ROTATION AGE ANALYSIS OF FIRST-GENERATION IMPROVED LOBLOLLY PINE (*PINUS TAEDA* L.) GENETICS WITH SILVICULTURAL INTERACTIONS

by

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(Under the Direction of Bronson Bullock)

ABSTRACT

Loblolly pine is the most commercially important southern pine species in the southeastern United States. Genetic improvement began in the 1950s and continues today with decisions on which families to move forward into the next generation being made based on early rotation growth gains. Few studies look at rotation age data to determine if these early observed gains are realized at harvest. Growth gains are also traditionally expressed as gains over unimproved stock, however, unimproved stock is no longer commercially planted. This research aims to create a new benchmark of comparison with a still commonly operationally planted first-generation open-pollinated loblolly pine family rather than the traditionally used unimproved stock and to further evaluate rotation age impacts of first-generation selections and their interactions with early silvicultural practices. Results concluded that appropriate silviculture is needed for improved genetic families to fully express their genetic potential. While gains can be seen due to genetics alone the combination of improved genetics and competition control yielded the greatest improvements in measures of growth and yield.

INDEX WORDS: Loblolly pine, improved genetics, first-generation, open-pollinated, diameter distribution, height-diameter relationship, Weibull distribution, mixed models, site index, GADA, rotation aged

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DEDICATION

I would like to dedicate this work to all of my friends and family that have supported me over the years. I would not be here without you guys!

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CHAPTER 1

INTRODUCTION

Loblolly Pine

Loblolly pine (*Pinus taeda*) is the most commercially important pine species in the U.S. with approximately 37 million acres planted in the Southeast (Farmer 2017). This species exhibits rapid juvenile growth, responds well to silvicultural treatments, artificial regeneration, and can be widely managed in a plantation setting. The wood is highly versatile and is commonly manufactured into a wide variety of products including pulp, lumber, and poles. The native range of loblolly pine extends through 14 states, however it is an adaptable species that has been successfully planted outside of its native range both in the United States and internationally, where it plays an important role in commercial forestry. The main limiting factors for growth in the northern part of its native range are low winter temperatures, ice damage, and cold damage during flowering, while its western range is limited by growing season precipitation. Drought is a major cause of mortality for planted loblolly pine seedlings, additionally prolonged flooding can also lead to seeding mortality (Burns and Honkala 1990).

Genetics

Early provenance studies showed differences in survival, growth, disease resistance, drought hardiness, and cold hardiness across the native geographical distribution attributable to the source of the seed; this led to recommended zones for seed collection and planting (Dorman and Zobel 1973, Wells and Wakeley 1966). Within these zones seed orchards were established starting in the 1950s, and at that time approximately 1.8 million acres of pine plantations were in operation in the U.S. South (Fox et al. 2007). With the installation of the first seed orchards came the first tree improvement programs in the South, their primary focus was on improving volume growth through increased height and diameter, tree form through straighter boles, disease resistance, and wood quality through better self-pruning and smaller branch diameter (Zobel and Talbert 1984). Due to the length of time required for breeding and testing, initial gains took many years to be realized. Seed from first-generation selections were not widely available for purchase and commercial deployment until the late 1960s to early 1970s (Fox et al. 2007).

Genetic improvement began with the establishment of seed production areas. Seed production areas were areas that had been identified as having a high-quality natural stand. These stands were then thinned to the best 10-20 trees per acre and managed for cone production. Estimated genetic gains were small, however, they were convenient and easy sources of above average trees within the growing zones. Growing zone recommendations are based on topography, climate, soils, vegetation, and existing plantation performance (Lantz and Kraus 1987). The first seed orchards of loblolly pine were primarily established by grafting. Parent trees were selected for growth, form, wood quality, and lack of obvious insect and disease symptoms, such as fusiform rust. Many tree improvement programs now have second-, third-, and even fourth-generation breeding cycles in progress (McKeand 2019a, Schmidtling 2001).

All planted loblolly pine seedings in the Southeast U.S. now originate from tree improvement programs (McKeand et al. 2006a). Loblolly pine seedlings on the market today fall into three classes of genetic improvement; open-pollinated, mass control pollinated, and clonal. Open-pollinated families, or half-sibling families, are families that generate from a known female tree, but the male pollen is unknown. Ideally the pollen comes from within the orchard and is another improved or selected superior tree, however pollen contamination by trees outside of the orchard is common, some estimates place the gene flow of neighboring stands to be greater than 30% (Friedman and Adams 1985). Mass control pollinated, or full-siblings, are families where both the female tree and the male pollen parent are known. This is accomplished by identifying the two desired parents, protecting the female flower from being exposed to undesired pollen by covering it with a specially designed paper bag, and then carefully collecting and introducing the desired pollen from another selected superior tree via a pollen injection. Once the cones have matured, the identified seeds are harvested. Clones are where a superior tree is identified and then through grafting, rooted cuttings, or other type of vegetative propagation techniques the target tree is exactly replicated, and all new individuals are exact genetic copies of the parent. A clonal propagation technique, somatic embryogenesis, it is an artificial process completed in a laboratory setting where one cell is processed and developed into plant tissue that is then replicated.

Landowners today have an unprecedented access to improved genetic material for establishing new pine plantations. Improvement does come with a cost, the highest performing full-sibling family can sell for more than four times that of open-pollinated and lower performing families (McKeand 2019b). Third-generation seedlings are currently the most advanced seedling generation available for purchase, however, depending on the land managers goals some first-generation open-pollinated selections are still being deployed in plantation settings. At this time unimproved stock is no longer being produced or planted.

Site preparation and stand management

Prior to the 1950's, commercial plantations were predominately limited to old fields and cutover sites and often had high mortality due to hardwood competition. The importance of the financial investment in site preparation became apparent when it was observed that plantations on old fields had improved growth versus cutover sites due to the residual fertilizer and lime in the soil and improved survival was noted with controlling hardwoods. The earliest forms of site preparation were mechanical means such as chopping, disking, and root raking intended to mimic conditions of the old fields (Balmer and Little 1978). Mechanical site preparation techniques intensified and diversified over the decades in pursuit of increased growth and yield, however in the 1980's concern arose not only of the high costs of mechanical site preparation but also of the effects of nutrient displacement and declines of second rotation stands. Around this time chemical site preparation began development and was found to be effective. Combined with the previous concerns of mechanical site preparations, and the lowered cost of the chemical site preparation techniques, and chemical site preparation techniques began to gain favor (Fox et al. 1989, Lowery and Gjerstad 1991, Tippin 1978, Vitousek and Matson 1985).

Management of plantations has continued to evolve rapidly over the past few decades with greater understanding of environmental and silvicultural effects on productivity and with improvements in information technologies. Today remote sensing measurements combined with spatial modeling tools have drastically altered how plantations are managed (Rubilar et al. 2018). Management now not only includes consideration for site preparations, competition control, and fertilization at time of establishment but also additional competition control, pest control, fertilizer, and thinning as mid-rotation treatments needed to support the crop trees through rotation with the goal of obtaining the largest economic return in the shortest time.

Unmanaged pine stands can take up to 50 years to mature into sawtimber sized trees however managed stands cut that time down to 25-40 years (Cunningham et al. 2008). Assuming the stand conditions of the earliest first-generation genetic selections were tending towards the 40-year rotation length, those trees would not have matured to sawtimber size until the late 1990s to the early 2000s. Second- and third-generation selections are just starting to mature or are still maturing and generally have not reached rotation age. Herein lies a significant hurdle for foresters and forestland managers to assess realized genetic gain and it is the reason rotation age analysis is still uncommon in the literature. Decisions on which genetics to recommend and stand management techniques to use are often based on plantation performance at young ages because waiting for full rotation performance information is not a feasible option. Progeny tests and mid-rotation analysis are the primary drivers of decision-making processes and models. Now that rotation age data are available from first-generation selection pine plantations, it is important to know if expectations for growth gains are being met.

Objectives

The overall objectives of this dissertations are to:

1) Characterize loblolly pine family OP 7-56 for the piedmont and coastal plain regions to establish an operationally relevant baseline of comparison for improved loblolly pine to aid forest land managers and owners in determining if improvement gains are being met.
2) Determine if effects of genetics, competition control, and the interaction of first-generation open-pollinated loblolly pine genetics and competition control have impacts through rotation age on measures of growth and yield.

3) Determine if variables for level of competition control and level of genetic improvement can improve the fit of a generalized algebraic difference approach site index model, used for estimating the average height of dominant and codominant trees at age 25 to estimate a sites potential productivity.

CHAPTER 2

ASSESSING STAND CHARACTERISTICS OF ENHANCED GENETICS IN LOBLOLLY PINE PLANTATIONS IN THE SOUTHEAST[1]

[1] Shockey, M., Bullock, B., Montes, C., Kane, M., De La Torre, R. To be submitted to *Annals of Forest Science*.

Abstract

Developing a benchmark of comparison among improved genotypes of loblolly pine (*Pinus taeda* L.) is important to quantify genetic gains as future selections aim to improve growth characteristics. Local wild seed checklots have been used as a benchmark but wild seed is no longer operationally planted or readily available. A well-performing, early selection, open-pollinated loblolly pine family would be a more meaningful baseline of comparison for forest land managers. This study characterizes a widely planted first-generation open-pollinated loblolly pine family, OP 7-56, across a range of sites and ages by describing diameter distributions and height-diameter relationships.

Diameter distributions were modeled using the two-parameter Weibull distribution as a function of the 25^{th} and 97^{th} percentiles of the distribution. The 25^{th} percentile had a pseudo-R^2 value of 0.985 and the 97^{th} percentile model had a pseudo-R^2 of 0.991. Height-diameter relationships models residual standard error of 1.1 m in the upper coastal plain and 1.128m in the lower coastal plain. A system of equations is presented using the derived models for diameter distributions and height-diameter relationships for the selected open-pollinated loblolly pine family of interest. To complete the system of equations, a volume equation was selected from existing literature to estimate volume per hectare.

Management and Policy

Genetic improvement is a continual process, having a baseline for comparison of expected stand characteristics to an operationally relevant family is of particular importance. Currently, growth gains are expressed as gains over a local unimproved checklot to the genetic entry where individual tree height and/or volume are used for expressing genetic gain. Having a more commonly planted baseline would be a more representative means of comparison, as the authors know of no organizations currently growing, selling, or planting unimproved loblolly pine stock. This research used a high-performing, first-generation open-pollinated loblolly pine family widely planted across the southeastern United States to develop a system of equations to establish a baseline of comparison to quantify if growth gain estimates are being met with current and future selections. The open-pollinated family used in this research is well known as a fast grower with relatively good stem form and rust resistance.

Introduction

Genetic selection and breeding of loblolly pine (*Pinus taeda*) began in the 1950's and has since become standard in southern forestry. As a direct result of the genetic gains from these efforts along with improved silvicultural practices, the productivity of pine plantations has significantly increased during this time period with mean annual increment doubling and rotation lengths being cut by over half (Fox et al. 2007). Harvesting of plantations containing open-pollinated progeny of first-generation selections began in the 1980's. Seed from these first-generation orchards on average produced 8-12% more volume at harvest than trees grown from wild seed (Fox et al. 2007). The estimated increase in value from these first-generation selections exceeds 20% when gains from other traits such as stem straightness are considered

(Squillace 1989, Todd et al. 1995). Nearly all of the planted loblolly pine seedlings in the southeastern United States now come from tree improvement programs (McKeand et al. 2003). Continued selection and breeding of trees exhibiting rapid growth and desirable characteristics such as resistance to fusiform rust, improved stem form, and desirable wood quality traits further improve the economic value of loblolly pine plantations (McKeand et al. 2006a).

There are hundreds of improved genetic loblolly pine families available to landowners and managers today. Most of these families are open-pollinated but full-sibling and varietal material are also available. Open-pollinated families are those where the mother tree is known while the father tree is unknown. In an ideal scenario the improved trees within the orchard are the only contributing members to the pollen cloud that fertilizes the female flowers, however in reality these pollen clouds often contain contaminating pollen from unimproved trees outside the orchard as well. Full-sibling families are where both the mother and father tree are known. The desired parents are identified, manually cross-pollinated via controlled pollination, and documented for accurate collection at seed maturity. Varietal material are clonal reproductions of a high performing trees in a controlled laboratory setting. Tree breeders aim to increase genetic gains by recurrent selection. In each new generation of selections, the objective is to improve the population. The general understanding to many is that second-generation is better than first, third is better than second and so on, however, there is substantial overlap in performance among families from one generation to the next and a third-generation selection is not necessarily superior to those that came before. Systems such as the Performance Rating System (PRS) from the North Carolina State University Cooperative Tree Improvement Program attempt to quantify performance traits for these different families so land managers can decide which genetic selection is best for their objectives (NCSU Cooperative Tree Improvement Program 2018).

As new selections and seedling families become available to land managers, a way to quantify the growth and yield gain will be needed. Waiting an entire rotation, 20-30 years or more, to obtain family specific yield gains would be the most accurate method, however, it is not practical. Due to the length of time it takes for a stand to mature in the southeastern United States, few studies have looked at genetically improved families at maturity to evaluate and characterize stand properties to see if developmental gains observed at early ages in progeny tests, typically aged 5-6 years, carry through and result in proportional gains in growth and yield at rotation age. Models, most typically, are based on data collected at these early ages to make estimates at maturity (McKeand et al. 2006a, McKeand et al. 2006b).

Understanding and characterizing diameter distributions is essential when evaluating the potential growth gains of improved genetic families. Diameter distributions provide size class information that enables the evaluation of stand yield. Using the Weibull distribution in modeling diameter distributions was first introduced by Bailey and Dell (1973) because of its flexibility and ease of producing probabilities without the need for numerical integration. Bullock and Burkhart (2005) found that modeling diameter distributions of juvenile loblolly pine using the two-parameter Weibull function was an adequate solution. Several other distributions were initially considered in their analysis including the three-parameter Weibull, Normal, Lognormal, Gamma, and Johnson S_b distributions. However, goodness-of-fit criteria and the ease of parameter estimation led to the selection of the two-parameter Weibull distribution. The flexibility of the Weibull distribution to assume a variety of unimodal shapes makes it a desirable distribution to use for estimating diameter distributions. Numerous treatments can affect diameter, data in this study combine both control and treatment observations to estimate these overall distributions. Predictive ability for these diameter distributions are limited to the geographical range of the data, Figure 2.1.

Height-diameter relationships are another useful tool for evaluating potential growth gains. Tree height is an essential and informative measurement; however, measuring the height of a tree is more time consuming and expensive than measuring diameter at breast height (dbh). Once a stand reaches crown closure, factors such as stems per unit area and high leaf area can make seeing the top of the tree difficult, potentially introducing errors into measurements (Arabatzis and Burkhart 1992, Carlson et al. 2009). Being able to quickly and accurately predict heights given a dbh is a highly desired deliverable for land managers.

Two types of height-diameter models exist: those that express the height as a function of tree diameter alone and models that include additional stand-level predictors in the model (Mehtatalo et al. 2015). Both model types can be expressed as linear and non-linear functions. Traditionally, linear functions were preferred for ease of model fitting. With current computing power and available software programs, non-linear functions are no longer cumbersome to fit. Considerable time and research effort has been spent on modeling height-diameter relationships over the years (Arabatzis and Burkhart 1992, Buford and Burkhart 1987, Egbäck et al. 2015, Mehtatalo et al. 2015, Sabatia and Burkhart 2013a, Sabatia and Burkhart 2013b). Some of the early work modeling height-diameter relationships of genetically improved loblolly pine stand characteristics found that at the family level, the shape of the height-diameter relationship at a given age was influenced by initial density (Buford and Burkhart 1987). A more recent study of loblolly pine at age six found that there were significant effects for the asymptote and slope parameters due to genetics, but that spacing only had a significant effect on the slope (Egbäck et al. 2015). No interactions between spacing and genetic background were found, suggesting that height-diameter relationships across spacings remained stable for different families.

