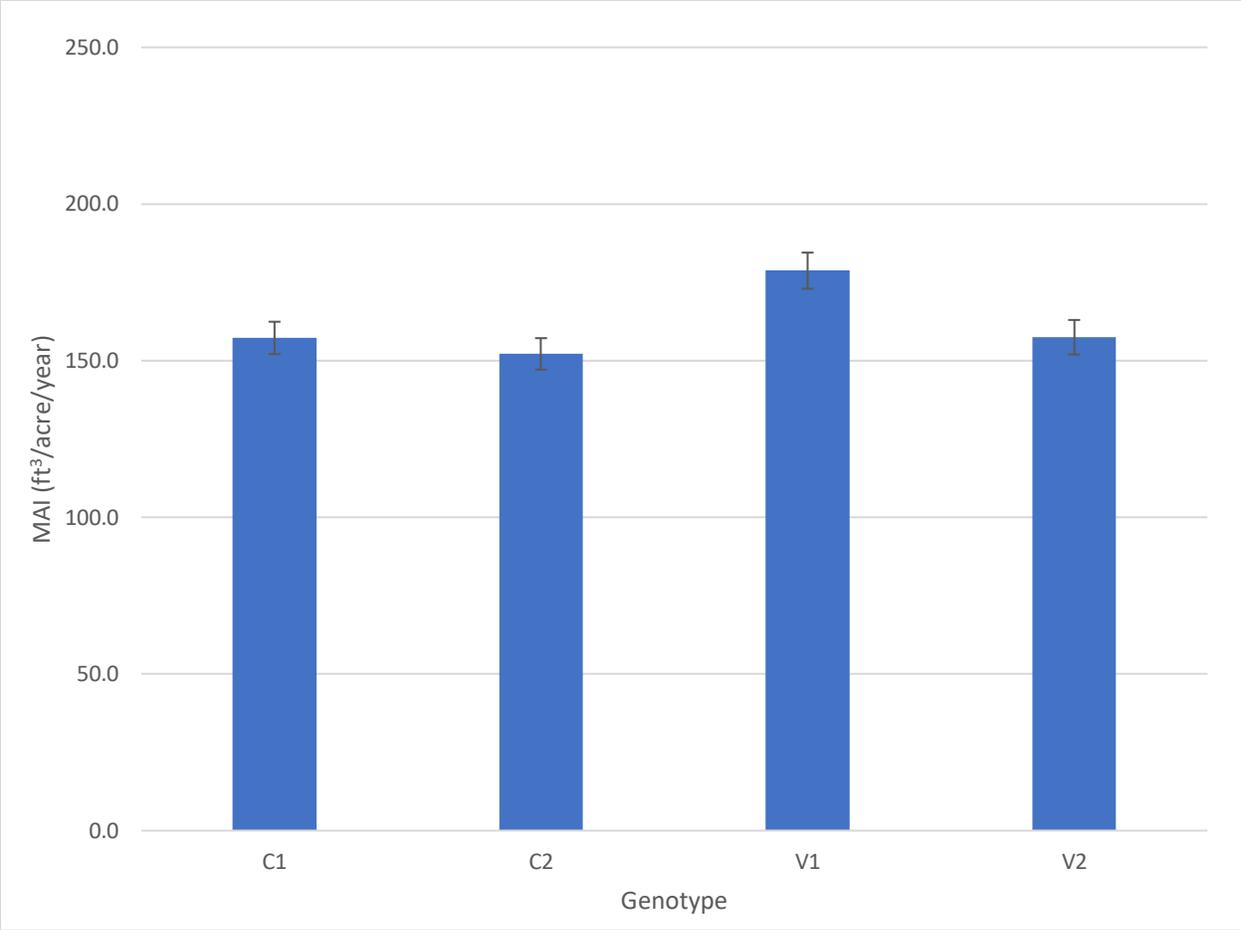


Figure 16. Mean annual increment (MAI) of 9-year old loblolly pine grown at UCP by genotype. Genotype V1 was able to grow 14.67% faster than the average of the other three genotypes.

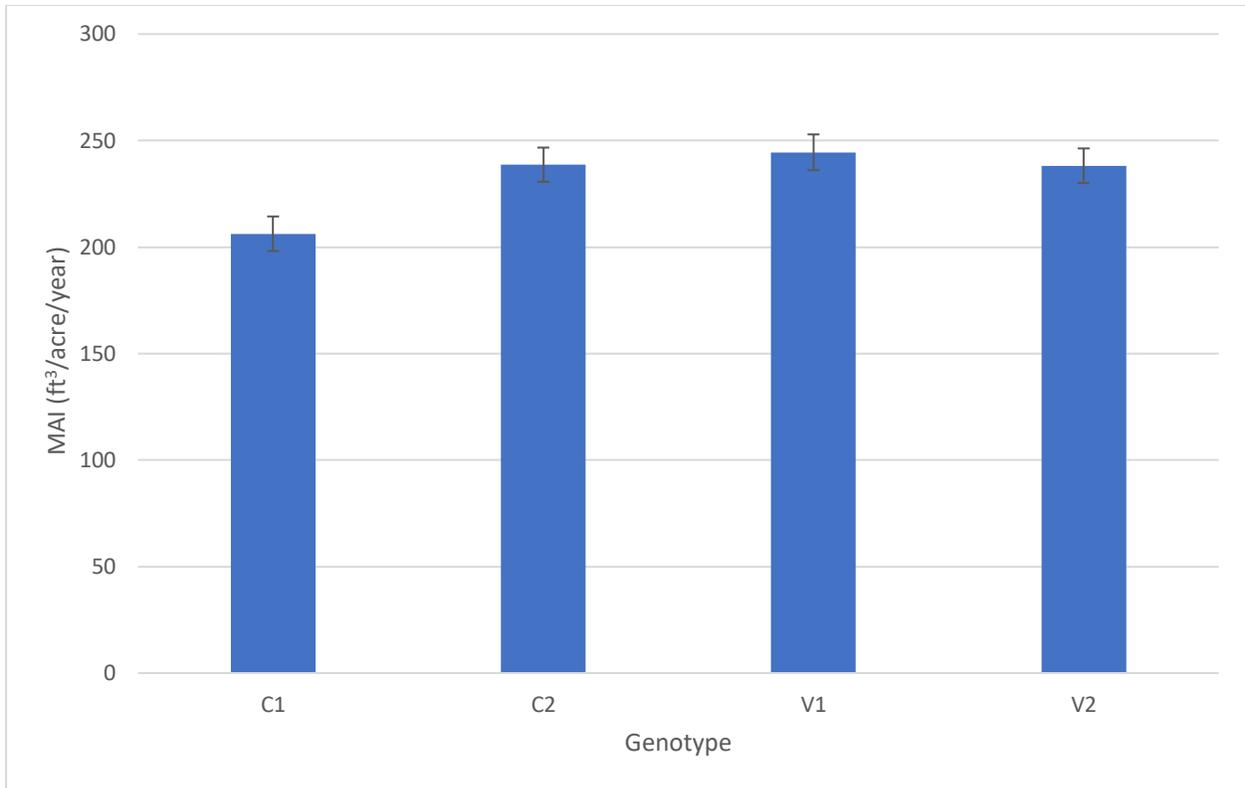


Figure 17. Mean annual increment (MAI) (SE) ft³/acre/year of 9-year old loblolly pine grown at LCP by genotype. Genotype V1 was able to grow 9.92% faster than the average of the other three genotypes. Mean annual increments (ft³/acre/year) for C2 238.67(6.02), V1 244.5 (6.21), and V2 238.18(6.01) are likely not significantly different however C1 grew 14.4% slower than the average of the other three genotypes.

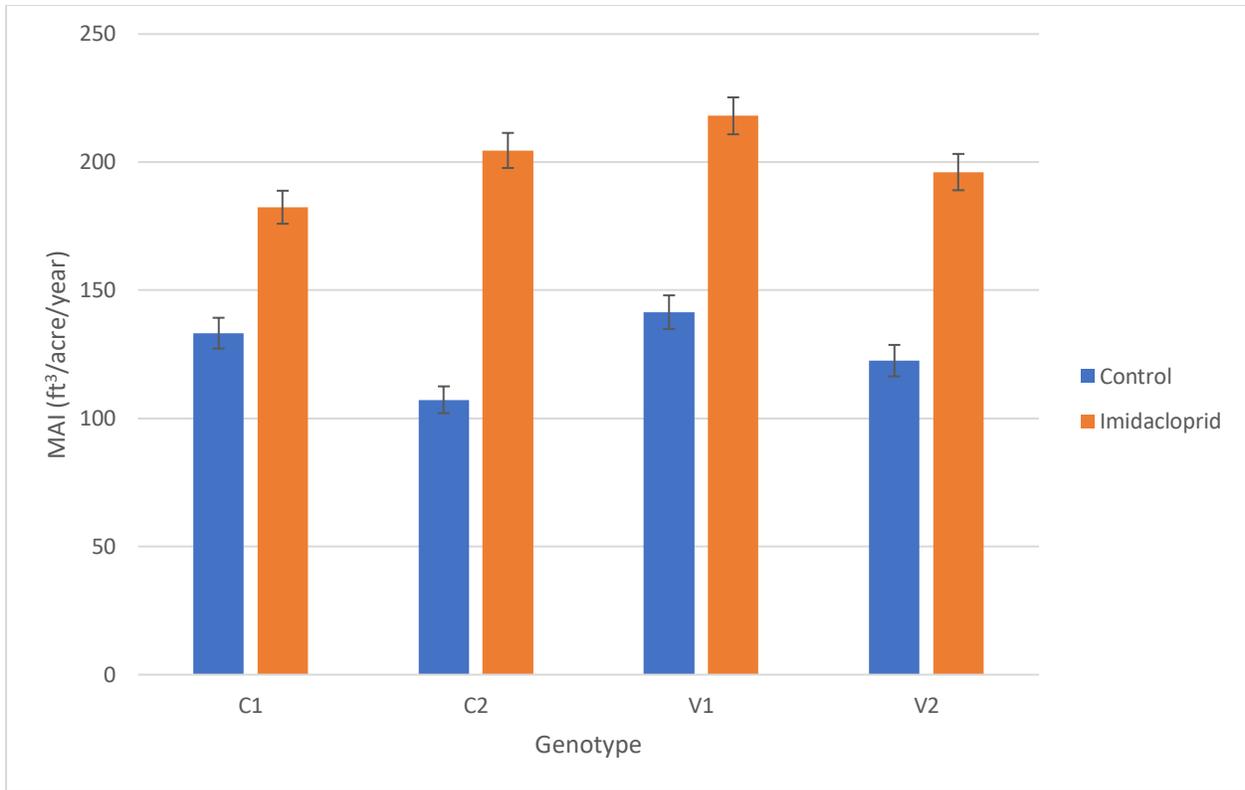


Figure 18. MAI(SE) ft³/acre/year of 9-year-old loblolly pine by imidacloprid treatment and genotype at UCP. Tip moth treatment significantly improved growth rate across all genotypes. The greatest improvement was in genotype C2 which in control treatment grew at 107.28(6.87) ft³/acre/year and with imidacloprid grew at 204.58(8.94) ft³/acre/year, a 48% increase in growth rate. Practically we see that imidacloprid treated pines are growing at a faster rate, meaning stands are moving towards the period of canopy closure faster than their untreated counterparts thus, imidacloprid is shortening the rotation length at UCP.

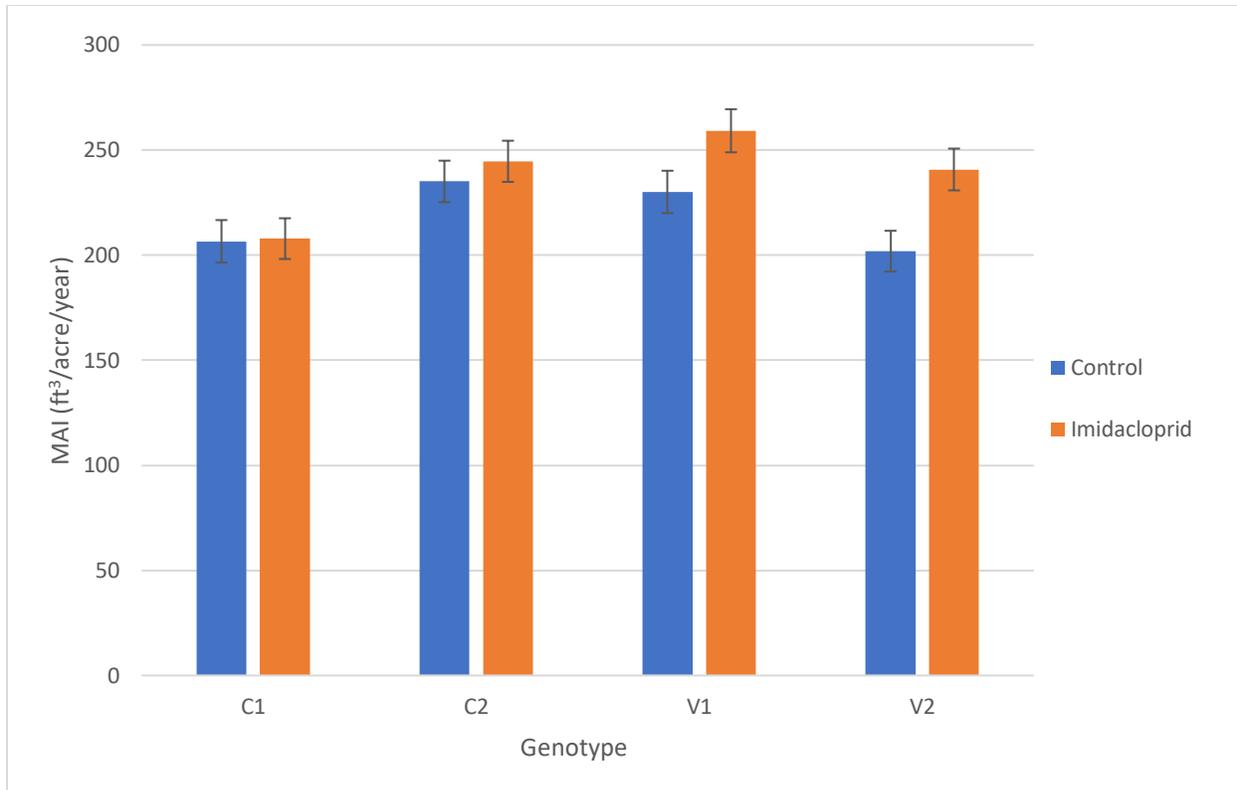


Figure 19. MAI (mean annual increment) in ft³ of 9-year-old loblolly pine by imidacloprid and genotype at LCP. Imidacloprid was able to significantly increase the growth rates of genotype V1 and V2 by 11.1% and 16.7%, respectively, however there are no real difference between imidacloprid and control trees within genotype C1 or C2. Genotype C1 was the slowest growing genotype at 206.58(8.79) in the control and 207.89(8.74) in the imidacloprid treated plot. The fastest growing combination was genotype V1 treated with imidacloprid which grew at 259.19(9.12) ft³/acre/year.



Figure 20. Fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) gall on a ramie branch on genotype C1 at UCP. Fusiform rust was a significant obstacle for achieving quality pine stands at UCP, especially in genotype C1 which was highly affected by the disease and only managed to produce low stems per acre without fusiform rust. Rust was also present in damaging levels in genotype C2 at the UCP. Fusiform rust was only documented on 11 test trees within our survey conducted at LCP. Edaphic, and climatic factors, as well as disease presence influence the severity of damage by fusiform rust done on pine plantations.



Figure 21. Ramicorn branch on control (no imidacloprid) genotype V1 (LCP). Large ramicorn branch defects degrade lumber quality substantially due to large knot formation and increased compression wood content. Ramicorn branch was a serious problem for all genotypes at UCP regardless of imidacloprid status. However, results show that imidacloprid treatment was effective in minimizing damage to future stands in the rotation by providing more trees per acre without ramicorn branches than control treatments. Ramicorn branches were generally not a problem at the LCP.



