A Comparison of Crown Attributes for Six Genotypes of *Pinus taeda* as Affected by Site and Management Intensity.

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Abstract

This study was designed to investigate the development of the crown architecture of six genotypes of loblolly pine across a variety of growing conditions, and also to investigate the stability of the crown ideotype for these genotypes over a range of site and silvicultural management regimes. The objectives were to determine whether the crown dimensions that determine the crown ideotype of four clones, a mass-control-pollinated family, and an open-pollinated family of *Pinus taeda* L. are consistent within their respective genotypes, and to determine whether those same crown dimensions and genotypes follow consistent patterns even when established on different sites with contrasting qualities and different silvicultural regimes. The study was conducted on a 5-year-old plantation with an initial spacing of 1,235 trees per hectare. The plots had not reached crown closure, which provided the opportunity to assess the crown characteristics of individual trees of each genotype and how they developed over in a variety of growing conditions, without the interactions of other individuals. The study was a split-split plot design with the whole plot divided between two sites of contrasting quality; one site established in the Virginia Piedmont and a second site established in the North Carolina Coastal Plain. The sub plots were divided between high and low intensity silviculture. The sub-sub plots were divided among the six genotypes of loblolly pine. Seventeen tree and crown characteristics were measured, and means were compared using analysis of variance and Tukey's HSD test. We hypothesized that the branch and crown attributes would follow consistent patterns among these genotypes on the two sites and between the two silvicultural regimes. The

results generally confirm these hypotheses. When the genotypes were compared, interactions only occurred with total branches, internode length, total foliage mass, and total leaf area. Tree height, diameter at breast height (dbh), stem volume, and crown volume averaged 4.8 m, 7.5 cm, 0.03 m^3, and 7.1 m^3, respectively at the site in Virginia, compared to values of 4.1 m, 6.2 cm, 0.02 m^3, and 4.9 m^3 at the site in North Carolina. Tree height, dbh, stem volume, branch diameter, branch length, and crown volume averaged 4.7 m, 7.5 cm, 0.03 m^3, 1.3 cm, 90.3 cm, and 7.3 m^3, respectively under high intensity silviculture compared to values of 4.3 m, 6.2 cm, 0.02 m^3, 1.1 cm, 68.7 cm, and 4.7 m^3 under low intensity silviculture. There were differences among the genotypes in branch diameter, branch length, and crown volume, with the branch diameter of clones 1 and 3 averaging 1.2 cm compared to an average of 1.3 cm for clones 2 and 4. Branch length for clone 1 averaged 72.4 cm and clone 3 averaged 77.0 cm, while branch length for clone 2 averaged 83.3 cm and clone 4 averaged 86.7 cm. Crown volume for clone 1 averaged 4.9 m^3 and clone 3 averaged 6.3 m^3, while clone 2 averaged 7.1 m^3 and clone 4 averaged 7.2 m^3. These differences conform to the crown ideotype for these clones, where clones 1 and 3 were considered narrow crowned and clones 2 and 4 were considered broad crowned. The branch diameter and branch length of the open pollinated family (OP) was similar in size to the broad crowned clones (1.3 cm and 84 cm, respectively), while the branch diameter and branch length of the mass control pollinated (MCP) family was smaller than the narrow crowned clones (1.1 cm and 71.2 cm, respectively). Crown volume for the OP family was intermediate between the clonal ideotypes, averaging 5.9 m^3, while the MCP family had the smallest crown volume, averaging 4.7 m^3. A single-degree-of-freedom ANOVA comparing the two clonal ideotypes yielded similar results. There were interactions with branch diameter, total branches, internode length, and total leaf area, but the broad crown ideotype was larger in every

measured parameter than the narrow crown ideotype. The lack of interactions and the general conformity to crown ideotype in this study indicated stability among these genotypes across this variety of growing conditions.

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Chapter 1: Introduction

Global demand for forest products is increasing because of population growth and economic development. Increasing economic prosperity leads to a higher standard of living and to greater per capita consumption of forest products (Jonsson, 2011). Much of the increased demand for forest products is in developing countries such as China. Between 1997 and 2005 the GDP in China grew at an annual rate of 9% (White, et al. 2006). During this period, there was a three-fold increase in roundwood imports from 40 million m^3 to 130 million m^3. This trend is expected to continue into the near future in China, where even conservative estimates project roundwood imports to reach 200 million m^3 by 2015. In addition, the growing concerns about greenhouse gas emissions are increasing the use of woody biomass as a carbon-neutral energy source (Hillring, 2006).

The total forest area in the world is decreasing as forests are converted to other land uses such as agriculture and urban development (Alig and Plantinga, 2004). Simultaneously, social and political pressures aimed toward environmental preservation are restricting timber harvesting in many natural forest (Sedjo and Botkin, 1997). Therefore, higher growth in existing forests will be needed to meet the demand for forest products from a decreasing landbase. Intensively managed plantations can help meet the need for increased industrial wood production in the world. Improved tree genetics are one important technique for maximizing plantation productivity, and an understanding of the individual tree factors that can influence productivity, such as the crown ideotype, are important for maximizing plantation yield.

Crown Ideotype

A plant ideotype is a defined model of the architecture of a plant that is consistent among individuals within a population (Donald, 1967). Plants with a specific ideotype should

demonstrate consistent characteristics over a range of environmental conditions. An ideotype is usually defined morphologically (Dickmann, 1985). For example, a crop ideotype is a tree with a relatively narrow, compact crown that is adapted to grow in close proximity to other trees without excessive competition while a competition ideotype has a larger crown that enables it to out compete adjacent trees for growing space (Martin et al., 2001). This enables a relatively easy assessment of consistency in growth patterns. Plant ideotypes were developed as a tool to simplify management and increase the yield or quality of products when compared with conventional cultivars. The ideotype concept has been successfully used to improve the productivity and quality of annual agricultural crops (Donald, 1967).

Ideotypes were first used in the middle 1980's to describe woody perennials grown on long rotations (Dickmann, 1985). In forestry, an ideotype is defined by crown architecture (Martin et al., 2001), and can be quantified by measuring crown dimensions including branch diameter, branch length, branch angle relative to the bole, and branch azimuth. Quantification of crown architecture is important for at least three reasons: 1) it potentially has a direct impact on some important physiological processes such as light interception and photosynthesis (Chmura et al., 2007), 2) it is quantifiable, which may provide an indirect means of quantifying physiological processes and predicting tree growth (Doruska and Burkhart, 1994), and 3) the crown profile of individual trees will influence the nature of interactions with neighbors at different planting densities (Donald, 1967). Use of crown ideotypes may be especially important to varietal forestry because the high cost of developing, testing, and operationally deploying (Dougherty, 2007).

Trees within genotypes tend to display similar crown characteristics. The expression of those characteristics may be influenced by site quality and silvicultural intensity. However, it is

not known whether crown characteristics of individual trees remain consistent among genotypes on sites of contrasting quality or with differing silvicultural intensities. A successful ideotype must demonstrate consistency in crown architecture even when established in a variety of growing conditions. Silvicultural intensity, for example, could be expected to affect the size of crown dimensions, but should not change the basic growth form. In other words, certain degree of plasticity in growth form can be expected even within varieties, but narrow crown ideotypes should be narrower on average than broad crown ideotypes regardless of silvicultural treatments or site quality. It is hoped that trees within genotypes demonstrate enough consistency across a variety of growing conditions to justify the ideotype concept where genotypes could be classified according to crown ideotype, thereby reducing the need for empirical testing (Fox and Stape, 2012).

Leaf Area, Crown Size, and Growth of Forests

Leaves are the organs within the tree where photosynthesis and gas exchange occur, producing the carbohydrates needed for growth. The positive relationship between leaf area and growth has been well established by numerous studies (Albaugh et al., 1998; Cannell, 1989; Jokela and Martin, 2000; McGarvey et al., 2004; Vose and Allen, 1988; Will, 2005). Leaf area determines the maximum potential quantity of intercepted photosynthetically active radiation (IPAR), which determines the maximum potential gross primary productivity (GPP) and, ultimately, net primary productivity (NPP) (Landsberg, 1986).

The size of the crown influences potential total tree leaf area. The total number, size, and spatial distribution of branches will influence the quantity and spatial distribution of leaves within the crown, which will influence tree growth. Trees with a larger number of branches have potential to carry more leaves than trees with a smaller number of branches.

Foliage display also affects IPAR because the angle at which leaves are displayed relative to the angle of solar radiation influences the efficiency of light interception (Sprugal, 1996). Trees may have a large total leaf area, but if many of the leaves are partially shaded by other foliage or by surrounding branches, growth will be reduced (Chmura et al., 2007). Maximum growth is achieved when total leaf area and display angle of the foliage are optimal (Yu et al., 2003; Brix, 1981; Teskey et al., 1987; McCrady and Jokela, 1996; Sprugel et al., 1996).

Genotype

Crown architecture determines IPAR, which directly impacts NPP (Cannell, 1989; Chmura et al., 2007; Stenberg et al., 1994). The aggregate of branch characteristics determines crown architecture. Branch characteristics include features such as branch length, branch diameter, branch angle relative to the bole, and branch azimuth. While the size and spatial distribution of branch characteristics will be influenced by factors such as environmental conditions, genetics form the blueprint that ultimately defines growth potential. Since individual trees in a genotype share much of the same genetic structure, they often have similar crown architecture (Chmura et al., 2007; Yanez et al., 2015).

The effort to increase growth rates and improve the quality of loblolly pine began with identifying wild trees that displayed desirable characteristics. Open pollinated seed orchards were then established using grafted cuttings from these trees. This technique resulted in the development of half-sib families with a known mother and unknown father (Fox et al., 2007b). While this improved the quality and increased the uniformity of planting stock in comparison with wild trees, many undesirable characteristic still existed within the population since pollen from undesirable tree could not be excluded.

Mass control pollination was developed to control both the male and female genetic input to produce genotypes with desirable characteristics (McKeand et al., 2003; White et al., 2007). This technique results in full-sib families with a known mother and father. It is much more expensive and time consuming than open pollination (Dougherty, 2007; Harbard et al., 1999), but increases the proportion of offspring with desirable characteristics since undesirable genetic material from both sexes can be restricted. Since the offspring of these genotypes are more predictable, there is hope that a crown ideotype classification system can be effectively used with trees produced through control pollination (Dickmann et al., 1994).

Clonal reproduction is the most recent technique developed to improve the quality of planting stock (Fox et al., 2007b; Dougherty, 2007). Most clonal reproduction utilized rooted cuttings, but seedlings are also being produced through somatic embryogenesis (Pullman and Bucalo, 2014). The increased genetic uniformity among clonal genotypes makes the crown ideotype concept of classification more viable. For example, if a parent is genetically predisposed to express a narrow crown under a given set of growing conditions, then all clonal offspring of that parent should also express a narrow crown under similar growing conditions. This may enable landowners to select genotypes with characteristics that are compatible with the landowner objectives and growing conditions of a given site (Dougherty, 2007).

Clonal reproduction deployment may increase stand productivity and uniformity. Somatic embryogenesis is one method where lines of a selected parent can be reproduced as clones of the elite parent (Park et al., 1998; Pullman and Bucalo, 2014). Seedlings produced through somatic embryogenesis are expensive and therefore must grow substantially better than other seedlings in order to justify the cost. The crown ideotype concept may be most useful with seedlings produced through somatic embryogenesis because of the genetic uniformity of clones.

Site Quality

Climate and soil properties combine with management practices to determine whether a tree can develop its genetic potential. Trees require sunlight, appropriate temperatures, water, and nutrients in order to grow. The extent to which any one of those resources is limited will limit overall growth, and that limitation will define site quality for that location.

Latitude influences the sunlight available for photosynthesis during the growing season (Cannell, 1989; Monteith, 1972). Sites close to the equator will receive more direct radiation than sites at higher latitudes, which translates into greater potential IPAR. In addition, lower latitude sites will be warm for a greater portion of the year, which will either shorten or eliminate the dormancy period.

Climate is determined by the long-term temperature and rainfall patterns in a region (Landsberg, 1986). Trees grow best within a range of temperatures that are neither too hot nor too cold. Many factors can influence the range of temperatures for a given site. Latitude is one factor that influences average temperatures, with lower latitudes staying warm for more of the year than higher latitudes. Altitude will also affect temperature because higher altitudes will tend to be colder than lower altitudes. In addition, major water bodies tend to moderate the temperatures of adjacent land masses, while sites in locations far removed from large water bodies will fluctuate over a wider range of temperatures. If the water temperature is relatively warm, then the temperature of adjacent land masses will tend to remain warmer over longer periods of time. Soil properties influence nutrient and water availability and thus strongly influence tree growth (Landsberg, 1986). Bulk density, texture, organic matter, and mineral content combine to influence the ability for roots to penetrate the soil, water infiltration/retention

capacity, and the quantity of plant available nutrients. Sites with a favorable combination of these properties will have high growth potential.

Soil strength and bulk density must be low enough to enable root penetration (Taylor et al., 1966). Course textured, sandy soils tend to have low bulk density, which facilitates root penetration. In contrast, fine textured, clayey soils can have high bulk densities that may reduce or even prevent root penetration. Texture also strongly influences water holding capacity (Landsberg, 1986). Course textured, sandy soils have low water holding capacity because the combination of large pore spaces and low surface area reduces adhesion to water molecules. Fine textured, clayey soils, on the other hand, have very high water holding capacity. In fact, water molecules can be so tightly bound to clay particles that they become unavailable for plant uptake (Schaetzl and Anderson, 2005). It is also possible for heavy clay subsurface layers to prevent water infiltration, resulting in perched water tables that saturate upper surface layers beyond the tolerance of trees for growth and survival (Schaetzl and Anderson, 2005).

Plant available nutrients in the soil often limit plant growth (Fox et al., 2007b; Ågren, 1985; Miller, 1981). Numerous factors influence the quantity of nutrients that are available for plant uptake. Parent material of a soil strongly affects soil fertility. Soil nutrient supply is also affected by soil texture, organic matter, pH, soil moisture content, and cation exchange capacity.

Silviculture

Silvicultural practices such as weed control and fertilization are often required in order for trees to achieve their genetic potential. Nutrient deficiencies can be ameliorated artificially through fertilization. Competition control is often necessary on both high and low quality sites in order to achieve maximum growth potential of crop trees (Knowe et al., 1985; Swindel et al.,

1988). High quality sites have high water and nutrient availability that will provide ideal growing conditions for both crop trees and species that compete with the crop trees. The competing species must be removed, or growth of selected crop trees will be inhibited due to competition for finite resources. Lower quality sites can be dominated by competing species that thrive in poor growing conditions. Such species are often difficult to eradicate, and will severely hamper the growth of desirable species if not controlled.

Nutrient limitations will reduce tree growth by inhibiting essential metabolic functions (Ågren and Ingestad, 1987). Nutrients play a variety of roles in growth and development, and plants need larger quantities of some nutrients than others. For example, since nitrogen is an essential component of proteins when the supply is insufficient, protein manufacture is limited, which limits cell development. This results in smaller canopies, lower LAI, and less stem growth. Nutrient deficiencies can be ameliorated silviculturally through the application of fertilizers that augment the natural supply of the deficient nutrient (Fox et al., 2007b).

Research Objectives

The size and spatial distribution of branches influence the size of the crown and the growth of the individual trees. Stand level productivity will also be affected because the spatial and structural distribution of branches within individual crowns will influence the manner in which individual trees respond to competition following crown closure. If genotypes express consistent crown ideotypes over a wide variety of growing conditions, then the ideotype concept could be used to tailor silvicultural practices that optimize plantation growth. Therefore, we propose the following objectives and hypotheses.

Our objectives were to:

1) Determine whether crown dimensions that determine the crown ideotype of four clones, a mass-control-pollinated family, and an open-pollinated family of *Pinus taeda* are consistent within their respective genotypes.
2) Determine whether crown dimensions that determine the crown ideotype of four clones, a mass-control-pollinated family, and an open-pollinated family of *Pinus taeda* follow consistent patterns even when established on different sites with contrasting qualities.
3) Determine whether crown dimensions that determine the crown ideotype differ for four clones, a mass-control-pollinated family, and an open-pollinated family of *Pinus taeda* with high intensity silviculture in comparison to low intensity silviculture practices.

Hypotheses Tested

We hypothesized that:

1) H_o1: Crown attributes such as branch diameter, crown volume, and leaf area will not differ in *Pinus taeda* due to genotypes.
2) H_o2: Crown attributes of individual *Pinus taeda* genotypes will not differ when grown on different sites.
3) H_o3: Crown attributes for individual *Pinus taeda* genotypes will not differ due to management intensity.
4) H_o4: Crown attributes for *Pinus taeda* within crown ideotypes do not do not differ due to site or management intensity.

Chapter 2: Materials and Methods

This study was conducted within a larger study designed to evaluate the effects of climate, site quality, spacing, and management intensity on the growth of loblolly pine. The larger study included three sites, two levels of management, six genotypes, and three different initial tree spacings. We included the two levels of management and six genotypes, but only two sites and one initial spacing in this study. A complete description of the larger study is available in Yanez et al. (2015).

Study Site Description

The study plots were located at two sites in the southern Unites States. The first site is located in the Piedmont at Virginia at the Reynolds Homestead Research Center near Critz, VA ($30^o38'$ 37"N, 80^o 08' 55"W). The mean annual temperature is 12.8^o C with a mean maximum of 30.6^o C in July and a mean minimum of -3.3^o C in January. On average, there are 193 frost-free days, and the frost-free period is between mid-April and the end of October. Annual rainfall averages 1,245 mm, which is evenly distributed throughout the year. Soils are mapped as Fairview series (Fine, kaolinitic, mesic, Typic Kandihapludult). Site Index (base age 25 years) for loblolly pine is 22 m based on growth of the previous stand. Prior to the establishment of this plantation, the site supported a several stands of loblolly pine (*Pinus taeda*) , pitch (*Pinus rigida*) x loblolly pine (*Pinus taeda*) hybrids, white pine (*Pins strobus*), and Virginia pine (*Pinus virginiana*) that were harvested in 2007

The second site is located in the Atlantic Coastal Plain in North Carolina at the Bladen Lakes State Forest near Ammon, NC ($34^o49'$ 49"N, 78^o 35' 19"W). The mean annual temperature is 15.0^o C with a mean maximum of 32.2^o C in July and a mean minimum of -1.1^o C in January. On average, there are 238 frost-free days, and the frost-free period is between late-

March and early November. Average annual rainfall is 1,194 mm, which is evenly distributed throughout the year. Soils are mapped as Raines series (Fine-loamy, silicaceous, semi-active, thermic Typic Paleaquults). Site Index (base age 25 years) for loblolly pine is 26 m based on growth of the previous stand. Prior to the establishment of this plantation, the site supported a loblolly pine plantation that was harvested in 2007.

Experimental Design

At each site, the study design was a Randomized Complete Block Design arranged as a split plot with three replications (blocks). The main plots at each installment were established to compare two levels of silvicultural intensity – low vs. high intensity. The specific treatments were tailored to each site as described below. Six genotypes including one open pollinated family, one control mass pollinated family, and four clonal varieties were established as the split plot. The specific genotypes used are described in Table 1.

Main Plots

Two silvicultural treatments, one representing a lower intensity management and the second a higher intensity, were used in this study as the main plots. While site preparation treatments were the same in the low and high intensity management regimes at each site, the silvicultural regimes differed among the two sites, and were developed for the specific conditions at each site. The lower intensity treatment included a minimum amount of additional weed control believed necessary to insure good survival of the planted seedlings. The higher intensity treatment included additional weed control and fertilization designed to increase growth of the planted seedlings.

Virginia Piedmont Site

Low Intensity Treatment: Chemical site preparation with a tank mix of Chopper™, Accord™, and Milestone™ was applied aerially in 2008. The site was broadcast burned in November 2008. Seedlings were hand planted in February 2009. Banded herbaceous weed control with a tank mix of Arsenal™ and Oust™ was applied during the spring of the first growing season. A broadcast application of Escort™ was applied in year two to control blackberry (*Rubus allegheniensis*). The details on specific treatments are summarized in Table 2.

High Intensity treatment: Chemical site preparation with the same tank mix of Arsenal, Accord™, and Milestone™ as was used in the low intensity treatment was applied in 2008. The site was broadcast burned in November 2008. Broadcast weed control was applied during the first two years using a mixture of Arsenal™, Oust™, and Escort™. The intensive treatment was fertilized with nitrogen (N), phosphorus (P), boron (B), + micronutrients during the first growing season. Fertilizer was applied by hand at the base of each tree and added 93g N, 10g P, and 0.28g B per tree. The details of the specific treatments are summarized in Table 2.

North Carolina Coastal Plain Site

Low Intensity Treatment: The site was V-blade bedded using a Savannah bedder on 3.7-meter centers. Residual slash was raked as needed prior to bedding. Chemical site preparation with a tank mix of Chopper™, Krenite™, Garlon™, and methylated seed oil was applied by ground in 2008. Banded herbaceous weed control with a tank mix of Arsenal™ and Oust™ was applied in the spring of the first growing season. The details on specific rates of herbicides used are in Table 3.

High Intensity Treatment: The site was V-blade bedded using a Savannah bedder on 3.7-meter centers. Residual slash was raked as needed prior to bedding. Chemical site preparation with the same tank mix of Chopper™, Krenate™, Garlon™, and methylated seed oil as was used in the low intensity treatment was applied by ground in 2008. Tip moth control was applied in the spring of the first growing season using PTM insecticide. Broadcast weed control was applied during year one using a mixture of Arsenal™, Oust™, and Escort™ and in year two using a mixture of Arsenal™ and Oust™. The intensive treatment was fertilized with N, P, B, + micronutrients during the first growing season. Fertilizer was applied by hand at the base of each tree and added 93g N, 10g P, and 0.28g B per tree. The details on specific rates of herbicides used are in Table 3.