The objective of this study was to characterize diameter distributions, and height-diameter relationships of an operationally commonly planted first-generation open-pollinated loblolly pine family, OP 7-56, in the upper and lower coastal plain region of Georgia and South Carolina.

Methods

Five long term Plantation Management Research Cooperative (PMRC) research studies were used for this analysis. Though these five trials are independent studies, their use in one meta-analysis was deemed appropriate because all trials were measured by the PMRC field crew. This ensures that while the studies themselves vary; the data collection methods are consistent. All studies had at least one block plot planted entirely with OP 7-56 with repeated measurements over time. The selected studies represent a wide geographical range and are located in the upper coastal plain and lower coastal plain of Georgia, South Carolina, and Florida, Figure 2.1. The upper coastal plain had over 12,000 individual tree records over time and the lower coastal plain had over 87,000 individual tree records over time. While the lower coastal plain has a much larger dataset it was determined the approximately 12,000 records in the upper coastal plain were sufficient for modeling efforts.

Silvicultural management varied greatly among the different studies since they were all initially designed for other research objectives Table 2.1. Some plots that served as control plots for their study received no silvicultural inputs beyond initial site preparation, some received operational level of competition control and/or fertilizer, and others received annual fertilizer and/or competition control applications for the length of the study. Planting densities ranged from 741 trees per hectare (tph) to 4446 tph, with all data being collected from non-thinned research plots in loblolly pine plantations. If a plot was thinned at any age, that age and all subsequent data were removed from analysis and only the prior unthinned measurements were used.

Summary statistics were calculated for each block plot within each treatment over all study sites for each age where data was available. Plot size varied from 0.027 ha to 0.107 ha in size. Due to the varying plot size summary stats for basal area were calculated and compared at the per hectare level. The plot level data were used in modeling to establish a baseline of comparison using the improved open-pollinated loblolly pine family from these research trials as a means of comparison among other genetically improved families.

A two-parameter Weibull distribution was fit to each plot at each age to characterize the diameter distribution and a Kolmogorov-Smirnov test was performed to determine if each of the plot samples probability distribution was statistically significantly different than a Weibull distribution of the fitted parameters The two-parameter Weibull distribution was chosen because it can assume a variety of shapes, so it is desirable to describe the data at early ages where the distribution can be relatively uniform, and at later ages where more variation and skewness is inherently present in the data (Miguel et al. 2010). To estimate the shape and scale parameters of the two-parameter Weibull distribution, methods from Bullock and Burkhart (2005) research in juvenile loblolly pine were used. Their methods suggest estimating the empirical 25^{th} and 97^{th} dbh percentiles, modeled as a function of the stand descriptors; basal area per hectare (ba), tph, and age (A), (Equation 1, Equation 2). Equation 1 and Equation 2 were fit to each plot's observed 25th and 97th percentile values to provide a way to estimate these percentiles when no observations are available.

Parameter recovery methods were used to estimate the shape, (Equation 3) and scale parameters (Equation 4) using the 25th and 97th percentiles of the empirical diameter distributions and quadratic mean diameter.

$$ln(\widehat{D}_{25}) = \hat{\beta}_1 + \hat{\beta}_2 * ln\left(\frac{ba}{tph}\right) + \hat{\beta}_3 * (A) \quad (1)$$

$$ln(\widehat{D}_{97}) = \hat{\beta}_1 + \hat{\beta}_2 * ln\left(\frac{ba}{tph}\right) + \hat{\beta}_3 * ln(A) \quad (2)$$

$$\hat{c} = \frac{2.500534}{ln(\widehat{D}_{97}) - ln(\widehat{D}_{25})} \quad (3)$$

$$\hat{b} = \sqrt{\frac{(\overline{D}_q)^2}{\Gamma\left(1 + {}^{2}/_{\hat{c}}\right)}} \quad (4)$$

Where,

$\hat{c}$ = Shape parameter

$\hat{b}$ = Scale parameter

$\widehat{D}_i$= The ith percentile of the diameter distribution, i = 25, 97

$\overline{D}_q$= Quadratic mean diameter, cm

Γ = Gamma Function

ln(·) = The natural logarithm

ba = Basal area, m^2/ha

tph = Trees per hectare

A = Age, years

Once the empirically estimated shape and scale parameters were obtained for each plot, a Kolmogorov-Smirnov (KS) goodness-of-fit test was used to determine if the dataset significantly differs from a general Weibull distribution with those same parameters. The KS test is a non-parametric and distribution free test, with the null hypothesis of no significant difference between the empirical distribution and the hypothetical distribution (Massey Jr. 1951).

Height-diameter relationships were characterized for each physiographic region as a function of intensity of silvicultural management, site index (SI), dbh, age, and tph, based off a model from Bennett (1968) (Equation 5). SI was estimated using existing PMRC formulas (Borders et al. 2014). Management was classified into three categories: low, moderate, and high. Low management inputs were sites that had only site preparation as silvicultural inputs, moderate management were sites that had operational levels of fertilizer and/or competition control applied, and high management stands were sites that were intensively managed so that the stand was not nutrient limited and/or was under no competition from hardwoods or waxy leaved species at any point during the stand's lifetime. To determine if an indicator variable was necessary for the management term, Equation 5 was fit to the full dataset and to three subsetted datasets, one representing each of the management intensity categories. An F-test performed on the four resulting fitted models indicated that variances between all models were significantly different. Therefore, a categorical variable, management intensity (MI) was created. The terms MI_{mod} and MI_{high} function as dummy variables. If management intensity is low then both b_1 and b_2 in Equation 5 are 0, if management intensity is medium or high, the respective b_i becomes 1, while the other b_i is 0, thereby adjusting the intercept of the model accordingly for the different management levels.

$$\widehat{Ht}_{adj} = \left(\hat{\beta}_1 + \hat{\beta}_2 * MI_{mod} + \hat{\beta}_3 * MI_{high}\right) + e^{\left(\hat{\beta}_4 + \hat{\beta}_5 SI + \hat{\beta}_6 \frac{tph}{1000} + \hat{\beta}_7 \frac{1}{A} + \hat{\beta}_8 \frac{1}{dbh}\right)} \quad (5)$$

Where,

ht_{adj} = total tree height minus 1.3716 m

MI_{mod} = operational levels of silviculture applied (fertilization and/or herbicide)

MI_{high} = intensive levels of silviculture applied (fertilization and/or herbicide)

SI = site index

tph = the number of trees per hectare.

A = current age

dbh = diameter at breast height

If management inputs or site index is not known for a given stand, a reduced model can be used, (Equation 6). Equation 7 was also fit to the data along with several other height-diameter model forms to determine if they would accurately predict ht_{adj} for this dataset.

$$\widehat{ht}_{adj} = e^{\left(\hat{\beta}_1 + \hat{\beta}_2 \frac{tph}{1000} + \hat{\beta}_3 \frac{1}{A} + \hat{\beta}_4 \frac{1}{dbh}\right)} \quad (6)$$

$$ln\left(ht_{adj}\right) = \hat{\beta}_1 + \hat{\beta}_2 dbh^{-1} \quad (7)$$

Once diameter distribution and height-diameter relationships were fit, volume estimation per hectare was calculated using a volume equation. Following the methods of Sherrill et al. (2011), diameter and height (ht) was used in a combined-variable approach to model stem volume of open-pollinated loblolly pine in the coastal plain of the southeastern United States to estimate total outside bark volume ($\hat{V}_{tob}$), Equation 8. Appropriate unit conversions and expansion factors were applied as needed to get values on a per hectare basis. Measures of sawtimber potential were not consistently available across all studies so stem quality was not taken into account.

$$\hat{V}_{tob} = 0.20571 + 0.00237(dbh^2 ht) \qquad \textbf{(8)}$$

Model validation was the final step to ensure that the presented models, when used in combination as a system of equations, were accurate. Volume per hectare was estimated for each plot using the original empirical data. During field-measurement efforts of the five trials, the height of every third tree was collected. For records with an observed height recorded, that value was used for validation. For the records in which an observed height was not recorded, an existing PMRC height equation was used to predict height (Borders et al. 2014). The presented system of equations was used to predict volume per hectare for the same plots using only known stand level characteristics. The Reynold's Error Index, a weighted sum of the absolute differences between predicted and observed values, was used to evaluate the goodness-of-fit (Reynolds et al. 1988). The Reynolds Error Index will allow relative comparisons across time. The oldest ages will inherently have larger volume when compared to the younger ages and as such have the potential for larger residuals which skews direct comparisons.

Results

Summary statistics of the empirical estimations for fitting the two-parameter Weibull distribution for each plot are given in Table 2.3 through Table 2.6. As expected, both the shape and scale parameters increase with age. The KS goodness-of-fit statistic, at an alpha-level of 0.10, determined that the observed data did not significantly differ from the fitted distribution for the majority of the plots, therefore a two-parameter Weibull distribution was an appropriate distribution to use to characterize the data.

Equation 1, had an R^2 value of 0.994 and a residual standard error of 0.053 cm and Equation 2, had an R^2 of 0.994 and a residual standard error of 0.044 cm, (Figure 2.2 and Figure 2.3). Figure 2.4 and Figure 2.5 show the predicted shape and scale parameters versus the empirically estimated parameters over all plots and ages.

The height-diameter model, Equation 5, had a residual standard error of 1.081 m in the upper coastal plain and 1.08m in the lower coastal plain, (Figure 2.6). The residual standard error of the reduced model, Equation 6, using only dbh, tph, and age is 1.385 m for the upper coastal plain and 1.442 m for the lower coastal plain (Figure 2.7). A height-diameter equation relying on only diameter poorly characterized the relationships for this dataset, Equation 7, and had a R^2 value of 0.6138 for the upper coastal plain and 0.5432 for the lower coastal plain. The predicted heights associated with the tallest trees were highly under predicted, thus underestimating volume as well. Coefficients for all models can be found in Table 2.8. The average Reynold's error index for volume per hectare for the upper coastal plain was 4.8% and the lower coastal plain had a mean of 4.1% (Figure 2.8). All tables and figures have been converted to English units and can be found in Appendix A.

Application

To facilitate use of this system of equations, an example application is presented. Assume we had a stand that was known to be 20 years old, estimated SI of 25 m, managed at a moderate intensity, with a current tph of 1600, and a ba of 45 m^2/ha in the lower coastal plain. The 25^{th} and 97^{th} percentiles are estimated from Equation 3 and Equation 4, respectively.

$$ln\left(\widehat{D}_{25}\right) = 4.9858429 + 0.5706826 * \ln\left(\frac{45}{1600}\right) - 0.0091234 * ln(20) \quad (9)$$

$$\left(\widehat{D}_{25}\right) = 15.89\ cm$$

$$ln\left(\widehat{D}_{97}\right) = 4.310541 + 0.407139 * ln\left(\frac{45}{1600}\right) + 0.121113 * ln(20) \quad (10)$$

$$\left(\widehat{D}_{97}\right) = 25.01\ cm$$

The shape parameter is estimated from Equation 3 using the predicted percentiles (Equation 9 and Equation 10).

$$\hat{c} = \frac{2.500534}{ln(25.01) - ln(15.89\ )} = 5.5076 \quad (11)$$

The scale parameter is estimated from Equation 4, using the quadratic mean diameter for the stand, the predicted shape parameter, and the Gamma function. The quadratic mean diameter can be obtained from the mean basal area of the stand or from the current trees per hectare and basal area per hectare estimates: for this example, assume a quadratic mean diameter of 18.9 cm.

$$\hat{b} = \sqrt{\frac{(18.9)^2}{\Gamma(1 + 2/5.5076)}} = \sqrt{\frac{358.2803}{0.889901}} = 20.0651 \quad (12)$$

The predicted two-parameter Weibull cumulative distribution function (*cdf*) is then given by:

$$F(x) = 1 - exp\left[-\left(\frac{x}{20.0651}\right)^{5.5076}\right] \quad (13)$$

The proportion of trees per hectare in the 20 cm diameter class (2-cm classes) is obtained by subtracting the lower diameter class limit *cdf* from the upper diameter class limit *cdf*.

$$TPH_{20} = \text{F}(21.0) - \text{F}(19.0) \qquad \textbf{(14)}$$

$$TPH_{20} = \left\{1 - exp\left[-\left(\frac{21.0}{20.0651}\right)^{5.5076}\right]\right\} - \left\{1 - exp\left[-\left(\frac{19.0}{20.0651}\right)^{5.5076}\right]\right\}$$

$$TPH_{20} = (0.7234 - 0.5231) = 0.2002$$

Where,

tph_{20} = the proportion of trees in the 20 cm diameter class

From Equation 12, we know that 20.02% of the trees per hectare fall into the 20 cm diameter class for this stand. Multiplying the current estimated stand density of 1600 TPH by the derived proportion we conclude that approximately 321 trees per hectare fall in the 20 cm diameter class. Using Equation 5 we can estimate the average height for a 20 cm diameter tree.

$$\widehat{ht}_{adj} = (1.42 - 0.27 * 1 + 0.71 * 0) + e^{\left(3.37 + 0.02*25 - 0.03\frac{1600}{1000} - 10.08\frac{1}{20} - 9.61\ \frac{1}{20}\right)} \qquad \textbf{(15)}$$

$$\widehat{ht}_{adj} = 18.22\ m$$

$$ht = 19.59m$$

Using the total outside bark volume equation from Sherrill et al. (2011) and converting appropriately, it can be estimated that for a tree in the 20 cm diameter class, with an average total height of 16.87m, the outside bark volume is 0.2361 m^3 per stem. Since it was already estimated that 321 stems per hectare reside in the 20 cm diameter class, it can be calculated that there is approximately 75.79 m^3/ha of volume in the 20 cm diameter class. For comparison of the three height models using this hypothetical stand see, Table 2.9. All other diameter classes are similarly calculated to create a full stand and stock table.

The presented system of equations using each of the different height equations was used to predict the total stand volume, Equation 5 estimated 491 m^3/ha, Equation 6 estimated 511 m^3/ha, and Equation 7 estimated 343 m^3/ha, illustrating the impact of the height-diameter equation has on predicted volume. Results have been converted to English units and can be found in Appendix A.

Discussion

Currently in southeastern United States forest management, genetic gains in growth are expressed as a percent increase above a local wild seed checklot. Wild seed is no longer operationally planted so we propose using a system of equations based on a commonly planted open-pollinated loblolly pine family, OP 7-56, as a benchmark of comparison. The system of equations uses the 25th and 97th diameter percentiles to predict shape and scale parameters of the two-parameter Weibull distribution, allowing for reliable estimates of stand diameter distributions. Height-diameter relationships for a stand can be developed using an estimated diameter and age; however, if silvicultural inputs and site index are known, estimates can be improved. Once diameter distributions and height-diameter relationships are established for a given stand, it is then possible to estimate volume per hectare for the stand to be used for comparison. Data used for these modeling efforts came from five independent studies not originally designed for this analysis but were deemed appropriate for use due to all trials being measured by the same field crew which provides data structure and measurement consistency. However due to variations in the timing of each studies data collection protocols plot numbers across time vary. Thinning and harvesting regimes over time drastically reduce the number of plots above age 20 compared to earlier ages. Therefore, caution should be used when applying this system of equations outside the geographical and temporal range of the data used in the model fitting process. While the lower coastal plain had over 87,000 individual tree records over time, the upper coastal plain only had a little over 12,000. Even though the data locations are unbalanced we still feel like 12,000 records can produce a robust system of equations for the upper coastal plain. This system of equations also does not consider, nor does it try to make predictions for the stem quality, and specific product distribution of the volume being estimated. Empirically within this dataset at harvestable ages, around half of the trees were observed to have had some notable defect such as rust, forking, crook, sweep, excessive branching, or broken top that would have prevented the trees from becoming sawtimber.