Figure 22. Broken top defect in 9-year-old loblolly pine at grown at UCP. Broken top defects occur to some degree in virtually all pine stands, however cultural treatments, nutrient status, pest pressure, genotype as well as edaphic and climactic factors influence the presence of this defect. Broken top defects are particularly damaging for several reasons to pine stands grown in a sawtimber rotation. First, when a dominant or co-dominant crop tree loses its top during a high wind event or after heavy accumulation of frozen precipitation its canopy status is reduced to an inferior position (intermediate, overtopped or suppressed). Inferior canopy position will put the crop tree at a competitive disadvantage to intercept light and grow biomass thus reducing its growth rate. Second, the resulting wound left after the top breaks is an infection court for diseases, and the loss in vigor may signal secondary insect pests such as *Ips* engraver beetles (*Ips* sp.) to consume the tree. Third, when a tree survives a broken top the lateral branches upturn and assume dominance, when this happens the tree loses significant value in quality because the future stem will have a large crook or fork defect.



Figure 23. Crook defects and large ramicorn branches on 9-year old loblolly pine (genotype V1-Control) grown at UCP. Multiple stem defects were much more common on control group trees (personal observation) and are the result of multiple years of heavy infestation by pine tip moth. In this case, (as with many tip moth infestations) damage was not lethal but the loss in form has rendered this tree unsuitable for both solid wood products and pulp products alike. Defects such as crook, ramicorn branch and fork increase the amount of compression wood in a stem and are problematic for processing equipment and transportation. Trees with more than 2 defects on the lower bole (lower 17 feet) are removed from harvest volume as cull.



Figure 24. Fork defect on genotype V1 (control) at the UCP. The union of the three stems in this fork represents a weak point that is subject to breakage in extreme weather events. Additionally, the smaller stem situated between the larger co-dominant stems will eventually lose vigor as a result of its inferior canopy position, possibly exposing this tree to attack by *Ips* engraver and other secondary pest of pine plantations. This tree should be harvested during a first thinning operation where it will be utilized as pulp.



Sinuosity 0



Sinuosity 1



Sinuosity 2



Sinuosity 3

Figure 25. Sinuosity index used to judge sweep in 9-year-old loblolly pine at UCP and LCP. Trees in the “0” and “1” category are of good and acceptable quality. Trees in the “2” category are of low quality, and trees in the “3” category are considered cull due to the constraints of processing equipment and transportation and are removed from harvest volume.

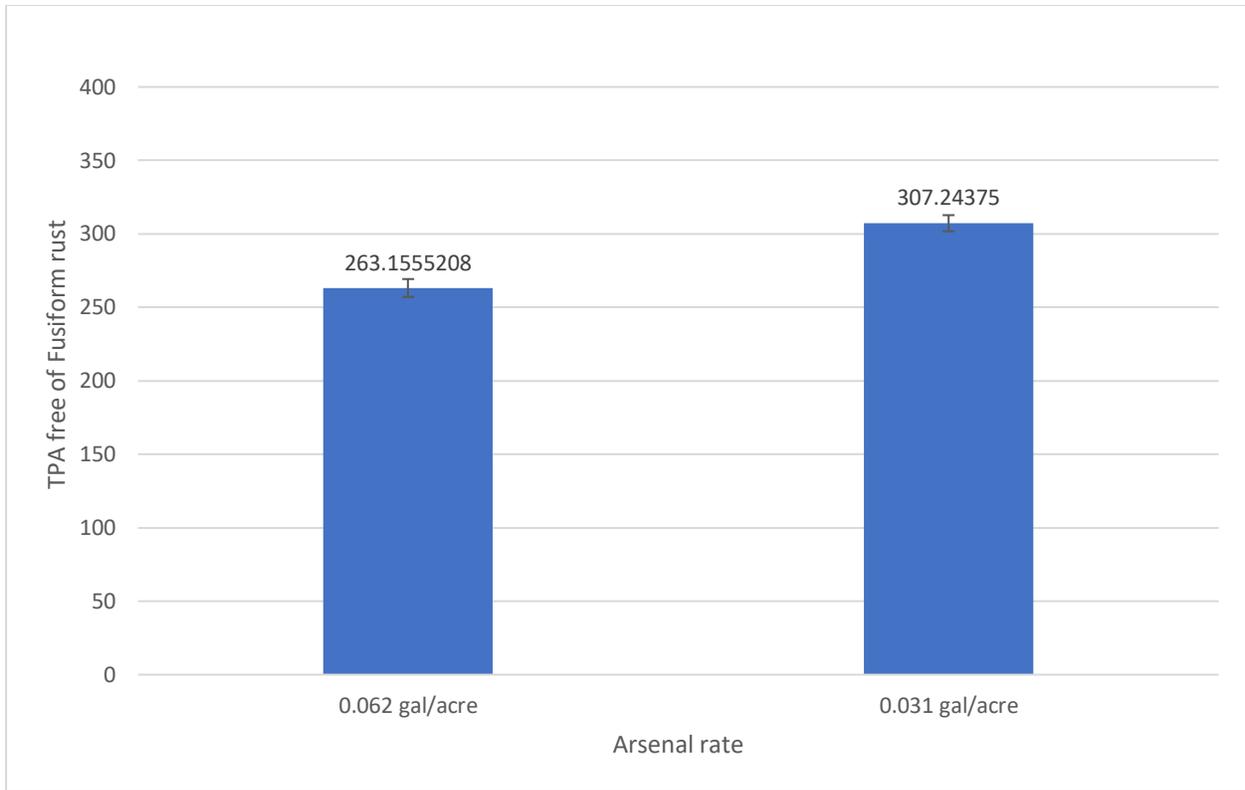


Figure 26. Trees per acre (SE) of 9-year-old loblolly pine free of fusiform rust at UCP by Arsenal application rate. Arsenal application rate was significant for the presence of fusiform rust occurring on 9-year old loblolly pine growing in the upper coastal plain of North Carolina. ($P=0.001$, Table 7). A total of 77(1.7)% of trees given the label rate of Arsenal (0.062 gal/acre) were free of fusiform rust, whereas 82(1.4)% of trees given half the label rate (0.031 gal/acre) were free of fusiform rust. When adjusted for survival, stands receiving the label rate of Arsenal possessed 263(6) trees per acre free of fusiform rust, whereas stands treated with half the label rate possessed 307(5) trees per acre.

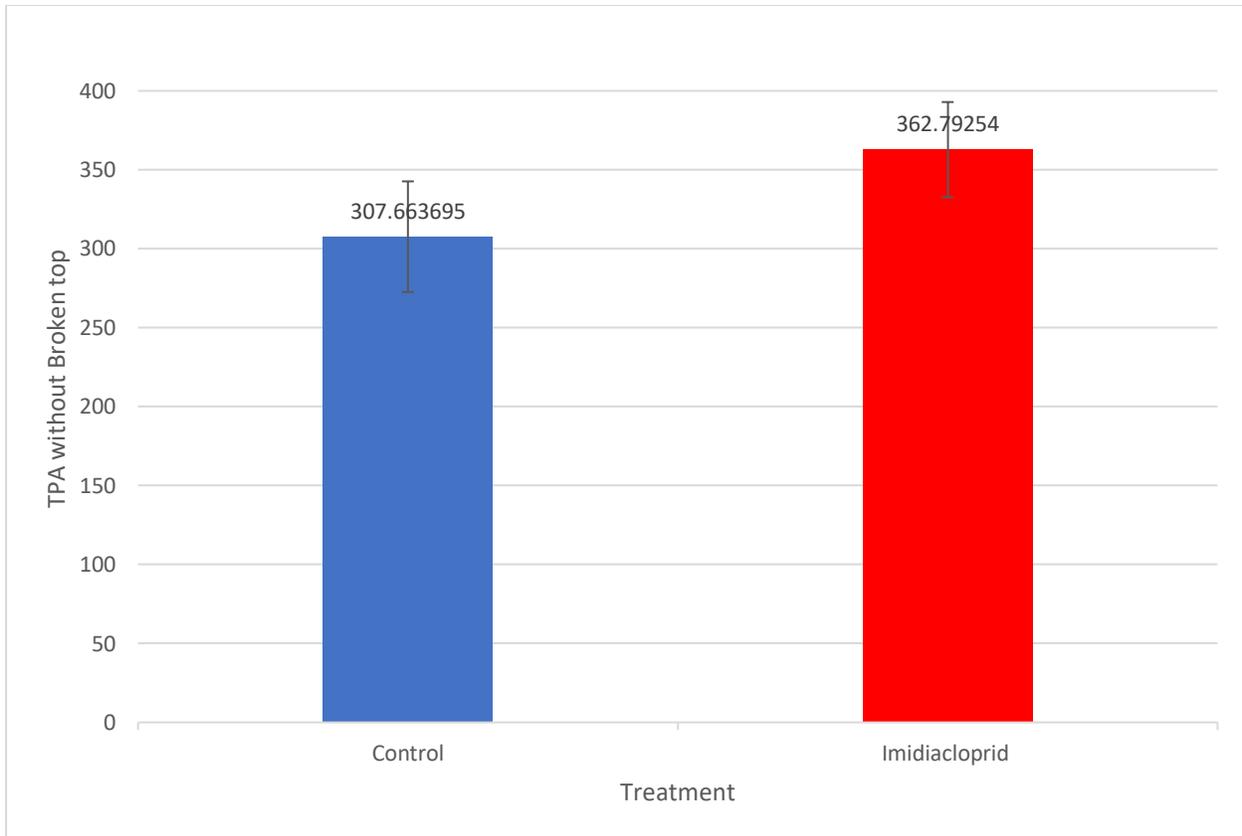


Figure 27. Trees per acre (SE) of 9-year-old loblolly pine without broken top at UCP by imidacloprid treatment. Imidacloprid treatment was found to influence the presence of broken top in 9 year-old loblolly pine growing in the upper coastal plain of North Carolina ($P= 0.011$, Table 7) A total of 95(0.9)% of trees in the control group were free of broken top, and 92(1.0)% of trees in the imidacloprid group were free of broken top. When adjusted for survival, control stands possessed 307(35) trees per acre without broken top and imidacloprid stands possessed 362(30) trees per acre.

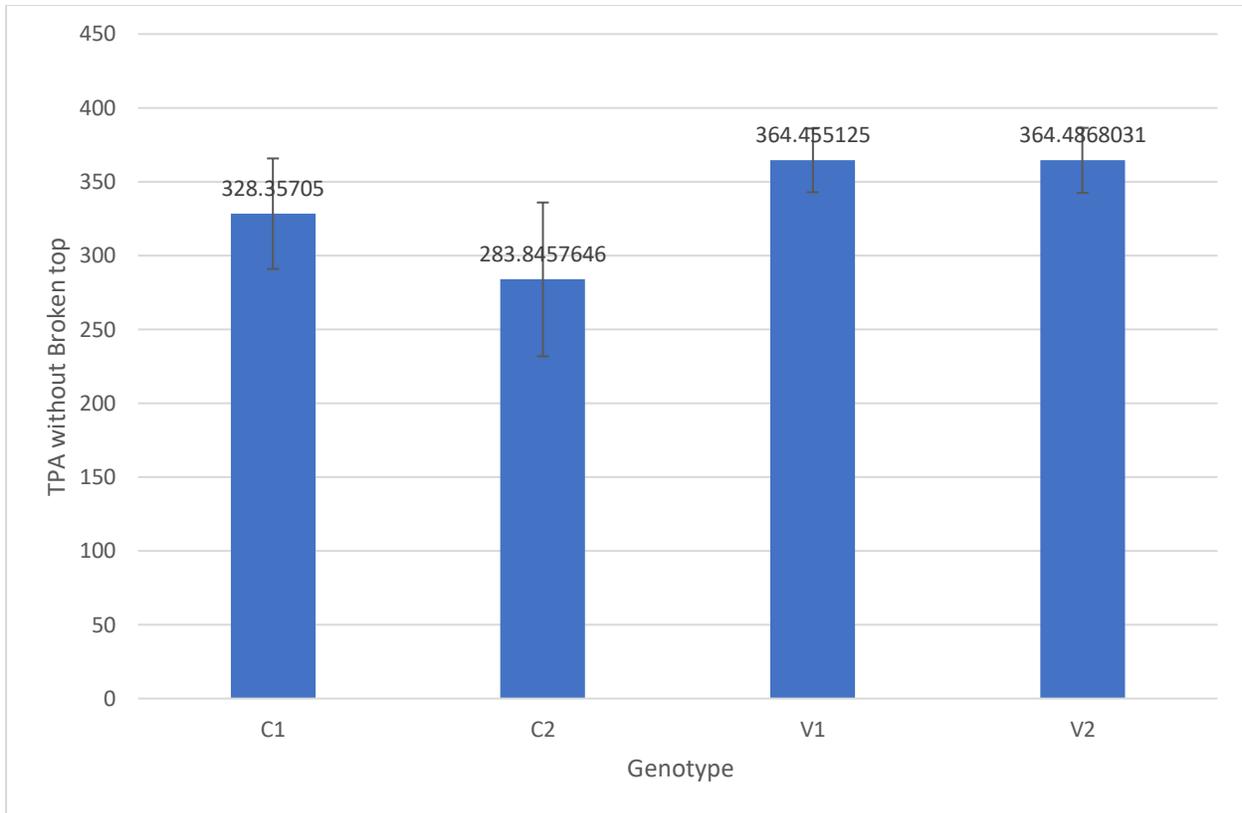


Figure 28. Trees per acre(SE) of 9-year-old loblolly pine without broken top at UCP by genotype. The main effect genotype significantly influenced the presence of broken top defects occurring on 9- year-old loblolly pine growing in the upper coastal plain of North Carolina. (P=0.000, Table 7). Broken top was absent on 96 (1.2) percent of trees in genotype C1, 87(2.0) percent of trees in genotype C2, 93(1.4) percent of genotype V1 and 98(0.74) percent of genotype V2. When adjusted for survival, stands of genotype C1 possessed 328(37) trees per acre without broken top. Stands planted with genotype C2 possessed 283(52) trees per acre without broken tops. Stands planted with genotype V1 had 364(21) without broken top and stands planted with genotype V2 also contained 364(22) trees per acre without broken tops. Genotype C2 seemingly has less trees per acre without broken top when compared to C1,V1,V2. However, there are likely enough good quality trees per acre to move forward in stand development regardless of genotype.