Genotypes

Six genotypes were used as the split plot factor. The genotypes included one open pollinated family, one control pollinated family, and four clones. The clones, provided by Arborgen, were produced via somatic embryogenesis. The parents of each genotype are shown in Table 1.

Individual genotypes were hand planted in blocks with either 81 trees per plot in a 9 x 9 array (VA) or 63 trees per plot in a 9 x 7 array (NC). Seedlings were planted at 3.66m x 2.21m spacing, resulting in an initial density of 1235 trees per hectare. The interior 5 x 5 array of seedlings was used as the measurement plot, with the remaining trees in the plot serving as a buffer. This study of crown architecture was conducted during the fifth growing season in 2013. The trees had not yet achieved crown closure at that age, so it provided the opportunity to assess the impact of site, silvicultural intensity, and genotypes on the crown characteristics of these trees without the effect of interaction with adjacent trees.

Sample Tree Selection for Crown Measurements

Three trees were selected from each plot for detailed crown measurements. Selection of the three trees from each measurement plot was based on height (one short, one medium, and one tall) in order to cover the range of size classes in each plot. The trees were selected as follows: the height of every tree in each plot was measured and the trees were ordered from shortest to tallest. The fourth tallest, the median, and the fourth shortest trees were selected for sampling. This procedure resulted in the selection of one short, one medium, and one tall tree from each measurement plot. Any selected trees with extensive crown damage (e.g. a broken top) were excluded from the study, and an alternative of similar size was selected.

The tree characteristics measured for this study included total tree height and diameter at breast height (dbh). Total height was measured from the ground to the topmost bud using a height pole set parallel to the stem. Dbh was measured on one side at 1.4 meters from the ground using digital calipers. Stem volume was calculated from the total height and dbh values using the formula: (stem volume) = $(\text{dbh})^2$ x (height), where all units were meters. Branch measurements included branch diameter and branch length. All branches on the selected trees were measured for branch diameter at a point approximately two centimeters from the main stem using digital calipers. This measurement position was selected in order to prevent measurement bias due to the branch swell that often occurs at the node. The calipers were held parallel to the main stem in order to promote consistency in the measurements in the event that the branches were not perfectly circular. Straight-line branch length was measured using a meter stick held parallel to the branch, and the measurement was taken from the point of attachment to the main stem to the tip of the outermost bud. The total branches per tree were determined from the sum of the branches measured for each tree. The internode length was determined by measuring the

height of each whorl above the ground and subtracting the height above the ground of the whorl immediately below. The difference between these values constituted the distance between whorls (i.e. internode length).

The crown of each tree was also divided into sections representing the top 1/3rd, middle 1/3rd, and bottom 1/3rd of the crown. The upper height of the bottom crown section was determined using the formula: (bottom section upper height) = (total height) – (total height x 0.66), and the total height of the bottom section would have been the distance from the ground to the upper height. The upper height of the middle section was determined using the formula: (middle section) = (total height) – (total height x 0.33), and the middle section was determined as the difference between upper height of the middle section and the upper height of the bottom section. The top section was the difference between the total height and the upper height of the middle section. In this manner, the crown was divided into one-third sections, and crown attributes were averaged within those sections for the comparison of means. Crown volume was determined using the formula: (volume) = ½[(cross-sectional area at maximum crown width) x (height)], where all units were meters. Maximum crown width was estimated by determining mean branch length for each crown section, and comparing the means to determine the widest crown section. The middle section was the widest crown section for these trees.

Sample Tree Selection for Foliage Mass and Specific Leaf Area

Foliage mass and specific leaf area (SLA) were determined by destructively sampling branches collected randomly from selected trees within the plot buffers. The sample foliage was obtained by harvesting fifteen branches from trees of the same genotype in the buffer area of each plot. Five branches were harvested from two tall trees (three from one tree, and two from the second), two medium height trees and two short trees. Foliage was stripped from the

branches, dried at 65^{o}C, and the total dry mass of the foliage on each branch was determined. Prior to drying, a subsample of the green foliage was scanned using a LiCor area meter in order to estimate leaf area. The sub-samples were oven-dried and weighed. SLA (cm^2/g) was determined by dividing the leaf area of the sub-sample by the weight of each sub-sample. The sum of sub-sample and main sample weights determined foliage mass per branch.

Statistical Analysis

Total Tree Foliage Mass, Foliage Density, and Leaf Area

Total tree foliage mass was estimated for each tree. This was accomplished through multiple linear regression analysis to develop an equation to predict foliage mass per branch for the measurement trees using data derived from the destructively sampled branches. Branch foliage mass was summed to estimate total foliage mass. Foliage mass data from each site was analyzed separately. The analysis began with a full model including the following independent variables: Genotype, silviculture, branch height above ground, stem volume (m^3 $stem^{-1}$), and branch volume (m^3 $branch^{-1}$).

Variables were removed from the full model until all remaining terms were significant ($\alpha = 0.05$. The equation resulting from this analysis was used to predict values for foliage mass per branch for the selected measurement trees. The sum of estimated foliage mass per branch was used to estimate total tree foliage mass. Foliage density was estimated from the formula: (foliage density) = (total foliage mass)/(crown volume).

Total tree leaf area was estimated from the product of total tree foliage mass and SLA. SLA (cm^2 $gram^{-1}$) was estimated from the quotient of leaf area and foliage mass from a subsample of the foliage obtained from the destructively sampled branches. Analysis of variance was used to assess differences in means among the genotypes and silviculture treatments for

SLA per branch in both Virginia and North Carolina. In Virginia, there were no statistical differences in means among either genotypes or silviculture; therefore, all SLA values were averaged to produce a single SLA estimate. There was a silviculture x genotype interaction among North Carolina SLA values, necessitating the use of multiple SLA estimates for different genotypes and levels of silviculture.

Comparison of Means for Crown Attributes

Analysis of variance using Proc Mixed SAS 9.4 where site, silvicultural treatments, and genotype were considered fixed effects and block was considered a random effect was used to compare crown attributes among sites, silviculture, and genotypes. Statistical significance was evaluated at $\alpha = 0.05$. Tukey's HSD test was used to separate means by site, silviculture, and genotype. A summary of the analysis of variance for genotype crown attribute comparisons the combined sites is provided in Table 7.

Comparison of Crown Attributes between Crown Ideotypes

The data on crown attributes were also analyzed in a second step by grouping the four clones into two crown ideotypes: narrow vs. broad. Genotypes C1 and C3 were classified as narrow crown ideotypes. Genotypes C2 and C4 were classified as broad crown ideotypes. Data for each crown ideotype were consolidated under the new variable "ideotype," and compared for differences between means. This created a single-degree-of-freedom contrast between ideotypes. Analysis of variance using Proc Mixed SAS 9.4 where site, silvicultural treatments, and genotype were considered fixed effects and block was considered a random effect was used to compare crown ideotypes between sites, silviculture, and between ideotypes. Statistical significance was evaluated at $\alpha = 0.05$. A summary of the analysis of variance for ideotype crown attribute comparisons the combined sites is provided in Table 8.

Chapter 3: Results

Stem Attributes

Trees were significantly taller and larger in diameter at the site in Virginia than the site in North Carolina (Table 7). Trees averaged 4.8 m tall and 7.3 cm dbh at Virginia and only 4.1 m tall and 6.2 cm dbh at North Carolina (Table 9, Figure 1a, Figure 2a). As a result, average stem volume was greater at the site in Virginia than the site in North Carolina (Table 9, Figure 3a). There were no site x silviculture x genotype, site x silviculture, site x genotype, or silviculture x genotype interactions for mean tree height or mean tree dbh (Table 7). There was no significant difference in tree height or dbh among the genotypes; consequently, there was no significant difference in stem volume among the genotypes (Table 7).

Trees were significantly taller and larger in diameter under high intensity silviculture than under low intensity silviculture (Table 7). Trees averaged 4.7 m tall and 7.5 cm dbh under high intensity silviculture and only 4.3 m tall and 6.2 cm dbh under low intensity silviculture (Table 9, Figure 1b, Figure 2b). As a result, average stem volume was greater under high intensity silviculture than under low intensity silviculture (Table 7, Table 9, Figure 3b).

Branch Diameter and Length

Mean branch diameter was significantly larger under high intensity silviculture than under low intensity silviculture, but there was no significant difference in mean branch diameter between the Virginia and North Carolina sites (Table 7). There were no site x silviculture x genotype, site x silviculture, site x genotype, or silviculture x genotype interactions for mean branch diameter or mean branch length (Table 7). Branches averaged 1.3 cm under high intensity silviculture and 1.1 cm under low intensity silviculture (Table 9, Figure 4b). Mean

branch diameter was significantly different among the genotypes (Table 7), with C2, C4, and OP averaging 1.3 cm, genotypes C1 and C3 averaging 1.2 cm, and MCP averaging 1.1 cm (Table 10, Figure 4a). Clones C1 and C3 had smaller branch diameters than clones C2 and C4 (Table 12).

Branches were significantly longer on average under high intensity silviculture than under low intensity silviculture, but there was no significant difference in mean branch length between sites (Table 7, Table 9). High intensity silviculture averaged 90.3 cm and low intensity silviculture averaged 68.7 cm (Table 9, Figure 5b). Mean branch length was significantly different among the genotypes (Table 7), with genotype C4 averaging 86.7 cm, OP averaging 84 cm, C2 averaging 83.3 cm, C3 averaging 77 cm, C1 averaging 72.4 cm, and MCP averaging 71.2 cm (Table 10, Figure 5a).

Effects of Crown Position on Branch Diameter and Length

When the crowns were divided into sections equaling 1/3rd of the total height, branch diameter generally increased from top to bottom in all treatments (Table 9). Mean branch diameter in the bottom section was significantly larger under high intensity silviculture than under low intensity silviculture (Table 7), with high intensity silviculture averaging 1.6 cm and low intensity silviculture averaging 1.1 cm (Table 9). Mean branch diameter in middle section was significantly larger under high intensity silviculture than under low intensity silviculture (Table 7), with high intensity silviculture averaging 1.4 cm and low intensity silviculture averaging 1.2 cm (Table 9). Mean branch diameter in the bottom section was significantly different among the genotypes (Table 7), with genotypes C2, C4, and OP averaging 1.4 cm, genotype C1 averaging 1.3 cm, and genotypes C3 and MCP averaging 1.2 cm (Table 10). Clones C1 and C3 also have smaller mean branch diameter than clones C2 and C4 in each of the

crown sections (Table 12). Branch length was generally greater in the middle section of the crown for all treatments (Table 7, Table 9).

Mean branch length was significantly longer under high intensity silviculture than under low silviculture, but there was no significant difference in mean branch length between sites in the bottom section (Table 7), with high intensity silviculture averaging 104.0 cm and low intensity silviculture averaging 72.8 cm (Table 9). Mean branch length was significantly different among the six genotypes in all three sections of the crown (Table 7). In the bottom section of the crown, genotype C4 averaged 97.0 cm, OP averaged 96.6 cm, C2 averaged 96.4 cm, C3 averaged 85.1 cm, C1 averaged 77.1 cm, and MCP averaged 78.1 cm (Table 10). Mean branch length was significantly longer in the middle section for the site in Virginia than for the site in North Carolina (Table 7). Branches averaged 91.9 cm long in Virginia and 80.8 cm in North Carolina (Table 9). Mean branch length in the middle section was significantly longer under high intensity silviculture than under low intensity silviculture (Table 7). Branches averaged 94.2 cm under high intensity silviculture and 78.4 cm under low intensity silviculture (Table 9). In the middle section, genotype C4 averaged 93.1 cm, C2 averaged 91.6 cm, OP averaged 90.2 cm, C3 averaged 87.4 cm, MCP averaged 79.7 cm, and C1 averaged 76.3 cm (Table 10). Mean branch length was significantly longer in the top section for the site in Virginia than for the site in North Carolina (Table 7). Branches averaged 50.1 cm long in Virginia and 42.9 cm in North Carolina (Table 9). In the top section, genotype C2 averaged 52.1 cm, C4 averaged 50.8 cm, OP averaged 45.2 cm, MCP averaged 44.6 cm, C3 averaged 43.9 cm, and C1 averaged 42.6 cm (Table 10). Clones C1 and C3 also have smaller mean branch length than clones C2 and C4 in each of the crown sections (Table 12). There were no site x silviculture x genotype, site x silviculture, site x genotype, or silviculture x genotype interactions

for branch diameter or length in any crown section (Table 7). There was no significant difference in mean branch diameter between sites for any of the three crown sections. (Table 7).

Crown Volume

The trees had significantly larger crowns at the site in Virginia than at the site in North Carolina (Table 7). Crown volume averaged 7.1 m^3 at the site in Virginia and 4.9 m^3 at the site in North Carolina (Table 9, Figure 6b). The trees had significantly larger crowns under high intensity silviculture than under low intensity silviculture (Table 7). There were no site x silviculture x genotype, site x silviculture, site x genotype, or silviculture x genotype interactions for crown volume (Table 7). Crown volume averaged 7.3 m^3 under high intensity silviculture and 4.7 m^3 under low intensity silviculture (Table 9, Figure 6c). Crown volume was greatest for genotype C4, followed by genotype C2, C3, OP, C1, and MCP (Table 10, Figure 6a). Crown volume for genotype C4 was 7.2 m^3, 7.1 m^3 for genotype C2, 6.3 m^3 for genotype C3, 5.9 m^3 for genotype OP, 4.9 m^3 for genotype C1, and 4.7 m^3 for genotype MCP (Table 10).

Total Branches and Internode Length

There was a site x genotype interaction for both the mean total number of branches per tree and mean internode length (Table 7, Figure 8). Trees had significantly more branches at the site in Virginia than at the site in North Carolina (Table 7). There were no site x silviculture x genotype, site x silviculture, or silviculture x genotype interactions for the total number of branches or internode length (Table 7). Trees averaged 48 branches per tree at Virginia and only 42 branches per tree at North Carolina (Table 9). Trees had significantly more branches per tree under high intensity silviculture than under low intensity silviculture (Table 7). Trees averaged 47 branches per tree under high intensity silviculture and only 41 branches per tree under low

intensity silviculture (Table 9). Mean total branches per tree were significantly different among the genotypes, with genotype MCP averaging 51 branches per tree, C4 averaging 49, C3 averaging 46, OP averaging 43, C1 averaging 41, and C2 averaging 38 (Table 10).

Trees had longer internode lengths at the site in Virginia than at the site in North Carolina. Internode length averaged 31.2 cm per tree at Virginia and only 28.7 cm per tree at North Carolina (Table 9). Trees had longer internode lengths per tree under high intensity silviculture than under low intensity silviculture. Internode length averaged 30.6 cm per tree under high intensity silviculture and only 29.3 cm per tree under low intensity silviculture (Table 9). Mean internode length per tree was significantly different among the genotypes, with genotype C2 averaging 35 cm per tree, OP averaging 31.8, MCP averaging 29.3 cm, C1 averaging 29 cm, and both C3 and C4 averaging 27.4 cm (Table 10).

Branch Foliage

The predictive equation used to estimate branch foliage mass for the Virginia site included branch volume (m^3 $branch^{-1}$) and stem volume (m^3 $stem^{-1}$) as the independent variables. Branch volume was estimated from the volume equation: V = $(\text{branch diameter})^2$ x (branch length). Stem volume was estimated from the volume equation: V = $(\text{tree dbh})^2$ x (tree height). Values for this regression included Adjusted R^2 = 0.701, RMSE = 40.61, and PRESS = 429885 (Table 6). The resulting equation was:

Branch foliar mass = 23.182 + 548.96 x (stem volume) + 124778.06 x (branch volume).

The predictive equation used to estimate branch foliage mass for the North Carolina site included branch volume (m^3 $branch^{-1}$) as the independent variable. Branch volume was estimated from the volume equation: V = (branch diameter)^2 x (branch length). Values for this regression included Adjusted R^2 = 0.75, RMSE = 37.56, and PRESS = 315204.12 (Table 6). The resulting equation (using the untransformed branch_foliar_mass dependent variable) was:

Branch foliar mass = 26.853 + 124169.58 x (branch volume).

Tree Foliage Mass and Leaf Area

There was a site x silviculture interaction for both the mean total foliage mass and mean total leaf area (Table 7), and the response of trees to high intensity silviculture was greater at the site in Virginia than at the site in North Carolina for both mean foliage mass and mean leaf area (Figures 9b, c). Trees had significantly greater foliage mass at the site in Virginia than at the site in North Carolina (Table 7). Trees averaged 3.3 kg per tree at Virginia and only 2.5 kg per tree at North Carolina (Table 9). Trees had significantly greater foliage mass per tree under high intensity silviculture than under low intensity silviculture (Table 7). Trees averaged 3.6 kg per tree under high intensity silviculture and only 2.2 kg per tree under low intensity silviculture (Table 9). Mean total foliage mass per tree was significantly different among the genotypes (Table 7), with genotype C4 averaging 3.5 kg per tree, C3 averaging 3 kg, OP averaging 2.9 kg, MCP averaging 2.8 kg, C2 averaging 2.7 kg, and C1 averaging 2.6 kg (Table 10). Trees had significantly greater leaf area per tree at the site in Virginia than at the site in North Carolina (Table 7). Trees averaged 12.3 m^2 total leaf area per tree at Virginia and only 8.8 m^2 per tree at North Carolina (Table 9). Trees had significantly greater leaf area per tree under high intensity

silviculture than under low intensity silviculture (Table 7). Trees averaged 13.4 m^2 per tree under high intensity silviculture and only 8 m^2 per tree under low intensity silviculture (Table 9). Mean total leaf area per tree was significantly different among the genotypes, with genotype C4 averaging 13 m^2 per tree, C3 averaging 10.8 m^2, OP averaging 10.7 m^2, MCP averaging 10.4 m^2, C1 averaging 9.7 m^2, and C2 averaging 9.5 m^2 (Table 10). There were no site x silviculture x genotype, site x genotype, or silviculture x genotype interactions for mean foliage mass or mean leaf area (Table 7).

Crown Ideotype Comparison

There was a consistent pattern in crown attributes among the four clones (Table 12). Clones C1 and C3 consistently had smaller branches than clones C2 and C4. Therefore, C1 and C3 were considered narrow crown ideotype and C2 and C4 were considered broad crown ideotype and a new classification variable was created based on crown ideotype. A separate analysis was conducted to compare differences between ideotypes.

Branch Diameter and Branch Length for Ideotype Comparison

There was a site x ideotype interaction for mean branch diameter (Table 8), where the differences between ideotypes was more pronounced at the site in Virginia than at the site in North Carolina (Figure 11a). There were no site x silviculture x ideotype, site x silviculture, or silviculture x ideotype interactions for mean branch diameter (Table 8). There was no significant difference in mean branch diameter between sites, but there was a significant difference between silvicultural intensities (Table 8). There was also a significant difference between ideotypes (Table 8), where the narrow crown ideotype averaged 1.2 cm and the broad crowned ideotype averaged 1.3 cm (Table 11).

There were no site x silviculture x ideotype, site x silviculture, site x ideotype, or silviculture x ideotype interactions for mean branch length (Table 8). Mean branch length for the narrow and broad crown ideotypes was not significantly different between sites (Table 8), but was different between high and low intensity silviculture (Table 8). Mean branch length was 90.3 cm under high intensity silviculture and 68.7 cm under low intensity silviculture (Figure 11d). Mean branch length was significantly greater for the broad crown ideotypes than for the narrow crown ideotypes (Table 8). Mean branch length was 85.1 cm for the broad crown ideotype and 73.9 cm for the narrow crown ideotype (Table 11, Figure 11c).

Effects of Crown Position on Branch Diameter and Length for Ideotype Comparison

There were no site x silviculture x ideotype, site x silviculture, or silviculture x ideotype interactions for mean branch diameter in any of the crown sections (Table 8). There was no site x ideotype interaction for mean branch diameter in the bottom or middle sections (Table 8), but there was a site x ideotype interaction for mean branch diameter in the top section (Table 8). Mean branch diameter was for all three sections were not significantly different between sites (Table 8). Mean branch diameter for the bottom and middle sections were significantly different between silvicultural intensities (Table 8), but was not significantly different for the top section (Table 8). Mean branch diameter was significantly different between ideotypes for the bottom and top sections (Table 8), but was not significantly different between ideotypes for the middle section (Table 8). Mean branch diameter for the bottom section was 14.1 cm for the broad crowned ideotype and 12.4 cm for the narrow crowned ideotype (Table 11). Mean branch diameter for the top section was 9.2 cm for the broad crowned ideotype and 8.4 cm for the narrow crowned ideotype (Table 11).

There were no site x silviculture or silviculture x ideotype interactions for mean branch length in any of the crown sections (Table 8). There was no site x silviculture x ideotype or site x ideotype interactions for mean branch length in the bottom or middle sections (Table 8), but there were site x silviculture x ideotype and site x ideotype interactions for mean branch length in the top section (Table 8). Mean branch length for all three sections were not significantly different between sites (Table 8), but were significantly different between silvicultural intensities and ideotypes (Table 8). Mean branch length for the bottom section was 97.6 cm for the broad crown ideotype and 81.1 cm for the narrow crown ideotype (Table 11). Mean branch length for the middle section was 93.5 cm for the broad crown ideotype and 81.9 cm for the narrow crown ideotype (Table 11). Mean branch length for the top section was 51.3 cm for the broad crown ideotype and 43.2 cm for the narrow crown ideotype (Table 11).