Conclusions

A system of equations to predict diameter distributions and height-diameter relationships of a commonly planted open-pollinated family, OP 7-56, of loblolly pine in the upper coastal plain, and lower coastal plain, of Georgia, South Carolina, and Florida were developed using dbh, basal area, trees per hectare, age, site index, and management intensity. A two-parameter Weibull distribution is flexible enough to describe diameter distributions throughout the stand's life from the relatively uniform early years to rotation age where more variation and skewness is inherently present. A slightly modified formula from Bennett (1968) is used to predict height-diameter relationships using management, site index, density, age, and dbh, all readily available information for most stands.   This system of equations is recommended as an operational benchmark of comparison for families of improved loblolly pine. Rather than describing potential growth gains over an unimproved local checklot, stand-level gains can now be compared to a commonly planted open-pollinated, first-generation family.

Table 2.1.Study methods of each of the five trials in this study.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Year Planted	1996	2007	1987	2001, 2003, 2005	1987
Planting TPH	741, 1482, 2223, 2965, 3706, 4447	1074, 1793	1682	958, 1121, 1280	1853
Ages of data collection	2, 4, 6, 8, 10, 12, 15, 16, 17, 18, 21	2, 4, 6, 8	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 23, 25, 27, 29	4, 5, 7, 8, 9, 10, 11, 13, 15	3, 6, 9, 12, 15, 18, 21, 25
Site Preparation	Bed + chemical	Chemical	Operational site prep	(1) shear and bed + chemical (2) bed + chemical (3) drummed and bedded (4) shear and chop	Applied by cooperator prior to planting. (1) Lower Coastal Plain: primarily bedding (2) Upper Coastal Plain: ranged from chop and burn to shear, rake, and disc
Fertilization	(1) Operational application of competition control and fertilizer (2) Intensive application: annual application of competition control, and additional fertilization in first two growing seasons	Applied first growing season	(1) Control: no treatments (2) Fertilization: Yearly application for entire length of study, additional mid-summer treatment applied first two growing seasons (3) Herbicide: complete vegetation control for entire length of study (4) Fertilization and herbicide - combination of the fertilization and herbicide treatments	None	None
Competition Control		Herbaceous weed control applied first two growing seasons		(1) None (2) Applied first growing season	(1) None (2) Complete control of all competing vegetation: spraying in first three growing seasons and targeted application as needed yearly after

Table 2.2. Research trials grouped by management intensity.

Management intensity	Studies with at least one plot treated at management level
Low	Trial 3 Trial 4 Trial 5
Moderate	Trial 1 Trial 2 Trial 4 Trial 5
High	Trial 1 Trial 3

Table 2.3 Empirical summary statistics for the two-parameter Weibull distribution for research Trial 1[1]. The number of plots decreases over time due to mortality events, thinning activity, or harvesting activity.

		DBH 25th quantile (cm)			DBH 97th quantile (cm)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
4	201	6.57	1.27	12.19	9.72	5.08	15.92	6.05	1.74	14.04	7.96	2.91	13.70
6	192	9.68	4.57	17.53	13.81	8.87	21.53	6.80	2.36	13.26	11.51	6.16	19.23
8	192	11.54	6.10	20.57	16.52	11.09	25.54	6.79	3.50	12.19	13.77	8.23	22.49
10	180	13.06	7.37	23.37	18.87	12.92	31.13	6.69	3.50	12.25	15.67	10.03	26.76
12	168	14.22	7.62	26.23	20.84	13.72	35.60	6.53	3.45	12.52	17.20	10.60	29.93
15	155	16.23	8.83	27.43	24.02	16.00	40.19	6.42	3.62	13.98	19.73	12.40	32.21
16	46	16.80	9.65	25.91	25.23	18.13	34.54	6.36	4.14	9.43	20.68	13.52	29.85
17	44	18.13	9.65	25.65	27.08	18.81	35.10	6.51	3.80	12.65	22.29	13.70	30.77
18	153	17.86	9.72	30.86	26.73	18.06	43.22	6.21	3.52	14.29	21.86	13.92	36.13
21	128	19.98	11.18	33.02	29.81	20.24	45.70	6.31	3.55	11.55	24.45	15.52	39.14

[1] Across all ages, n=1258 plots.

Table 2.4. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 2[1]

		DBH 25th quantile (cm)			DBH 97th quantile (cm)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
2	6	6.56	5.84	7.11	9.15	8.38	9.96	7.25	6.53	8.78	7.80	7.17	8.42
4	6	11.61	10.16	13.72	15.47	13.76	16.71	8.30	7.22	9.74	13.30	11.97	14.99
6	6	14.23	12.19	16.51	19.16	17.42	20.97	8.37	7.17	10.35	16.32	14.67	18.35
8	6	15.86	13.34	18.29	21.65	19.20	23.62	7.86	6.57	9.67	18.34	16.26	20.64

1 Across all ages, n=24 plots.

Table 2.5. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 3[1]. The number of plots increased from age 3 to age 4 as the trees reached heights over 1.3m. After age 11 the plot number gradually decreases over time due thinning and harvesting.

		DBH 25th quantile (cm)			DBH 97th quantile (cm)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
4	66	6.05	1.02	10.67	8.90	4.06	14.13	6.14	1.91	12.60	7.29	2.38	12.13
5	66	8.50	2.54	12.70	11.97	7.11	16.68	7.08	2.35	13.31	10.03	4.59	14.02
6	66	10.28	4.32	13.97	14.21	9.40	17.69	7.45	3.05	13.65	12.01	6.64	15.30
7	66	11.71	5.59	14.99	16.13	10.40	19.56	7.63	3.41	13.39	13.67	7.92	17.03
8	66	12.78	6.54	16.26	17.50	11.43	21.52	7.65	3.69	13.32	14.86	9.08	18.85
9	66	13.66	7.62	17.72	18.85	12.70	23.58	7.53	3.68	12.08	15.94	10.04	20.54
10	66	14.38	8.38	19.30	19.95	13.46	26.34	7.52	3.81	12.34	16.82	10.72	22.73
11	66	14.92	8.89	20.07	20.95	14.46	28.12	7.34	3.85	11.30	17.55	11.42	24.02
12	62	15.48	9.78	21.08	21.88	14.99	29.79	7.10	4.24	10.36	18.30	12.16	25.29
13	62	15.95	10.03	21.34	22.72	15.50	30.22	7.00	4.09	10.00	18.97	12.74	25.90
14	62	16.40	10.29	22.35	23.46	16.26	31.94	6.91	4.24	9.69	19.53	13.18	27.30
15	62	16.81	10.29	22.80	24.24	17.03	33.17	6.86	4.13	9.29	20.10	13.73	27.90
16	62	17.23	10.54	23.50	25.02	17.28	34.23	6.73	4.16	9.26	20.71	13.98	28.66
17	58	17.79	10.73	23.62	25.94	18.05	35.43	6.61	3.97	9.02	21.41	14.44	29.34
18	58	18.17	10.92	25.15	26.57	18.33	36.39	6.60	3.87	9.55	21.92	14.88	29.87
19	54	18.73	10.99	25.40	27.50	19.08	36.72	6.47	3.73	9.40	22.62	15.18	30.48
20	54	18.94	11.24	26.04	28.01	19.56	36.96	6.39	3.68	9.38	22.96	15.50	30.70
21	38	18.95	11.43	26.86	28.27	19.57	37.63	6.21	3.66	9.01	23.11	15.63	30.92
23	38	19.42	11.94	27.94	29.52	21.38	38.06	6.01	3.44	9.04	23.97	16.56	31.87
25	8	20.52	12.00	27.75	31.08	22.86	39.77	6.13	3.29	8.77	25.30	17.52	33.41
27	12	23.47	20.51	29.08	34.09	28.68	42.19	6.58	5.78	8.50	28.38	24.14	34.97
29	8	24.49	21.21	29.97	35.03	29.98	43.38	6.78	5.88	8.50	29.40	25.10	36.02

[1] Across all ages, n=1120 plots.

Table 2.6. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 4[1]. The plots that are included in this study had different measurement schedules, so n varies over time based on data collection.

		DBH 25th quantile (cm)			DBH 97th quantile (cm)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
5	9	8.88	6.60	10.41	12.79	10.92	14.03	6.33	3.28	8.30	10.68	9.52	11.96
7	10	11.85	6.86	16.45	15.79	11.21	21.59	7.95	4.92	10.64	13.59	9.05	18.41
8	6	14.55	12.26	16.76	20.50	18.88	22.53	6.77	4.05	9.06	17.23	16.44	18.58
9	7	14.93	13.84	16.26	19.96	19.21	20.97	8.27	7.17	10.04	17.20	16.36	18.13
10	4	17.94	16.64	19.69	23.96	22.61	25.87	7.92	6.36	9.46	20.46	19.68	22.05
11	12	15.57	12.70	17.97	21.14	17.95	24.64	7.71	4.18	11.46	18.16	15.37	20.31
13	15	17.50	14.86	21.34	23.21	21.19	28.19	8.44	6.06	11.81	20.11	17.86	24.11
15	5	16.98	15.24	18.92	22.79	21.76	24.00	7.86	6.81	9.14	19.53	18.40	20.97

[1] Across all ages, n=77 plots.

Table 2.7 Empirical summary statistics for the two-parameter Weibull distribution for research Trial 5[1].

		DBH 25th quantile (cm)			DBH 97th quantile (cm)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
6	7	8.12	4.57	11.43	12.18	8.05	16.48	5.83	3.90	8.41	9.88	5.89	13.11
9	7	10.84	8.13	14.03	16.18	12.51	20.27	5.88	4.14	7.93	13.19	10.25	16.31
12	7	12.66	10.16	15.75	19.13	15.54	23.98	5.76	3.95	7.47	15.45	12.42	18.38
15	7	13.90	11.43	17.02	21.65	17.78	26.94	5.47	3.89	7.17	17.23	13.86	20.11
18	7	14.75	12.19	17.78	23.50	19.30	29.25	5.39	4.15	7.63	18.55	15.01	21.40
21	6	16.07	13.97	18.54	25.91	23.86	31.38	5.45	4.35	7.41	20.43	18.88	22.76
25	6	17.88	15.75	19.75	28.15	25.65	33.99	5.74	4.48	6.80	22.40	20.72	25.16

[1] Across all ages, n=54 plots.

Table 2.8. Coefficients of presented equations. Region appropriate coefficients are given for Equations 5, 6, and 7.

			UCP			LCP		
	Equation 1	Equation 2	Equation 5	Equation 6	Equation 7	Equation 5	Equation 6	Equation 7
$\hat{\beta}_1$	4.9858	4.3105	1.4225	3.7714	2.5983	2.3375	3.6329	2.8139
$\hat{\beta}_2$	0.5707	0.4071	-0.2703	-0.0103	-4.4635	-0.1232	0.0255	-5.5420
$\hat{\beta}_3$	-0.0091	0.1211	0.7091	-7.6394		0.5511	-5.7955	
$\hat{\beta}_4$			3.3747	-7.9708		3.0402	-7.3678	
$\hat{\beta}_5$			0.0187			0.0233		
$\hat{\beta}_6$			0.0273			0.0557		
$\hat{\beta}_7$			-10.0813			-9.2242		
$\hat{\beta}_8$			-9.6083			-8.0775		

Table 2.9. Practical application of the system of equations presented for a hypothetical stand in the upper coastal plain where SI=25, TPH=1600, A=20, BA=45, and MI=moderate. The respective equations were used to predict the height in meters of a tree in each D-class. The predicted Weibull distribution parameters were used to estimate the D-class distribution. Volume per hectare estimates were based on each of the three different height equations and one common individual tree volume equation.

		Height (m)			Volume (m^3/ha)		
D-class	**D-class Distribution**	**Equation 5**	**Equation 6**	**Equation 7**	**Using Ht Equation 5**	**Using Ht Equation 6**	**Using Ht Equation 7**
8	0.90%	14.1	14.4	10.4	0.70	0.71	0.55
10	2.38%	16.0	16.5	11.4	2.95	3.02	2.24
12	5.17%	17.4	18.1	12.3	9.45	9.77	6.98
14	9.49%	18.6	19.4	12.9	24.23	25.12	17.52
16	14.81%	19.6	20.5	13.4	50.47	52.47	35.92
18	19.26%	20.5	21.4	13.8	84.66	88.17	59.50
20	20.02%	21.2	22.1	14.2	110.45	115.18	76.83
22	15.67%	21.8	22.8	14.5	106.12	110.76	73.19
24	8.50%	22.3	23.3	14.7	67.86	70.84	46.76
26	2.89%	22.7	23.8	15.0	27.98	29.25	19.05
28	0.54%	23.1	24.2	15.1	6.12	6.40	4.15
	99.63%[1]			**Total**	**490.99**	**511.69**	**342.69**

[1] Due to small proportions in D-classes less than 8 cm and greater than 28 cm, total does not equal 100%.

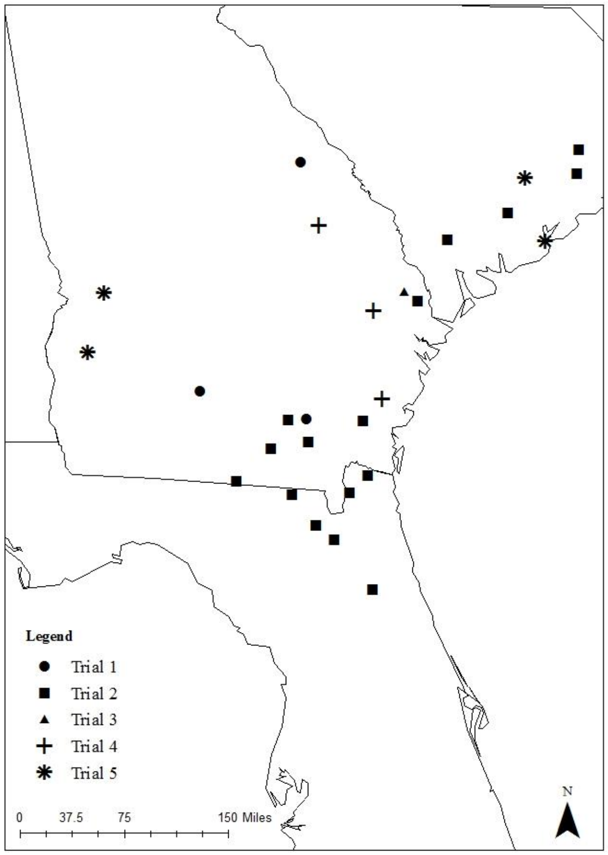


Figure 2.1. Location of research trials with the open-pollinated loblolly pine family of interest.