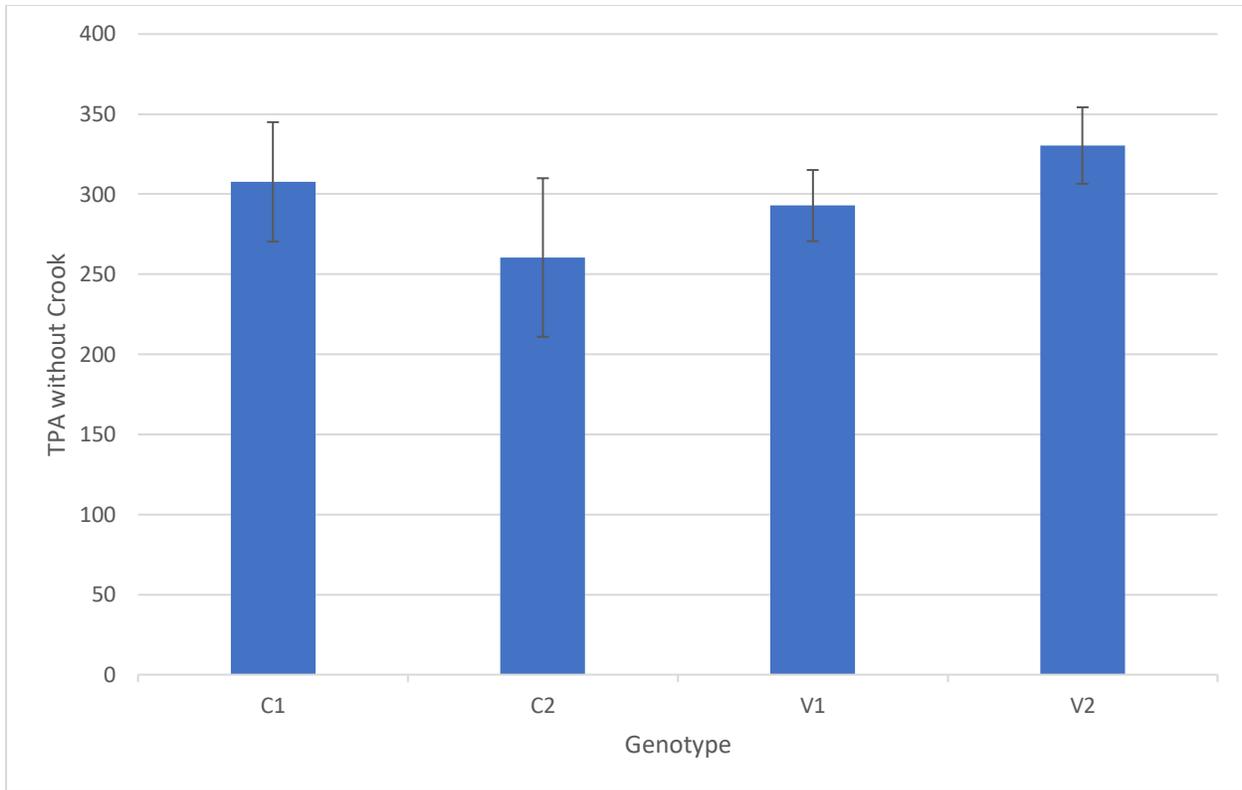


Figure 29. Trees per acre without crook at UCP by genotype, again C2 seemingly has less trees per acre free from defect than other genotypes. The main effect genotype significantly influenced the presence of crook defects occurring on 9-year-old loblolly pine growing in the upper coastal plain of North Carolina ($P < 0.0001$, Table 7). A total of 89(1.75)% of trees of genotype C1 were free from crook, when adjusted for survival C1 possessed 307(37) trees per acre free of crook. Likewise, 80(2.33) percent of genotype C2 were free from fork, when adjusted for survival genotype, and C2 produced 260(49) trees per acre free of crook. Similarly, 74(2.33) percent of trees of genotype V1 were free of fork, when adjusted for survival, genotype V1 possessed 292(22) trees per acre free from crook. A total of 88(1.75) percent of trees of genotype V2 were free of crook defects, when adjusted for survival genotype V2 produced 330(23) trees per acre free of crook. The clones are less variable than the mass control pollinated genotypes.

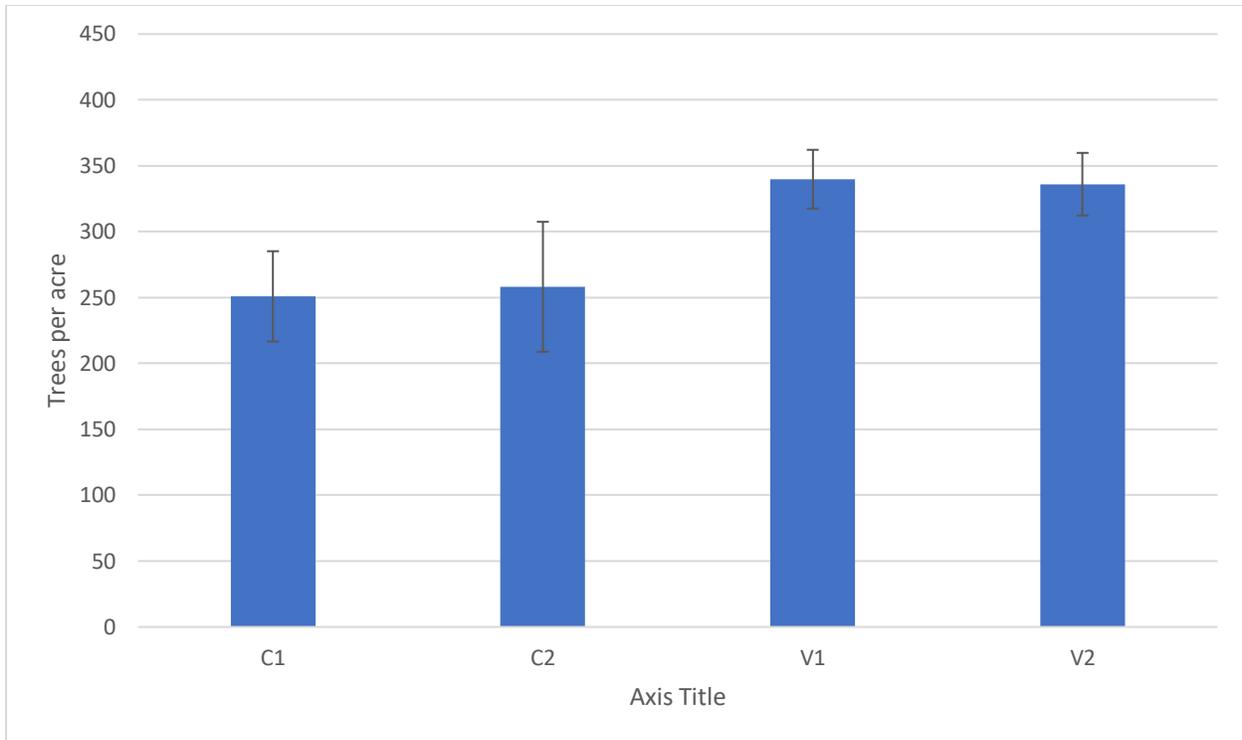


Figure 30. Trees per acre without fork at UCP. The clonal genotypes V1 and V2 have more trees per acre without fork defect than the mass control pollinated varieties C1 and C2. The main effect genotype significant influenced the presence of fork defects occurring on 9- year-old loblolly pine growing in the upper coastal plain of North Carolina. ($P < 0.0001$, Table 7). Fork defects were absent on 73(2.55) percent of trees of genotype C1, when adjusted for survival, genotype C1 possessed 250(34) trees per acre free from fork. Fork defects were absent on 79(2.38) percent of trees of genotype C2, and when adjusted for survival genotype C2 possessed 258(49) trees per acre free from fork. Fork defects were absent on 86(1.86) percent of trees of genotype V1. When adjusted for survival genotype V1 possessed 339(22) trees per acre free from fork. Fork was absent on 90(1.62) percent of trees of genotype V2, when adjusted for survival, genotype C1 possessed 336(23) trees per acre free from fork. Forking defect are genetically linked and these numbers of trees per acre without forking may be due to the intensity of selection for clones that do not fork and the narrow genetic variation of clones. The MCP varieties are more genetically diverse and therefore may carry genes that influence forking defects. The MCP varieties C1 and C2 may be marginally affected by forked stems after a thinning has taken place.

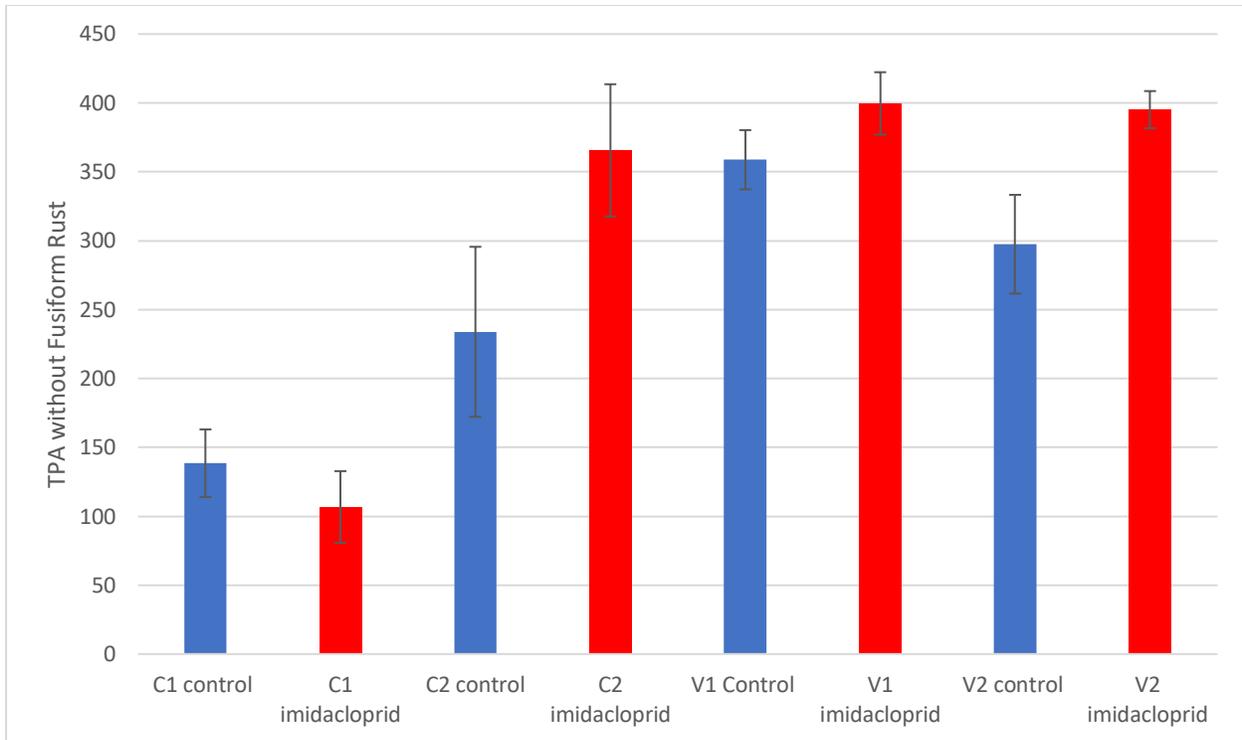


Figure 31. Trees per acre without fusiform rust by genotype and imidacloprid treatment at UCP. A total of 42(4.12) percent of trees in the C1 control group were free of fusiform rust, and C1 trees treated with imidacloprid only managed 29(3.64) percent of trees without rust. Likewise, 88(3) percent of C2 control trees were without fusiform rust, and when treated with imidacloprid 94(1.79) percent of C2 trees were free of fusiform rust. Similarly, 96(1.42) percent of V1 control trees did not have fusiform rust, and V1 imidacloprid trees were 97(1.22) percent free of the disease. Genotype V2 control trees were 88(2.62) percent free from fusiform rust, and imidacloprid treated trees were 97(1.23) percent free from disease. When adjusted for survival, genotype C1 produced 138(24) trees per acre and 106(26) trees per acre in the control and imidacloprid treatments, respectively. Genotype C2 produced 233(61) trees per acre and 365(48) trees per acre in the control and imidacloprid treatments, respectively. Stands planted with genotype V1 possessed 358(21) trees per acre without rust in the control group and 399(22) trees per acre without rust in the imidacloprid group. Stands planted with genotype V2 had 297 (35) trees per acre in the control group and 395(13) trees per acre free of fusiform rust in the imidacloprid treated plots. Fusiform rust was highly damaging to genotype C1 regardless of imidacloprid treatment. Fusiform rust was so severe that it negatively affects genotype C1 yield and will likely influence the future value of stands planted with C1. C2 and V2 were practically improved with imidacloprid in that they now likely have enough trees per acre without rust to remove the disease during a first thinning.

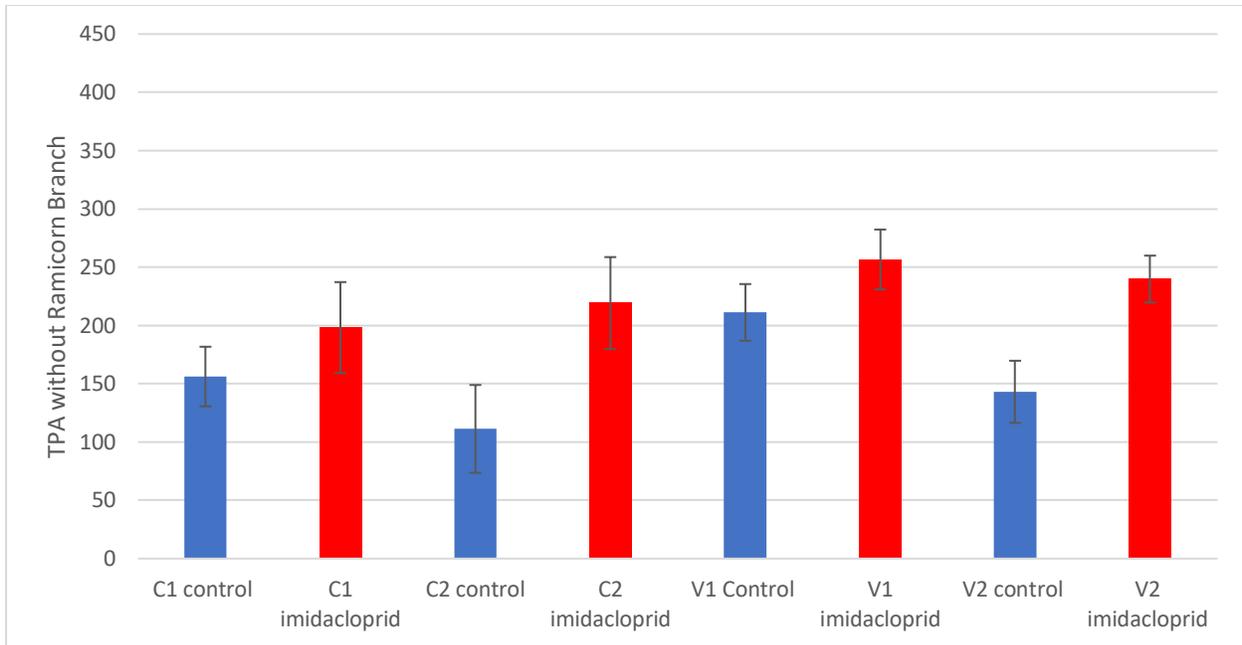


Figure 32. Trees per acre without ramicorn branch at UCP by genotype and imidacloprid treatment. A total of 47(3.99) percent of trees in the C1 control group were free of ramicorn branch, and C1 trees treated with imidacloprid only managed 55(4.16) percent of trees without ramicorn branch. Likewise, 44(4.65) percent of C2 control trees were without ramicorn branch, and when treated with imidacloprid 56(3.8) percent of C2 trees were free of ramicorn branch. Similarly, 57(3.89) percent of V1 control trees did not have ramicorn branch, and V1 imidacloprid trees were 61(3.89) percent free of the ramicorn branch. Genotype V2 control trees were 42(4.06) percent free from ramicorn branch, and imidacloprid treated trees were 58(3.69) percent free from disease. When adjusted for survival, genotype C1 produced 156(25), and 198(39) trees per acre in the control and imidacloprid treatments, respectively. Genotype C2 produced 111(37) trees per acre and 219(39) trees per acre in the control and imidacloprid treatments, respectively. Stands planted with genotype V1 possessed 211(24) trees per acre without ramicorn branch in the control group and 256(25) trees per acre without ramicorn branch in the imidacloprid group. Stands planted with genotype V2 had 143(26) trees per acre in the control group and 239(20) trees per acre free of ramicorn branch in the imidacloprid treated plots. Looking ahead to the next stage in stand development, a sawtimber rotation would retain approximately 225 crop trees per acre to grow after a first thinning. Ramicorn branches are solid wood potential limiting defects, their presence greatly reduces the value of timber because it cannot be made into solid wood or pulp. Ramicorn branching was numerous at the UCP regardless of treatment or genotype, however, my results show that imidacloprid treated stands produce roughly enough trees per acre to retain a stand with few if any ramicorn branch. From a quality and value standpoint imidacloprid treatment did improve the quality of pre-thinned stands more than enough to increase the value of timber later in the rotation by minimizing ramicorn branches in crop trees.