Crown Volume for Ideotype Comparison

There were no site x silviculture x ideotype, site x silviculture, site x ideotype, or silviculture x ideotype interactions for mean crown volume (Table 8). There were no significant differences between sites (Table 8), but there were significant differences between silvicultural intensities and ideotypes (Table 8). Mean crown volume was 7.4 m^3 for the broad crowned ideotype and 5.6 m^3 for the narrow crowned ideotype (Table 11).

Tree Foliage Mass and Leaf Area for Ideotype Comparison

There were no site x silviculture x ideotype, site x silviculture, site x ideotype, or silviculture x ideotype interactions for mean foliage mass (Table 8). There were significant differences between sites and silvicultural intensities (Table 8), but there were no significant differences between ideotypes (Table 8). Mean foliage mass was 3.3 kg at the site in Virginia

and 2.5 kg at the site in North Carolina (Figure 13a). Mean foliage mass was 3.7 kg under high intensity silviculture and 2.2 kg under low intensity silviculture (Figure 13b).

There were no site x silviculture x ideotype, site x silviculture, or silviculture x ideotype interactions for mean leaf area (Table 8). There was a site x ideotype interaction for mean leaf area (Table 8). Both the broad and narrow crowned ideotypes developed more leaf area at the site in Virginia than at the site in North Carolina (Figure 13c), but the gains were greater for the broad crowned ideotype than for the narrow crowned ideotype at the site in Virginia (Figure 14c). There were significant differences between sites and silvicultural intensities for mean leaf area (Table 8), but there were no significant differences between ideotypes (Table 8). Mean leaf area was 13.6 m^2 under high intensity silviculture and 7.8 m^2 under low intensity silviculture (Figure 13d).

Chapter 4: Discussion

The purpose of this study was to investigate whether the crown attributes of different loblolly pine genotypes including two families (open-pollinated and mass-control-pollinated) and four clones were consistent when planted at two different sites under two different silvicultural regimes. An additional purpose was to investigate the crown ideotype for four clones (two narrow and two broad) when established in different site qualities and management regimes.

We hypothesized that crown characteristics would follow consistent patterns among the genotypes at the two sites and between the two silvicultural regimes. This would result in some genotypes having consistently smaller diameter branches relative to other genotypes. The results generally conform to this hypothesis. Clones 2 and 4 consistently had larger branches than clones 1 and 3. The OP family was generally intermediate between the groups of clones while the MCP family had the smallest diameter branches but intermediate length branches. We also hypothesized that crown characteristics would not differ between sites and silvicultural regimes. The results do not conform to these hypotheses. Branch length and diameter were generally greater in all genotypes at the site in Virginia where trees grew faster compared to the site in North Carolina. Similarly, branch size was generally greater in the higher intensity silviculture treatment where growth was faster compared to the lower intensity treatment where growth was slower. However, the pattern among genotypes remained consistent with clones 1 and 3 consistently having smaller branches compared to clones 2 and 4 regardless of site or level of silviculture. There were no significant site x genotype (except for total branches and internode length) or silviculture x genotype interactions detected for this study.

Crown Characteristics

There are plentiful data demonstrating that most sites are nutrient limited (Fox, et al., 2007; Fox, et al., 2011; Jokela, 2004), and, in the absence of sufficient nutrients, trees will not achieve their growth potential. However, when nutrient requirements are met through fertilization, trees will respond with increased growth, and the fertilization and weed control applied in this study were expected to contribute to meeting the nutrient requirements of the established trees (Amishev and Fox, 2006). Many studies also demonstrate that tree and branch characteristics increase in size as silvicultural intensity increases. For example, Jokela et al. (2010) discuss the results of a rotation length study of slash and loblolly pine at a site in Florida where untreated trees were compared with combinations of weed control and fertilization. Stem volume growth in this study was markedly greater for every combination of treatments when compared to the untreated trees, but the greatest growth occurred with the combination of weed control and fertilization. Similar results have been observed even in studies conducted much earlier in the rotation of loblolly pine (Zhai et al., 2015). Fertilization is necessary in order to ameliorate nutrient deficits that occur on most plantation sites (Fox et al., 2007a), while weed control increases the quantity of nutrients available to the crop trees (Bacon and Zedaker, 1987; Knowe et al., 1985). Differences in growth responses among sites (environments) are also well documented (Yanez et al., 2015; Zhai et al., 2015), and many of these site differences are due to nutrient deficiencies that can be ameliorated through fertilization.

An important objective of the current study was to go a step further than previous studies by investigating whether the growth responses of the tree and crown attributes of these genotypes to differences in site quality and silvicultural regimes were consistent. Of the seventeen variables measured for this study, every crown attribute except branch diameter, branch length,

branch diameter by section (bottom, middle, and top), branch length by bottom section, and internode length were significantly different between sites. Stem and crown volume provided a more comprehensive measure of overall growth and each of these parameters were significantly larger for the trees at the site in Virginia than for the trees at the site in North Carolina. The difference in total height, dbh, and stem volume between these two sites may be explained by the fact that since the measurements were obtained in the early part of the rotation and the North Carolina site is on a poorly drained soil, the high water table could be inhibiting root penetration (Morris and Lowery, 1988). Tree growth will be somewhat stunted until these trees achieve a size that reduces the water table through evapotranspiration (Outcalt, 1984). Once the water table no longer prevents root penetration, it is expected that the growth of the trees in North Carolina will surpass the growth of the Virginia trees. Previous work with loblolly pine in the Lower Coastal Plain has shown this pattern of initial slower growth followed by an increase as crown size and evapotranspiration increase (McKee and White, 1986).

Furthermore, when these same attributes were compared between silvicultural regimes, every crown attribute was significantly different between management regimes except branch diameter (top section), branch length (top section), internode length, and foliage density. The height and dbh differences associated with silvicultural intensity were not surprising, since the high intensity silviculture resulted in taller and larger diameter trees at both sites in this study as has been observed in many other studies (e.g. Jokela et al., 2000). In addition, the crown attributes of branch diameter and branch length, as well as the more comprehensive measurements of stem and crown volume were also significantly larger under high intensity silviculture than under low intensity silviculture. When the crowns were analyzed by section, both branch diameter and branch length were significantly larger under high intensity silviculture

than under low intensity silviculture in the bottom and middle section, but not in the top section. This pattern in crown shape has been observed in other studies (Xiao et al., 2003).

Very few studies have analyzed in detail the relationship of tree and crown attributes among loblolly pine genotypes and how those attributes respond with differences in site quality and silvicultural intensity, although some have compared basic growth parameters such as stem volume, crown width, and crown volume (Aspinwal et al., 2013; Emhart et al., 2007). In the current study, there were no differences among the genotypes in dbh, total height, and stem volume. This contrasts with the results from Aspinwal et al. (2013) who found differences in height and stem volume among three year old half-sib, full-sib, and clonal loblolly pine on a single site under high intensity silviculture. Emhart et al. (2007) conducted a large study that compared half-sib, full-sib, and clonal loblolly pine tree and crown attributes including leaf area, stem volume, and crown size and shape at ages 4, 5 and 6 under a high intensity silvicultural regime. She also observed highly significant differences among these genotypes in each measured parameter over time, but did not attempt to determine whether patterns existed in terms of crown ideotype. The similarity of dbh, height, and stem volume among the genotypes in the current study was unexpected. Although mean branch diameter, mean branch length, and mean crown volume were consistently larger for the genotypes considered to be broad crowned ideotypes than for those considered to be narrow crowned ideotypes, all genotypes responded similarly to the treatment in terms of stem growth. The similarity of growth responses in stem volume among the genotypes is difficult to explain, but may reflect genotypic differences in carbon allocation, differences in water use efficiency, or differences in photosynthetic efficiency (Yanez et al., 2015). For example, it is possible that the broad crowned genotypes to produce

more total biomass than the narrow crowned genotypes, but redirect the sequestered carbon to below ground components rather than to the main stem.

The greatest plasticity of branch diameter was in the bottom 1/3rd crown section. Moving up through the crown, branch diameter became less likely to respond to differences in site quality, silvicultural intensity, or genetics. In contrast, branch length was significantly different among the genotypes in each crown section. It is interesting to note the ranking of genotypes for overall branch diameter and branch length, as well as by crown section, especially in light of the crown ideotype classifications. A pattern quickly becomes apparent where the broad crowned genotypes (C2 and C4) consistently had larger branch diameter and length, while the narrow crowned genotypes (C1 and C3) consistently had smaller branch diameter and length (Table 12). Similar patterns in crown shape among genotypes of slash and loblolly pine were reported in a study in Florida (Xiao et al., 2003). These rankings are consistent with the crown ideotype classifications for these genotypes (Fox and Stape, 2012). Table 12 demonstrates the rankings of crown volume by genotype, where, once again, the broad crowned genotypes are larger than the narrow crowned genotypes. This is also consistent with the crown ideotype classifications for these genotypes.

The number of branches throughout a tree and the spatial distribution of those branches may affect both the quantity of foliage a tree can carry, as well as their capacity to intercept solar radiation (Baldwin and Peterson, 1997). In the current study, total branches and internode length were the least consistent variables. There was a site x genotype interaction for both total branches per tree and internode length. There is no consistency in the response of total branches and internode length between site quality and silvicultural intensity for the crown ideotype classifications. Both ideotypes increased in total branches and internode length under high

intensity silviculture at the site in Virginia, but the narrow crowned ideotype had more total branches than the broad crowned ideotype under both levels of silviculture. In contrast, total branches actually decreased for the narrow crowned ideotype under high intensity silviculture at the site in North Carolina, while mean internode length did not respond to increased silvicultural intensity for either ideotype. Figure 11 illustrates some interesting patterns of responses of total branches and internode length of these genotypes to site quality. The most striking pattern involves genotype C2, which shows no significant difference in the total number of branches between sites, but a highly significant increase in internode length at the site in VA compared to the site in NC. Given the fact of the significant increase in height at the VA site versus the NC site, this seems to indicate that the trees of genotype C2 have strong apical dominance resulting in longer stem growth before a whorl of branches is produced. It is also interesting to note from Figure 11 that, other than genotype C2, there is very little difference in internode length between sites or among genotypes; however, there are highly significant differences in total number of branches between sites and among genotypes. The response to differences in site quality of each genotype in total branches formed was very different.

The comparison of crown ideotypes yielded very similar results to the individual genotypes, at least where the branch attributes are concerned. Although there was a site x silviculture x ideotype interaction in branch length in the middle section of the crown, and site x ideotype interactions with crown volume, branch diameter middle section, and branch length middle section, there were no interactions for the majority of tree and crown attributes. Figure 10 demonstrates that the crown ideotype classification of these ideotypes is accurate for branch length in the middle crown section at the site in Virginia under both silvicultural intensities, and for branch length in the middle crown section at the site in North Carolina under low silvicultural

intensity. However, the response of the two ideotypes to branch length in the middle crown at the North Carolina site under high intensity silviculture is very different. The narrow crowned ideotype responded strongly to high intensity silviculture, and the broad crowned genotype did not respond at all. It may be that the poor soil drainage at the site in North Carolina limits root growth such that the trees are not able to take advantage of the nutrients provided by the high intensity silviculture.

Genotype x environment interactions were expected to be prevalent among the varieties (Allard and Bradshaw, 1964; Bridgwater and Stonecypher, 1978). A salient feature of this study was the absence of interactions for the majority of crown attributes. This conforms to the findings of McKeand et al. (2006) who observed that neither families nor clones of loblolly pine had substantial genotype x environment interactions. Numerous other studies have found that genotype x environment does not seem to strongly affect the growth traits of open pollinated genotypes of loblolly pine (Yeiser et al., 1981; Li and McKeand, 1989; McKeand et al., 1990). The stem attributes of this study concur with those findings at this stage of the rotation. Furthermore, when the genotypes were analyzed specifically by ideotype classification in the single degree of freedom analysis, there is no significant difference in stem attributes between broad crowned and narrow crowned ideotypes. The fact that so few interactions occurred in this study suggests a substantial degree of consistency in growth responses for these genotypes. When the individual genotypes were compared, only the attributes of total branches, internode length, foliage mass, and leaf area had interactions.

Although the differences in the growth of the crown attributes between sites contradicts the null hypothesis, they do indicate consistency in the growth responses for these genotypes

because, in every instance of significant differences in growth, the crown attributes at the site in Virginia were larger than the crown attributes at the site in North Carolina.

Foliage Characteristics

Measurements of foliage mass and leaf area provided the ability to correlate growth with photosynthetic potential. Both foliage mass and leaf area were greater at the site in Virginia than at the site in North Carolina, with corresponding increases in dbh, mean height, and stem volume. The site x silviculture interaction for both total foliage mass and total leaf area among genotypes is illustrated by Figure 10, which shows the strong increase in foliage mass and leaf area at both sites under high intensity silviculture. The response was much stronger at the site in Virginia than the site in North Carolina. It is probable that the Virginia site was more nutrient limited than the North Carolina site, which would explain the fact that both sites were roughly the same in both foliage mass under low intensity silviculture, but, under high intensity silviculture, the Virginia site developed greater foliage mass and leaf area than the North Carolina site. The poorly drained nature of the North Carolina site would have also been likely to contribute to the differential. Since these measurements were taken at age 5, every growth parameter was probably being stunted at the North Carolina site, and it is reasonable to assume the cause to be a high water table (Burger and Pritchett, 1988).

Foliage mass and leaf area were also significantly larger under high intensity silviculture than under low intensity silviculture. While there are only a limited number of studies analyzing in detail the development of crown attributes in response to high intensity silviculture, the relationship between growth and leaf area is well established (Vose and Allen, 1988). The primary purpose of silvicultural inputs is to provide trees with the necessary nutrients with which

to produce leaves (Fox et al., 2007a), and it is the leaves that actually produce the woody biomass through photosynthesis (Cannell, 1989). This relationship is consistent in the current study as observed in Figure 7, where increases in foliage mass and leaf area always coincide with increases in the size of tree and branch characteristics, and the trees subjected to high intensity silviculture always averaged more leaf area as well as larger tree and branch characteristics. Thus the relationship between leaf area and growth that is widely observed in trees (e.g. Vose and Allen, 1988) holds true in this study. Although the evidence clearly contradicts the null hypothesis concerning growth responses due to management intensity, the growth responses of these genotypes were consistent in that whenever significant differences did occur, growth was always greater under high intensity silviculture, which tended to have higher foliage mass.

Figure 7 also clearly demonstrates that growth efficiency is higher for low intensity silviculture than for high intensity silviculture. This seems counterintuitive on initial reflection because it would be reasonable to expect increased growth efficiency under high intensity silviculture. There may, however, be a simple physiological explanation for the actual response that relates to the shape of loblolly pine crowns. The branches of loblolly pine tend to be longer in middle section than in either the upper or lower sections, resulting in a paraboloid shape (Appendix A). As a consequence, the top and middle sections will tend to be strongly exposed to IPAR, but the lower section will be somewhat shaded by the middle section, which will reduce the photosynthetic productivity of leaves located in the lower section. If the crown is narrow as occurred under low intensity silviculture, then the self-shading effect will be reduced, and the growth efficiency of existing foliage will remain high. However, if the crown is broad as occurred under high intensity silviculture, then the increased width of the middle crown will increase the self-shading effect on the lower crown, resulting in lower growth efficiency. Under

these conditions, growth efficiency may be lower for the larger crowns, while absolute volume growth may be greater.

There was little consistency in foliage attributes among the genotypes. Clone C4 developed significantly more foliage mass than clones C1 and C2, but did not develop significantly more foliage than Clone 3, MCP, or OP (Table 10, Figure 9). This development is not consistent with the crown ideotype classifications for these genotypes. Genotype C3 is classified as narrow crowned, and genotypes C2 and C4 are classified as broad crowned. According to these classifications, it would be reasonable to expect clones C2 and C4 to have significantly more foliage mass than clones C1 and C3. It is interesting to note that, despite the significantly higher foliage mass, clone C4 has not produced significantly greater stem volume than the other genotypes. This implies that there are differences in crown and foliage density, which leads to differences in growth efficiency among the genotypes. Additional work would be needed to quantify differences in crown density among clones and how that influences growth efficiency and carbon allocation.

It is particularly interesting that these genotypes produced roughly the same amount of foliage mass and leaf area at each level of site quality and silvicultural intensity, despite the differences in crown attributes. It would have been reasonable to expect broad crowned ideotypes to have greater leaf area and stem growth. However, that was not the case. The lack of interaction indicates that the stem attributes of each genotype responded to differences in site quality and silvicultural intensity in a similar fashion to the other genotypes, and that the crown ideotype classification for these varietal genotypes is not relevant to stem attributes. This study was designed to investigate whether the crown attributes of these genotypes grew in a consistent manner when compared among themselves, and the results generally support this hypothesis.

There were significant differences among the genotypes for most of the crown attributes, but many of these differences conformed to the crown ideotype of these clones. The stem attributes, on the other hand, were not different among these genotypes. At this point in the rotation, the crown ideotype seems to be validated by this study, although the clones at the site in Virginia seem to conform more strongly to the crown ideotype for these clones than the clones at the site in North Carolina.

Knowledge of the growth responses of loblolly pine clones to a variety of growing conditions is important for the operational deployment of clonal genotypes because of the expense associated with clonal reproduction. For example, if the growth of clones is predictable, less progeny testing may be necessary, and deployment expense can be reduced. Predictability of the growth characteristics of varieties will also facilitate landowners' decisions in choosing a variety to plant and the appropriate planting density. Decisions could be made exclusively according to the desired final product rather than having to sort through the additional complications of trying to match varieties to their ideal growing conditions. It is important to note that these results have been obtained in the early stages of this rotation, and many characteristics can and will change as the rotation progresses due to factors including crown closure. It will be necessary to follow this study throughout the rotation in order to document the growth responses and developments. From an operational standpoint, the most important growth characteristics will be those present at the time of harvest when the stand reaches maturity. Therefore, data should be collected from this stand prior to final harvest. A study of this nature is very expensive to deploy; however, if funding could be obtained, it would be highly instructive to establish additional studies of identical design across a broader variety of growing

conditions in order to increase the range of inference that could be applied to varietal loblolly pine plantation forestry.

Chapter 5: Summary

This study was designed to investigate crown architecture of genotypes of loblolly pine in a variety of growing conditions. The objectives were to determine whether the crown parameters such as branch diameter and branch length that determine the crown ideotype are consistent when the same genotypes are grown at different sites and with different silvicultural regimes. We hypothesized that the crown architecture would not vary among the genotypes, that it would not vary depending on the planting location, and that it would not be affected by silvicultural such as weed control and fertilization.

The study was conducted on two loblolly pine plantations in the Southeastern United States. One site was located in the Coastal Plain of North Carolina and the second site was located in the Piedmont of Virginia. The site in North Carolina had poorly drained soil and all plots were chemically site prepared and bedded. The site in Virginia had well drained soils and was chemically site prepared. Six different genotypes were planted at each site: one OP family, one MCP family, and four clones. At both sites, trees were planted at an initial spacing of 1,235 trees per hectare. At each site, two levels of silviculture were compared. The low intensity treatment had banded weed control and no fertilization and the high intensity treatment had broadcast weed control and was fertilized at planting. Tree measurements included tree height and diameter, and individual branch diameter and length of each branch were made at age 5. The plots had not reached crown closure and the live crown ratio tended to be near one for all measurement trees (i.e. the crowns had not begun self-pruning, so the crowns extended to the ground or close to it). This provided the opportunity to assess the crown characteristics of individual trees of each genotype and how they developed in a variety of growing conditions, without the interactions of other individuals. We tested three specific hypotheses in this study:

$H_0$1: There was no effect of the different planting sites on tree and branch characteristics;

$H_0$2: There was no effect of silviculture intensity on tree and branch characteristics;

$H_0$3: There was no effect of genotype on tree and branch characteristics.

H_o4: Tree and branch characteristics were consistent within crown ideotypes even with differences in site and management intensity.

Generally, the main effects of site, genotype and silviculture were significant for most of the response variables that were measured. Therefore, we rejected hypotheses one, two, and three. The main effects of site, ideotype, and silviculture were significant for most of the response variables that were measured, with the broad crowned ideotype being larger than the narrow crowned ideotype. Therefore, we failed to reject hypothesis four.

Effect of Planting Location on Tree and Crown Parameters

The null hypothesis that there were no differences due to planting site was rejected because the trees were larger in height and diameter and generally had larger branches at the site in Virginia compared to the site in North Carolina. The differences in branch diameter and branch length between the two sites were larger in the middle of the crown than in the upper or the lower crown. Consequently, the trees in Virginia also had larger crown volume, larger mass of foliage and higher leaf area than the trees in North Carolina. The differences in tree and branch size between the two locations may be due to the differences in soils. The site in North Carolina had poorly drained soils with a high water table close the soil surface. This would likely have created anaerobic conditions in the soil that limited root growth which would have affect tree growth of the young trees. The soils at the site in Virginia were well drained thus had better initial growth which resulted in larger tree and branches.