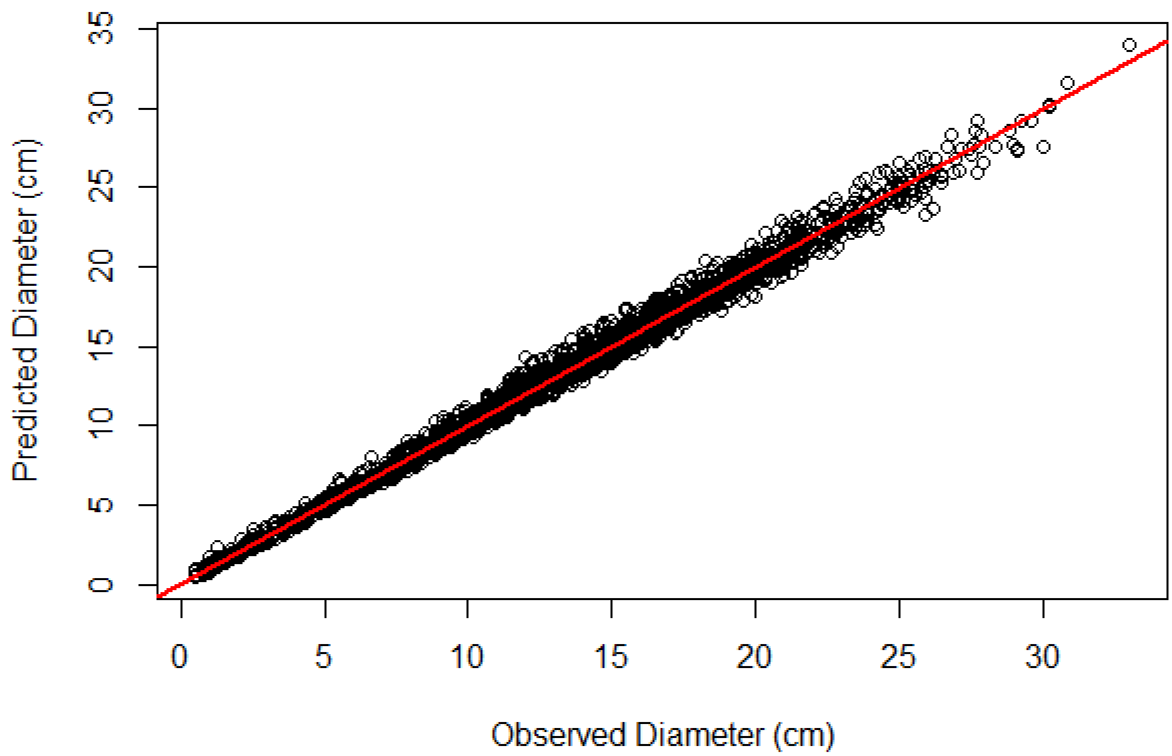


Figure 2.2. Predicted vs. observed data points for the 25th DBH percentile (cm) for all plots (Equation 1). A 1:1 relationship is indicated by the red line.

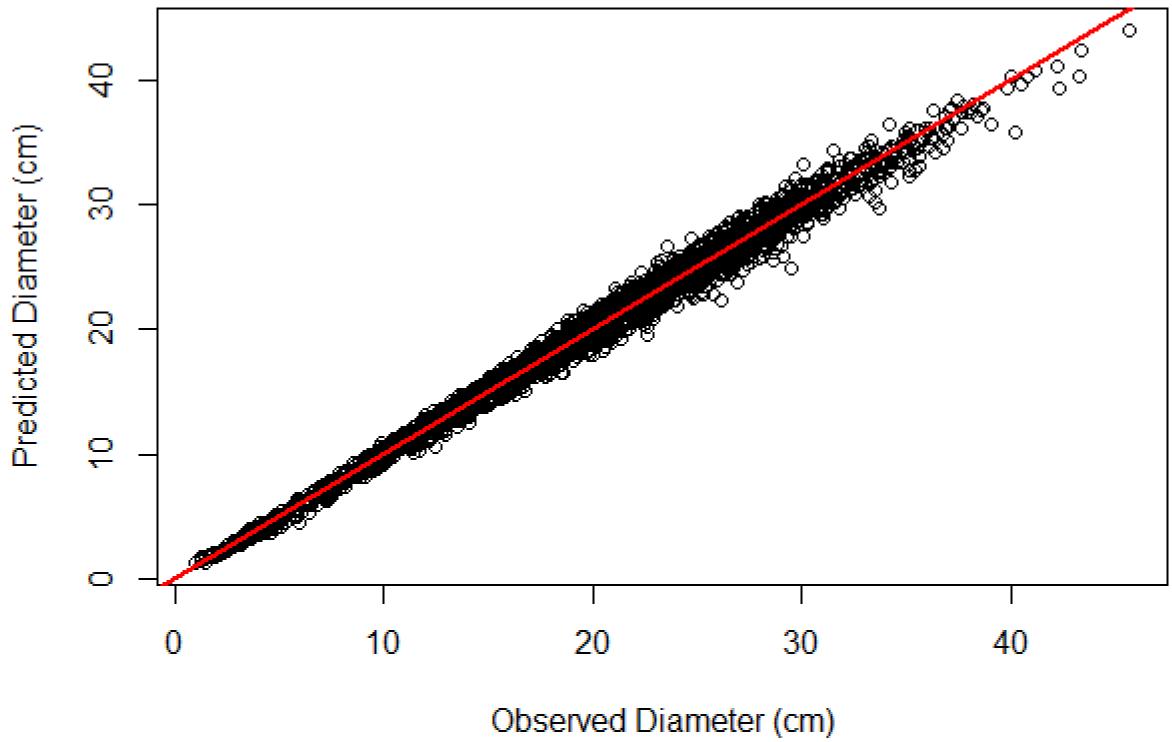


Figure 2.3. Predicted vs observed data points for the 97th DBH percentile for all plots (Equation 2). A 1:1 relationship is indicated by the red line.

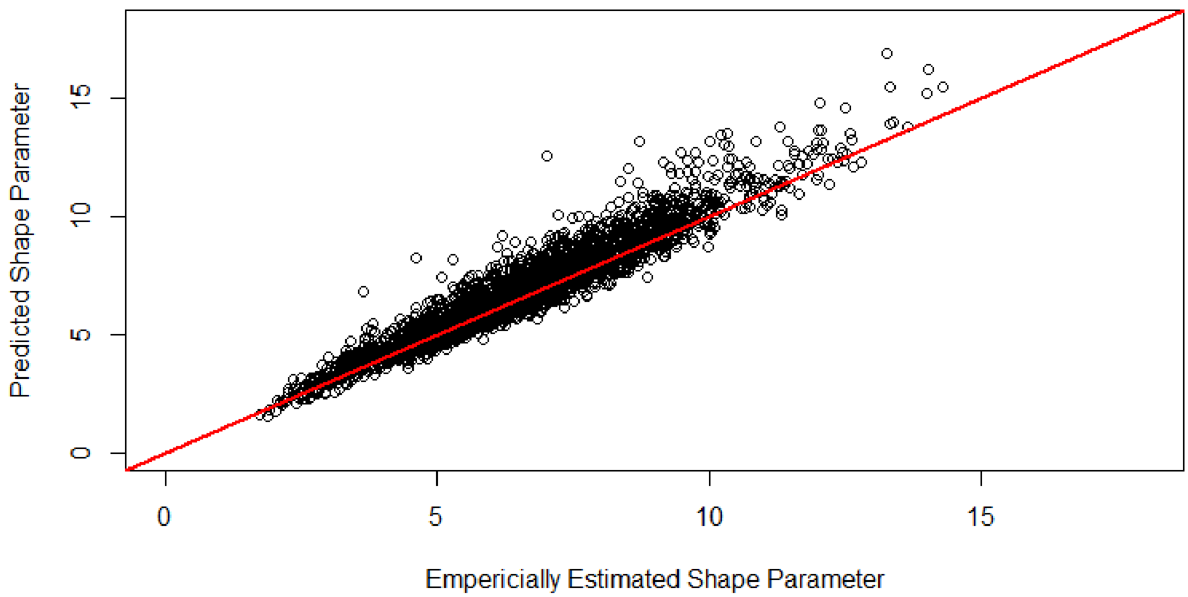


Figure 2.4. Predicted shape parameter (cm) vs. empirically estimated shape parameter (cm) for two-parameter Weibull distribution for all plots (Equation 5). A 1:1 relationship is indicated by the red line.

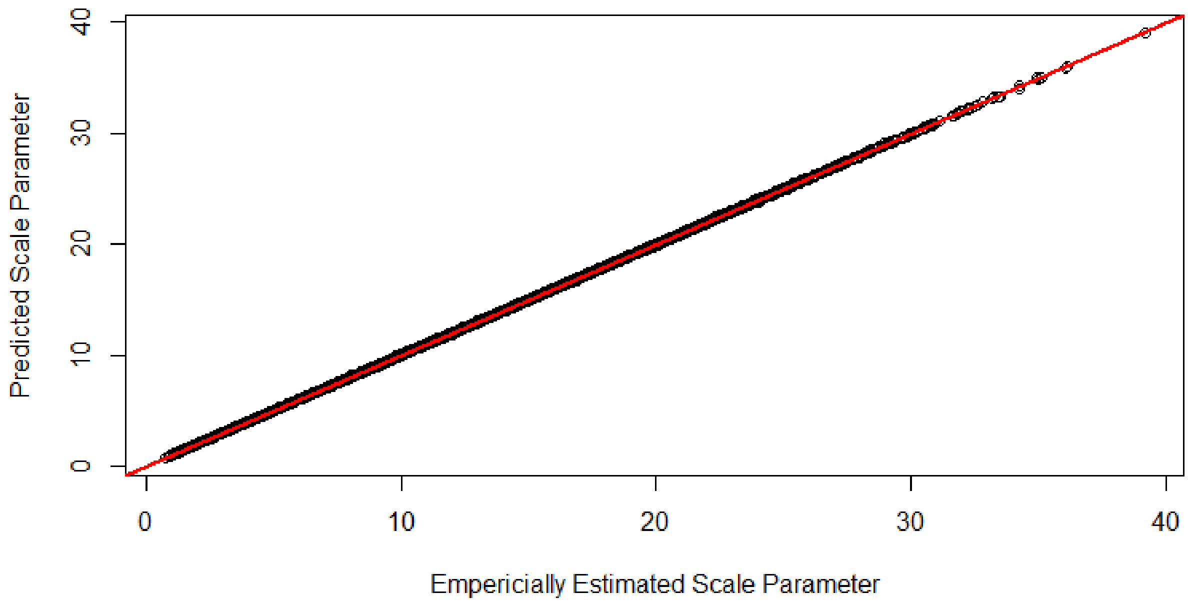


Figure 2.5. Predicted scale parameter (cm) vs. empirically estimated scale parameter (cm) for the two parameter Weibull distribution for all plots (Equation 6). A 1:1 relationship is indicated by the red line.

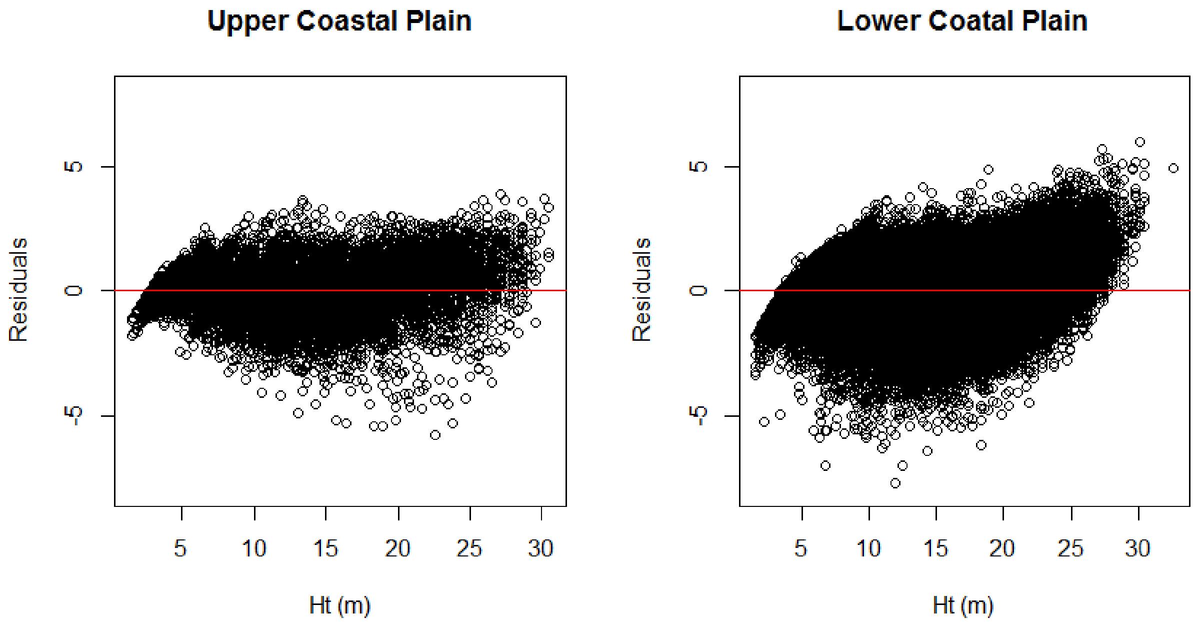


Figure 2.6. Residual plot for Equation 5 by height for all plots.

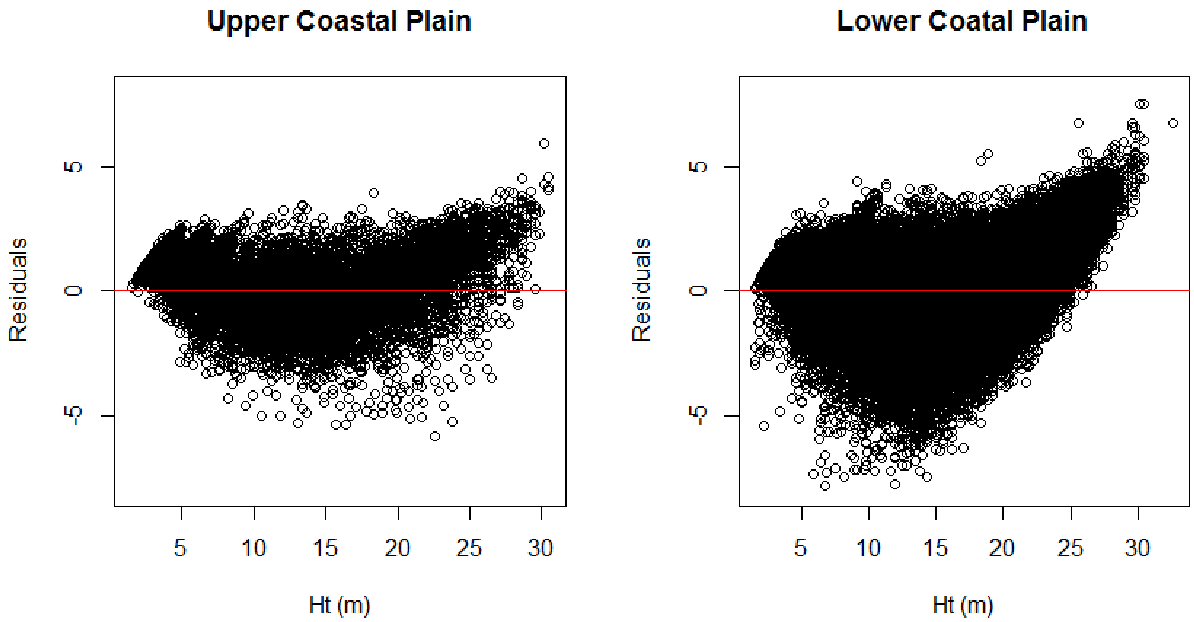


Figure 2.7. Residual plot for Equation 6 by height for all plots.