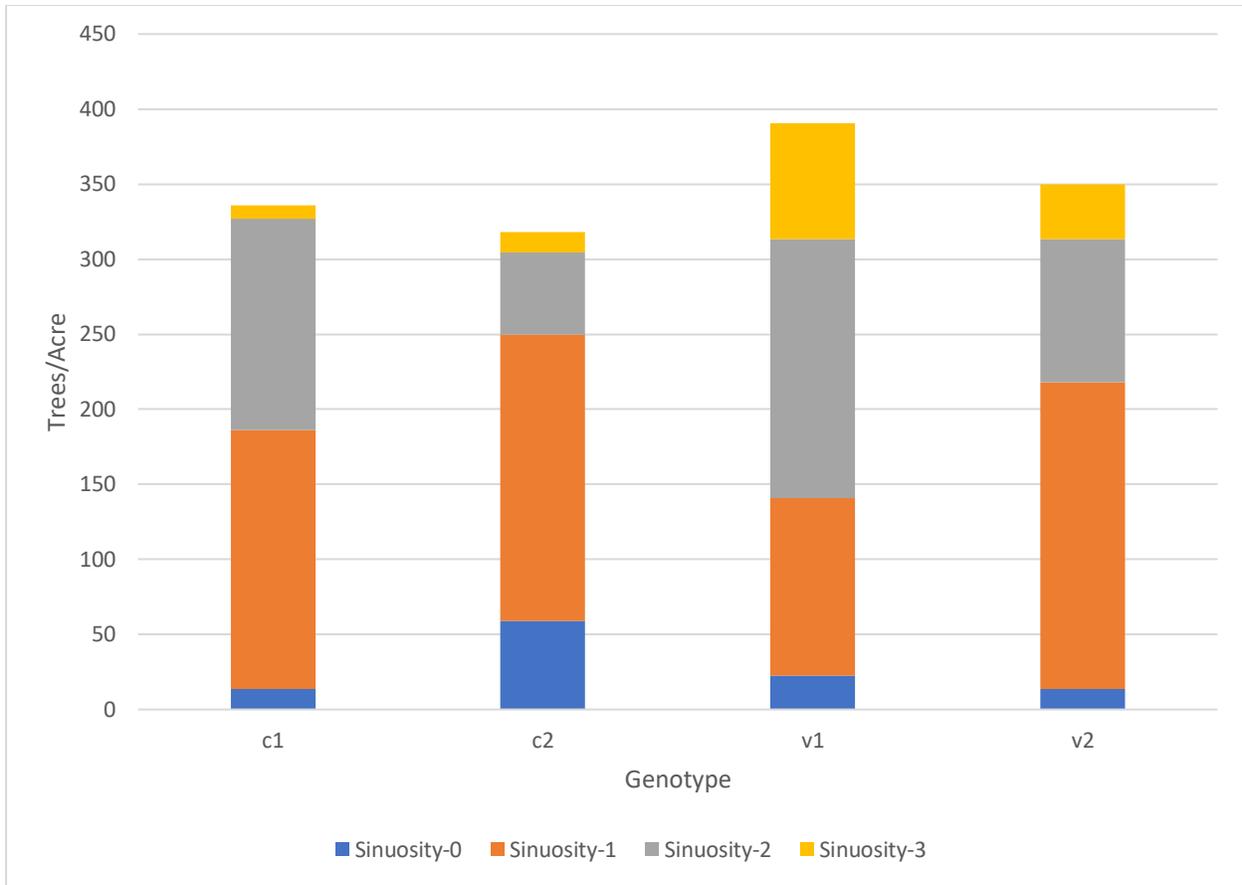


Figure 33. Sinuosity of 9-year-old loblolly pine treated with 0.031gal/acre arsenal in the spring of the 1st and 2nd growing season and not given imidacloprid (control) by genotype at UCP. Of trees receiving low-arsenal treatment and not given imidacloprid, genotype C2 was the highest quality in terms of stem form with 250 good quality stems per acre. Genotype C1 had 14 trees per acre of sinuosity class 0, and 173 TPA in form class 1, 141 TPA form class 2, and 9 TPA form class 3. Genotype C2 had 59 TPA of sinuosity class 0, and 191 TPA in form class 1, 55 TPA form class 2, and 14 TPA form class 3. Genotype V1 had 23 trees per acre of sinuosity class 0, and 118 TPA in form class 1, 173 TPA form class 2, and 77 TPA form class 3. Genotype V2 had 14 trees per acre of sinuosity class 0, and 204 TPA in form class 1, 95 TPA form class 2, and 36 TPA form class 3.

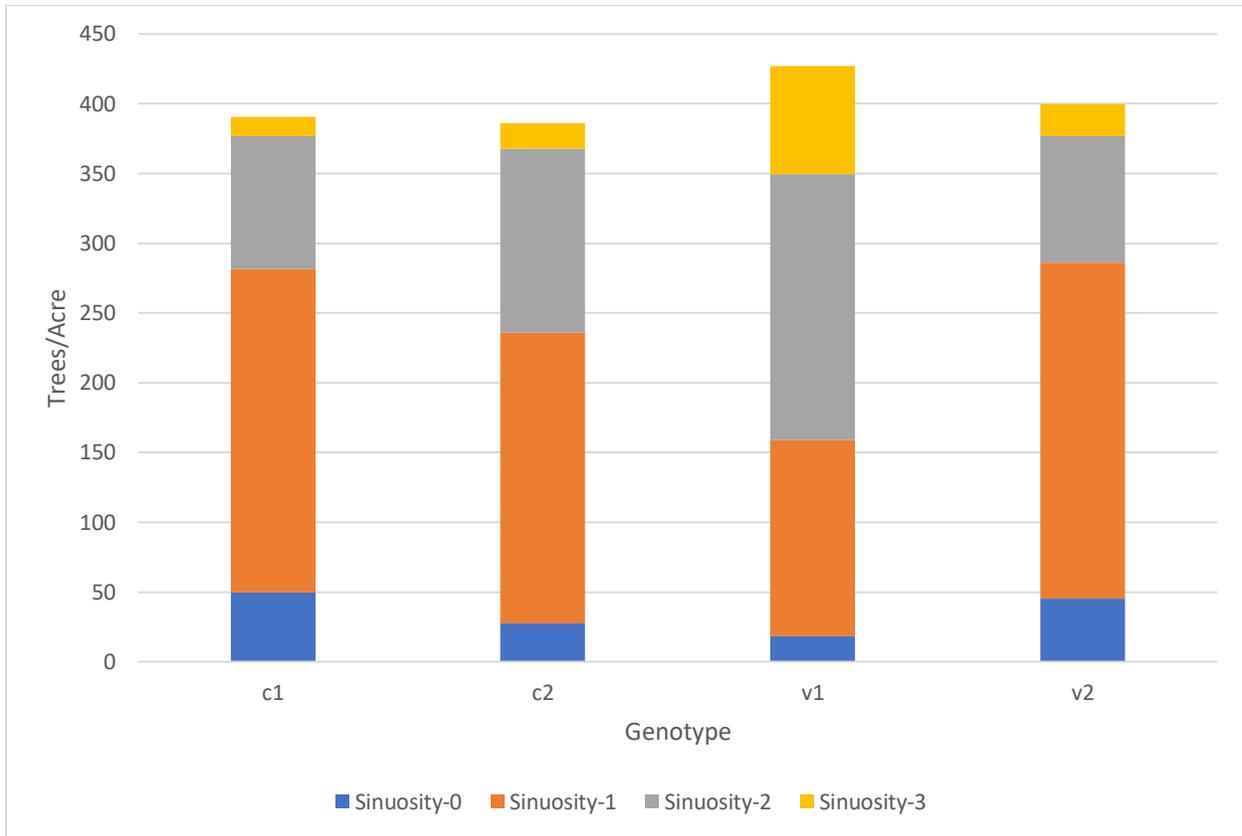


Figure 34. Sinuosity of 9-year-old loblolly pine treated with 0.031gal/acre arsenal in the spring of the 1st and 2nd growing season and given imidacloprid (treatment) by genotype at UCP. Of trees receiving low-arsenal treatment and imidacloprid, genotype V2 was slightly better quality than genotype C1, producing 286 and 282 good quality trees per acre, respectively, in terms of sinuosity index. Genotype C1 had 50 trees per acre of sinuosity class 0, and 232 TPA in form class 1, 95 TPA form class 2, and 14 TPA form class 3. Genotype C2 had 27 TPA of sinuosity class 0, and 209 TPA in form class 1, 132 TPA form class 2, and 18 TPA form class 3. Genotype V1 had 18 trees per acre of sinuosity class 0, and 141 TPA in form class 1, 191 TPA form class 2, and 77 TPA form class 3. Genotype V2 had 45 trees per acre of sinuosity class 0, and 241 TPA in form class 1, 91 TPA form class 2, and 23 TPA form class 3.

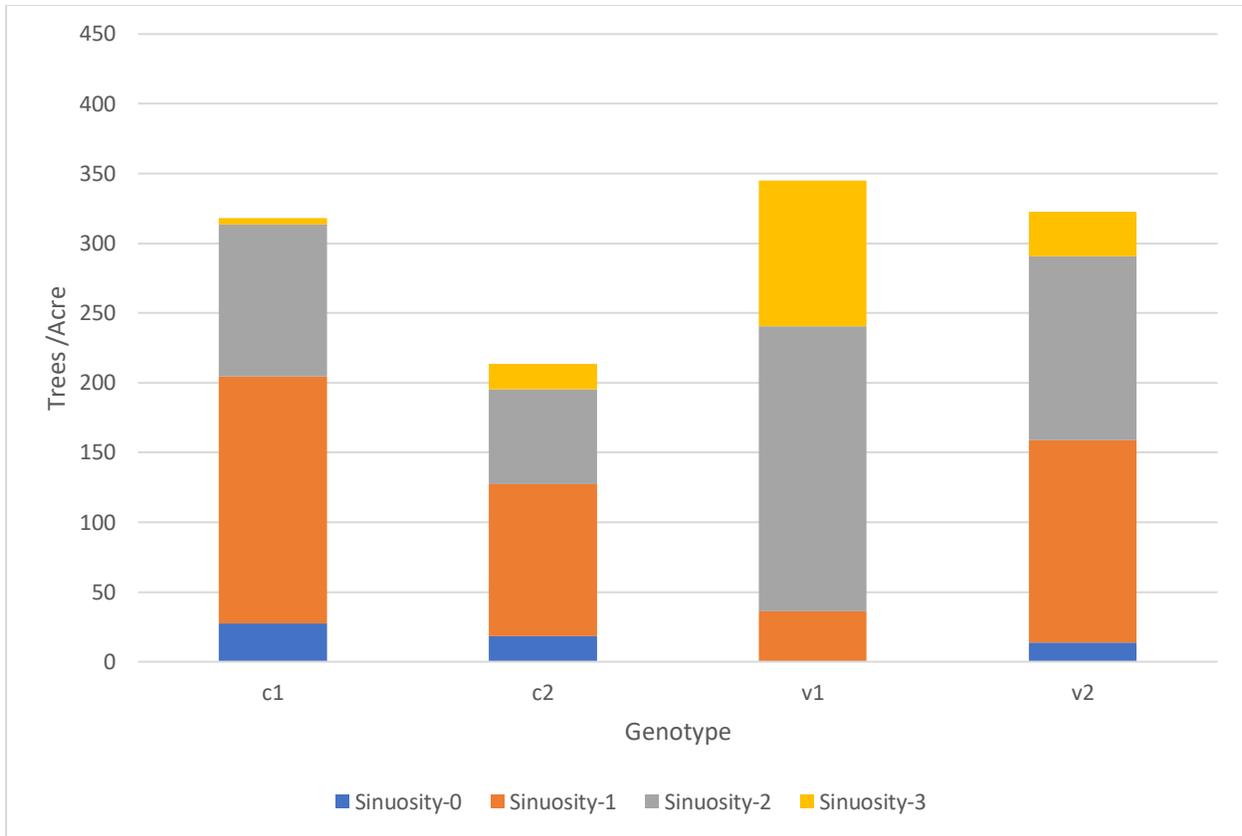


Figure 35. Sinuosity of 9-year-old loblolly pine treated with 0.062gal/acre Arsenal in the spring of the 1st and 2nd growing season and not given imidacloprid (control) by genotype at UCP. Of trees receiving high-Arsenal treatment and no imidacloprid, genotype C1 was the highest quality in terms of stem form with 204 good quality trees per acre in terms of sinuosity index. Genotype C1 had 27 trees per acre of sinuosity class 0, and 177 TPA in form class 1, 109 TPA form class 2, and 5 TPA form class 3. Genotype C2 had 18 TPA of sinuosity class 0, and 109 TPA in form class 1, 68 TPA form class 2, and 18 TPA form class 3. Genotype V1 had 0 trees per acre of sinuosity class 0, and 36 TPA in form class 1, 204 TPA form class 2, and 104 TPA form class 3. Genotype V2 had 14 trees per acre of sinuosity class 0, and 145 TPA in form class 1, 132 TPA form class 2, and 32 TPA form class 3. Only stands of genotype C1 in this treatment come close to having enough quality TPA (approximately 200 TPA required) to move to the next stage of stand development (but they lack the basal area) after removals of trees with broken top and large ramicorn branches and crooks it is unlikely these stands would have enough trees per acre to justify managing stands for saw timber. This supports my hypothesis that trees given the highest levels of cultural treatment and no imidacloprid would be lowest quality.

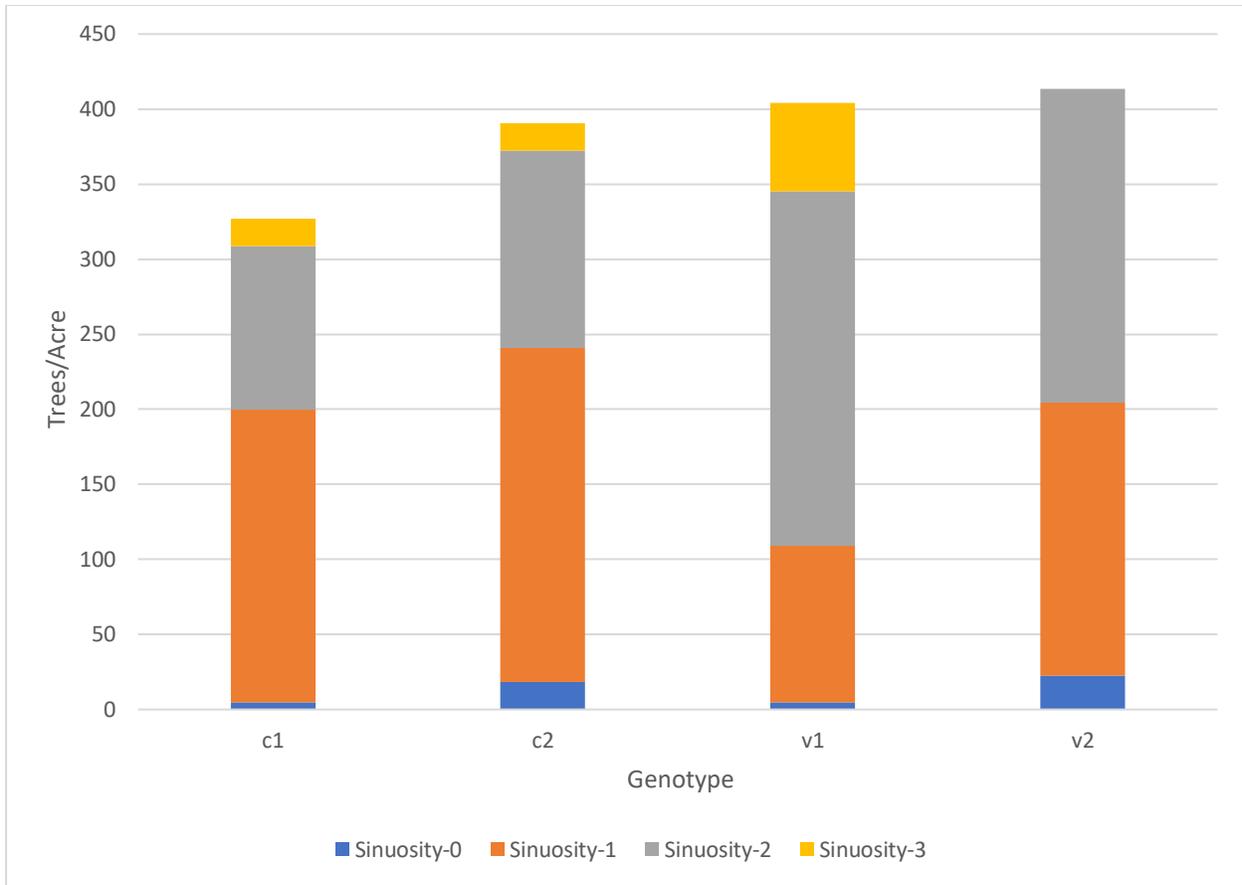


Figure 36. Sinuosity of 9-year-old loblolly pine treated with 0.062 gal/acre arsenal in the spring of the 1st and 2nd growing season and given imidacloprid (treatment) by genotype at UCP. Of trees receiving high-arsenal treatment and imidacloprid, genotype C2 was the highest quality in terms of stem form with 241 good quality trees per acre. Genotype C1 had 5 trees per acre of sinuosity class 0, and 195 TPA in form class 1, 109 TPA form class 2, and 18 TPA form class 3. Genotype C2 had 18 TPA of sinuosity class 0, and 223 TPA in form class 1, 132 TPA form class 2, and 18 TPA form class 3. Genotype V1 had 5 trees per acre of sinuosity class 0, and 104 TPA in form class 1, 236 TPA form class 2, and 59 TPA form class 3. Genotype V2 had 23 trees per acre of sinuosity class 0, and 182 TPA in form class 1, 209 TPA form class 2, and 0 TPA form class 3. Genotype V1 does not have stem quality to justify moving on with a sawtimber rotation and this limits its value. Genotypes C1 and V2 only just meet the requirement of approximately 200 good quality TPA and will likely not meet that guideline after cull for other defects.