Effects of Silvicultural Intensity on Tree and Crown Parameters

The null hypothesis that there were no differences due to silvicultural intensity was rejected because the trees were larger in height and diameter with larger branches under high intensity silviculture than under low intensity silviculture. The differences in silvicultural intensity had a stronger effect on growth than differences in planting site quality. The differences in branch diameter and branch length between the two silvicultural treatments were larger in the middle of the crown than in the upper or the lower crown. Consequently, the trees under high intensity silviculture also had larger crown volume, larger mass of foliage and higher leaf area than the trees under low intensity silviculture. Although increases in foliage mass did increase stem volume growth, the growth efficiency of stem volume was greater under low intensity silviculture than under high intensity silviculture. The trees at the site in Virginia developed more foliage mass and leaf area under high intensity silviculture than the trees at the site in North Carolina. The difference in the response of foliage mass and leaf area to high intensity silviculture may be due to greater nutrient deficiencies at the site in Virginia. It is also possible that a high water table at the site in North Carolina created anaerobic conditions that prevented the trees from fully utilizing the advantages produced by high intensity silviculture. When analyzed by crown ideotype, most of the crown attributes also increased under high intensity silviculture.

Effects of Genotype on Tree and Crown Parameters

The null hypothesis that there were no differences due to genotype was rejected because differences in tree and branch size did occur among the genotypes. Tree height and diameter were not different among the genotypes; however, differences did occur in branch diameter and length among the genotypes. Consequently, differences occurred in crown size among the

genotypes. Two of these clones were considered narrow crowned ideotypes and two were considered broad crowned ideotypes. Generally, the differences in crown size, branch diameter, and branch length conformed to the crown ideotype for these clones, and the crown ideotype for the four clonal genotypes in this study was validated at that point of the rotation. There were differences in foliage mass and leaf area, but these differences did not conform to the crown ideotype for these clones because only one broad crowned clone produced greater foliage mass than the narrow crowned clones. Despite having more foliage mass, this clone did not produce greater stem volume.

The null hypothesis that that crown attributes would be consistent within crown ideotypes was not rejected because the differences that occurred in crown attributes generally conform to the crown ideotypes for these varieties. Table 12 demonstrates that branch diameter and length fall into a clear pattern that conforms to the crown ideotypes for these genotypes. Although some variability does occur among the crown sections, clones 2 and 4 always averaged larger diameter and longer branches than clones 1 and 3. This pattern continues for crown volume. In addition, Table 11 demonstrates that foliage mass and leaf area were greater for the broad crowned ideotypes, and that translated into greater stem volume when averaged between crown ideotypes.

Conclusions

Clonal reproduction through somatic embryogenesis has the potential to improve plantation productivity, reduce susceptibility to disease, and improve quality in loblolly pine planting stock. However, the process is expensive, which reduces the viability of these clones for operational deployment. Some of the production expenses could be defrayed if the necessity for progeny testing could be reduced. In addition, it will be easier for landowners to choose

varieties if they only need to make decisions based on their desired final product. The key to achieving these advantages is consistency in the growth and development of tree and crown attributes across a variety of growing conditions. The focus of this study was to begin the process of determining whether the growth responses were consistent with differences in site quality and silvicultural intensity. In general, the responses were consistent for these genotypes at this stage of the rotation. It will be necessary to carry this study throughout the full rotation in order to determine whether these genotypes are truly consistent.

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Tables

Table 1. The genotypes used in this study of crown ideotypes. Parents of each genotype used in this study were coded.

Genotype	Code	Mother	Father	Crown Ideotype
Open Pollinated	OP	A	unknown	--------
Control Mass Pollinated	CMP	B	C	--------
Clone 1	C1	D	A	Narrow
Clone 2	C2	A	C	Broad
Clone 3	C3	D	E	Narrow
Clone 4	C4	D	B	Broad

Table 2. Description of silvicultural treatments for the Virginia site.

Operation	DATE	TRT_APPLIED	RATE	UNITS	SOURCE
Low Intensity Treatment Reynolds (Block)					
Site prep	2008	Site burnt			
Site prep	2008	Herbicide	1,418	g/ha	Chopper
Site prep	2008	Herbicide	9.5	L/ha	Milestone
Site prep	2008	Herbicide	9.5	L/ha	Accord XRT
Site prep	2008	Herbicide	1,418	g/ha	DLZ oil
Planting	26-Feb-09	Planting			
Herbicide after planting	Mar-09	Herbicide	283	g/ha	Arsenal AC
Herbicide after planting	Mar-09	Herbicide	143	g/ha	Oust XP
Herbicide at 2.5 years	Sep-11	Herbicide	53	g/ha	Escort
High Intensity Treatment Reynolds (block + Nelders)					
Site prep	2008	Site burnt			
Site prep	2008	Herbicide	1,418	g/ha	Chopper
Site prep	2008	Herbicide	9.5	L/ha	Milestone
Site prep	2008	Herbicide	9.5	L/ha	Accord XRT II
Site prep	2008	Herbicide	1,418	g/ha	DLZ oil
Planting	26-Feb-09	Planting			
Herbicide after planting	Mar-09	Herbicide	283	g/ha	Arsenal AC
Herbicide after planting	Mar-09	Herbicide	143	g/ha	Oust XP
Tip Moth control after planting	Mar-09	Insecticide	1.5	ml/tree	PTM Insecticide
Fertilization at 1 year	Mar-10	N	238	g/tree	CUF Blend (93g N)
Fertilization at 1 year	Mar-10	P	238	g/tree	CUF Blend (10g P)
Fertilization at 1 year	Mar-10	B	238	g/tree	CUF Blend (0.28g B)
Fill In Planting in Block Plots	Mar-10				
Herbicide at 1 year	Apr-10	Herbicide	283	g/ha	Arsenal AC
Herbicide at 1 year	Apr-10	Herbicide	143	g/ha	Oust XP
Herbicide at 1 year	Apr-10	Herbicide	18	g/ha	Escort
Herbicide at 2 years	Apr-11	Herbicide	283	g/ha	Arsenal AC
Herbicide at 2 years	Apr-11	Herbicide	143	g/ha	Oust XP
Herbicide at 2.5 years	Sep-11	Herbicide	53	g/ha	Escort

Table 3. Description of silvicultural treatments for the North Carolina site.

Operation	DATE	TRT_APPLIED	RATE	UNITS	SOURCE
Low Intensity Treatment Bladen (Block + STP)					
Site prep	??	Bedding			
Site prep	Sep-08	Herbicide	2,268	g/h	Chopper
Site prep	Sep-08	Herbicide	12	L/ha	Krenite
Site prep	Sep-08	Herbicide	1.487	g/ha	Garlon XRT
Planting	9-Mar-09	Planting			
Herbicide after planting	Apr-09	Herbicide	283	g/ha	Arsenal AC
Herbicide after planting	Apr-09	Herbicide	143	g/ha	Oust XP
High Intensity Treatment Bladen (Block + STP)					
Site prep	??	Bedding			
Site prep	Sep-08	Herbicide	2,268	g/h	Chopper
Site prep	Sep-08	Herbicide	12	L/ha	Krenite
Site prep	Sep-08	Herbicide	1.487	g/ha	Garlon XRT
Planting	9-Mar-09	Planting			
Herbicide after planting	Apr-09	Herbicide	283	g/ha	Arsenal AC
Herbicide after planting	Apr-09	Herbicide	143	g/ha	Oust XP
Tip Moth control after planting	Apr-09	Insecticide	1.5	ml/tree	PTM Insecticide
Fertilization at 1 year	Mar-10	N	238	g/tree	CUF Blend (93g N)
Fertilization at 1 year	Mar-10	P	238	g/tree	CUF Blend (10g P)
Fertilization at 1 year	Mar-10	B	238	g/tree	CUF Blend(0.28g B)
Herbicide at 1 year	Mar-10	Herbicide	283	g/ha	Arsenal AC
Herbicide at 1 year	Mar-10	Herbicide	143	g/ha	Oust XP
Herbicide at 1 year	Mar-10	Herbicide	18	g/ha	Escort
Herbicide at 2 years	May-11	Herbicide	283	g/ha	Arsenal AC
Herbicide at 2 years	May-11	Herbicide	143	g/ha	Oust XP

Table 4. Analysis of variance for comparison of six genotypes across two sites and two silviculture treatments.

Source of Variance	Degree of Freedom
Site (s = 2)	(s-1) = 1
Blocks Within Site (r = 3)	(b - 1) = 2
Error A	(b – 1)(s – 1) = 2
Silviculture (c = 2)	(c - 1) = 1
Site x Silviculture	(s - 1)(c - 1) = 1
Error B	s(b – 1)(c – 1) = 4
Genotype	(g -1) = 5
Genotype x Silviculture	(g – 1)(c – 1) = 5
Genotype x Site	(g – 1)(s – 1) = 5
Genotype x Silviculture x Site	(g – 1)(c – 1)(s – 1) = 5
Error C	sc(b – 1)(g – 1) = 40
Total Corrected	(sbcg – 1) = 71

Table 5. Analysis of variance for comparison of two crown ideotypes across two sites and two silviculture treatments.

Source of Variance	Degree of Freedom
Site (s = 2)	(s-1) = 1
Blocks Within Site (r = 3)	(b - 1) = 2
Error A	(b – 1)(s – 1) = 2
Silviculture (c = 2)	(c - 1) = 1
Site x Silviculture	(s - 1)(c - 1) = 1
Error B	s(b – 1)(c – 1) = 4
Ideotype	(g -1) = 1
Ideotype x Silviculture	(g – 1)(c – 1) = 1
Ideotype x Site	(g – 1)(s – 1) = 1
Ideotype x Silviculture x Site	(g – 1)(c – 1)(s – 1) = 1
Error C	sc(b – 1)(g – 1) = 4
Total Corrected	(sbcg – 1) = 16

Table 6. Fit statistics for regression equations developed to predict foliage mass on individual branches.

Site	Adjusted R^2	RMSE	PRESS
VA	0.701	40.61	429886
NC	0.75	37.56	124778

Table 7. Summary of statistical significance of crown characteristics with p-values from analysis of variance of loblolly pine at age 5 planted at two sites (Virginia vs. North Carolina), two levels of silvicultural intensity (high vs. low), and six levels of genotype (OP, MCP, and four clones).

Response (units)	Treatment effects						
	site	silviculture	site x silviculture	genotype	site x genotype	silviculture x genotype	site x silviculture x genotype
Tree dbh (cm)	**0.0055**	**0.0039**	0.4184	0.7118	0.4537	0.9491	0.6457
Tree height (cm)	**0.0011**	**0.0277**	0.4021	0.627	0.4025	0.9901	0.4851
Stem volume (m^3)	**0.0035**	**0.0042**	0.0903	0.2456	0.5241	0.9301	0.3892
Branch diameter (cm)	0.4736	**0.0002**	0.3468	**0.0346**	0.4668	0.7798	0.1822
Bottom (cm)	0.0514	**<0.0001**	0.9968	**0.0283**	0.4422	0.9168	0.294
Middle (cm)	0.4253	**0.0139**	0.4204	0.265	0.0819	0.374	0.4809
Top (cm)	0.1768	0.4141	0.9462	0.1398	0.9686	0.21	0.8047
Branch length (cm)	0.2193	**0.0001**	0.1473	**0.0002**	0.3788	0.5381	0.3131
Bottom (cm)	0.253	**<0.0001**	0.6956	**0.0001**	0.3495	0.7369	0.2509
Middle (cm)	**0.0451**	**0.0104**	0.2519	**0.0054**	0.0617	0.3302	0.7606
Top (cm)	**0.0007**	0.0598	0.4014	**0.0432**	0.9161	0.6479	0.9398
Crown volume (m^3)	**0.0094**	**0.0052**	0.0691	**0.0151**	0.0576	0.3675	0.4233
Total branches	**0.0218**	**0.0154**	0.2126	**<0.0001**	**0.0024**	0.2076	**0.0248**
Internode length (cm)	0.0899	0.3514	0.8361	**<0.0001**	**0.0004**	0.866	0.2745
Total foliage mass (kg)	**<0.0001**	**<0.0001**	**<0.0001**	**0.01**	0.1564	0.2572	0.3137
Total leaf area (m^2)	**<0.0001**	**<0.0001**	**0.0005**	**0.0025**	0.149	0.155	0.0827
Foliage density (kg/m^3)	0.1219	0.7647	0.7348	0.5448	0.1352	0.9721	0.9733

Table 8. Summary of statistical significance of crown characteristics with p-values from analysis of variance of loblolly pine at age 5 planted at two sites (Virginia vs. North Carolina), two levels of silvicultural intensity (high vs. low), and two crown ideotypes (narrow vs. broad).

Response (units)	Treatment effects						
	site	silviculture	Site x silviculture	ideotype	site x ideotype	silviculture x ideotype	site x silviculture x ideotype
Tree dbh (cm)	**0.0092**	**0.0123**	0.2676	0.2018	0.6939	0.8175	0.2806
Tree height (cm)	**0.0013**	0.0565	0.3029	0.4153	0.8046	0.773	0.7353
Stem volume (m^3)	**0.0044**	**0.0091**	0.0572	0.1994	0.1821	0.9099	0.7465
Branch diameter (cm)	0.9151	**0.0019**	0.4284	**0.0203**	**0.0205**	0.3955	0.1184
Bottom (cm)	0.0721	**<0.0001**	0.1575	**0.0096**	0.1972	0.6869	0.2857
Middle (cm)	0.3573	**0.0106**	0.0937	0.0703	0.1147	0.5112	0.0846
Top (cm)	0.1899	0.2571	0.5192	**0.0357**	**0.0227**	0.3954	0.119
Branch length (cm)	0.2063	**0.0012**	0.2606	**0.0005**	0.3764	0.3764	0.1501
Bottom (cm)	0.0561	**<0.0001**	0.1117	**0.0002**	0.1126	0.6403	0.2287
Middle (cm)	0.8532	**0.0056**	0.1146	**0.0089**	0.0984	0.5098	0.0827
Top (cm)	0.4197	0.1576	0.6652	**0.0021**	**0.0127**	0.5623	**0.0476**
Crown volume (m^3)	0.8396	**0.0067**	0.0613	**0.0242**	0.0819	0.7532	0.2077
Total branches	**0.0004**	**0.0042**	0.3042	1	0.1137	0.0784	**0.0242**
Internode length (cm)	**0.0346**	0.3904	0.5552	**0.0037**	0.979	0.7539	**0.0336**
Total foliage mass (kg)	**0.0071**	**0.0001**	0.0555	0.1739	0.0614	0.4201	0.5466
Total leaf area (m^2)	**<0.0001**	**<0.0001**	0.1043	0.1048	**0.029**	0.2487	0.2254
Foliage density (kg/m^3)	0.0664	0.8555	0.4278	0.2559	0.2938	0.7486	0.3167

Table 9. Summary of means of tree and crown characteristics averaged across six different genotypes of loblolly pine (OP, MCP, and four clones) at age 5 for two sites and two levels of silviculture. Mean values are followed by standard errors in parentheses. Values in a row with the same letter are not significantly different ($\alpha = 0.05$).

Response (units)	Treatment means (Standard error)			
	Site		Silvicultural Intensity	
	Virginia	North Carolina	Low	High
Tree dbh (cm)	7.5 (0.2)^{A}	6.2 (0.3)^{B}	6.2 (0.2)^{A}	7.5 (0.2)^{B}
Tree height (m)	4.8 (0.07)^{A}	4.1 (0.08)^{B}	4.3 (0.08)^{A}	4.7 (0.08)^{B}
Stem volume (m^3)	0.03 (0.002)^{A}	0.02 (0.001)^{B}	0.02 (0.001)^{A}	0.03 (0.002)^{B}
Branch diameter (cm)	1.2 (0.01)^{A}	1.2 (0.01)^{A}	1.1 (0.03)^{A}	1.3 (0.03)^{B}
Bottom (cm)	1.2 (0.04)^{A}	1.4 (0.04)^{A}	1.1 (0.03)^{A}	1.6 (0.04)^{B}
Middle (cm)	1.4 (0.03)^{A}	1.3 (0.03)^{A}	1.2 (0.03)^{A}	1.4 (0.03)^{B}
Top (cm)	0.9 (0.02)^{A}	0.8 (0.02)^{A}	0.9 (0.02)	0.9 (0.02)^{A}
Branch length (cm)	80.9 (2.8)^{A}	76.8 (2.7)^{A}	68.7 (2.3)^{A}	90.3 (2.6)^{B}
Bottom (cm)	86.4 (2.8)^{A}	90.3 (3.0)^{A}	72.8 (2.1)^{A}	104.0 (2.5)^{B}
Middle (cm)	91.9 (2.5)^{A}	80.8 (2.3)^{B}	78.4 (2.1)^{A}	94.2 (2.5)^{B}
Top (cm)	50.1 (1.6)	42.9 (1.3)	44.5 (1.4)	48.5 (1.6)
Crown volume (m^3)	7.1 (0.5)^{A}	4.9 (0.3)^{B}	4.7 (0.3)^{A}	7.3 (0.5)^{B}
Total branches	48 (1)^{A}	42 (1)^{B}	42 (1)^{A}	47 (1)^{B}
Internode length (cm)	31.2 (0.6)^{A}	28.7 (0.6)^{A}	29.3 (0.6)^{A}	30.6 (0.6)^{A}
Total foliage mass (kg)	3.3 (0.1)^{A}	2.5 (0.1)^{B}	2.2 (0.1)^{A}	3.6 (0.1)^{B}
Total leaf area (m^2)	12.6 (0.6)^{A}	8.8 (0.4)^{B}	8.0 (0.3)^{A}	13.4 (0.5)^{B}
Foliage density (kg/m^3)	0.5 (0.02)^{A}	0.8 (0.06)^{A}	0.7 (0.06)^{A}	0.6 (0.4)^{A}

Table 10. Summary of means of tree and crown characteristics for six different genotypes of loblolly pine (OP, MCP, and four clones) at age 5 averaged across two sites (Virginia and North Carolina) and two levels of silviculture (high intensity and low intensity). Mean values are followed by standard error in parentheses. Values in a row with the same letter are not significantly different ($\alpha = 0.05$) based on Tukey's HSD test.

Response (units)	Treatment means (Standard error)					
	C1	C2	C3	C4	MCP	OP
Tree dbh (cm)	6.6 (0.4)^{A}	7.1 (0.4)^{A}	6.7 (0.3)^{A}	7.0 (0.3)^{A}	6.7 (0.3)^{A}	6.5 (0.3)^{A}
Tree height (m)	4.5 (0.16)^{A}	4.5 (0.16)^{A}	4.4 (0.14)^{A}	4.6 (0.15)^{A}	4.4 (0.10)^{A}	4.3 (0.12)^{A}
Stem volume (m^3)	0.02 (0.003)^{A}	0.03 (0.003)^{A}	0.02 (0.003)^{A}	0.03 (0.003)^{A}	0.02 (0.002)^{A}	0.02 (0.002)^{A}
Branch diameter (cm)	1.2 (0.02)^{AB}	1.3 (0.02)^{A}	1.2 (0.02)^{AB}	1.3 (0.02)^{A}	1.1 (0.01)^{B}	1.3 (0.02)^{AB}
Bottom (cm)	1.3 (0.07)^{AB}	1.4 (0.08)^{A}	1.2 (0.08)^{B}	1.4 (0.06)^{AB}	1.2 (0.07)^{B}	1.4 (0.07)^{A}
Middle (cm)	1.3 (0.06)^{A}	1.4 (0.08)^{A}	1.3 (0.06)^{A}	1.4 (0.05)^{A}	1.2 (0.05)^{A}	1.4 (0.05)^{A}
Top (cm)	0.8 (0.04)^{A}	0.9 (0.05)^{A}	0.8 (0.04)^{A}	0.9 (0.3)^{A}	0.8 (0.03)^{A}	0.9 (0.04)^{A}
Branch length (cm)	72.4 (1.2)^{A}	83.3 (1.4)^{B}	77 (1.2)^{AB}	86.7 (1.2)^{B}	71.2 (0.9)^{A}	84 (1.2)^{B}
Bottom (cm)	77.1 (4.6)^{A}	96.4 (5.7)^{B}	85.1 (5.8)^{AB}	97.0 (4.4)^{B}	78.1 4.0)^{A}	96.6 (4.4)^{B}
Middle (cm)	76.3 (4.1)^{A}	91.6 (5.3)^{AB}	87.4 (4.9)^{AB}	93.1 (4.0)^{B}	79.7 (2.0)^{AB}	90.2 (2.9)^{AB}
Top (cm)	42.6 (2.6)^{A}	52.1 (2.9)^{B}	43.9 (2.6)^{A}	50.8 (2.8)^{B}	44.6 (2.2)^{AB}	45.2 (2.5)^{AB}
Crown volume (m^3)	4.9 (0.6)^{A}	7.1 (0.9)^{B}	6.3 (0.9)^{AB}	7.2 (0.7)^{B}	4.7 (0.4)^{A}	5.9 (0.4)^{AB}
Total branches	41 (1)^{A}	38 (2)^{A}	46 (2)^{AB}	49 (1)^{B}	51 (2)^{B}	43 (1)^{A}
Internode length (cm)	29 (0.9)^{A}	35 (1.4)^{B}	27.4 (0.7)^{A}	27.4 (0.9)^{A}	29.3 (0.8)^{A}	31.8 (0.9)^{B}
Total foliage mass (kg)	2.6 (0.2)^{A}	2.7 (0.2)^{A}	3.0 (0.3)^{AB}	3.5 (0.3)^{B}	2.8 (0.3)^{AB}	2.9 (0.2)^{AB}
Total leaf area (m^2)	9.7 (0.9)^{A}	9.5 (0.8)^{A}	10.8 (1.0)^{AB}	13 (1.1)^{B}	10.4 (0.7)^{AB}	10.7 (0.7)^{AB}
Foliage density (kg/m^3)	0.7 (0.06)^{A}	0.6 (0.1)^{A}	0.7 (0.1)^{A}	0.6 (0.06)^{A}	0.7 (0.06)^{A}	0.5 (0.04)^{A}

Table 11. Means and standard errors in parentheses for the crown attributes of narrow vs. broad crown ideotypes. Values in a row with the same letter are not significantly different ($\alpha = 0.05$).