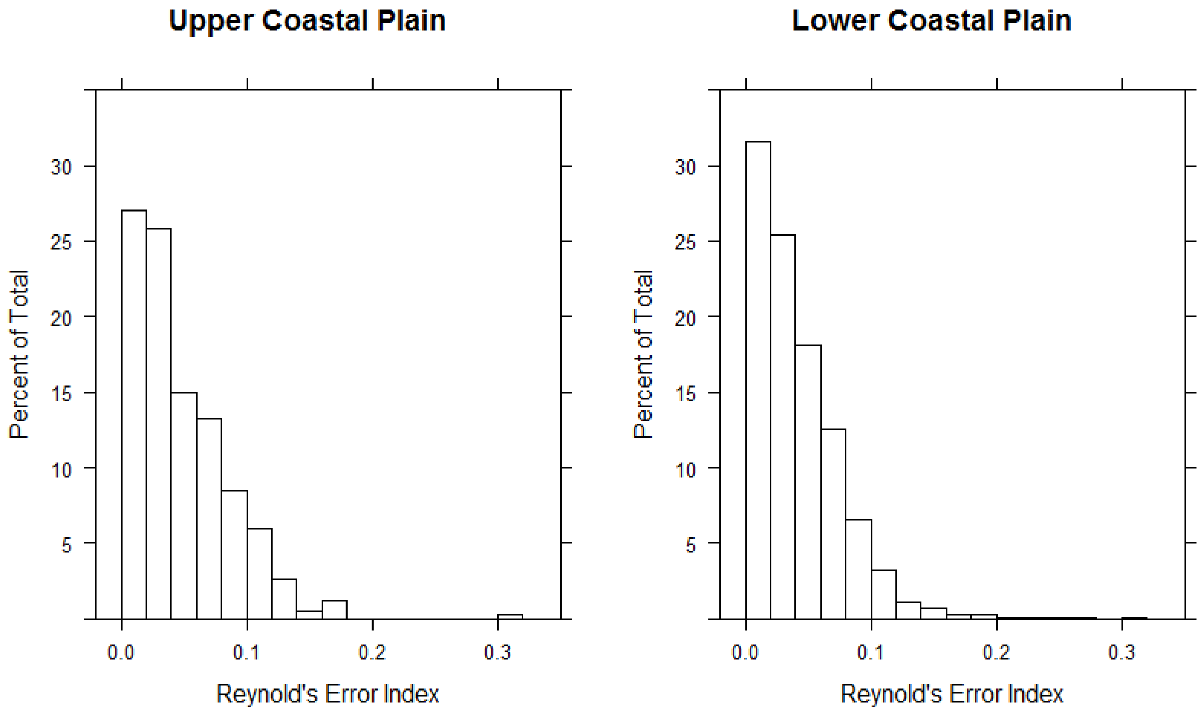


Figure 2.8. Histogram of the Reynold's Error Index distribution for volume per ha the upper and lower coastal plain.

CHAPTER 3

ROTATION AGE IMPACTS OF VEGETATION CONTROL, GENETIC IMPROVEMENT, AND THEIR INTERACTIONS ON LOBLOLLY PINE IN THE SOUTHEASTERN UNITED STATES[2]

[2] Shockey, M., Bullock, B., Montes, C., Kane, M. To be submitted to *Forests.*

Abstract

Genetic improvement in loblolly pine through selective breeding and management of seed orchards began in the 1950s, (McKeand et al. 2006a). Today 3rd generation seedlings are widely being planted, and 4th generation selections are being made by geneticists. Progeny tests aide in early selections, however rotation age analysis of the impact of genetics and their interaction with silviculture is still uncommon (Fox et al. 2007, Jokela et al. 2010). Data from the University of Georgia Plantation Management Research Cooperative's loblolly pine improved planting stock-vegetation control research study were analyzed to determine if early gains due to genetics, silviculture, and the interaction of genetics and silviculture on stand level characteristics carried through to rotation age in the coastal plain and piedmont regions of the Southeast U.S.

A mixed effects model was used to analyze six stand characteristics as measures of growth and yield at each age. An autocorrelation structure of the first order (AR1), with a continuous time covariate was added to the model and data were analyzed across time. It was found that genetics and competition control were significant across time in both regions. An analysis of least squared means showed competition control often had a greater effect than genetics but a greater than additive effect was present for the interaction of improved genetics plus competition control for height, merchantable volume, and total volume. Competing vegetation was quantified and discovered to be a major presence on the study site verifying why competition control was so important to stand growth and yield in this study. This indicates that effects of improved genetics need appropriate silviculture support to fully express their genetic potential in growth and yield. It was concluded that rotation age gains from genetics,

competition control, and the interaction of competition control and genetics are still present and significant through age 30.

Introduction

Pine plantation management practices have changed significantly over the last 70 years and continue to do so rapidly, however analysis of the effects of genetics, silviculture, and their interactions at rotation age are still relatively uncommon (Fox et al. 2007, Jokela et al. 2010). Establishment and management of seed orchards and the idea that genetic improvement through selective breeding would lead to significant gains in the growth and yield of southern pine were not commonly accepted until the 1950s. Now virtually all planted loblolly pine seedings in the southeast originate from tree improvement programs and are deployed in single family or clonal blocks to maximize genetic gains in productivity, stem form, wood quality, and disease resistance (McKeand et al. 2006a).

Through the work of tree geneticists and breeders, private landowners have greater access to purchasing genetically improved loblolly pine seedlings than ever before (McKeand 2019a). The North Carolina State University Cooperative Tree Improvement Program, one of the leading cooperatives in southern pine genetics and breeding, began their 4th breeding cycle in 2013. Progeny tests are used to identify and select superior families. Early studies in the 1980's concluded that under reasonable assumptions for age-age correlations and heritability over time selections for expected gain per year could be made between 6 and 8 years of age (McKeand 1988). Newer research shows that optimal selections for families can be made as young as age 3 for height and age 4 for volume based on age-age relationships with age 8 measurements (Xiang et al. 2003). With each successive breeding cycle, the goal is to create families that are in some way superior to the previous selections, however, often there are overlap and families from the latest generation selections are not necessarily guaranteed to be better than that of previous generation selections. Some first-generation selections are still being planted by landowners due to qualities such as rapid growth, relatively high resistance to fusiform rust, and lower cost.

Silvicultural techniques such as site preparation, fertilization, and competition control are often deployed in combination with these genetically improved seedlings with the goal of further increasing the yield and quality of the planted stands (Jokela et al. 2010). Competition from woody and herbaceous non-crop vegetation reduces the availability of site resources such as sunlight, nutrient, and water to crop trees slowing growth. Early control of these competing non-crop vegetation have been shown to have lasting impacts on a stands development. (Miller et al. 2003).

As plantations with the earliest genetic selections reach rotation age the timing is opportune to investigate how first-generation genetic selections are interacting with silviculture and what impact those interactions, if present, have been on growth and yield over time. Growth and yield of stands are evaluated by stand level characteristics such as average diameter at breast height (dbh), dominant height (ht), basal area (ba), survival rate as a function of trees per acre over time (tpa), and merchantable (V_{merch}) and total volume (V_{total}). The University of Georgia's Plantation Management Research Cooperative's (PMRC) loblolly pine improved planting stock-vegetation control study, better known as the HerbGen Study, has reached rotation age (30 years). A valuable opportunity exists to investigate rotation age results of first-generation improved genetics, competition control, and the interaction effects of these two factors on the growth and yield of loblolly pine plantations not only at a snapshot in time early in the rotation but over time and through rotation age. The hypothesis is that over time the growth gains from genetics and competition control will significantly impact stand characteristics and increase measures of growth and yield and survival over that of their unimproved counterparts in the piedmont and coastal plain regions.

Methods

The HerbGen study is a designed block plot experiment established in 1987 with multiple installations established across the coastal plain region of Georgia and Florida, and the piedmont regions of South Carolina, Georgia, and Alabama. Three categories of genetic improvement and two levels of competition control were deployed in a split plot design. The genetic component comprised of unimproved stock, open-pollinated first-generation half-sibling single families, and a bulk-lot mix of the open-pollinated first-generation half-sibling for that region. Families were chosen by polling the PMRC membership at the time for the top ten families by region for each company. The rankings of the nominated families were compared, and six families selected per region with emphasis on disease resistance. Competition control was operational site preparation with no additional silvicultural inputs over time or operational site preparation with complete and sustained competition control over time. Large woody competition was inventoried on subplots on all plots that did not receive sustained competition control. Large woody competition was defined as any non-crop vegetation having a dbh of 1.5 inches (in) or larger.

Sixteen installations from the coastal plain and fifteen installations from the piedmont were used for analysis, (Figure 3.1). Data were collected from all installations at ages 3, 6, 9, 12, 15, 18, 21, 25, and 30 years, however over time some installations were lost due to harvesting activity. At age 30 there were only six remaining installations in the coastal plain and four in the piedmont. Over 3,600 and 2,400 measurement trees were surviving respectively in each region so while the number of installations decrease, the remaining sample size was deemed sufficiently large for analysis, (Table 3.1). At age 3 and age 6 plots were subsampled per measurement protocol and therefore any per acre variables, tpa, ba, V_{tot} and V_{merch} were not calculated for those ages.

In preparation for further analysis a Tukey test was performed to determine if any significant differences existed between the three genetic categories. The bulk-lot mixed family genetic category was comprised of a randomized mixture all the single-family genetic entries, minimal differences were expected given the overlap in genetic material and potential. Any effects on stand composition, if present, due to individual family ideotype in the bulk-lot mixed category is beyond the scope of this project. Competition control was included in the model by using a dummy variable approach, 0 and 1 respectively for no silvicultural inputs beyond operational site preparation, and sustained competition control in addition to operational site preparation.

A mixed effects model was used to analyze all dependent variables of interest. A mixed effect model was chosen due to the flexibility of handling unbalanced designs as well as the ability to model fixed and random effects simultaneously (Seltman 2018). Installation main effects and all installation interactions were treated as random factors of the experiment since region-wide results were the objective of the study, while level of genetic improvement and competition control were treated as fixed effects.

$$Y_t = G_i + C_j + L_k + (GL)_{ik} + (CL)_{jk} + (GCL)_{ijk} + e_{ijk} \qquad (1)$$

Where:

Y_t is the stand characteristic of interest (dbh, ht, ba, tpa, V_{tot} or V_{merch}) at time *t*

G_i is the effect of the i^{th} fixed effect genetics

C_j is the effect of the j^{th} fixed effect competition control

e_{ij} is the experimental error, assumed iid with mean 0 and variance σ_e^2

Type III tests of fixed effects and least squares means were calculated to investigate the interaction between competition control and genetic improvement at all ages. A Type III test is the hypothesis test for the significance of each of the fixed effects. Methodology of analyzing each dependent variable, at each time period, by region followed the methods of Martin and Shiver (2002). The total outside bark (ob) and merchantable (4 inch minimum dbh and 3 inch top diameter) tree volumes were estimated using equations developed by Pienaar et al. (1987). Since the available dataset spanned an entire rotation and not just the first few years of the stand's history a time series analysis was completed. The same plots were repeatedly measured over time which introduces temporal autocorrelation due to the later measurements being dependent on the previous measurements which violates one of the basic assumptions of linear models, that observations are independent, (Burkhart et al. 2019). To account for this problem an autocorrelation structure of the first order (AR1), with a continuous time covariate was introduced into the mixed effect models to account for the temporal autocorrelation. Variables that were found to be not significant were removed from the time series analysis in a stepwise fashion until only significant variables remained and were reported. The starting model for all analysis,

$$Y = \mu + G_i + C + (GC)_{ij} + e_{ijk} + A_l + (GA)_{il} + (CA)_{jl} + (GCA)_{ijl} + f_{ijkl} \quad \textbf{(2)}$$

Where:

G_i is the effect of the i^{th} fixed effect "Genetics,"

C_j is the effect of the j^{th} fixed effect "Competition Control,"

e_{ijk} is the experimental error associated with "plot" k, assumed independently and normally distributed with mean 0 and variance σ_e^2,

τ_l is the effect of the l^{th} time point "Age",

f_{ijkl} is a random disturbance associated with the l^{th} repeated measurement for the k^{th} replicate, assumed independently and normally distributed with mean 0 and variance σ_f^2 (Schabenberger and Pierce 2001).

The large woody competing vegetation data, non-crop vegetation with a dbh of 1.5 inches or greater, were summarized to describe the overall installation average diameter and average height over time. Additional smaller woody vegetation was present on the sites that did not meet the criteria for inclusion, as well as competition from grasses. Large competing woody vegetation was chosen due to their greater impact to space and nutrient resources on the site.

Results

For all dependent variables, at all ages, a Tukey test found no significant differences between the single family and bulk-lot mixed genetic categories, therefore the two categories, bulk-lot mixed and single family, were combined into one "improved" genetic category and modeled as a 0-1 dummy variable moving forward. The mixed effects models for each independent age showed competition control was highly significant at all ages in both physiographic regions for dbh, ht, ba, V_{total} and V_{merch}. The competition control by genetic interaction term was significant at a 0.05 alpha-level, for V_{merch} in the piedmont at age 18 (p=0.04) and ba in the piedmont at age 12 (p=0.02). In the piedmont region genetics were significant through age 18 for dbh, from ages 12-18 for ba, through age 25 for ht, V_{merch} and V_{total}. In the coastal plain genetics were significant through age 25 for ht, ages 25 and 30 for tpa, ages 12-18 for ba, and the entire rotation for V_{merch} and V_{total}. P-values for competition control, genetics, and the interaction term for all dependent variables for both the piedmont and the coastal plain can be found in Tables 2-7. Analysis of least square means showed that the interaction of genetics and competition control at rotation age had a greater than additive effect on ht (Figure 3.2), and V_{total} and V_{merch} (Figure 3.3) in the coastal plain.

When the data were analyzed over time with the AR(1) correlation structure and not as independent points in time, the results showed that genetics were significant in all models, for all regions, with the exception of tpa in the piedmont. Genetics by age interaction was only significant in a few models, significance was found in the coastal plain for dbh and tpa and height in the piedmont. Competition control by age interaction was significant in the coastal plain models for dbh and ba and in the piedmont for dbh, ht, V_{merch}, and V_{total}. The genetics by competition control interaction term was found to be significant for the coastal plain in the dbh and ba models and in the piedmont the dbh, ht, ba, V_{merch}, V_{total} The interaction term genetics by competition control, by age was never significant in any of the models, (Table 3.8).

Analysis of least square means across time showed that for all dependent variables the combination of no competition control and no genetic improvement consistently had lower measures of growth for both regions while the combination of competition control and genetic improvement consistently had the highest measures of growth. The combination of genetics with no competition control saw slight improvements in measures of growth and yield but the combination of no genetic improvement but with competition control often had the larger impact on means, particularly for ht, V_{merch}, and V_{tot}. For those same variables the combination of improved genetics and competition control had a more than additive effect when compared to no genetic improvement and no competition control, (Figure 3.2 and Figure 3.3).

For some variables, the addition of competition control had a larger impact on measures of growth and yield than genetics so measures of large woody competing vegetation were graphed to investigate further on how much competition installations were experiencing. It was found that considerable competition was present on the HerbGen installations. At age 30 the average large woody competing vegetation stem dbh ranged from 2.4-4.3in in the piedmont, average ba ranged from 27-100 ft^2/ac, and average ht ranged from 20-37ft. At the same age in the coastal plain average large woody competing vegetation stem dbh ranged from 2.5-3.5in, average ba ranged from 29-93 ft^2/ac, and average ht ranged from 23-39ft. Figure 3.4. Additional small woody competing vegetation and grass competition was present on all sites. All tables and figures have been converted to Metric units and can be found in Appendix B.

Discussion

This is a region wide rotation aged study for the piedmont and the coastal plain in the southeastern United States aimed at investigating if growth gains could be detected in a research block plot experiment of first-generation open-pollinated loblolly pine families and if any interactions with competition control were present. A variety of site conditions and site indexes were inherently present in the data. Results therefore are reflective of general trends for the specified regions however extrapolation to other regions or species should be done with caution.