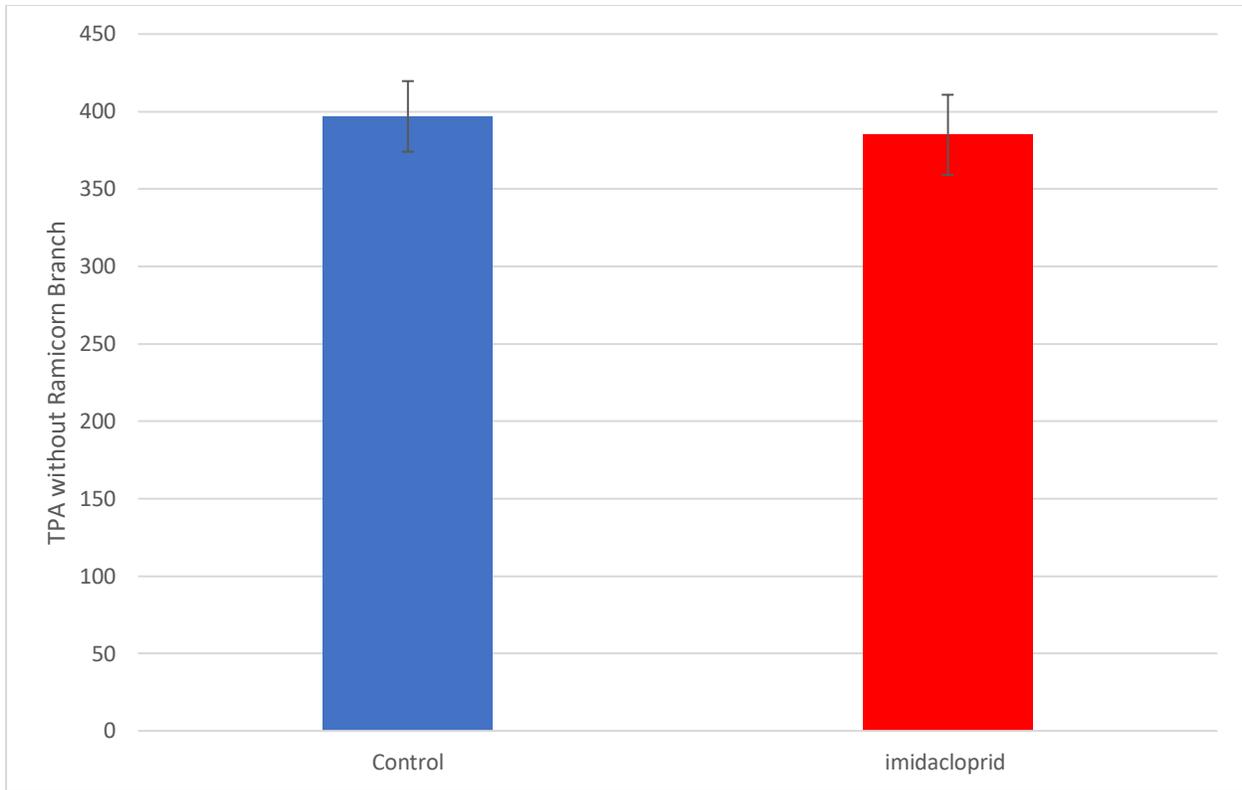


Figure 37. Proportion of trees affected by ramicorn branch between control and imidacloprid treatments. Trees planted in the control treatment were 99(0.3) percent free from ramicorn branch and imidacloprid trees were 96(0.7) percent free from ramicorn branch at LCP. When adjusted for survival and expanded to a per-acre basis, control plots contained 396(23) trees per acre without ramicorn branches, and imidacloprid trees contained 384(25) trees per acre without ramicorn branches. While the proportions of ramicorn branch present are technically significant, there is no practical difference between the number of trees per acre existing without ramicorn branches between control and imidacloprid treatments at the lower coastal plain. There is no practical difference between the number of trees per acre free of ramicorn branch regardless of imidacloprid treatment. It is likely that all trees with large ramicorn branches can be removed from the next stand during a first thinning regardless of treatment.

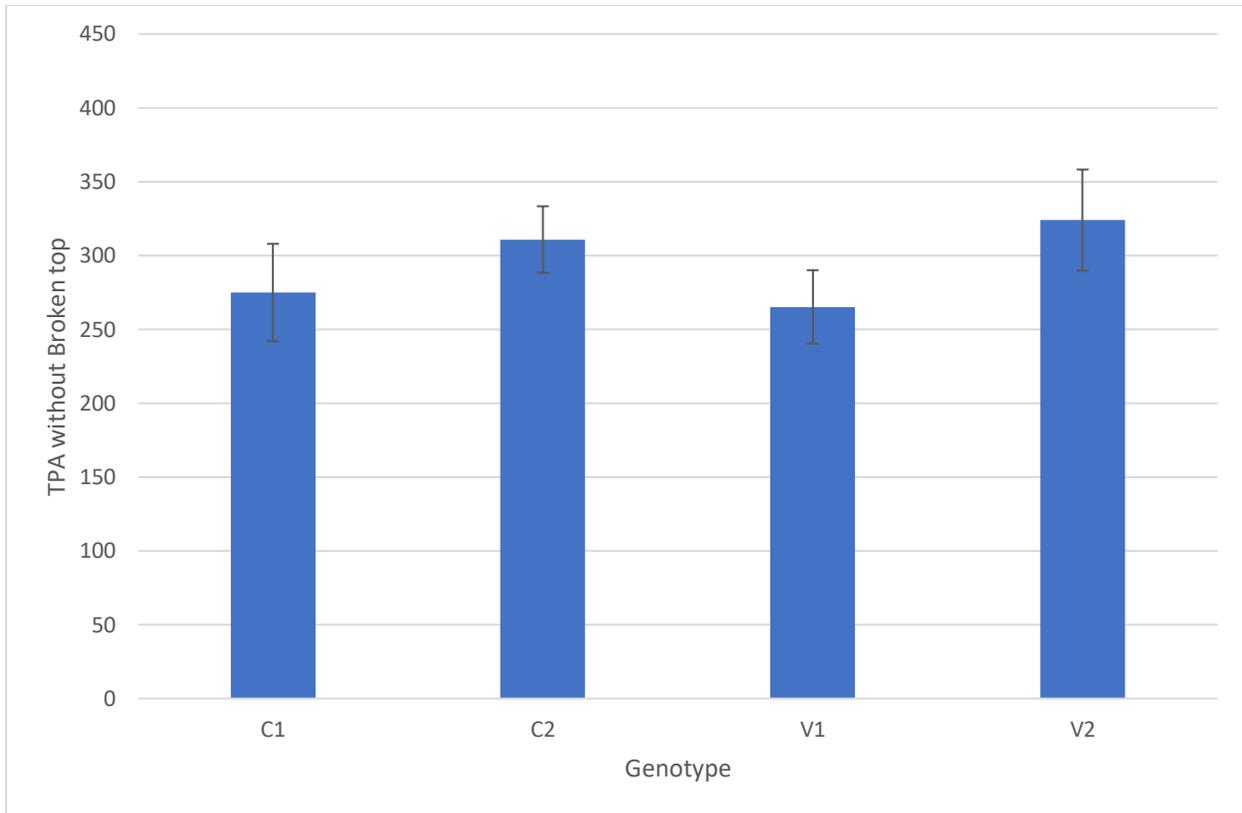


Figure 38. Trees per acre (SE) of 9-year-old loblolly pine without broken top by genotype at LCP. The main effect genotype was significant for the presence of broken top on 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p < 0.0001$, Table 8). Genotype C1 was 70(2.45) percent free from defect and produced 274(32) trees per acre without broken top at the lower coastal plain. Genotype C2 was 78(2.2) percent free from broken top and C2 stands contained 310(22) trees per acre without broken tops. Genotype V1 was 64(2.5) percent free from broken top and when adjusted for survival, produced 265(24) trees per acre without broken top. Genotype V2 was 82(2.05) percent free from broken top and stands planted with V2 contained 324(34) trees per acre without broken top.

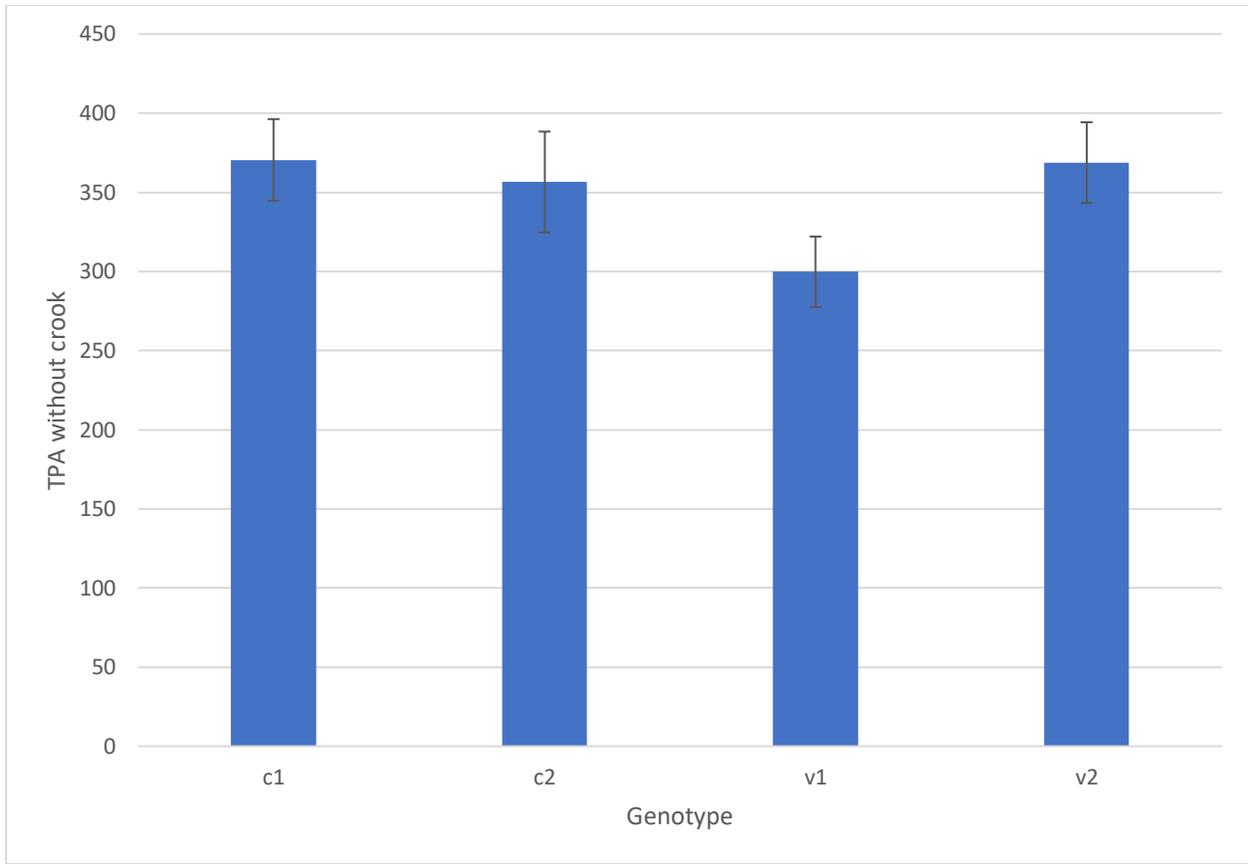


Figure 39. Trees per acre (SE) of 9-year-old loblolly pine without crook grown at LCP by genotype. The main effect genotype was significant for the presence of crook on 9-year old loblolly pine growing in the lower coastal plain of North Carolina ($p < 0.0001$, Table 8). Genotype C1 was 92(1.4) percent free from crook and stands planted with C1 contained 370(25) trees per acre without crook defects. Genotype C2 was 90(0.6) percent free from crook defect and stand planted with C2 contained 356(31) trees per acre without crook defect. Genotype V1 was 72(2.34) percent free from defect and stands planted with V1 contained 299(22) trees per acre without crook defects. Genotype V2 was 93(1.3) percent free from defect and stands planted with V2 contained 368(25) trees per acre without crook defects. Genotype V1 is estimated to have fewer trees per acre without crook defects than other genotypes however this is likely of small practical significance in that most, if not all the crooked trees can be removed during a first thinning.