Response (units)	Treatment means (Standard error)	
	Ideotype	
	Narrow	Broad
Tree dbh (cm)	6.7 (0.2)^{A}	7.0 (0.3)^{A}
Tree height (m)	4.5 (0.1^{A}	4.6 (0.1)^{A}
Stem volume (m^3)	0.02 (0.002)^{A}	0.03 (0.002)^{A}
Branch diameter (cm)	1.2 (0.04)^{A}	1.3 (0.04)^{B}
Bottom (cm)	12.4 (0.5)^{A}	14.1 (0.5)^{B}
Middle (cm)	12.9 (0.4)^{A}	14 (0.5)^{A}
Top (cm)	8.4 (0.3)^{A}	9.2 (0.3)^{B}
Branch length (cm)	73.9 (2.8)^{A}	85.1 (2.6)^{B}
Bottom (cm)	81.1 (3.6)^{A}	97.6 (3.7)^{B}
Middle (cm)	81.9 (3.4)^{A}	93.5 (3.2)^{B}
Top (cm)	43.2 (1.8)^{A}	51.3 (2.0)^{B}
Crown volume (m^3)	5.6 (0.6)^{A}	7.4 (0.6)^{B}
Total branches	43 (1)^{A}	43 (1)^{A}
Internode length (cm)	28.2 (0.6)^{A}	31.2 (0.9)^{B}
Total foliage mass (kg)	2.8 (0.2)^{A}	3.1 (0.2)^{A}
Total leaf area (m^2)	10.0 (0.7)^{A}	11.3 (0.7)^{A}
Foliage density (kg/m^3)	0.7 (0.07)^{A}	0.6 (0.06)^{A}

Table 12. Ranking of genotypes from largest to smallest by branch attributes and crown volume (derived from values found in Table 10). Codes in a row with the same letter are not significantly different ($\alpha = 0.05$) based on Tukey's HSD test.

Branch Diameter (mean)	Genotype					
	Largest ----------→Smallest					
Overall	$C2^{A}$	$C4^{A}$	OP^{AB}	$C1^{AB}$	$C3^{AB}$	MCP^{B}
Bottom	$C2^{A}$	OP^{A}	$C4^{AB}$	$C1^{AB}$	$C3^{B}$	MCP^{B}
Middle	$C2^{A}$	$C4^{A}$	OP^{A}	$C1^{A}$	$C3^{A}$	MCP^{A}
Top	$C2^{A}$	$C4^{A}$	OP^{A}	$C1^{A}$	$C3^{A}$	MCP^{A}

Branch Length (mean)	Genotype					
	Largest ----------→Smallest					
Overall	$C4^{B}$	OP^{B}	$C2^{B}$	$C3^{AB}$	MCP^{A}	$C1^{A}$
Bottom	$C4^{B}$	$C2^{B}$	OP^{B}	$C3^{AB}$	MCP^{A}	$C1^{A}$
Middle	$C4^{B}$	$C2^{AB}$	OP^{AB}	MCP^{AB}	$C3^{AB}$	$C1^{A}$
Top	$C4^{B}$	$C2^{B}$	OP^{AB}	MCP^{AB}	$C3^{A}$	$C1^{A}$

Crown Volume (mean)	Genotype					
	Largest ----------→Smallest					
Overall	$C4^{B}$	$C2^{B}$	$C3^{AB}$	OP^{AB}	$C1^{A}$	MCP^{A}

Foliage Mass (mean)	Genotype					
	Largest ----------→Smallest					
Overall	$C4^{B}$	$C3^{AB}$	OP^{AB}	MCP^{AB}	$C2^{A}$	$C1^{A}$

Leaf Area (mean)	Genotype					
	Largest ----------→Smallest					
Overall	$C4^{B}$	$C3^{AB}$	OP^{AB}	MCP^{A}	$C1^{A}$	$C2^{A}$

Figures

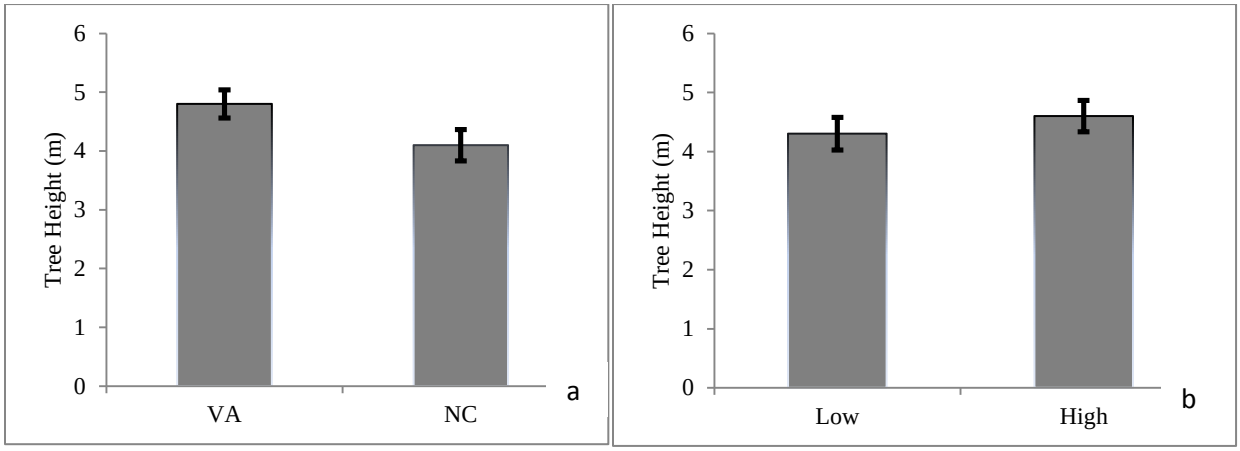

Figure 1. Mean tree height at age 5 averaged for the six loblolly pine genotypes (OP, MCP, and four clones) grown in the Virginia Piedmont and North Carolina Coastal Plain (a) under two levels of silviculture (b).

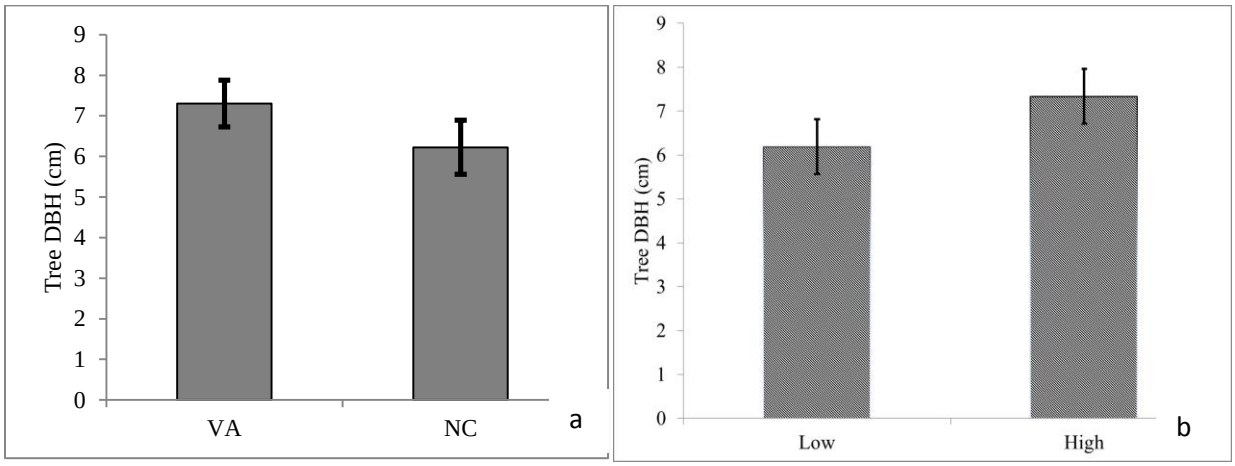

Figure 2. Mean tree dbh at age 5 averaged for the six loblolly pine genotypes (OP, MCP, and four clones) grown in the Virginia Piedmont and North Carolina Coastal Plain (a) under two levels of silviculture (b).

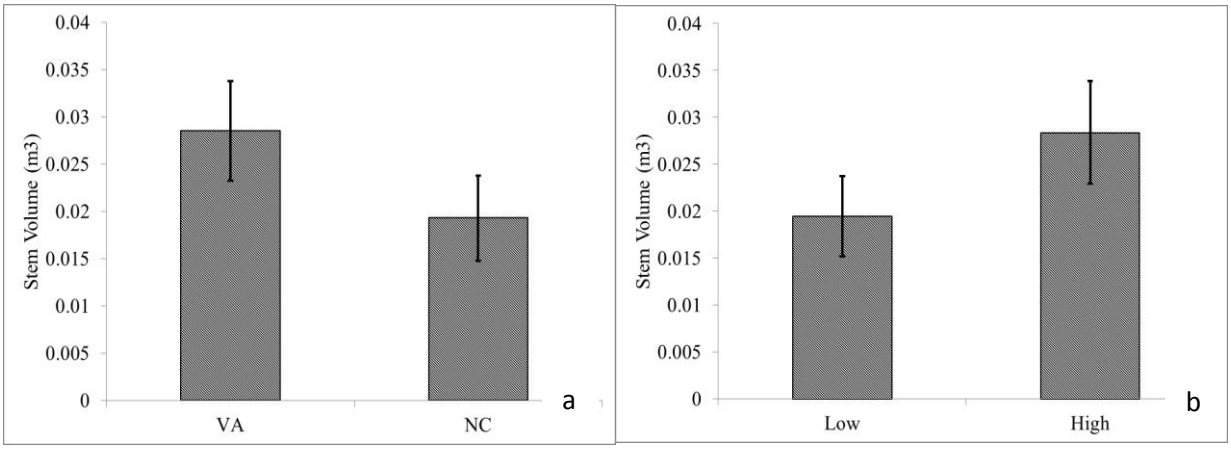

Figure 3. Mean stem volume at age 5 averaged for the six loblolly pine genotypes (OP, MCP, and four clones) grown in the Virginia Piedmont and North Carolina Coastal Plain (a) under two levels of silviculture (b).

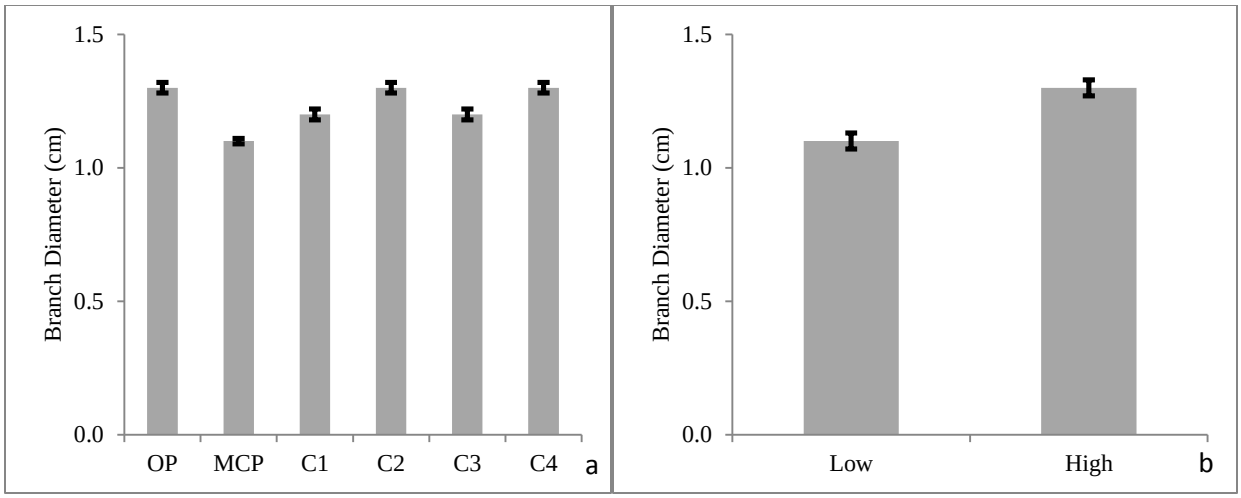

Figure 4. Mean branch diameter at age 5 of six loblolly pine genotypes (OP, MCP, and four clones) (a) grown under two levels of silviculture (b).

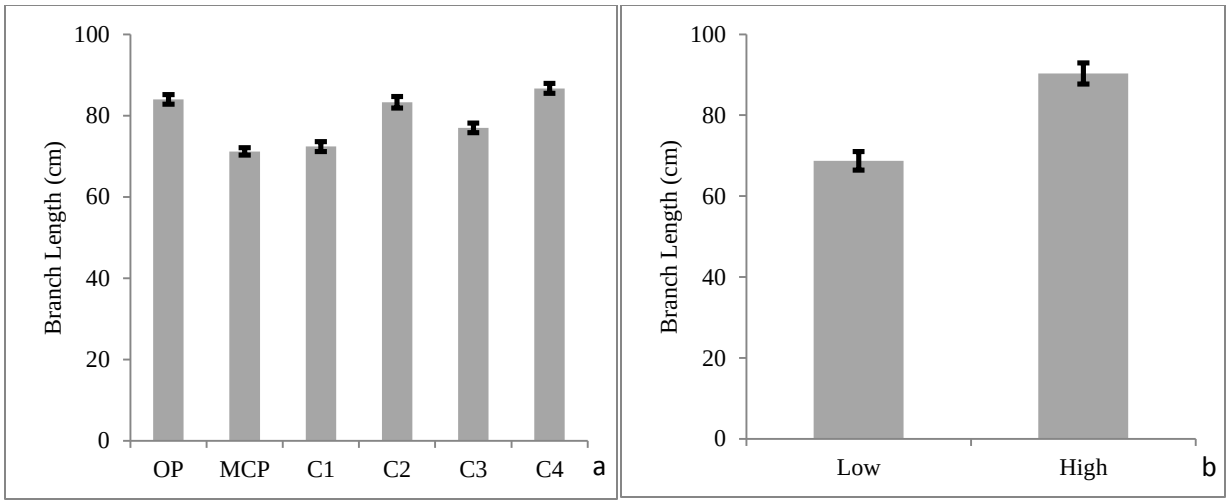

Figure 5. Mean branch length at age 5 of six loblolly pine genotypes (OP, MCP, and four clones) (a) grown under two levels of silviculture (b).

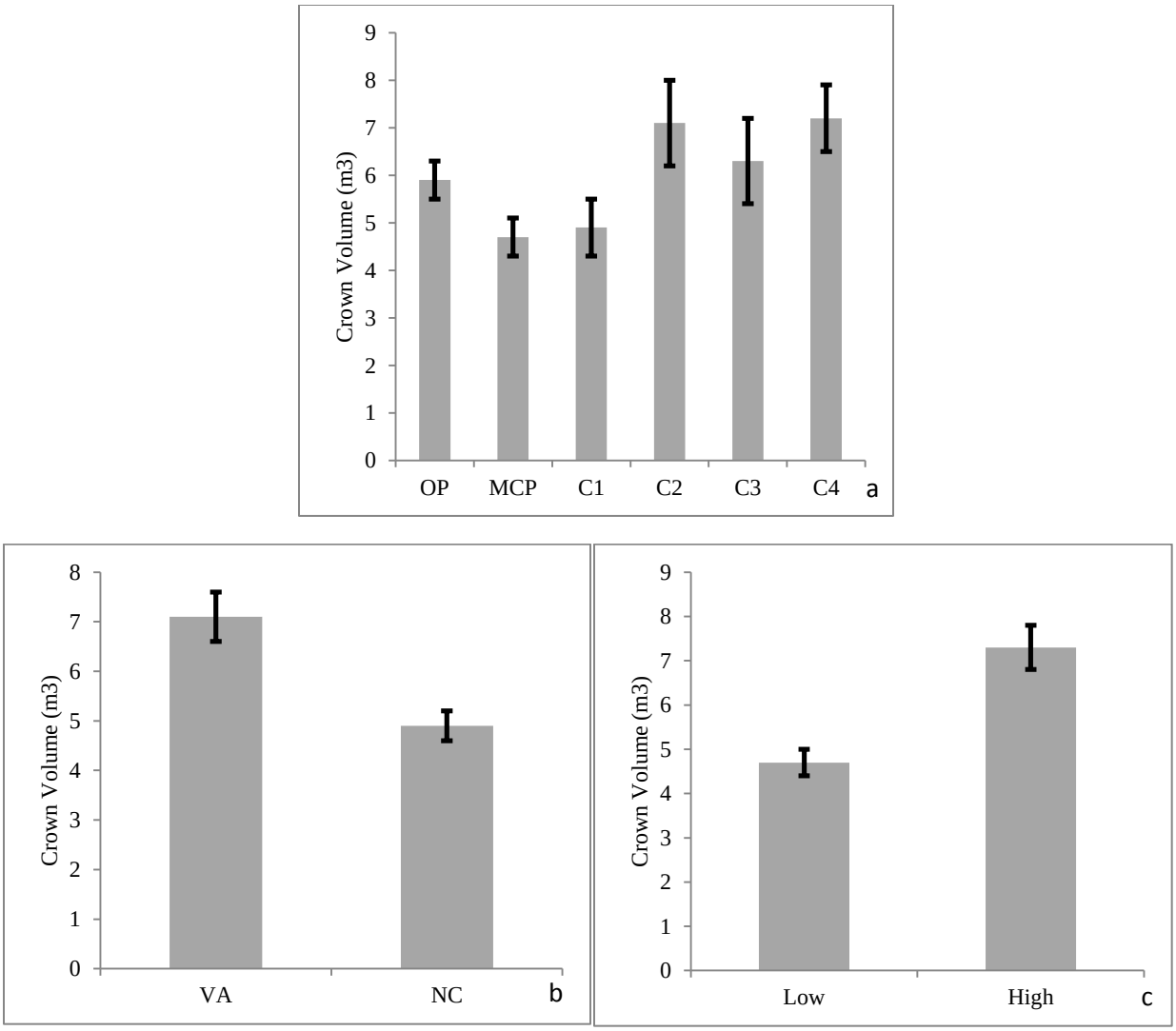

Figure 6. Mean crown volume at age 5 of six loblolly pine genotypes (OP, MCP, and four clones) (a) grown under two levels of silviculture (b) in the Virginia Piedmont and North Carolina Coastal Plain (c).

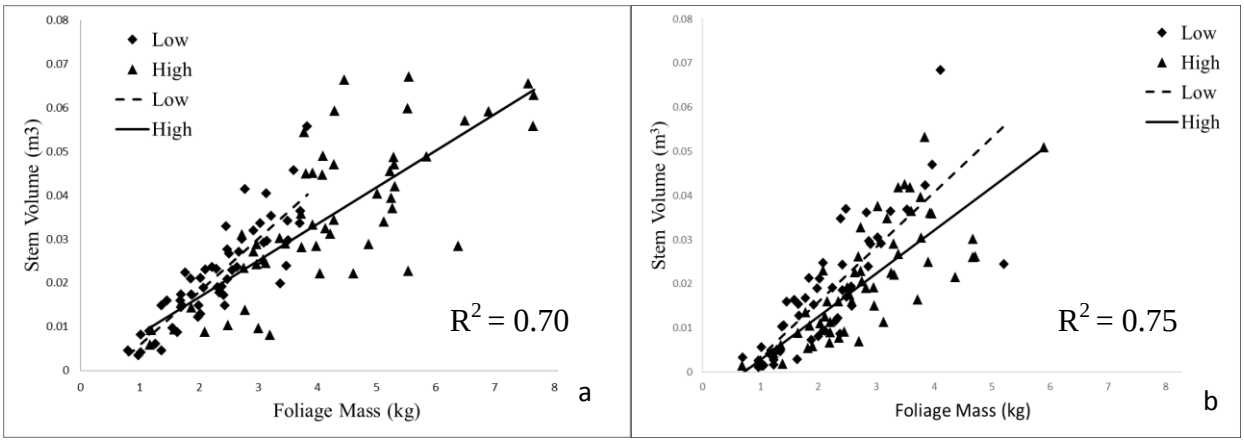

Figure 7. Stem Volume vs. Foliage Mass at age 5 of six loblolly pine genotypes grown under two levels of silviculture in the Virginia Piedmont (a) and North Carolina Coastal Plain (b).