Genetic improvement has continued far beyond the families in this study; however, rotation age data is limited to first-generation selections for now. Results are supportive that those early gains do in fact carry through rotation and therefore continued improvement should lead to continued gains. The interaction of silviculture and genetics when present had a more than additive effect on the stand characteristics indicating that maximum expression of genetic improvement will occur when supported with adequate silviculture. In this study on plots where there was no competition control there was high pressure for resources from competing vegetation as indicated in Figure 3.4.

Conclusions

While the scope of this analysis is limited to a select grouping of first-generation open-pollinated loblolly pine families, results are supportive of the expectation that genetic improvement in combination with appropriate silvicultural management will lead to greater stand growth and final yield at rotation. This result, while expected based on Martin and Shiver (2002) of their study at mid-rotation, is reassuring to confirm with rotation age data. Genetics alone can lead to an increase in gains, however having the silvicultural support to fully express genetic potential will provide greater gains at rotation age. Without proper silvicultural support genetic potential will be suppressed by effects due to competition for resources. Different levels of fertilization were not built into this study design nor was thinning; however, both silvicultural practices have the potential to further impact and increase the expression of genetic potential of these improved families by addressing any nutritional deficiencies inherently present on the site and by reducing competition for space with other crop trees after crown closure. Additional work will be needed to incorporate these scenarios into modeling efforts to explain additional variation in genetic expression and potential growth gains.

Table 3.1. Number of PMRC HerbGen installations, plots within installations, and trees within plots present in each region at each age. Decrease in sample size at later ages is due to harvesting activity and mortality.

	Coastal Plain			Piedmont		
Age	**Installation**	**Plot**	**Tree**	**Installation**	**Plot**	**Tree**
3	16	128	5,636	15	118	5,312
6	16	128	5,291	15	118	4,987
9	16	128	16,125	15	118	15,452
12	16	128	15,635	15	113	14,457
15	16	127	15,214	15	113	16,891
18	14	103	11,880	15	111	12,732
21	11	81	8,828	10	79	8,237
25	9	65	6,350	7	55	5,174
30	6	42	3,651	4	32	2,407

Table 3.2. Mixed model results by region and age for genetics, competition control, and the genetics and competition control interaction for dbh.

Age	Region	Genetics	Competition control	Genetics x competition interaction
3	Coastal Plain	0.0108	<0.0001	0.3015
	Piedmont	0.0180	<0.0001	0.6713
6	Coastal Plain	0.4388	<0.0001	0.4312
	Piedmont	0.0031	<0.0001	0.1865
9	Coastal Plain	0.4599	<0.0001	0.6133
	Piedmont	0.0024	<0.0001	0.5033
12	Coastal Plain	0.6222	<0.0001	0.7605
	Piedmont	0.0022	<0.0001	0.3575
15	Coastal Plain	0.2132	<0.0001	0.9677
	Piedmont	0.0021	<0.0001	0.3825
18	Coastal Plain	0.3667	<0.0001	0.9636
	Piedmont	0.0472	<0.0001	0.3679
21	Coastal Plain	0.9584	<0.0001	0.8401
	Piedmont	0.0579	<0.0001	0.4330
25	Coastal Plain	0.5019	<0.0001	0.9017
	Piedmont	0.0828	0.0005	0.7749
30	Coastal Plain	0.2543	0.0058	0.9526
	Piedmont	0.5959	0.0029	0.4486

Table 3.3 Mixed model results by region and age for genetics, competition control, and the genetics and competition control interaction for ht.

Age	Region	Genetics	Competition control	Genetics x competition interaction
3	Coastal Plain	0.0081	<0.0001	0.2952
	Piedmont	0.0007	<0.0001	0.6819
6	Coastal Plain	<0.0001	<0.0001	0.0680
	Piedmont	<0.0001	<0.0001	0.3719
9	Coastal Plain	<0.0001	<0.0001	0.4068
	Piedmont	<0.0001	<0.0001	0.5955
12	Coastal Plain	<0.0001	<0.0001	0.4946
	Piedmont	<0.0001	<0.0001	0.1545
15	Coastal Plain	<0.0001	<0.0001	0.5905
	Piedmont	<0.0001	<0.0001	0.2593
18	Coastal Plain	0.0018	<0.0001	0.5872
	Piedmont	<0.0001	<0.0001	0.0820
21	Coastal Plain	0.0043	<0.0001	0.5770
	Piedmont	<0.0001	0.0004	0.3016
25	Coastal Plain	0.0202	<0.0001	0.7730
	Piedmont	<0.0001	0.0005	0.5829
30	Coastal Plain	0.1577	0.0051	0.8460
	Piedmont	0.0046	0.0010	0.5323

Table 3.4 Mixed model results by region and age for genetics, competition control, and the genetics and competition control interaction for tpa.

Age	Region	Genetics	Competition control	Genetics x competition interaction
9	Coastal Plain	0.7121	0.4310	0.1644
	Piedmont	0.4245	0.6018	0.0915
12	Coastal Plain	0.6616	0.6137	0.0860
	Piedmont	0.4564	0.5175	0.1403
15	Coastal Plain	0.9572	0.4891	0.1996
	Piedmont	0.9934	0.3702	0.5900
18	Coastal Plain	0.7071	0.8419	0.7421
	Piedmont	0.4182	0.9565	0.4722
21	Coastal Plain	0.1456	0.0340	0.4979
	Piedmont	0.8734	0.6428	0.5601
25	Coastal Plain	0.0158	0.0211	0.2319
	Piedmont	0.6745	0.8561	0.9134
30	Coastal Plain	0.0315	0.4938	0.2368
	Piedmont	0.1992	0.9387	0.5893

Table 3.5 Mixed model results by region and age for genetics, competition control, and the genetics and competition control interaction for ba.

Age	Region	Genetics	Competition control	Genetics x competition interaction
9	**Coastal Plain**	0.1875	<0.0001	0.3223
	Piedmont	0.0538	<0.0001	0.0863
12	**Coastal Plain**	0.3295	<0.0001	0.4065
	Piedmont	0.0382	<0.0001	0.0200
15	**Coastal Plain**	0.1180	<0.0001	0.1791
	Piedmont	0.0126	<0.0001	0.0986
18	**Coastal Plain**	0.1726	<0.0001	0.6674
	Piedmont	0.0196	<0.0001	0.0615
21	**Coastal Plain**	0.1838	<0.0001	0.2742
	Piedmont	0.0756	<0.0001	0.1507
25	**Coastal Plain**	0.0381	<0.0001	0.0856
	Piedmont	0.1917	0.0092	0.7473
30	**Coastal Plain**	0.1672	0.0052	0.0523
	Piedmont	0.1450	0.0216	0.8859

Table 3.6 Mixed model results by region and age for genetics, competition control, and the genetics and competition control interaction for V_{MERCH}.

Age	Region	Genetics	Competition control	Genetics x competition interaction
6	Coastal Plain	0.0222	<0.0001	0.8408
	Piedmont	0.1142	<0.0001	0.8381
9	Coastal Plain	0.0006	<0.0001	0.2620
	Piedmont	0.0008	<0.0001	0.2620
12	Coastal Plain	0.0001	<0.0001	0.5189
	Piedmont	0.0001	<0.0001	0.0636
15	Coastal Plain	<0.0001	<0.0001	0.3570
	Piedmont	<0.0001	<0.0001	0.0817
18	Coastal Plain	0.0005	<0.00001	0.9393
	Piedmont	<0.0001	<0.00001	0.0436
21	Coastal Plain	0.0014	<0.0001	0.4590
	Piedmont	0.0006	<0.0001	0.1774
25	Coastal Plain	0.0004	<0.0001	0.5785
	Piedmont	0.0055	0.0022	0.7018
30	Coastal Plain	0.0230	0.0009	0.3061
	Piedmont	0.4979	0.0086	0.6884

Table 3.7 Mixed model results by region and age for genetics, competition control, and the genetics and competition control interaction for V_{Ttotal}.

Age	Region	Genetics	Competition control	Genetics x competition interaction
6	**Coastal Plain**	0.0180	<0.0001	0.8071
	Piedmont	0.0953	<0.0001	0.8422
9	**Coastal Plain**	0.0004	<0.0001	0.2463
	Piedmont	0.0006	<0.0001	0.2513
12	**Coastal Plain**	0.0001	<0.0001	0.4799
	Piedmont	0.0001	<0.0001	0.0602
15	**Coastal Plain**	<0.0001	<0.0001	0.3427
	Piedmont	<0.0001	<0.0001	0.0792
18	**Coastal Plain**	0.0005	<0.0001	0.9344
	Piedmont	<0.0001	<0.0001	0.0419
21	**Coastal Plain**	0.0011	<0.0001	0.4537
	Piedmont	0.0006	<0.0001	0.1798
25	**Coastal Plain**	0.0003	<0.0001	0.5592
	Piedmont	0.0057	0.0026	0.7025
30	**Coastal Plain**	0.0186	0.0010	0.2914
	Piedmont	0.4889	0.0099	0.7086

Table 3.8. P-values for mixed effects model across time through age 30 for each region for genetics (G), competition control (C), and age (A). Higher order variables were removed from the model and not reported if not significant.

Dependent Variable	Region	P-values						
		G	C	A	G x A	C x A	G x C	G x C x A
DBH	Coastal Plain	0.0029	0.0000	0.0000	0.0128	0.0040	--	--
	Piedmont	0.0000	0.0000	0.0000	--	0.0208	0.0112	--
HT	Coastal Plain	0.0000	0.0000	0.0000	--	--	0.0317	--
	Piedmont	0.0094	0.0000	0.0000	0.0000	0.0061	0.0072	--
TPA	Coastal Plain	0.0005	0.0061	0.0000	0.0006	--	0.0033	--
	Piedmont	--	0.0000	--	--	--	--	--
BA	Coastal Plain	0.0001	0.0000	0.0000	--	0.0001	--	--
	Piedmont	0.0000	0.0000	0.0000	--	--	0.0004	--
V_{MERCH}	Coastal Plain	0.0000	0.0000	0.0000	--	0.0003	--	--
	Piedmont	0.0000	0.0000	0.0000	--	0.0397	0.0018	--
V_{TOT}	Coastal Plain	0.0000	0.0000	0.0000	--	0.0012	--	--
	Piedmont	0.0000	0.0000	0.0000	--	--	0.0018	--

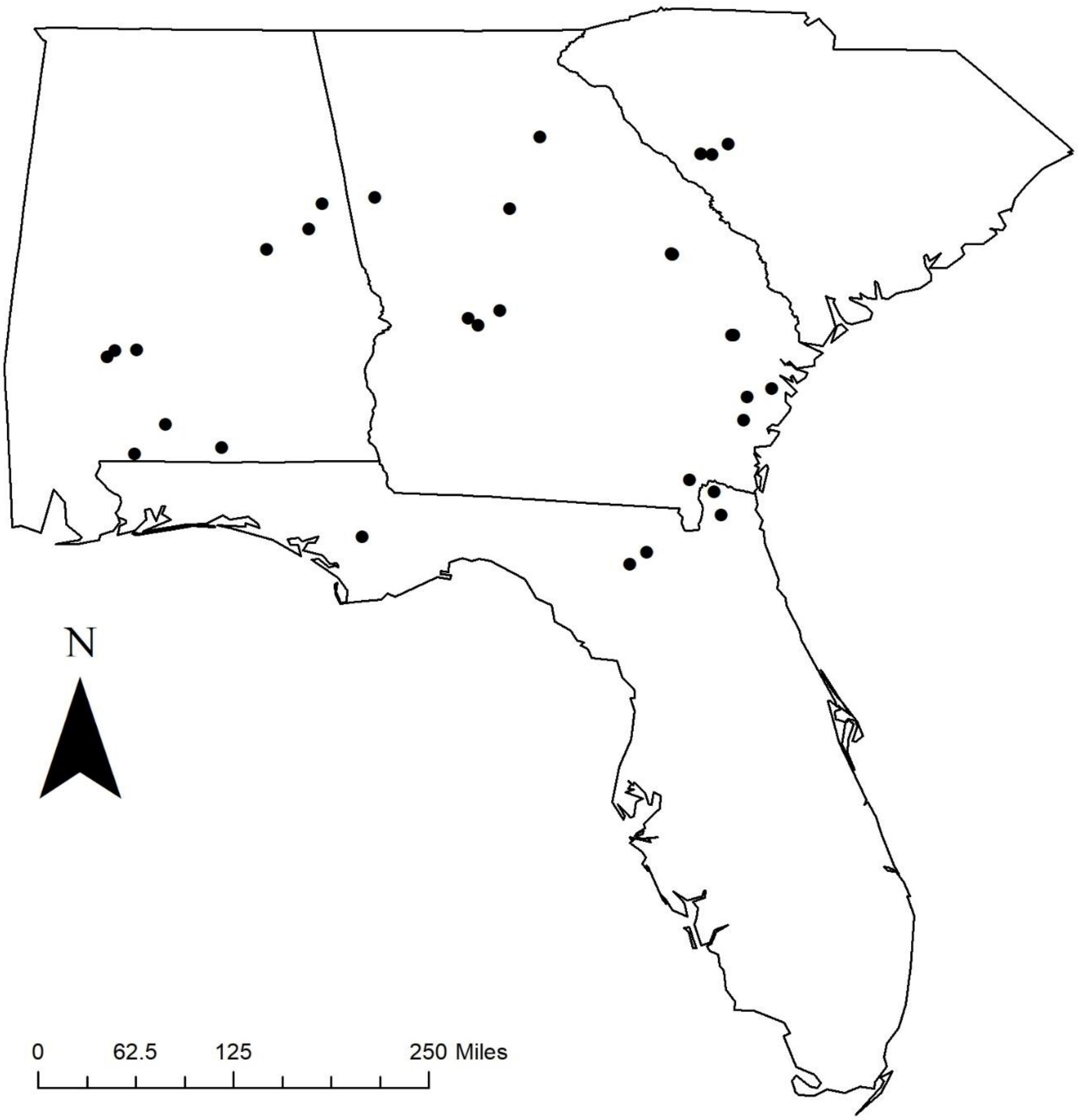


Figure 3.1. Map of PMRC HerbGen installation locations throughout the southeast.

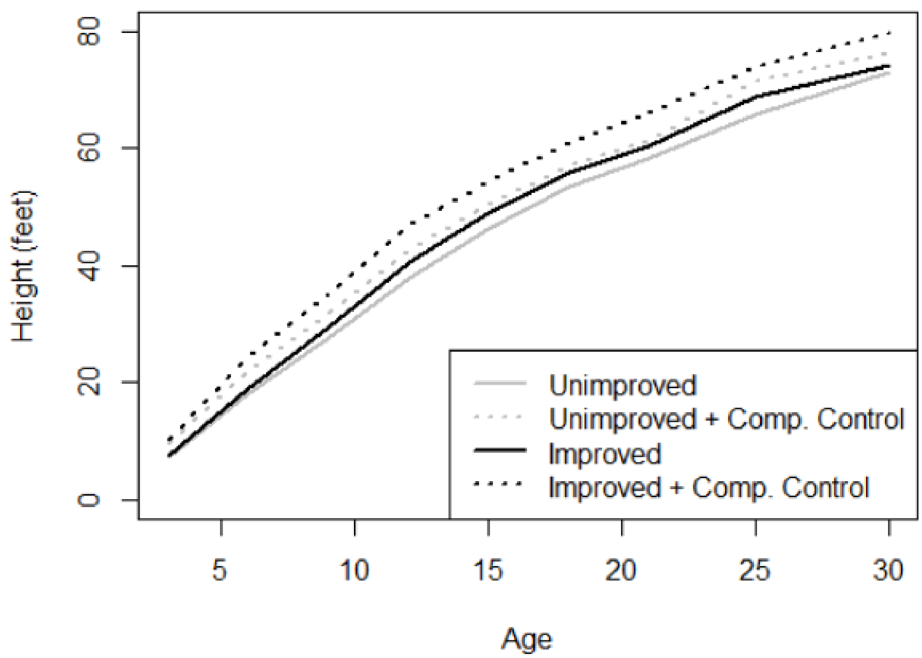


Figure 3.2. Least squares means for average dominant height across time in the PMRC HerbGen coastal plain installations.