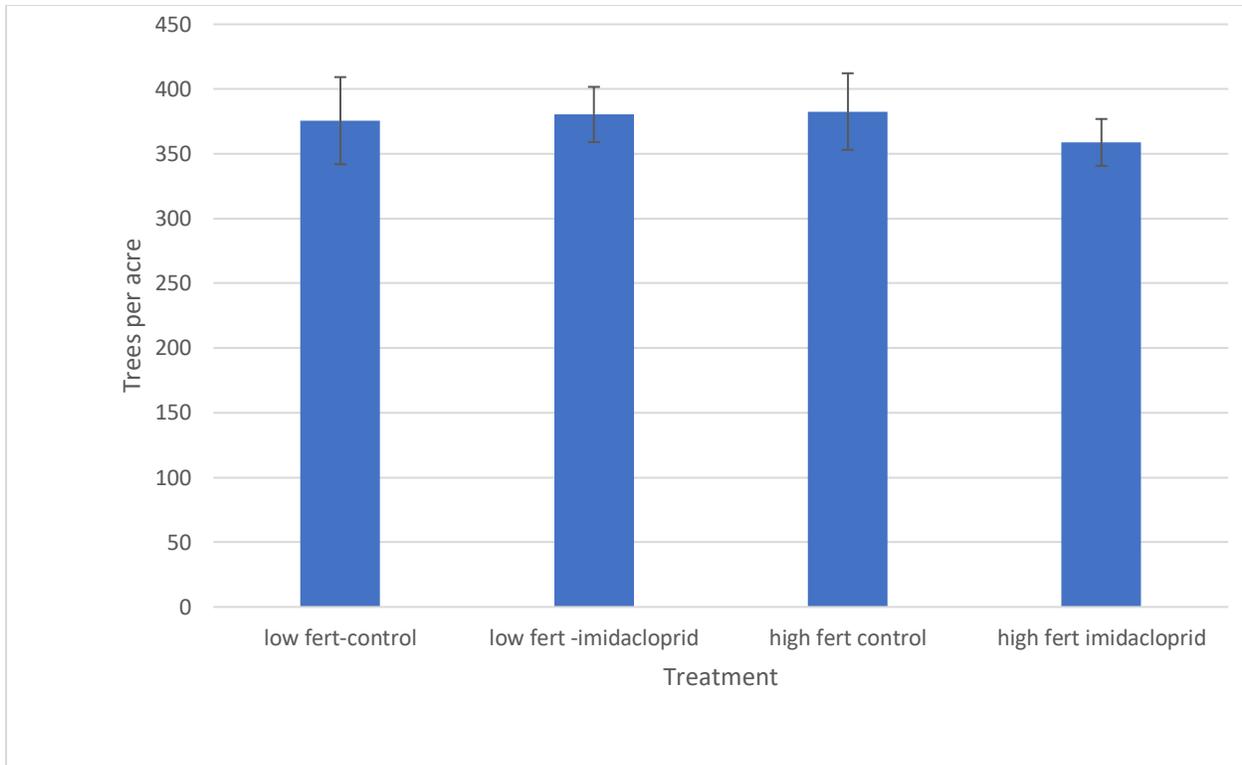


Figure 40. Trees per acre (SE) of 9-year-old loblolly pine without fork grown at LCP by genotype. The phosphorus* imidacloprid interaction was marginally significant for the presence of fork defects on 9-year-old loblolly pine growing in the lower coastal plain of North Carolina ($p=0.054$, Table 8). Trees planted in the low phosphorus- control plots were 94(1.21) percent free of fork defects, and when adjusted for survival produced 375(33) trees per acre without fork defects. Trees in the low phosphorus- imidacloprid treated plots were 94(1.20) percent free of fork defects and contained 380(21) trees per acre without fork defects. High phosphorus- control plots were 94(1.19) percent free from fork defects at the LCP and contained 382(29) trees per acre without forks. The high phosphorus- imidacloprid plots were 90(1.58) percent free from fork and contained 358(18) trees per acre without fork defects.

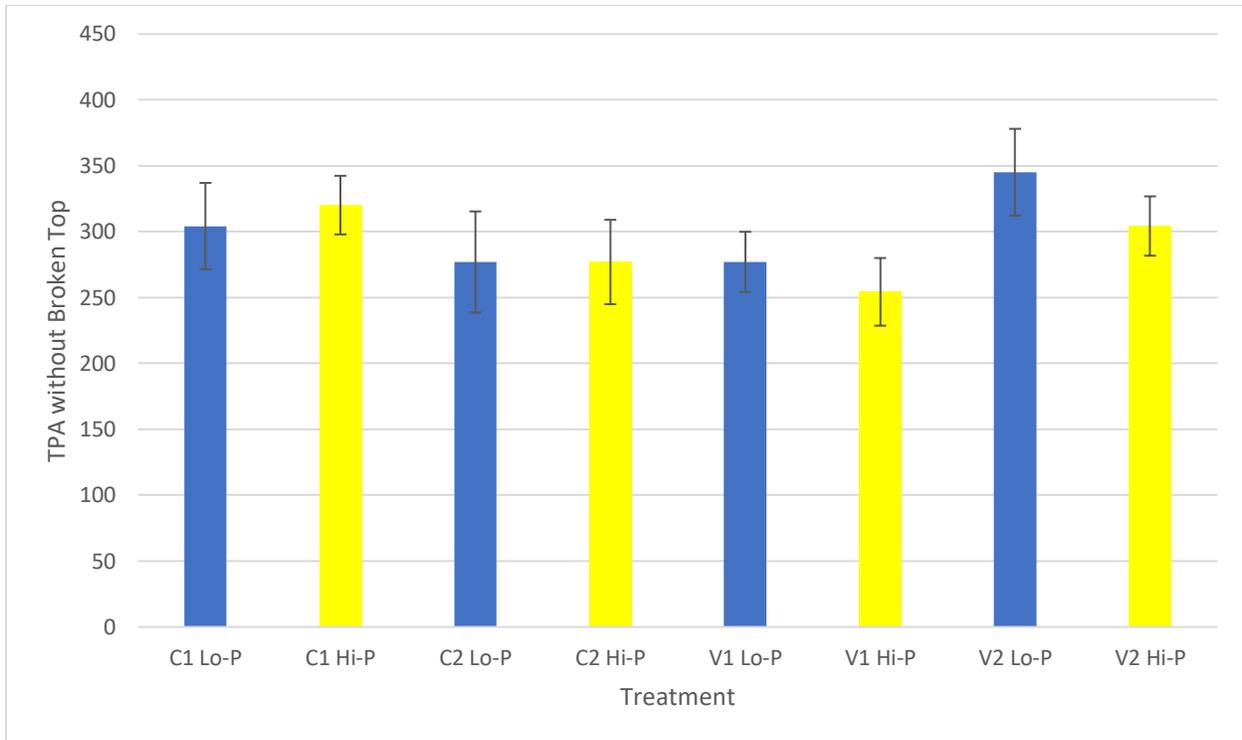


Figure 41. Trees per acre(SE) of 9-year-old loblolly pine grown in lower coastal plain by genotype and fertilization rate. The phosphorus*genotype interaction was significant for the presence of broken top defects ($p=0.031$, Table 8). A total of 75(3.23) percent of genotype C1 trees given low phosphorus did not have broken tops, and when adjusted for survival C1 low phosphorus had 304(32) trees per acre without broke top. Likewise, 81(2.95) percent of genotype C1 given high phosphorus did not have broken top, and when adjusted for survival genotype C1 with high phosphorus produced 320(22) trees per acre without broken top. Genotype C2 given low phosphorus was 71(3.46) percent free of broken top, and when adjusted for survival genotype C2 produced 277(38) trees per acre without broken tops. Genotype C2 given high phosphorus was 69(3.47) percent free of broken top and produced 277(32) trees per acre without broken top. V1 given low phosphorus was 68(3.43) percent free of broken top and produced 277(22) trees per acre without broken top. V1 given high phosphorus was 60(3.59) percent free from broken top and produced 254(25) trees per acre without broken top. Genotype V2 given low phosphorus was 86(2.56) percent free from broken top and produced 345(32) trees per acre without broken top. V2 given high phosphorus was 78(3.16) percent free of broken top and produced 304(22) trees per acre without broken top.

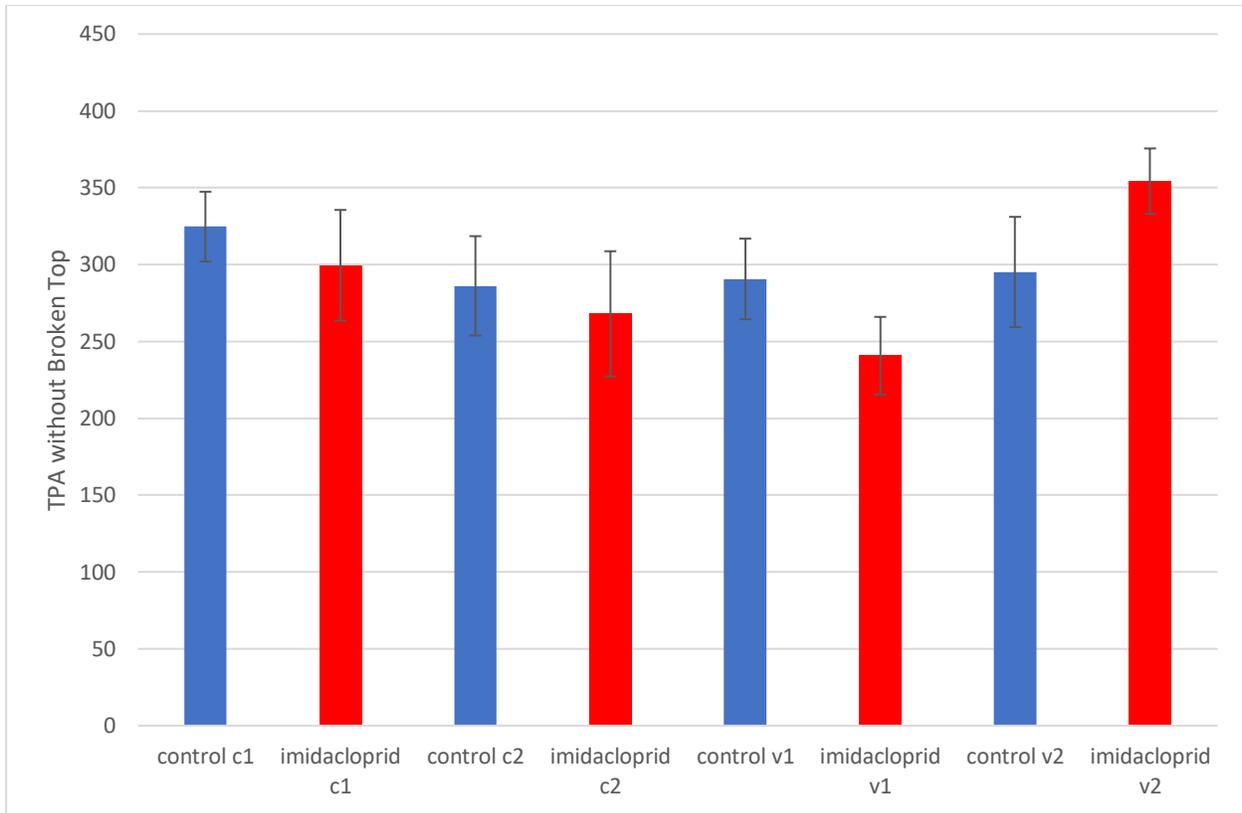


Figure 42. Trees per acre without broken top by imidacloprid treatment and genotype. The imidacloprid*genotype interaction was significant in influencing the presence of broken top in 9-year-old loblolly pine growing in the lower coastal plain of North Carolina. ($p=0.001$, Table 8). Genotype V1 with imidacloprid has the fewest estimated trees per acre without broken top. Overall, broken top was an issue at the LCP due largely to plantations proximity to the Atlantic Ocean and the extreme weather events associated with this physiographic region. Trees per acre without broken top at LCP generally did not improve with addition of imidacloprid. Genotype V2 may have been improved with imidacloprid but stand quality in genotype V1 seems to be lower with imidacloprid. Except for genotype V1 in the control treatment, all other combinations of genotype and imidacloprid will likely have adequate numbers of trees per acre to select crop trees without broken top to carry into the next stage of plantation management.

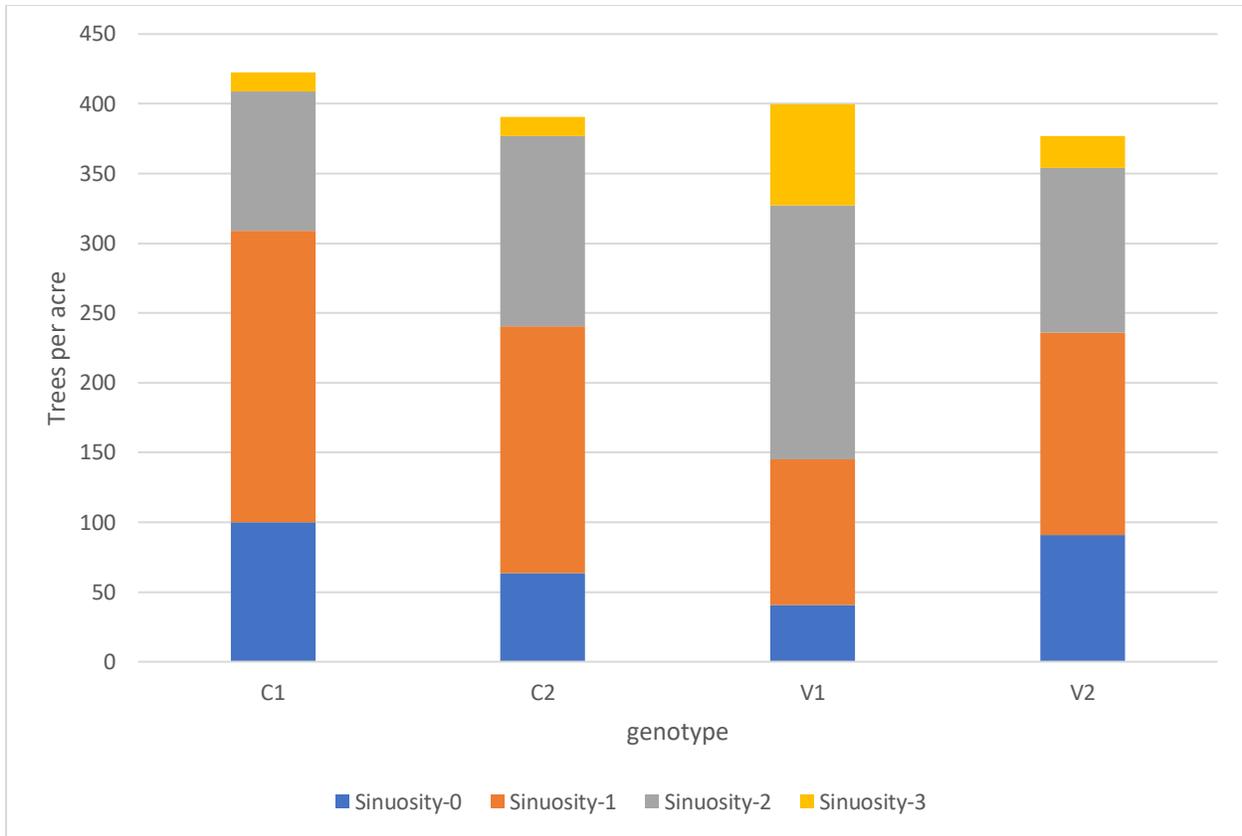


Figure 43. Sinuosity of 9-year-old loblolly pine fertilized with 8.1 lbs./acre elemental phosphorus and no imidacloprid (control) by genotype at LCP. Of trees receiving 8.1lbs elemental phosphorus per acre at planting and no imidacloprid, genotype C1 was the highest quality in terms of stem form. Genotype C1 had 100 trees per acre of sinuosity class 0, and 209 TPA in form class 1, 100 TPA form class 2, and 14 TPA form class 3. Genotype C2 had 64 TPA of sinuosity class 0, and 177 TPA in form class 1, 136 TPA form class 2, and 14 TPA form class 3. Genotype V1 had 41 trees per acre of sinuosity class 0, and 104 TPA in form class 1, 182 TPA form class 2, and 73 TPA form class 3. Genotype V2 had 100 trees per acre of sinuosity class 0, and 209 TPA in form class 1, 100 TPA form class 2, and 14 TPA form class 3.