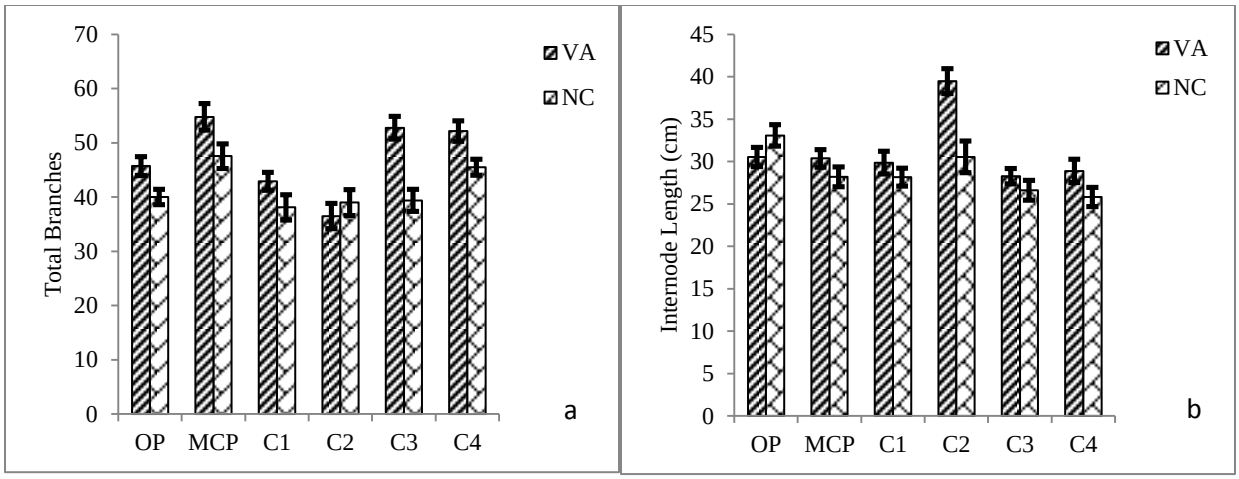

Figure 8. Mean Total Branches (a) and Mean Internode Length (b) at age 5 of six loblolly pine genotypes (OP, MCP, and four clones) grown in the Virginia Piedmont and North Carolina Coastal Plain.

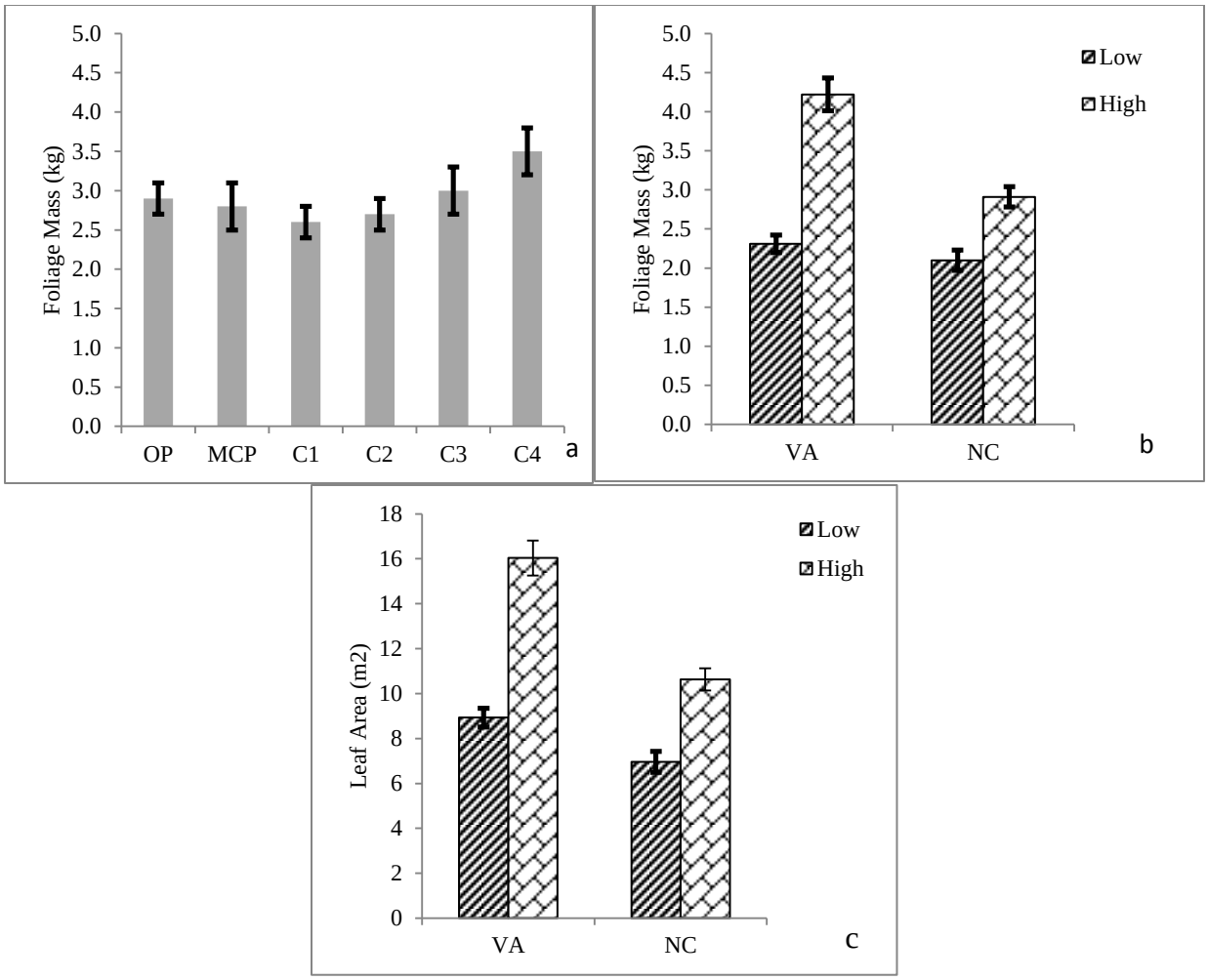

Figure 9. Mean foliage mass at age 5 of six loblolly pine genotypes (OP, MCP, and four clones) (a) grown under two levels of silviculture in the Virginia Piedmont and North Carolina Coastal Plain (b), and mean leaf area at age 5 of six loblolly pine genotypes (OP, MCP, and four clones) grown under two levels of silviculture in the Virginia Piedmont and North Carolina Coastal Plain (c).

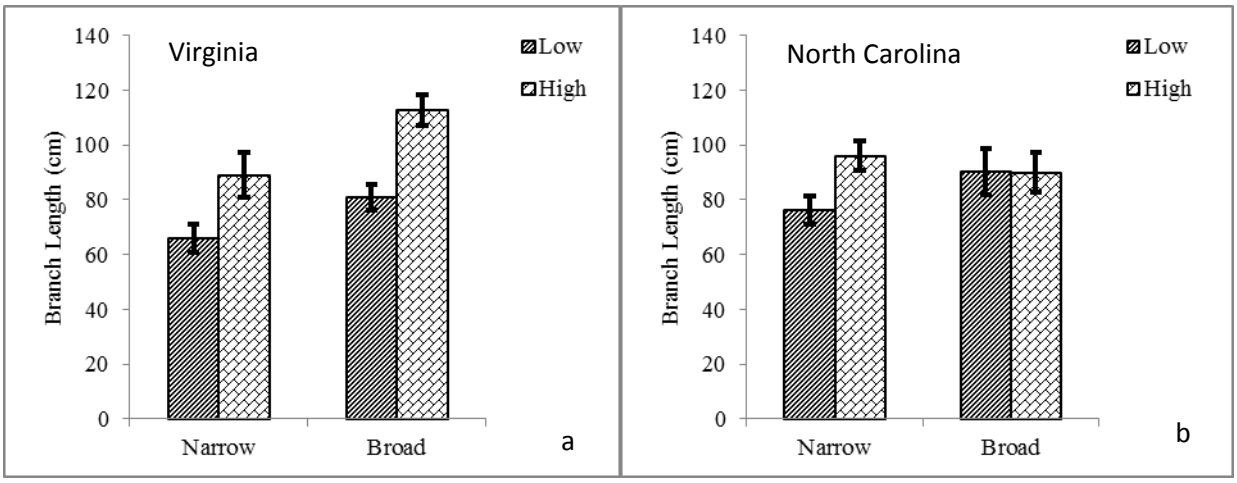

Figure 10. Mean branch length of the middle crown section at age 5 of two loblolly pine crown ideotypes (narrow and broad) grown under two levels of silviculture in the Virginia Piedmont (a) and North Carolina Coastal Plain (b).

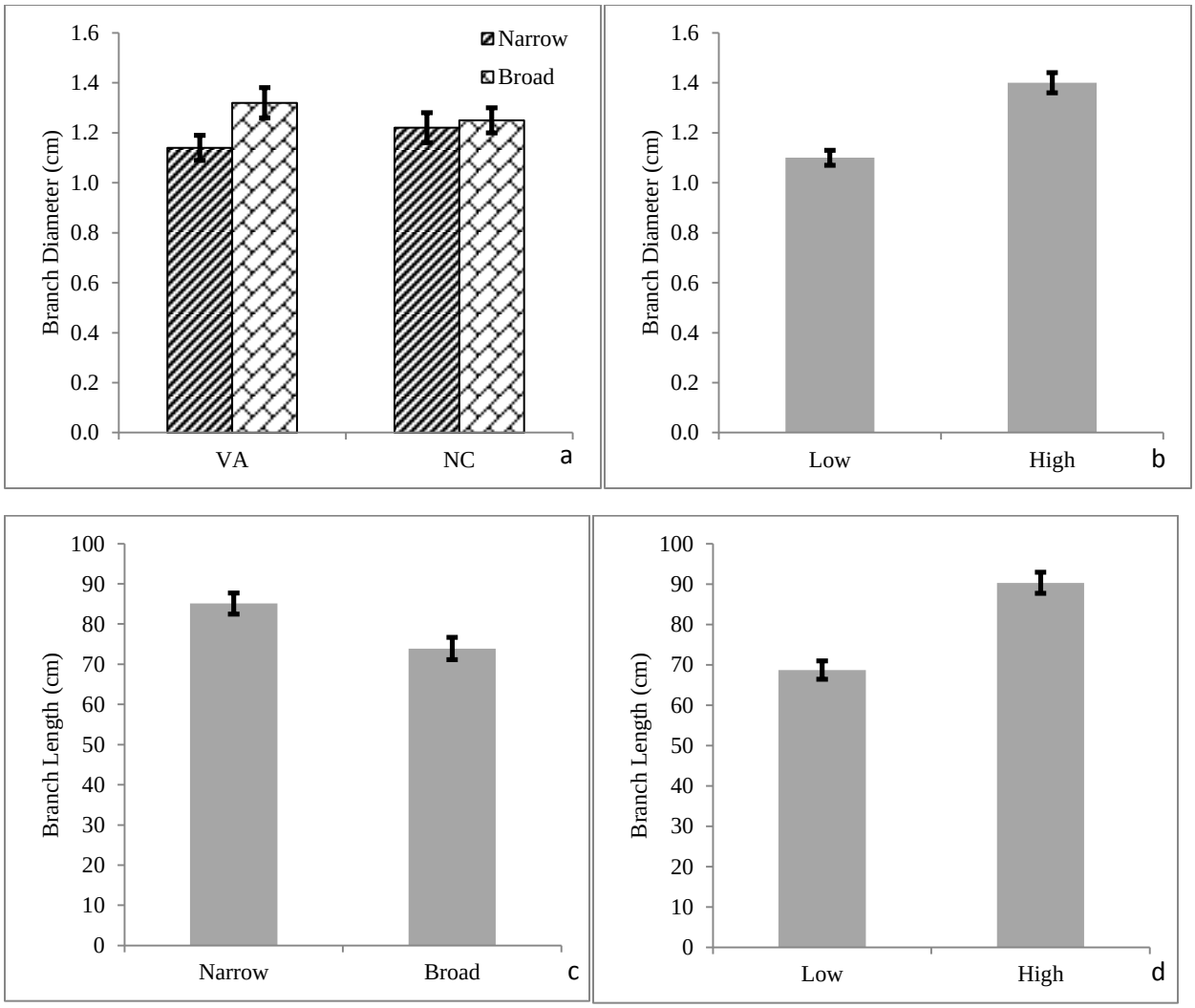

Figure 11. Mean branch diameter at age 5 of two loblolly pine crown ideotypes (narrow and broad) grown in the Virginia Piedmont and North Carolina Coastal Plain (a) under two levels of silviculture (b), and mean branch length at age 5 of two loblolly pine crown ideotypes (narrow and broad) (c) grown under two levels of silviculture (d).

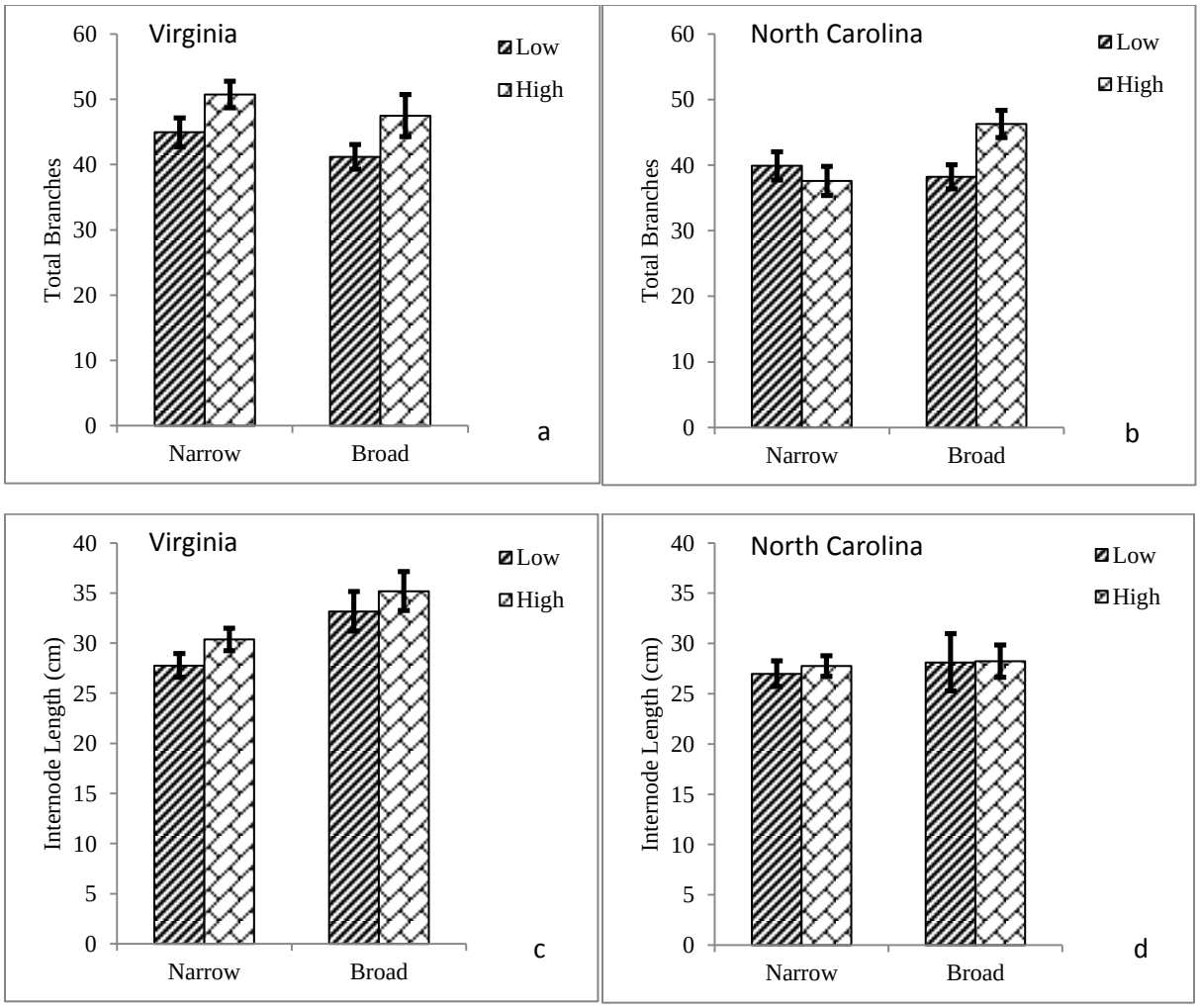

Figure 12. Mean total branches at age 5 of two loblolly pine crown ideotypes (narrow and broad) grown under two levels of silviculture in the Virginia Piedmont (a) and North Carolina Coastal Plain (b), and mean internode length at age 5 of two loblolly pine crown ideotypes (narrow and broad) grown under two levels of silviculture in the Virginia Piedmont (c) and North Carolina Coastal Plain (d).

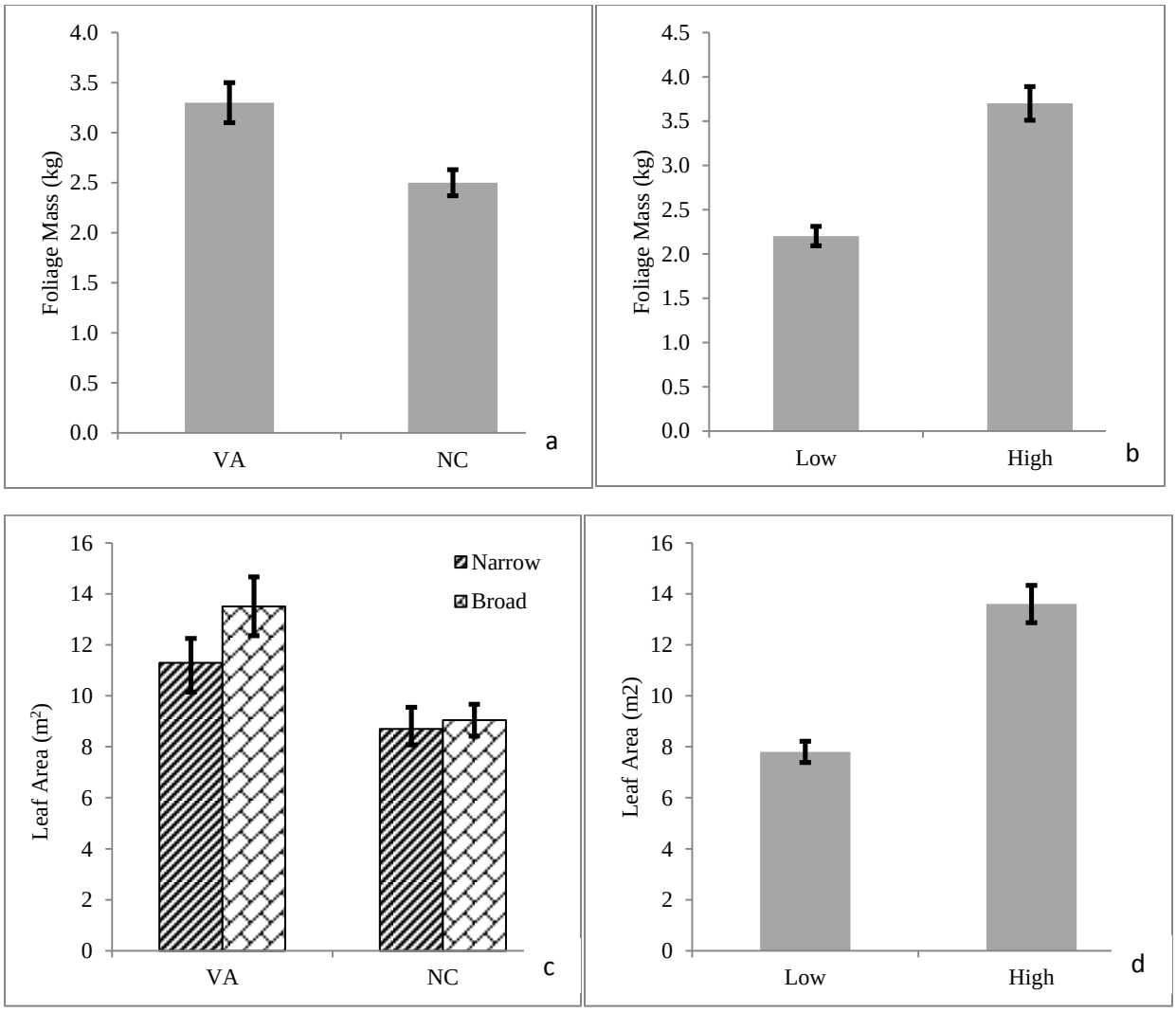

Figure 13. Mean foliage mass at age 5 of two loblolly pine crown ideotypes (narrow and broad) grown in the Virginia Piedmont and North Carolina Coastal Plain (a) under two levels of silviculture (b), and mean leaf area at age 5 of two loblolly pine crown ideotypes (narrow and broad) grown in the Virginia Piedmont and North Carolina Coastal Plain (c) under two levels of silviculture (d).

Appendix A: Polynomial Regression Analysis for Genotypes

A simple model designed to represent the crown profiles of the six genotypes (OP, MCP, and four clones) for the sites at Virginia and North Carolina was developed using a polynomial regression analysis. This was accomplished by plotting branch length vs. branch height in MS Excel and fitting a 2nd order polynomial regression line to the data. The resulting 2nd order polynomial equation was subsequently used to predict branch length where x = (branch height) (Figure A1). The predicted values for branch length were then plotted as the independent variable against branch height as the dependent variable for both high and low silviculture at both Virginia and North Carolina (Figures A2-A13).