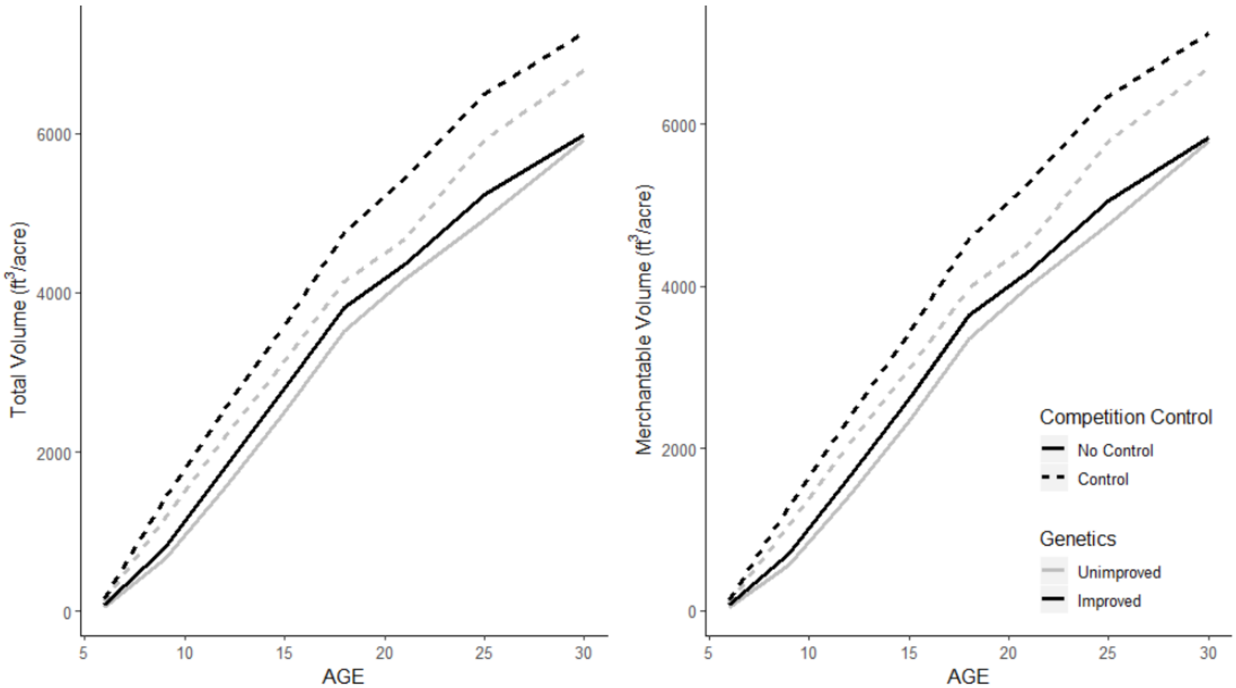


Figure 3.3. Least square means for total volume per acre and merchantable volume per acre over time for the PMRC HerbGen installations in the coastal plain.

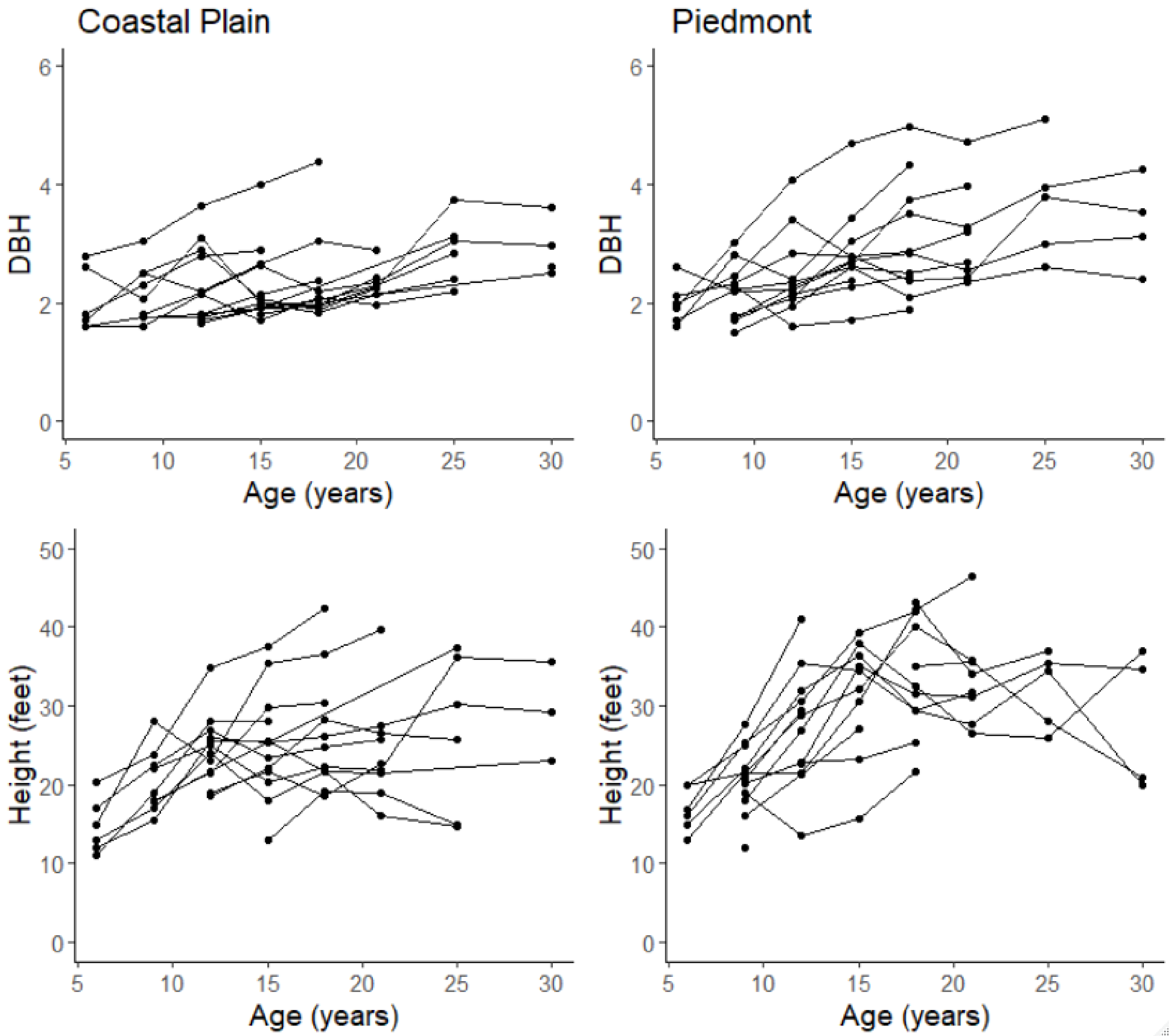


Figure 3.4. Overall PMRC HerbGen installation averages across time for large woody competition in plots that did not receive competition control. Large woody competition was defined as any unplanted woody species, broadleaf or evergreen, that had a minimum dbh of 1.5 inches.

CHAPTER 4

INCORPORATING GENETIC IMPROVEMENT AND COMPETITION CONTROL INTO GADA SITE INDEX MODELS FOR LOBLOLLY PINE[3]

[3] Shockey, M., Montes, C., Bullock, B., Kane, M. To be submitted to *Forest Science.*

Abstract

The most common measure of productivity in loblolly pine stands is site index (SI). SI gives forestland owners and managers the ability to quickly and easily compare multiple stands and their production potential to make informed decisions. Many factors can impact productivity so silvicultural management is deployed with the goal of changing these factors to improve and increase productivity. Much effort has gone into developing and identifying the optimal SI models based on regions, species, and other factors. Using a Chapman-Richards style generalized algebraic difference approach (GADA) four models were evaluated for the coastal plain and piedmont regions. Two levels of genetic improvement, unimproved and first-generation open-pollinated, and two levels of competition control, sustained control and no control were built into the theoretical variable for growth dynamics.

It was found that in both regions Model 4, the model where both variables for level of competition control and level of genetic improvement were included, had the highest R^2 and lowest root mean squared error. A likelihood ratio test supports that this model did perform better than other more parsimonious models with fewer variables. All four models in both regions had bias values that were negative and near zero, indicating a tendency to over predict tree height but overall, all models were able to accurately predict tree height. Some discrepancies were noted in Model 2 and Model 4 for the coastal plain region where unimproved genetic material with no competition control had unrealistic heights estimated at later ages. This was determined to be due to extrapolation because of low sample size.

Introduction

When describing the quality or productivity of a site one of the most common and simplest measures in forestry is site index. Site index (SI) is a measurement of the average height of the dominant and codominant trees at a specified reference age for a single species in an even aged undisturbed stand (Burkhart et al. 2019). Age 25 is the most common reference age, or base age, for loblolly pine, however base age 50 may be found in the literature among the oldest models (Bettinger et al. 2016, Sharma et al. 2002). Defining a base age allows for stands of different site qualities and at different ages to be compared at a common point in development to better understand relative productivity. Productivity of a site can be greatly impacted by factors such as topography, soil depth and texture, presence of a limiting layer such as a plow pan, drainage, fertility, climate, pressure from pests and diseases, and vegetative competition (Geyer and Lynch 1987, Hamilton 2019). Silvicultural management such as site preparation, fertilization, and competition control among other techniques such as improved genetics aim to improve the productivity of the site and therefore would represent an increase the expressed site index of stands (Jokela et al. 2010).

Much effort has been put into identifying the optimal equations for SI models depending on region, species, and other factors. The earliest method of estimating site index was the guide curve method (Burkhart and Tomé 2012). Guide curves were originally developed by plotting paired height-age values and drawing a curve depicting the general trend of the data. Today with the advent of modern computers, expansions in memory and processing capacity, and available statistical software packages, more advanced approaches to modeling SI have been developed. SI curves have two forms; anamorphic where the curves are proportional and have the same inflection point or shape for all curves or polymorphic where the curves are more flexible and can have different shapes.

Bailey and Clutter (1974) developed the base-age invariant polymorphic site index curves using a technique that is now known as the algebraic difference approach (ADA). Base-age invariant models are also known as dynamic site index equations, due to the equations being unaffected by arbitrary changes in base-age. The ADA model form passes through the origin, can have multiple asymptote values, and predicts the height at the base age equal to the site index value. Functions such as the Chapman-Richards, Schumacher, and others have been applied and different constraints on the model parameters have been evaluated (Burkhart and Tomé 2012). The main limitation of ADA models are that all models derived are either anamorphic or have single asymptotes (Bailey and Clutter 1974, Cieszewski and Bailey 2000).

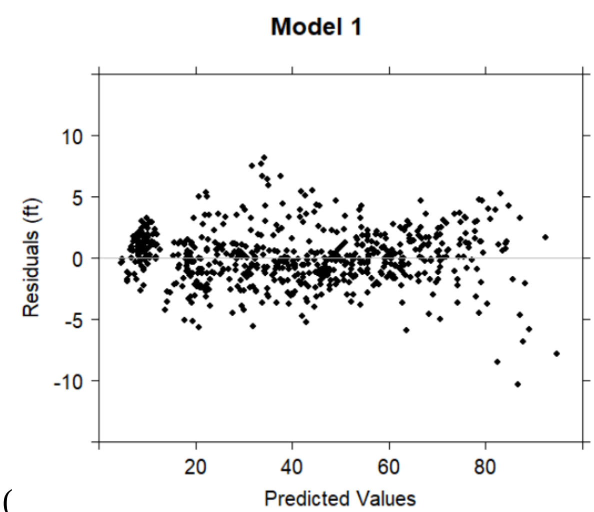
Cieszewski and Bailey (2000) improved upon the algebraic difference approach by creating the generalized algebraic difference approach (GADA). Their method allows for all the previously mentioned benefits of the ADA, with the addition of a theoretical variable defined to be the quantification of growth dynamics associated with a site. This theoretical value can be a single variable or a function of any number of variables such as climate, soils, or genetics. The equations can be simple or complex depending on the desired solution (Burkhart and Tomé 2012). The advantage of the GADA is that the base questions can be expanded with more than one site-specific parameter and the derivation was more flexible than the ADA allowing for polymorphism and multiple asymptotes (Cieszewski 2002). Diéguez-Aranda et al. (2006) found that for base-age invariant models such as the ADA and GADA, base-ages between 20-35 years were superior for predicting heights when compared to other ages, but even as young as 15 years could be used without markedly compromising accuracy in predictions.

Rotation age data from the University of Georgia's Plantation Management Research Cooperative's (PMRC) loblolly pine improved planting stock-vegetation control study, better known as the HerbGen Study, was used to develop four GADA SI models using a base age of 25. Dummy variables for the level of genetic improvement, the level of competition control, and the interaction of genetic improvement and competition control were added to the model as the site specific growth dynamic variables with the goal of improving the ability to predict SI. Genetic improvement and competition control aim to, and are typically successful at, improving stand productivity, so it is a natural conclusion that the addition of these variables will lead to improvements in predictive ability. The hypothesis is that the model containing variables for both level of genetic improvement and level of competition control will produce the best GADA SI model.

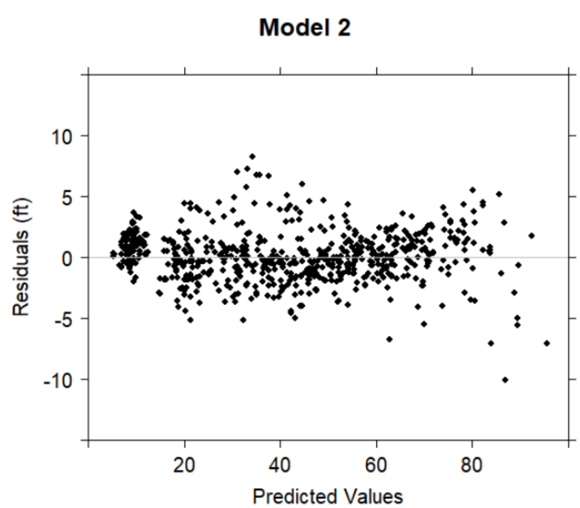
Methods

The HerbGen study is a designed block plot experiment established in 1987 with multiple installations established across the coastal plain region of Georgia and Florida, and the piedmont regions of South Carolina, Georgia, and Alabama. Three categories of genetic improvement and two levels of competition control were deployed in a split plot design. The genetic component comprised of unimproved stock, open-pollinated first-generation half-sibling single families, and a bulk-lot mix of the open-pollinated first-generation half-sibling for that region. Families were chosen by polling the PMRC membership at the time for the top ten families by region for each company. The rankings of the nominated families were compared, and six families selected per region with emphasis on disease resistance. Competition control was operational site preparation with no additional silvicultural inputs over time or operational site preparation with complete and sustained competition control over time.