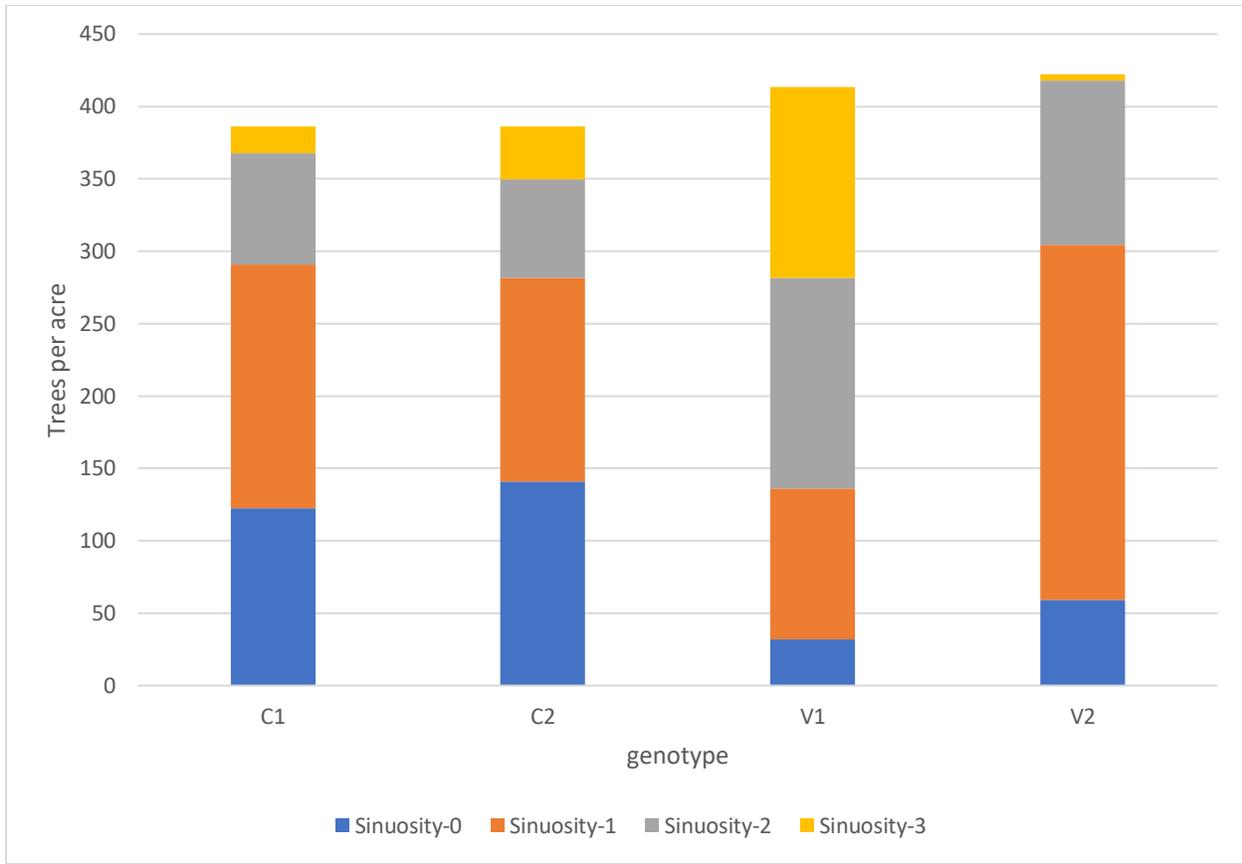


Figure 44. Sinuosity of 9-year-old loblolly pine fertilized with 8.1 lbs./acre elemental phosphorus and imidacloprid (treatment) by genotype at LCP. Of trees receiving 8.1lbs elemental phosphorus per acre at planting and imidacloprid, genotype V2 was the highest quality in terms of sinuosity with 304 TPA good quality stems. Genotype C1 had 123 trees per acre of sinuosity class 0, and 168 TPA in form class 1, 77 TPA form class 2, and 18 TPA form class 3. Genotype C2 had 141 TPA of sinuosity class 0, and 141 TPA in form class 1, 68 TPA form class 2, and 36 TPA form class 3. Genotype V1 had 32 trees per acre of sinuosity class 0, and 104 TPA in form class 1, 145 TPA form class 2, and 132 TPA form class 3. Genotype V2 had 59 trees per acre of sinuosity class 0, and 245 TPA in form class 1, 114 TPA form class 2, and 5 TPA form class 3

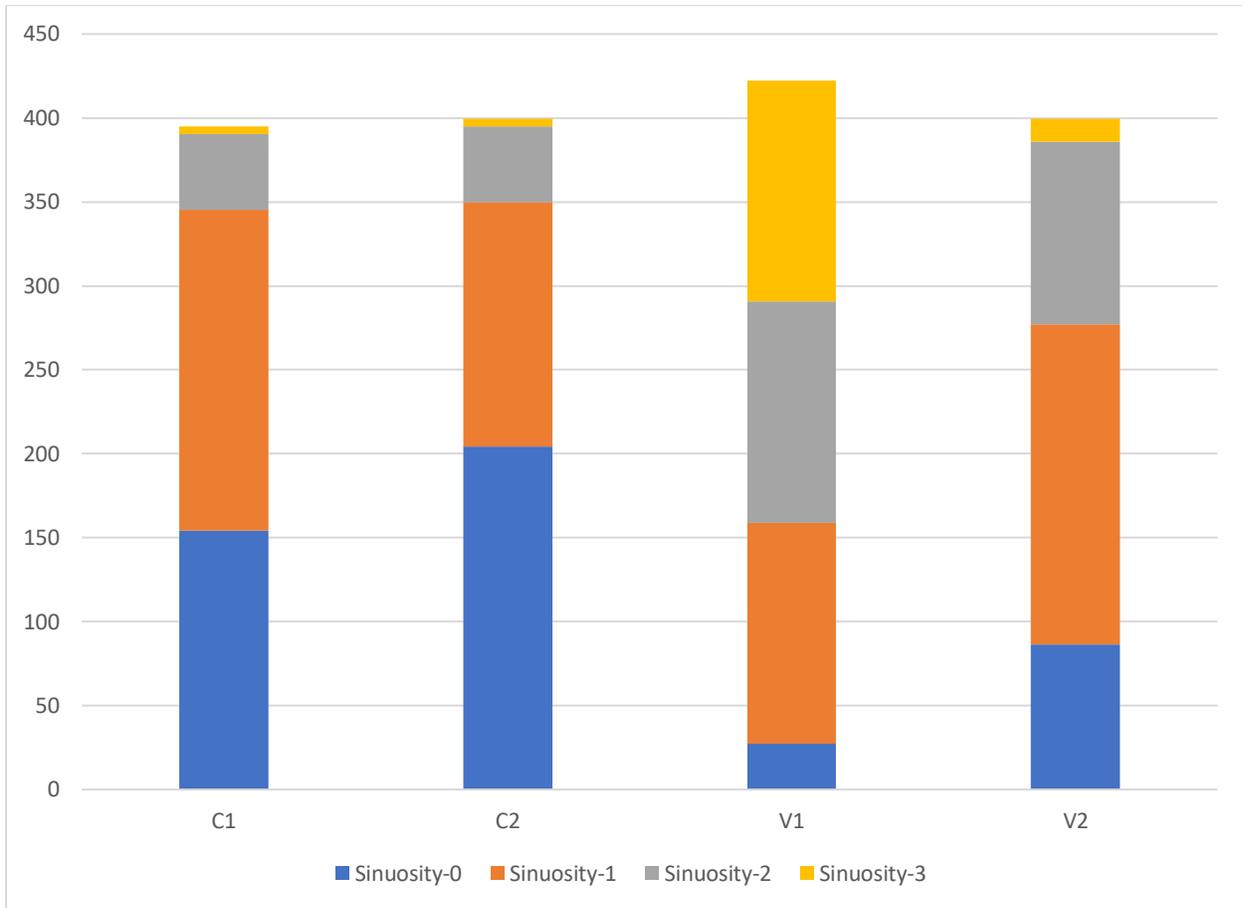


Figure 45. Sinuosity of 9-year-old loblolly pine fertilized with 16.2 lbs./acre elemental phosphorus and no imidacloprid (control) by genotype at LCP. Of trees receiving 16.2 lbs elemental phosphorus per acre at planting and no imidacloprid, genotype C2 was the highest quality in terms of stem form. Genotype C1 had 154 trees per acre of sinuosity class 0, and 191 TPA in form class 1, 45 TPA form class 2, and 5 TPA form class 3. Genotype C2 had 204 TPA of sinuosity class 0, and 145 TPA in form class 1, 45 TPA form class 2, and 5 TPA form class 3. Genotype V1 had 27 trees per acre of sinuosity class 0, and 132 TPA in form class 1, 132 TPA form class 2, and 132 TPA form class 3. Genotype V2 had 86 trees per acre of sinuosity class 0, and 191 TPA in form class 1, 109 TPA form class 2, and 14 TPA form class 3.

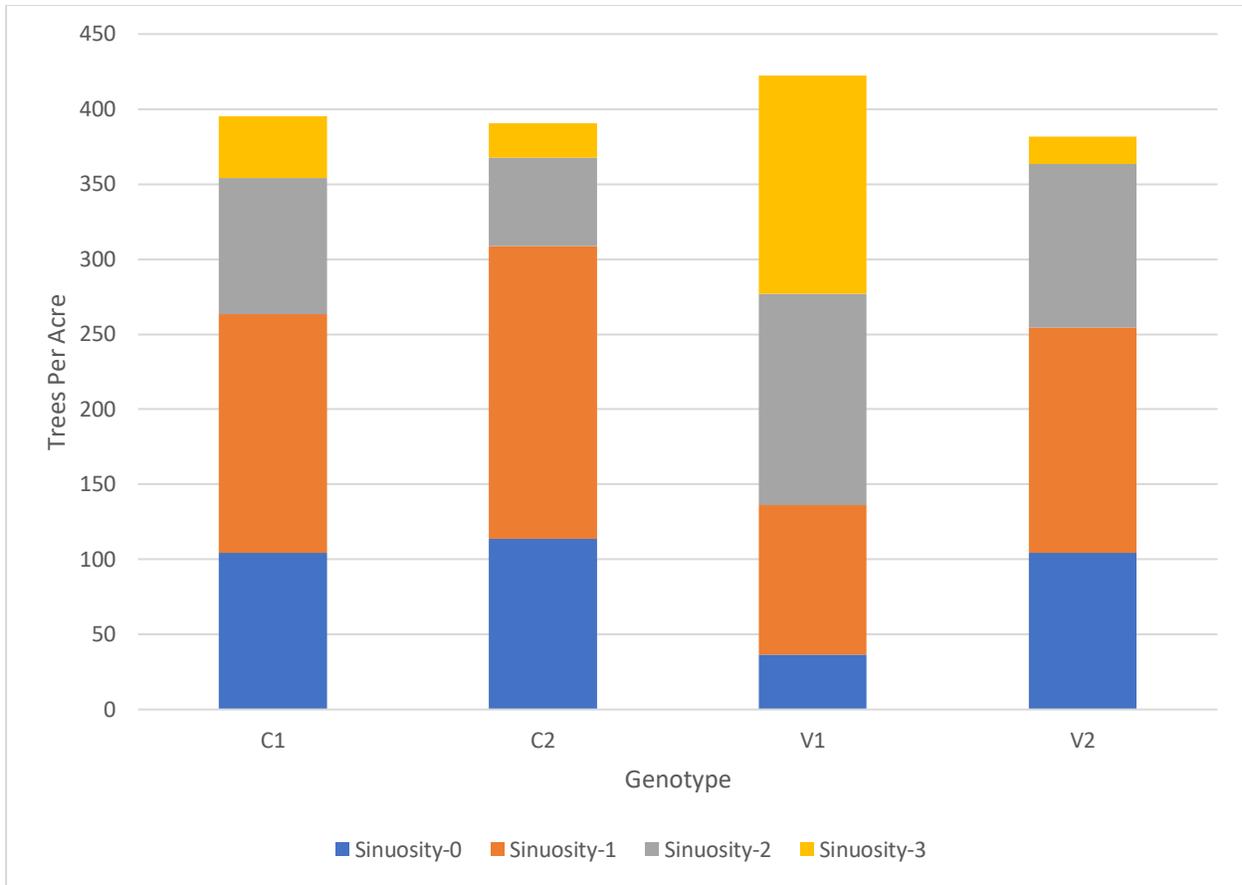


Figure 46. Sinuosity of 9-year-old loblolly pine fertilized with 16.2 lbs./acre elemental phosphorus per acre and imidacloprid (treatment) by genotype at LCP. Of trees receiving 16.2 lbs. elemental phosphorus per acre at planting and imidacloprid, genotype C2 was the highest quality in terms of sinuosity with 309 good quality stems per acre. Genotype C1 had 104 trees per acre of sinuosity class 0, and 159 TPA in form class 1, 91 TPA form class 2, and 41 TPA form class 3. Genotype C2 had 114 TPA of sinuosity class 0, and 195 TPA in form class 1, 59 TPA form class 2, and 23 TPA form class 3. Genotype V1 had 36 trees per acre of sinuosity class 0, and 100 TPA in form class 1, 141 TPA form class 2, and 145 TPA form class 3. Genotype V2 had 104 trees per acre of sinuosity class 0, and 150 TPA in form class 1, 109 TPA form class 2, and 18 TPA form class 3.

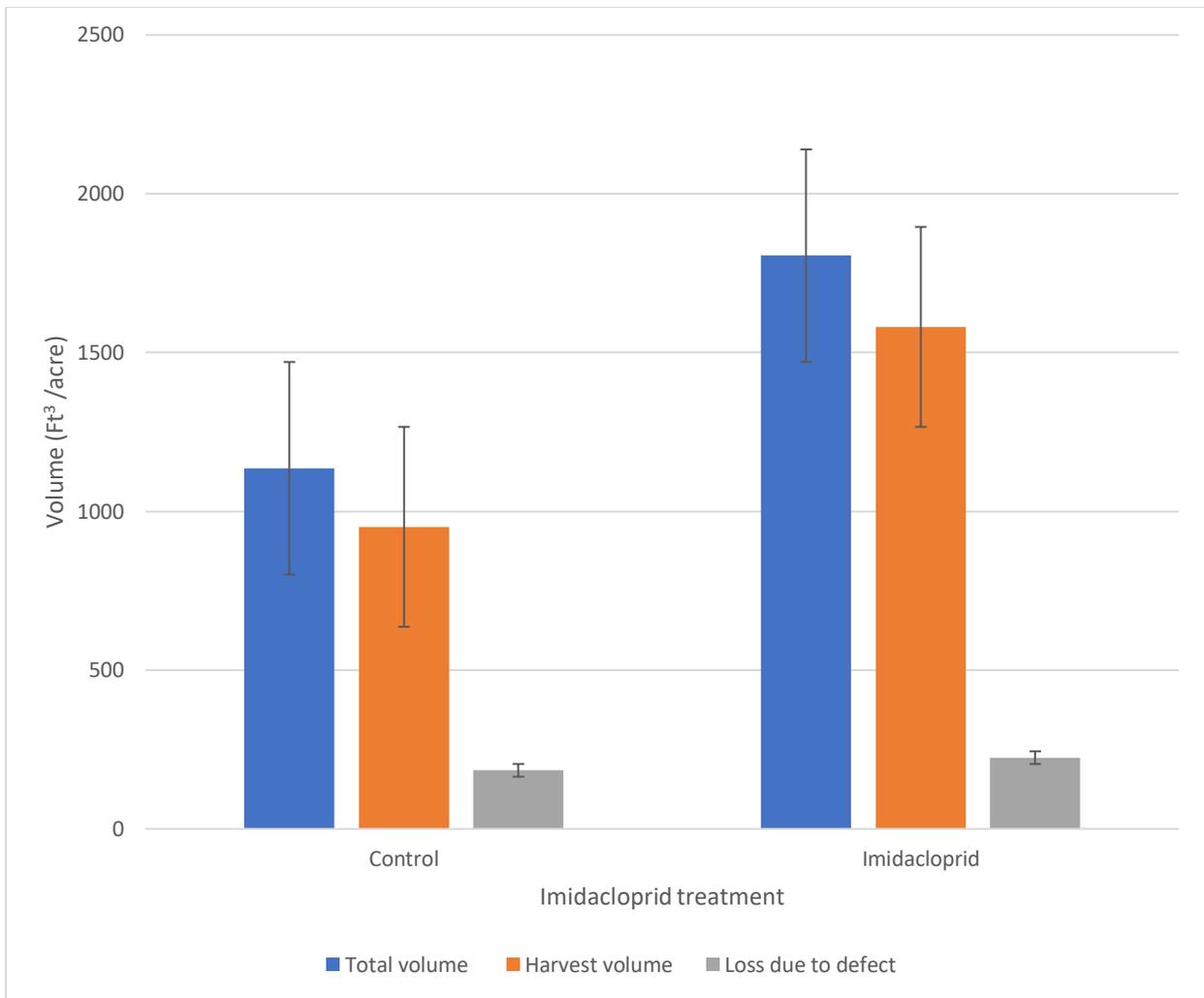


Figure 47. Total volume per acre, harvest volume per acre and loss removed due to defect per acre of 9-year-old loblolly pine by imidacloprid treatment at UCP. While loss due to defect is similar between control treatments with 184(45)ft³/acre lost due to defect and imidacloprid treatments with 224(22)ft³/acre lost due to defect in the control treatment is a larger proportion of the total volume due to lower survival and smaller trees in the control treatment. While these trees are only pulp wood size the benefit of imidacloprid is already beginning to become apparent. With time, the more productive and higher quality imidacloprid treated stands will grow into higher quality higher value products faster than untreated control stands.