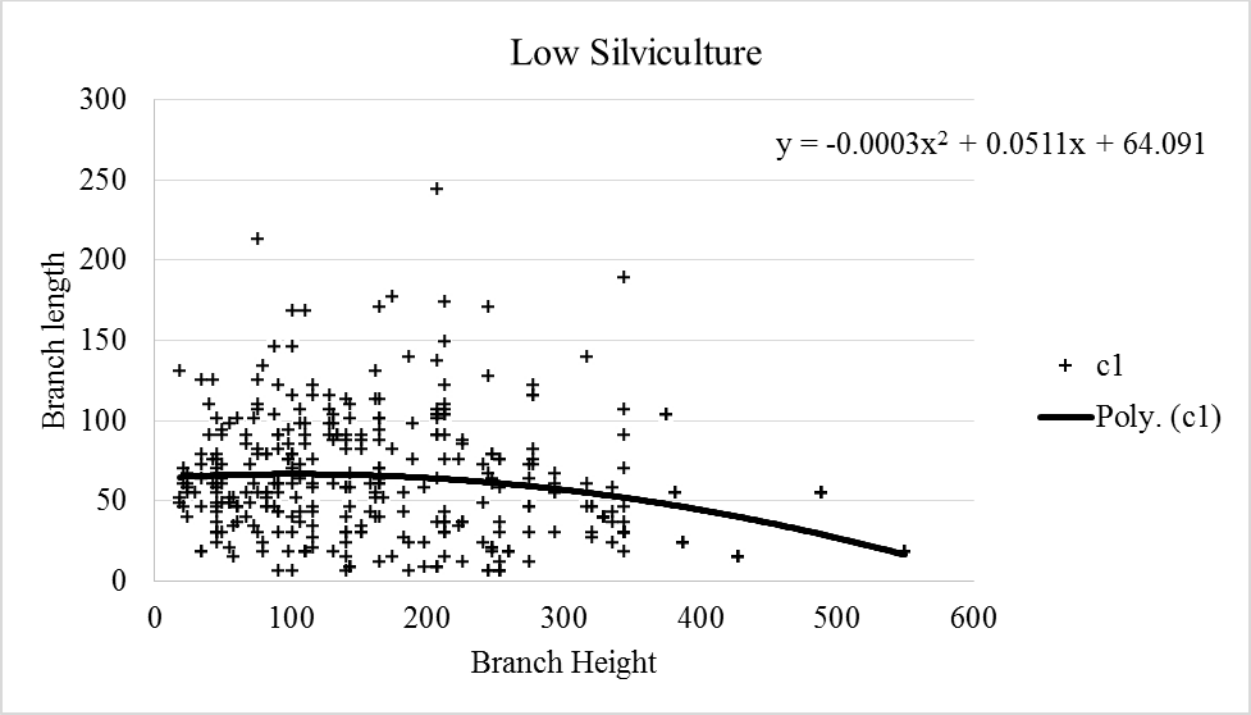

Figure A1. Example of the 2nd order polynomial regression analysis used to develop the polynomial regression equation for North Carolina low silviculture clone C1 in order to predict branch length values from the independent variable branch height. The profile was developed by plotting branch height vs. predicted branch length. All regression equations for this analysis were developed using this technique.

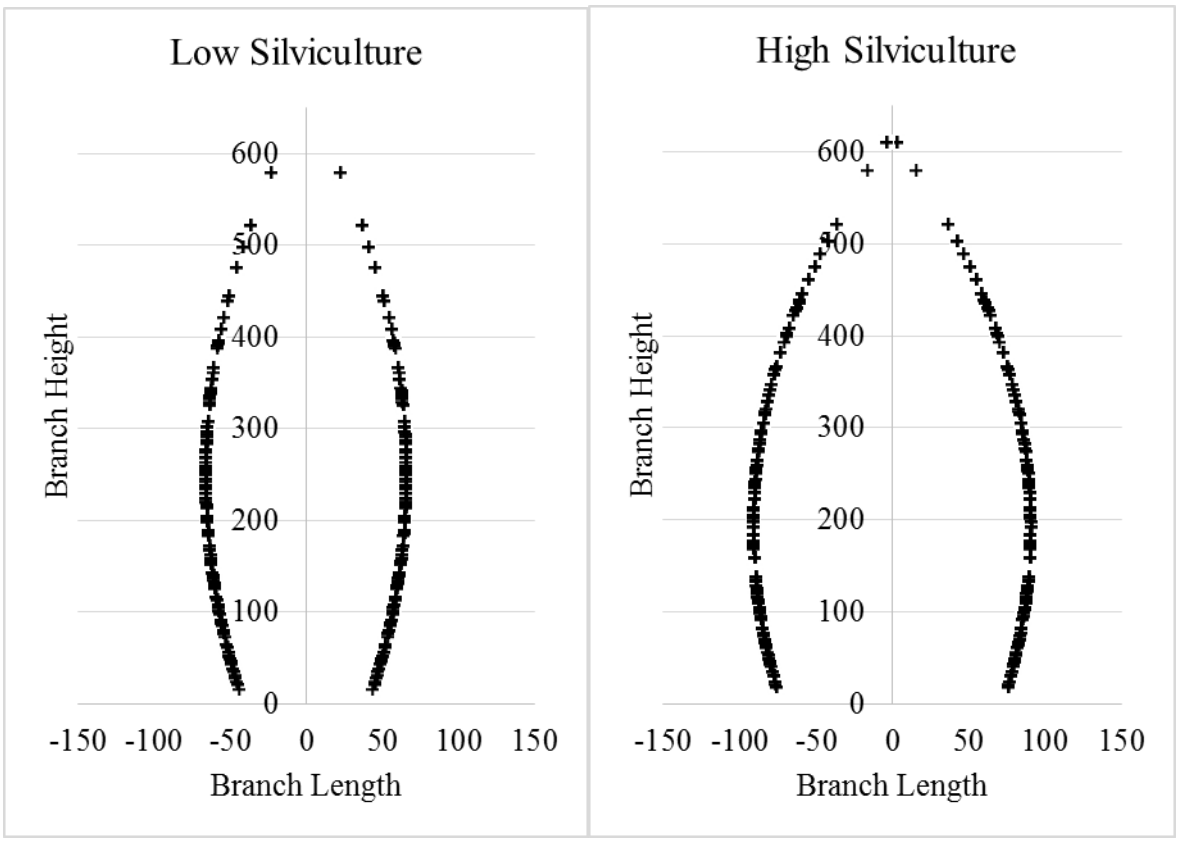

Figure A2. Predicted crown profile for clone C1 in Virginia using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0004 x (branch height)^2] + [0.1996 x (branch height)] + 41.112

to predict branch length from the independent variable branch height (a), and predicted Virginia high silviculture crown profile for clone C1 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0005 x (branch height)^2] + [0.0.1918 x (branch height)] + 72.403

to predict branch length from the independent variable branch height (b).

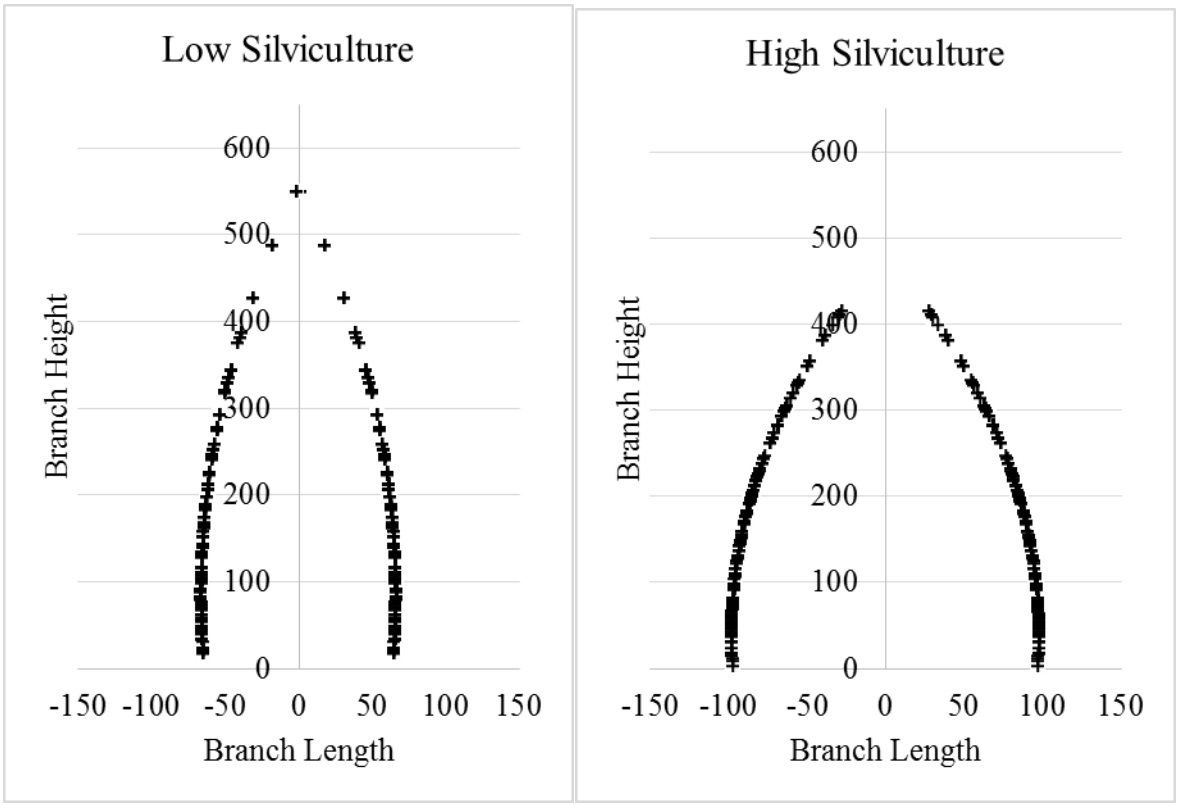

Figure A3. Predicted crown profile for clone C1 in North Carolina using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0003 x (branch height)^2] + [0.0511 x (branch height)] + 64.091

to predict branch length from the independent variable branch height (a), and predicted North Carolina high silviculture crown profile for clone C1 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0005 x (branch height)^2] + [0.0.0408 x (branch height)] + 97.197

to predict branch length from the independent variable branch height (b).

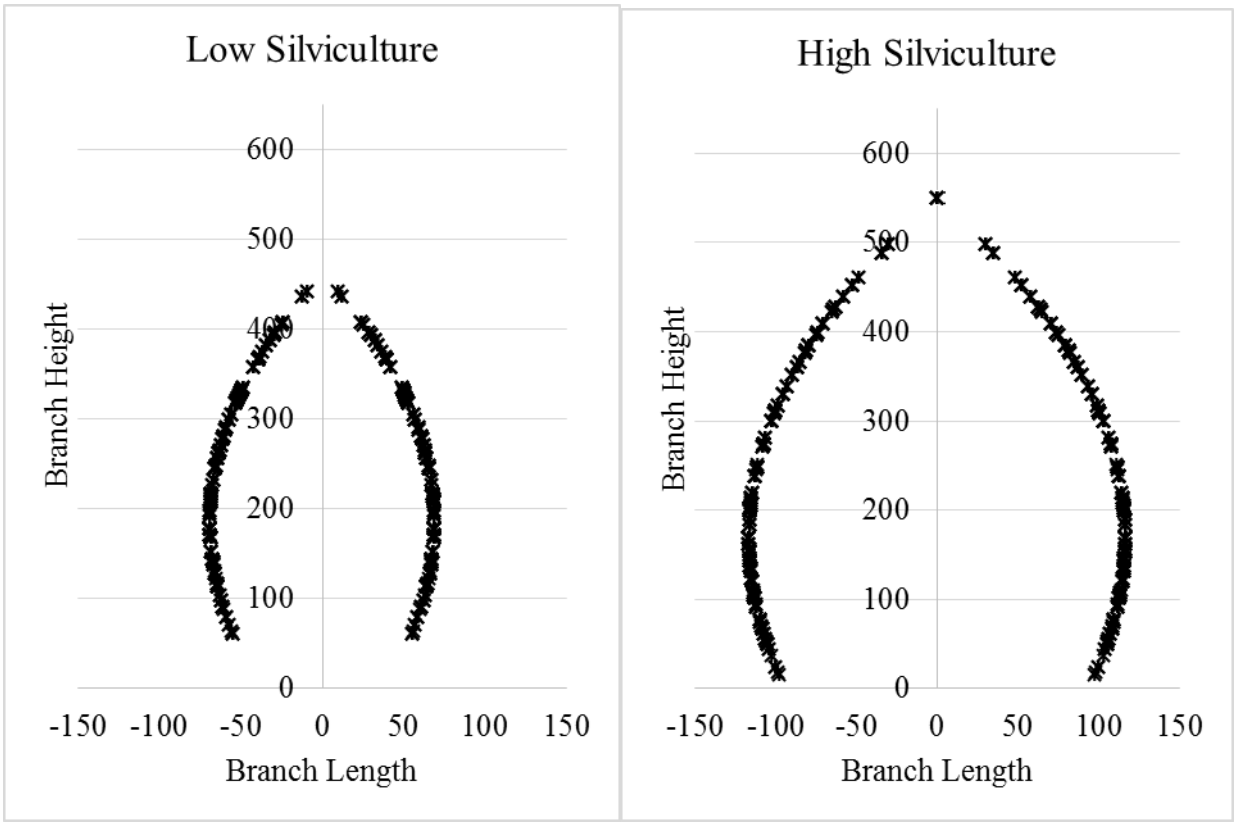

Figure A4. Predicted crown profile for clone C2 in Virginia using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0009 x (branch height)^2] + [0.3329 x (branch height)] + 38.172

to predict branch length from the independent variable branch height (a), and predicted Virginia high silviculture crown profile for clone C2 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0008 x (branch height)^2] + [0.0.2686 x (branch height)] + 94.106

to predict branch length from the independent variable branch height (b).

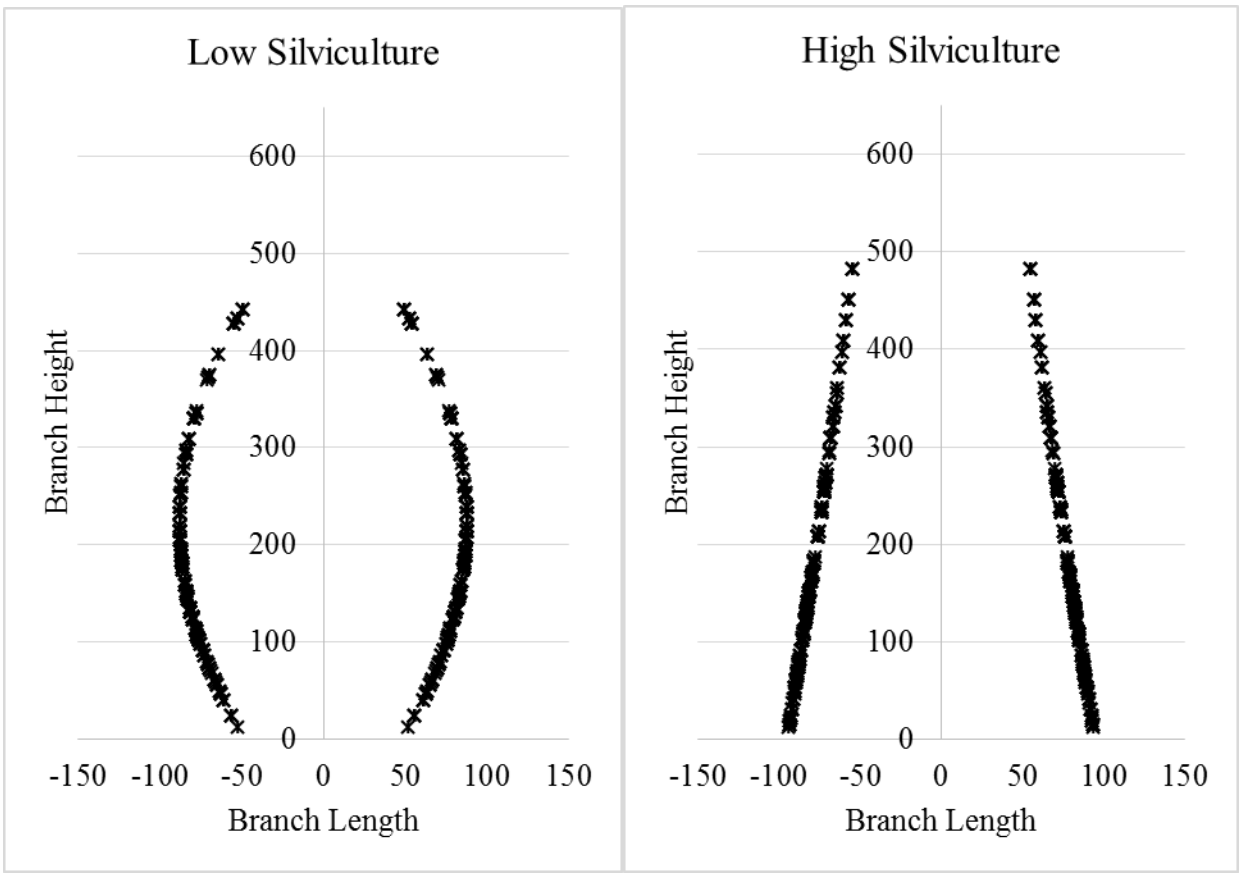

Figure A5. Predicted crown profile for clone C2 in North Carolina using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0008 x (branch height)^2] + [0.3569 x (branch height)] + 48.016

to predict branch length from the independent variable branch height (a), and predicted North Carolina high silviculture crown profile for clone C2 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [0.00003 x (branch height)^2] - [0.0.0975 x (branch height)] + 95.048

to predict branch length from the independent variable branch height (b).

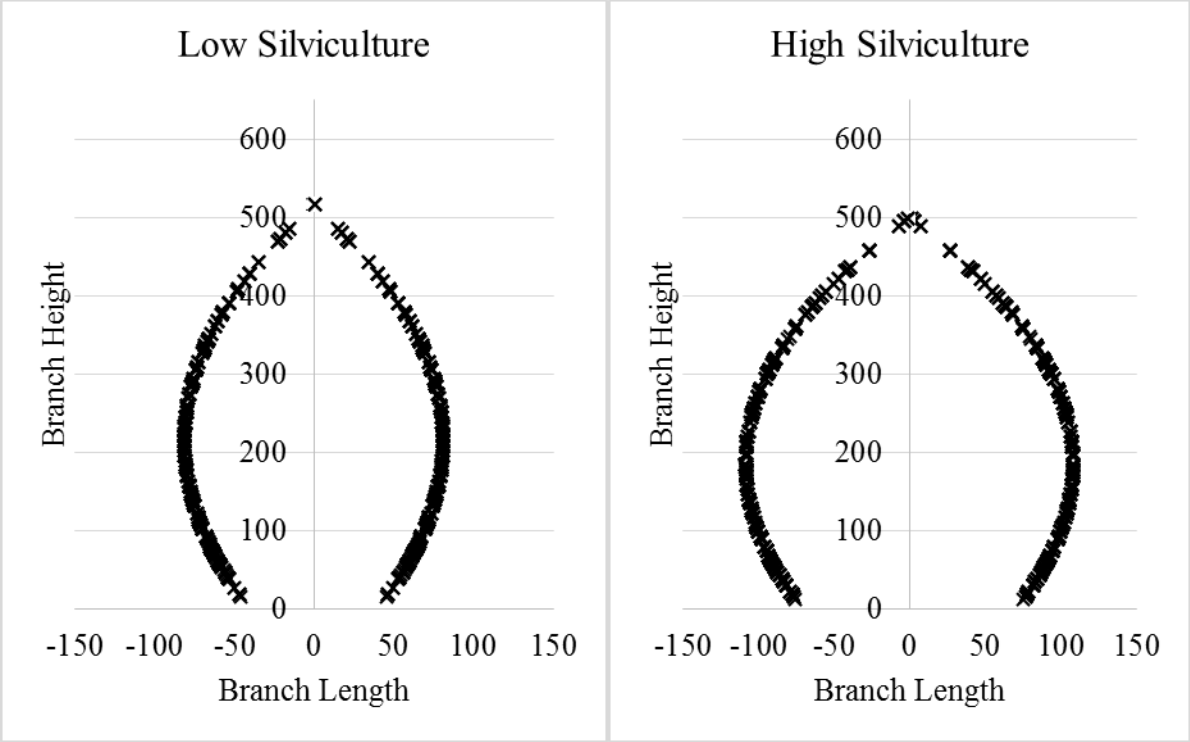

Figure A6. Predicted crown profile for clone C3 in Virginia using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0009 x (branch height)^2] + [0.385 x (branch height)] + 40.007

to predict branch length from the independent variable branch height (a), and predicted Virginia high silviculture crown profile for clone C3 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0011 x (branch height)^2] + [0.0.4065 x (branch height)] + 70.823

to predict branch length from the independent variable branch height (b).

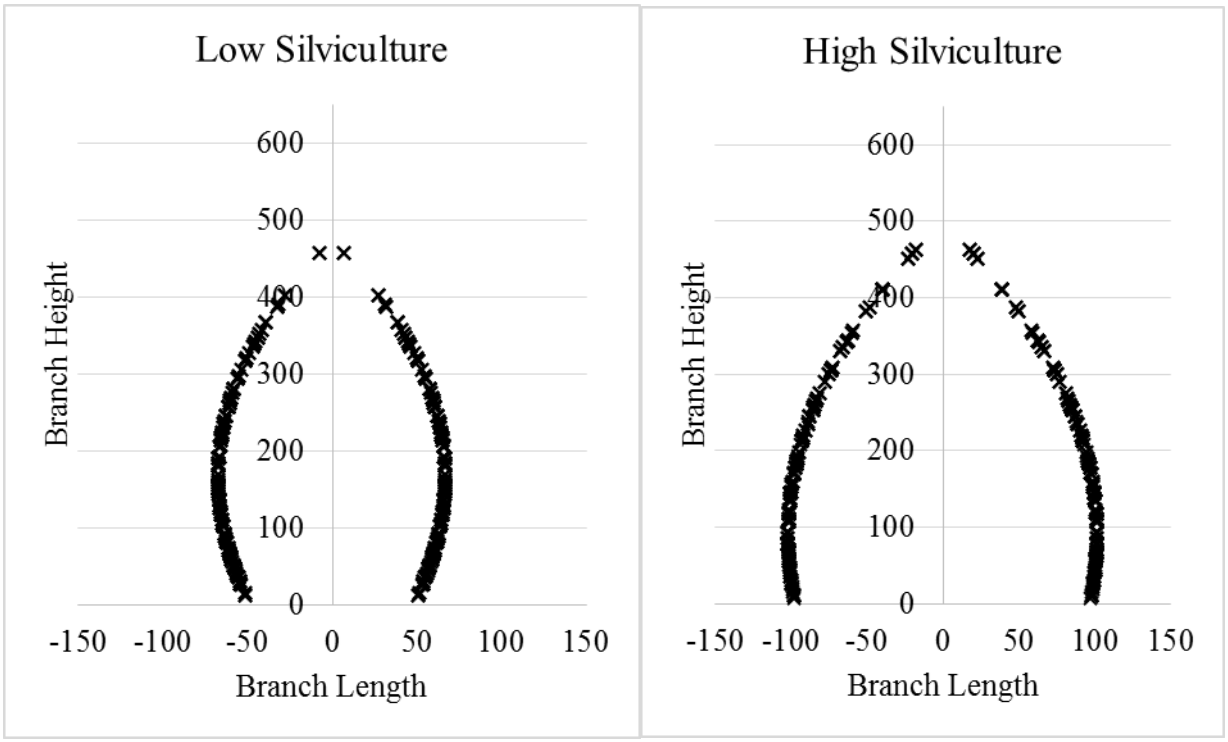

Figure A7. Predicted crown profile for clone C3 in North Carolina using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0007 x (branch height)^2] + [0.2304 x (branch height)] + 48.16

to predict branch length from the independent variable branch height (a), and predicted North Carolina high silviculture crown profile for clone C3 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0006 x (branch height)^2] + [0.0.1062 x (branch height)] + 97.13

to predict branch length from the independent variable branch height (b).

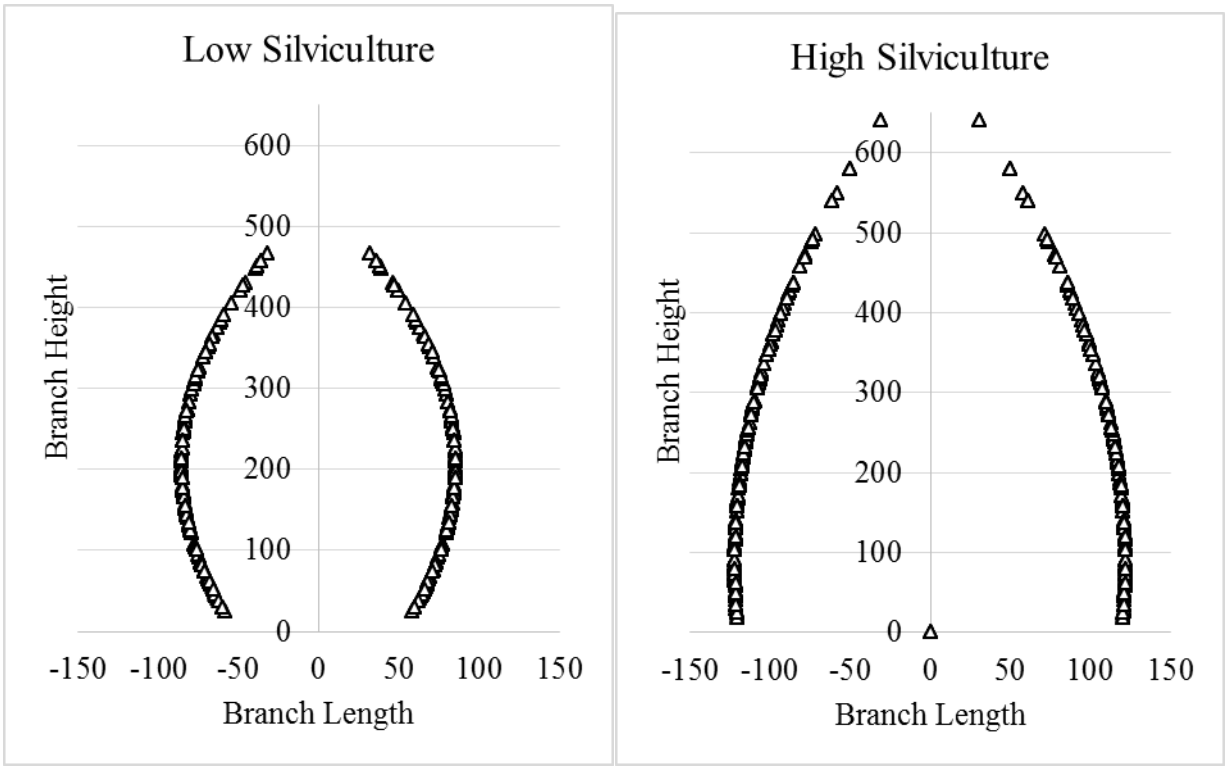

Figure A8. Predicted crown profile for clone C4in Virginia using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0008 x (branch height)^2] + [0.3329 x (branch height)] + 50.813

to predict branch length from the independent variable branch height (a), and predicted Virginia high silviculture crown profile for clone C4 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0003 x (branch height)^2] + [0.0.0528 x (branch height)] + 119.78

to predict branch length from the independent variable branch height (b).

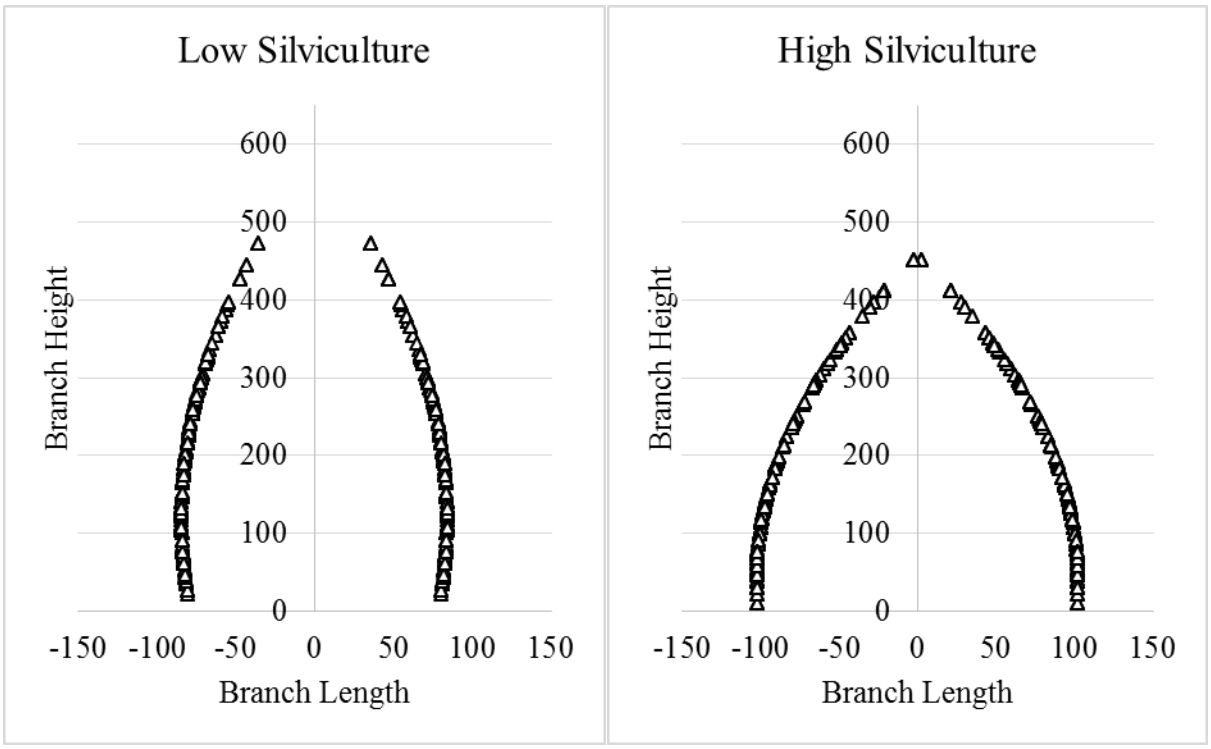

Figure A9. Predicted crown profile for clone C4 in North Carolina using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0004 x (branch height)^2] + [0.0985 x (branch height)] + 78.203

to predict branch length from the independent variable branch height (a), and predicted North Carolina high silviculture crown profile for clone C4 using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0006 x (branch height)^2] + [0.0.052 x (branch height)] + 101.37

to predict branch length from the independent variable branch height (b).

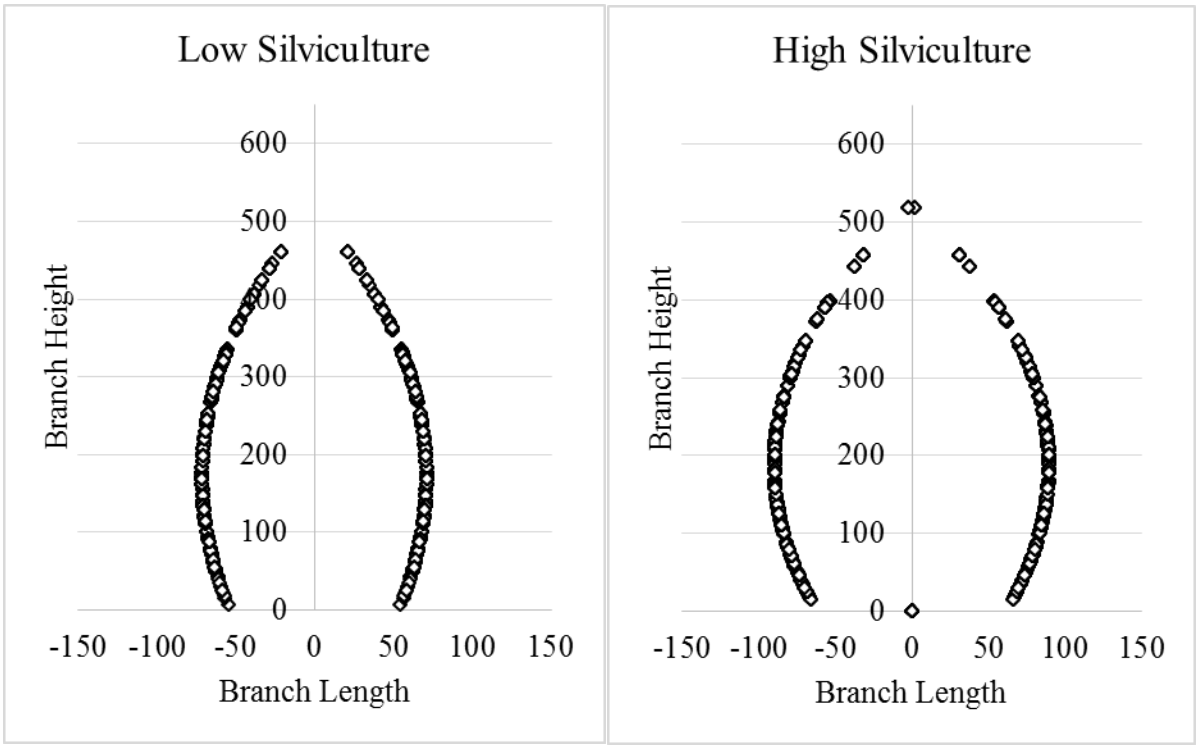

Figure A10. Predicted crown profile for MCP family in Virginia using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0006 x (branch height)^2] + [0.206 x (branch height)] + 53.561

to predict branch length from the independent variable branch height (a), and predicted Virginia high silviculture crown profile for clone MCP using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0008 x (branch height)^2] + [0.0.2992 x (branch height)] + 61.737

to predict branch length from the independent variable branch height (b).

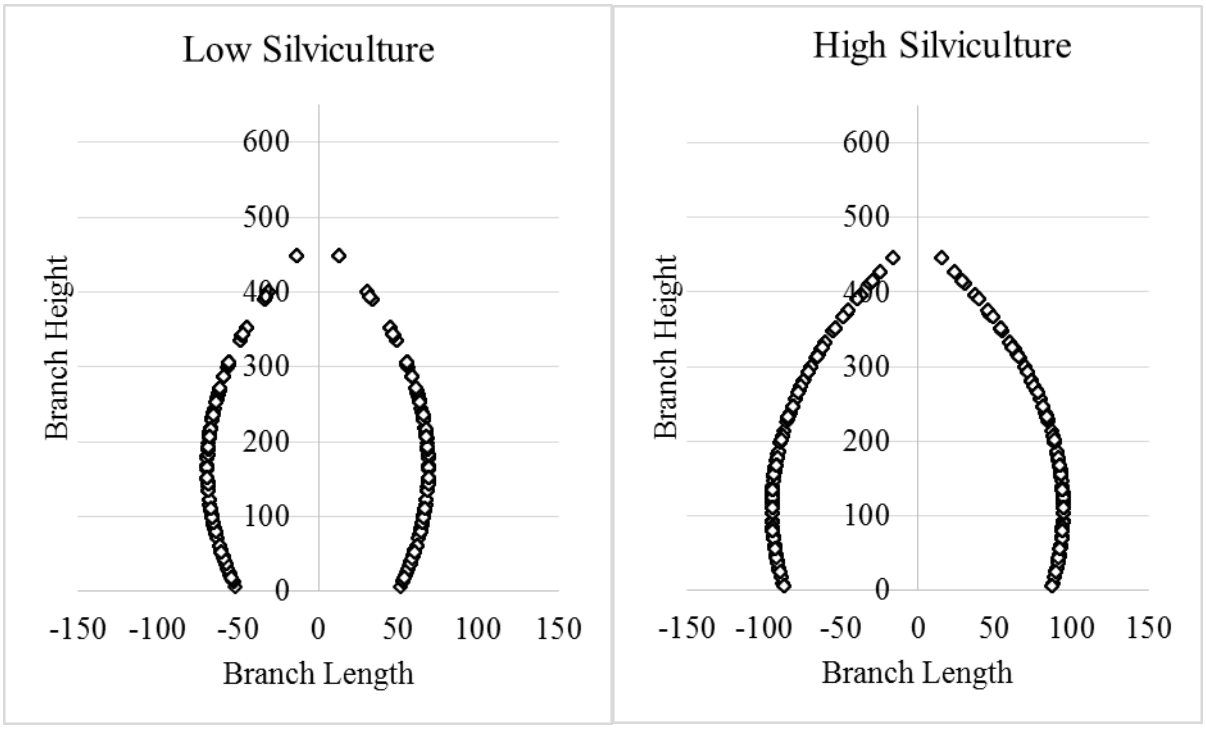

Figure A11. Predicted crown profile for MCP family in North Carolina using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0007 x (branch height)^2] + [0.2306 x (branch height)] + 50.194

to predict branch length from the independent variable branch height (a), and predicted North Carolina high silviculture crown profile for clone MCP using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0007 x (branch height)^2] + [0.0.1528 x (branch height)] + 86.419

to predict branch length from the independent variable branch height (b).

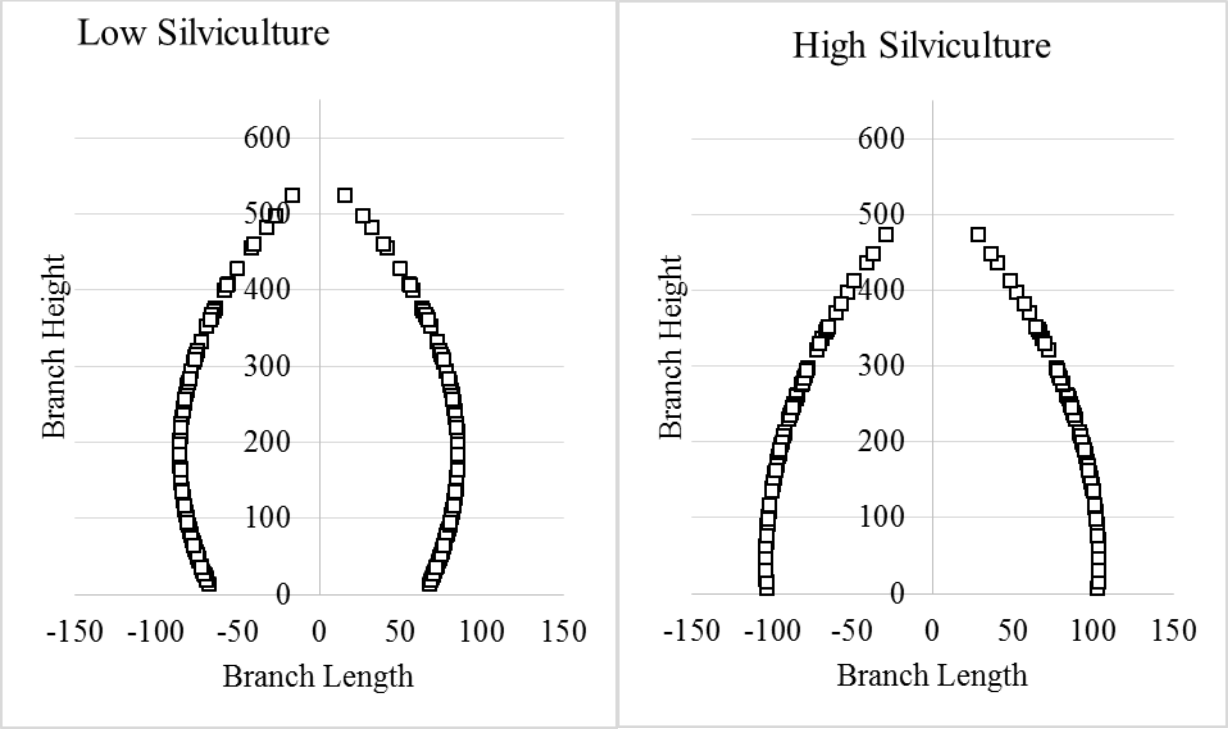

Figure A12. Predicted crown profile for OP family in Virginia using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0006 x (branch height)^2] + [0.221 x (branch height)] + 65.148

to predict branch length from the independent variable branch height (a), and predicted Virginia high silviculture crown profile for clone OP using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0004 x (branch height)^2] + [0.0.0315 x (branch height)] + 103.17

to predict branch length from the independent variable branch height (b).

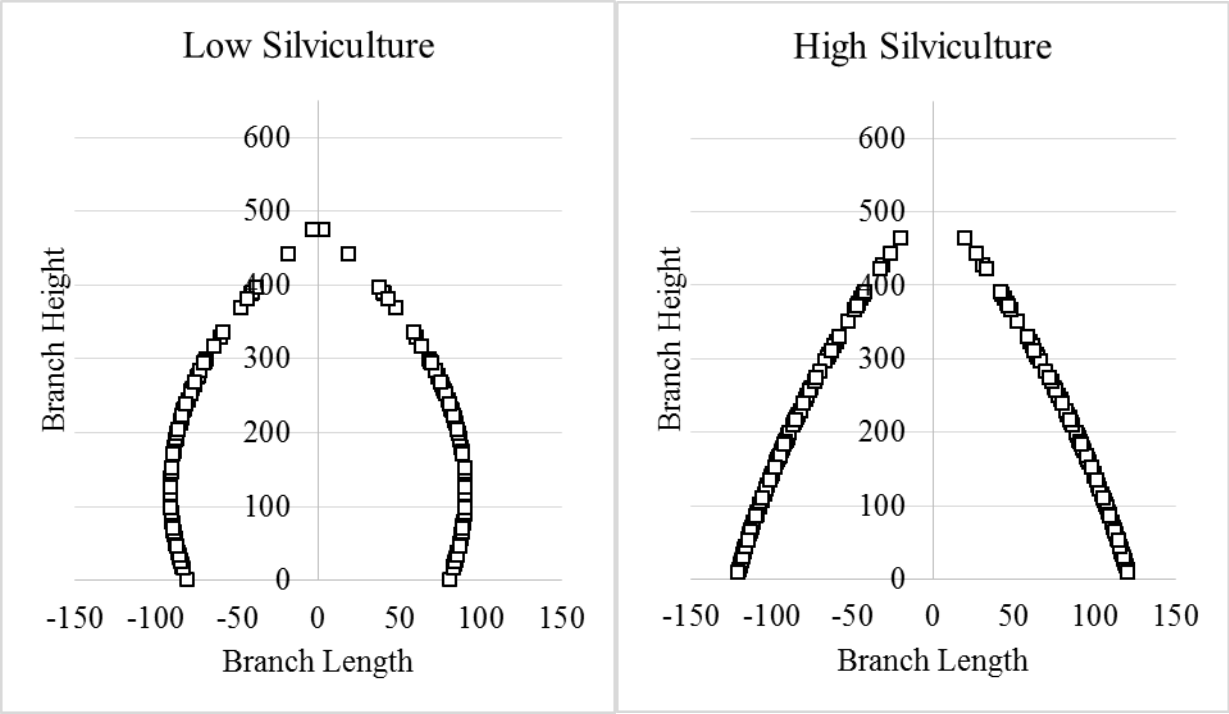

Figure A13. Predicted crown profile for OP family in North Carolina using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0007 x (branch height)^2] + [0.1682 x (branch height)] + 80.988

to predict branch length from the independent variable branch height (a), and predicted North Carolina high silviculture crown profile for clone OP using a polynomial regression analysis of branch length vs. branch height resulting in the 2nd order polynomial equation:

(branch length) = [-0.0002 x (branch height)^2] - [0.0.1276 x (branch height)] + 122.05

to predict branch length from the independent variable branch height (b).