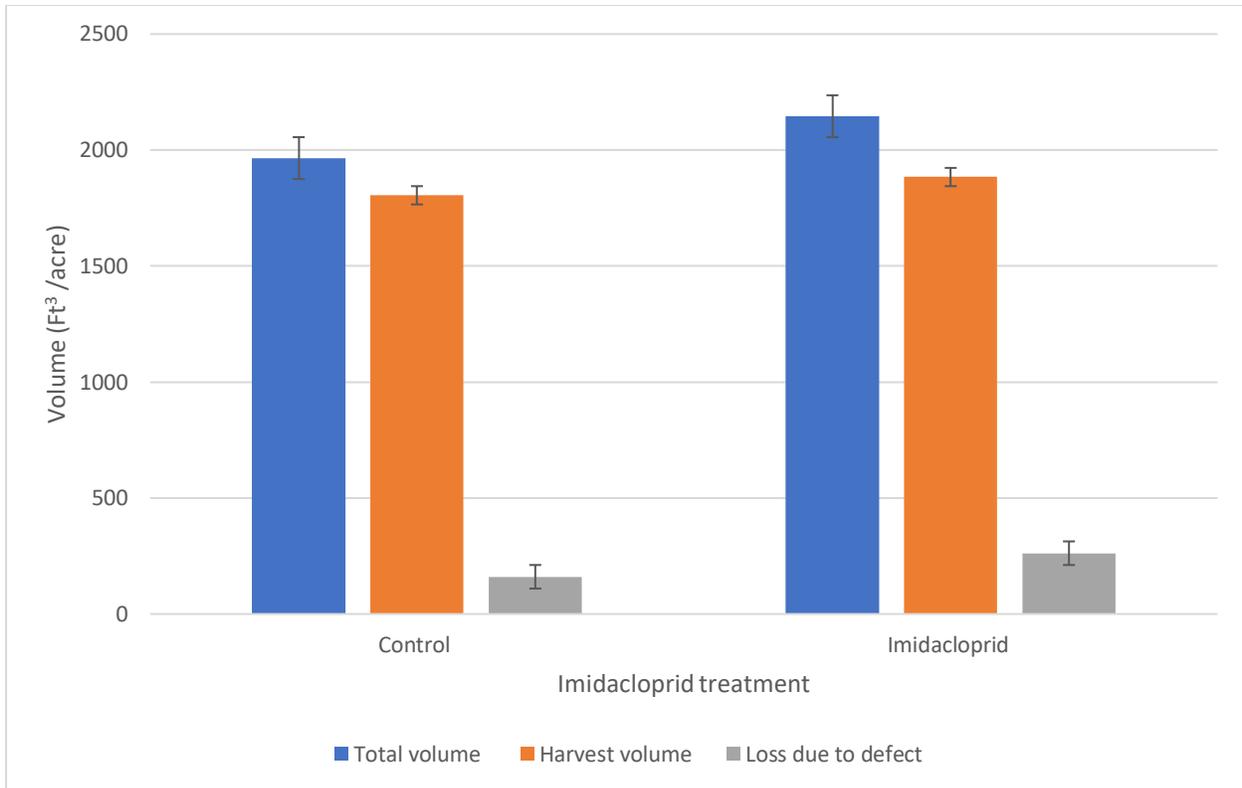


Figure 48. Total volume per acre, harvest volume per acre and loss removed due to defect per acre of 9-year-old loblolly pine by imidacloprid treatment at LCP. While imidacloprid treated stands produce more total volume, 2145(174) ft³/acre vs. 1965(101)ft³/acre in the control, they also lost more volume 262(73) ft³/acre vs 160(40) due to defect. Imidacloprid treated stand produced approximately 80 cubic feet more merchantable wood volume per acre after 9 years of growth at the lower coastal plain. My results indicate that systemic insecticides do not increase yield or subsequent value of pine plantations grown on high quality sites.

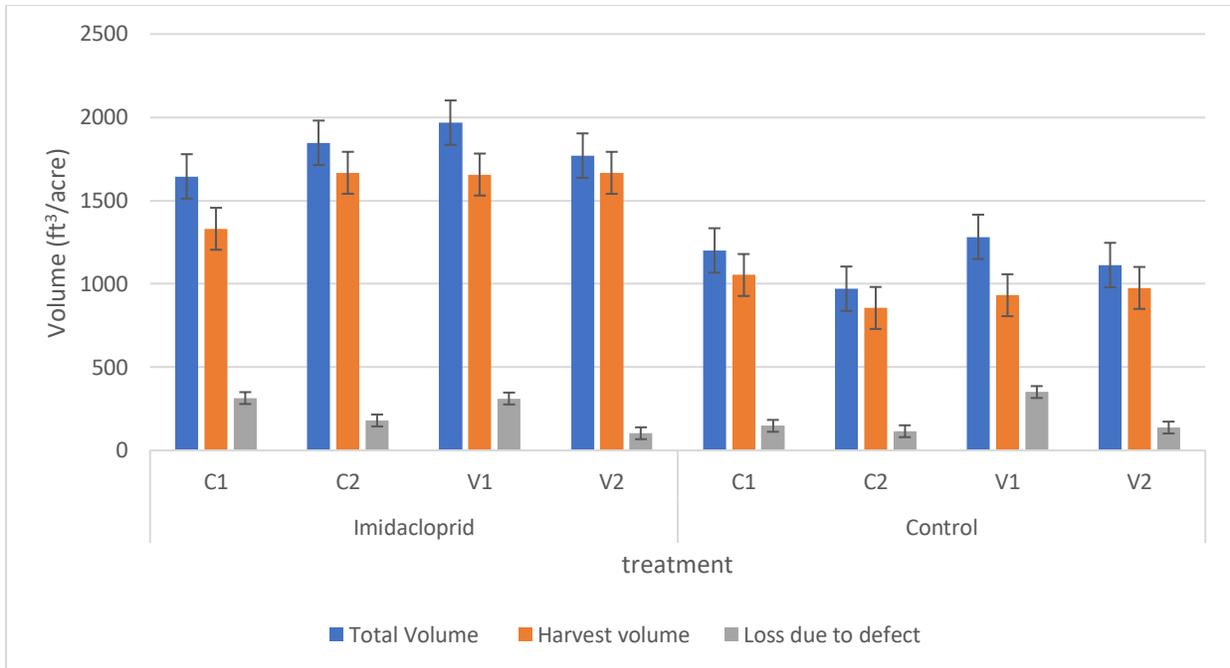


Figure 49. Total volume per acre harvest volume per acre and loss due to defect per acre by imidacloprid treatment and genotype at UCP. At the upper coastal plain site, imidacloprid trees produced more total volume due to greater survival and significantly larger size. They also produced more harvest volume but not because loss to defect was reduced but because loss to defect was smaller than the difference in growth between imidacloprid treated trees. Harvest volume was best in genotypes C2, V1, V2 treated with imidacloprid. Genotype C1 treated with imidacloprid was heavily damaged with fusiform rust and thus grew to smaller size and lost harvest volume yield. Genotype V1 was the most sinuous genotype which accounts for heavy (>300 ft³/acre) loss in yield.

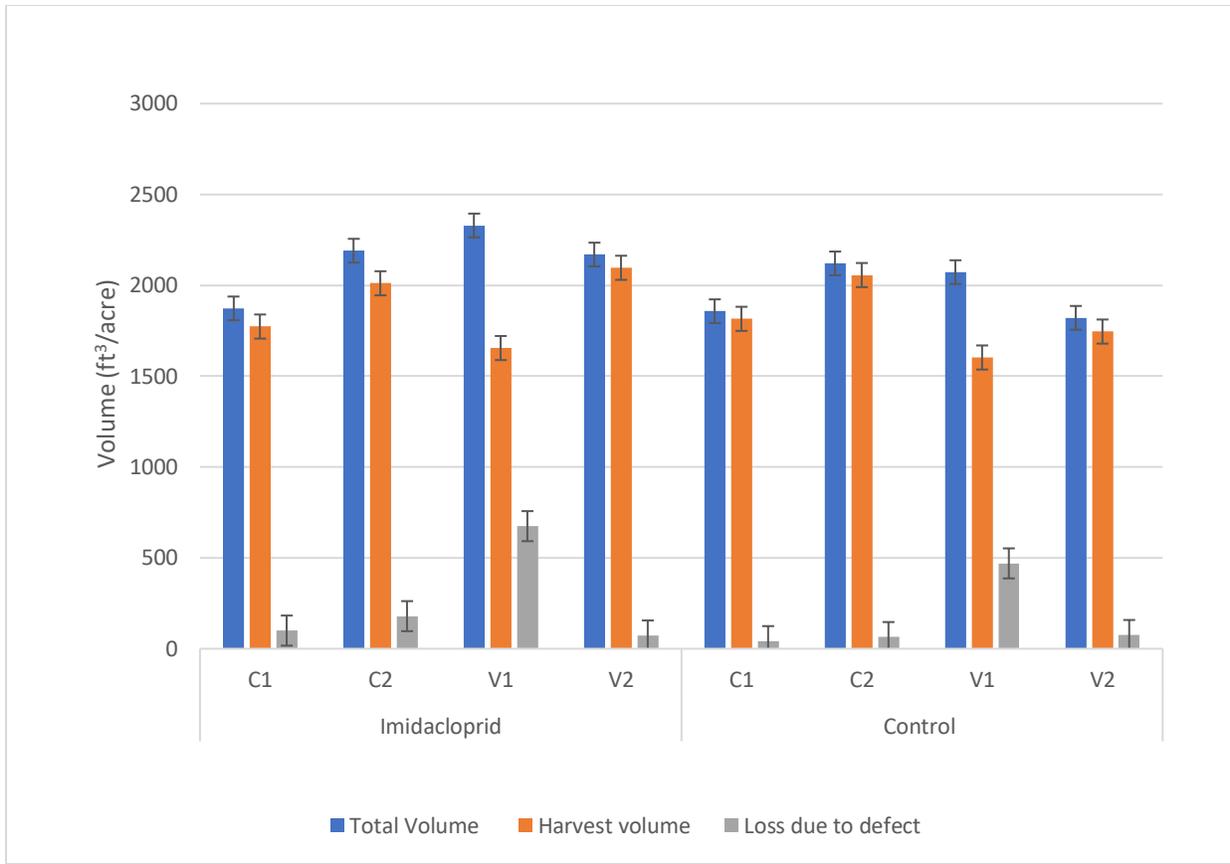


Figure 50. Total volume, harvest volume, and loss due to defect in ft³/acre by imidacloprid treatment and genotype at LCP. Most genotypes produced slightly more volume when treated with imidacloprid but also lost more volume to defect with imidacloprid treatment at LCP. Yield loss > 500 cubic feet per acre in V1 is due to high sinuosity. Sinuosity increased in genotype V1 with imidacloprid treatment, seemingly the fastest growing (V1) became more sinuous when protected from herbivory. However, notice the large differences in harvest volume due to genotype a clearly, closely matching productive genotypes to high quality sites is paramount for producing timber in high intensity plantations. In genotype V2, imidacloprid treatment produced more wood volume than V2 control not due to reduced loss to yield (72 cubic feet (imidacloprid) vs 75 cubic feet (control)), but because of the greater original total volume.

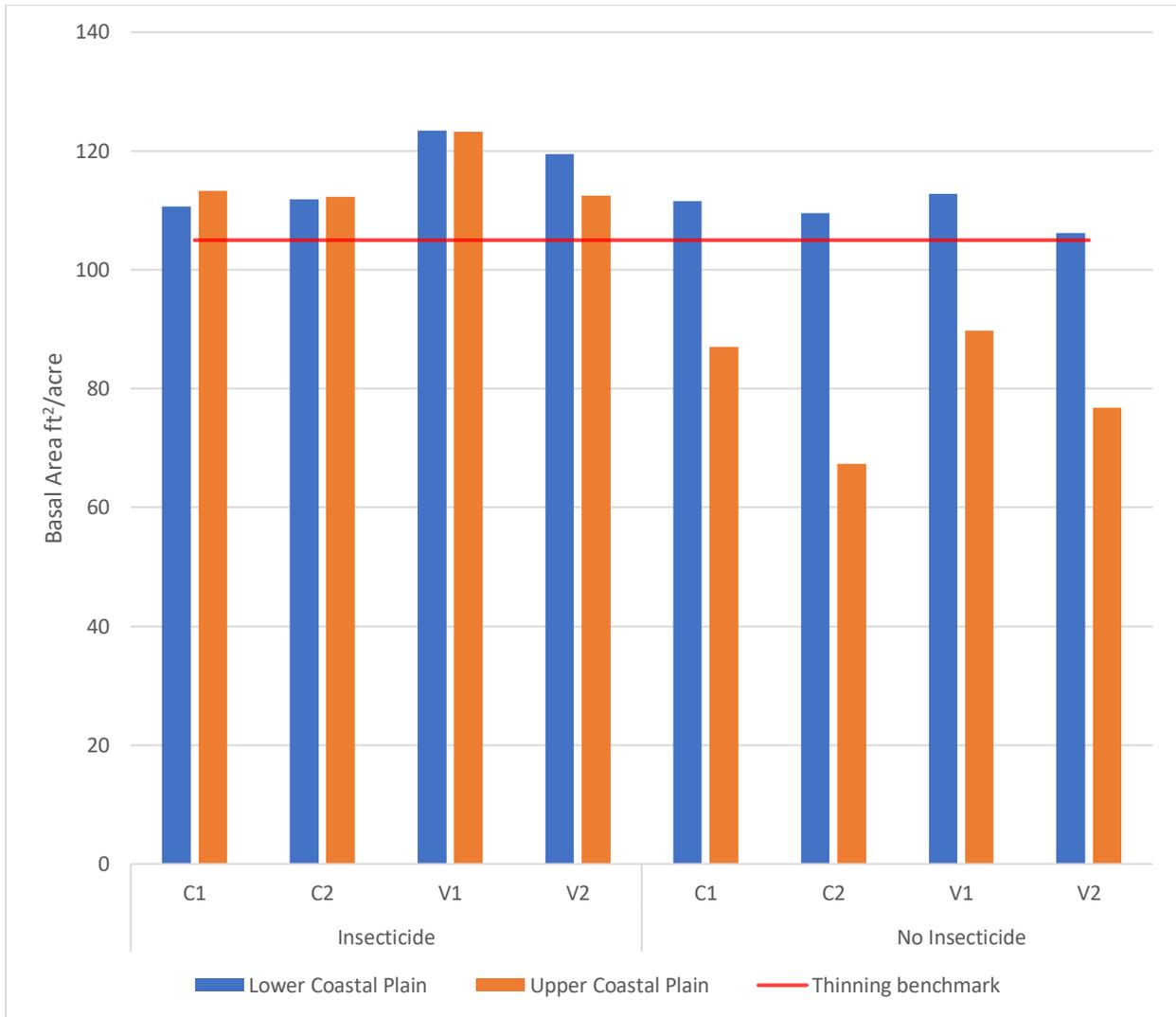


Figure 51. Basal area per acre by imidacloprid treatment and genotype. After 9 years of growth, all genotype*imidacloprid combinations at the LCP have met a milestone in plantation management, at LCP all stands have at least 105 square feet of basal and are approaching a first thinning. At the upper coastal plain only stands that were treated with imidacloprid have met the basal area requirement. Imidacloprid treatment has moved forward the timeline of stand development at the upper coastal plain, shortening the rotation time and thus increasing economic value. Imidacloprid treatment did not make such a difference for 9-year-old loblolly pine growing in the lower coastal plain. These results again suggest that imidacloprid treatment offers real benefits for progressing stand management and plantation development on medium quality sites but does not pay off on high quality sites.