Sixteen installations from the coastal plain and fifteen installations from the piedmont were used for analysis, (Figure 3.1). Height measurements were collected from all installations at ages 3, 6, 9, 12, 15, 18, 21, 25, and 30, however over time some installations were lost due to harvesting activity. At age 30 there were only six remaining installations in the coastal plain and four in the piedmont. Over 3,600 and 2,400 measurement trees were surviving respectively in each region so while the number of installations and plots decrease, the remaining sample size



was deemed sufficiently large for analysis, (



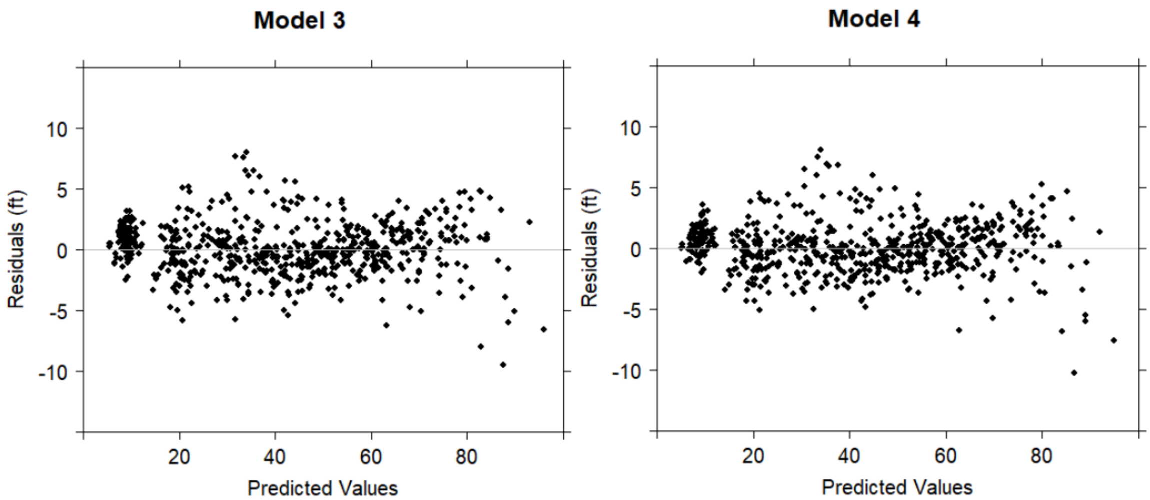


Figure 4.2 Residuals for piedmont GADA models 1-4. Model 1 is the base model fit with age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

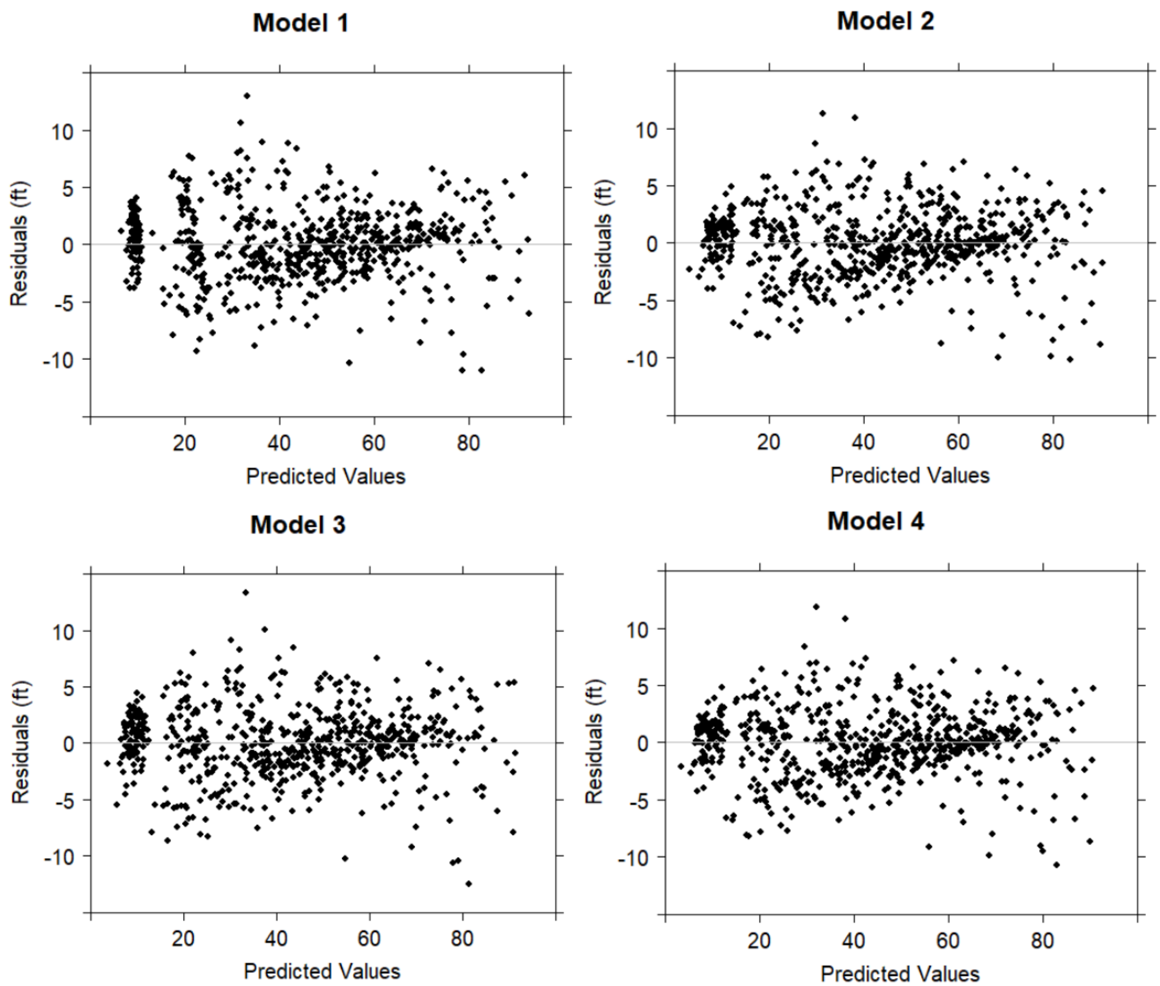


Figure 4.3 Residuals for coastal plain GADA models 1-4. Model 1 is the base model fit with age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

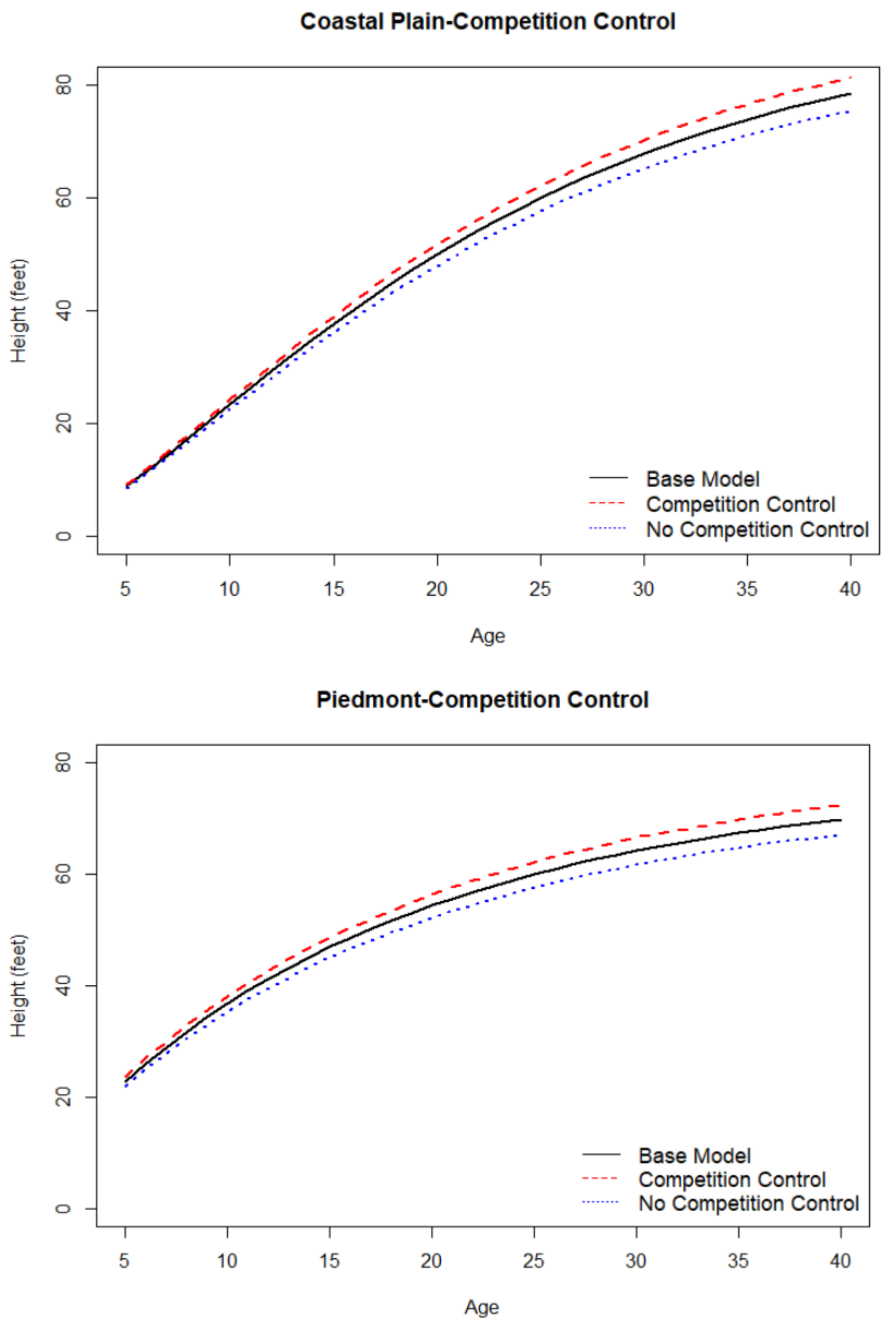


Figure 4.4. A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of competition control and no competition control were added to show the impact of competition control on height.

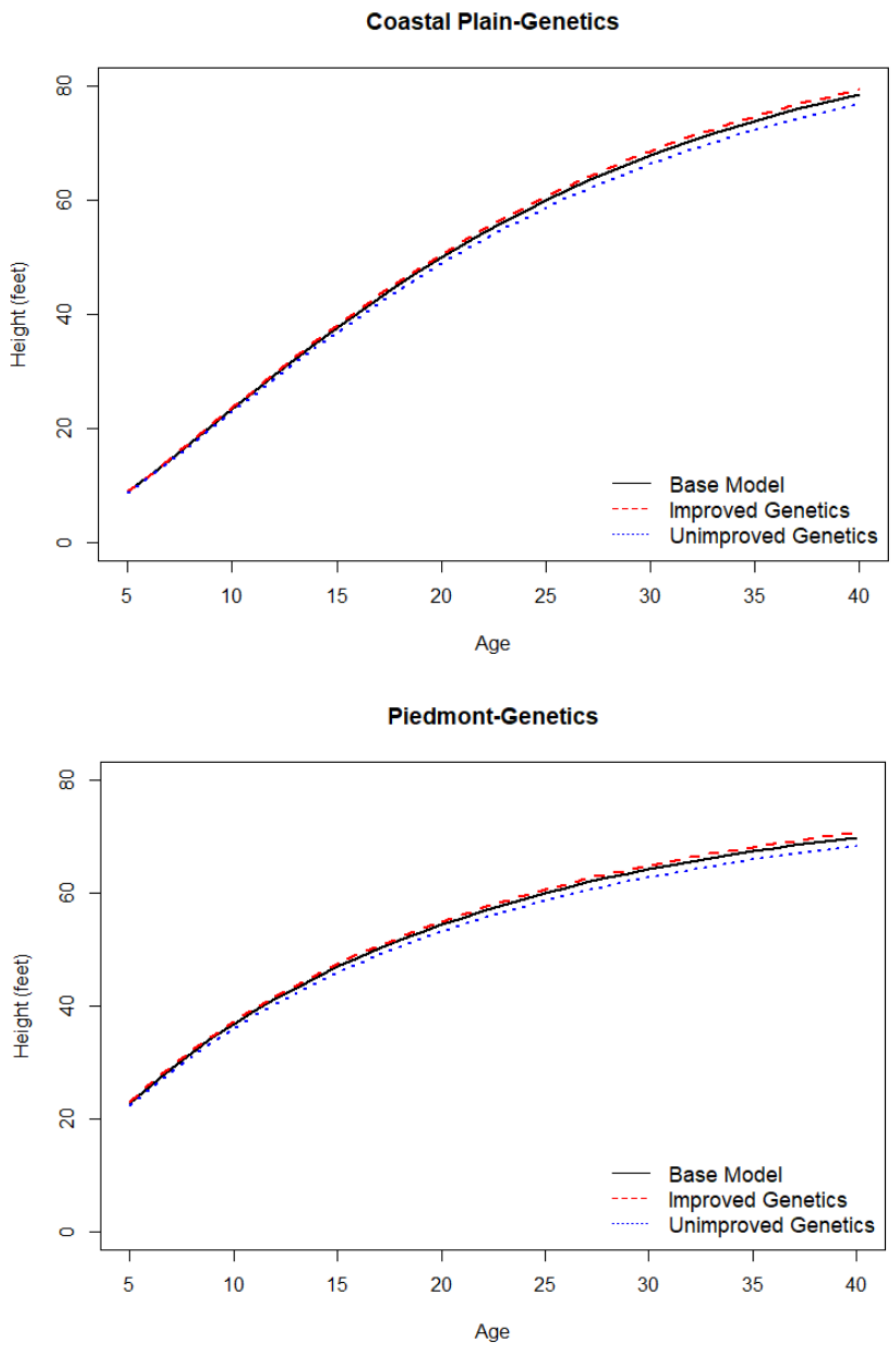
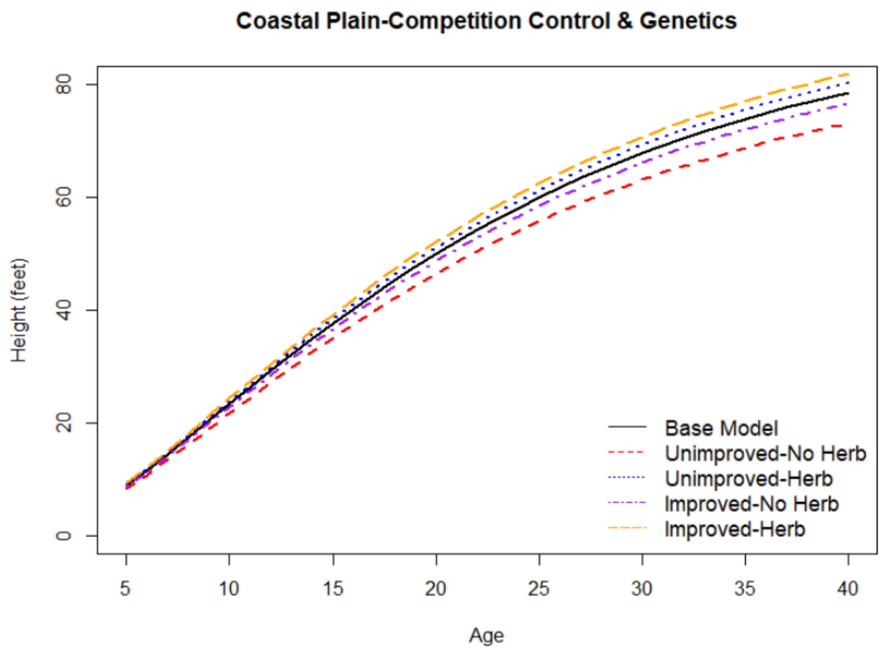


Figure 4.5 A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of unimproved genetics and improved genetics were added to show the impact of genetics on height.



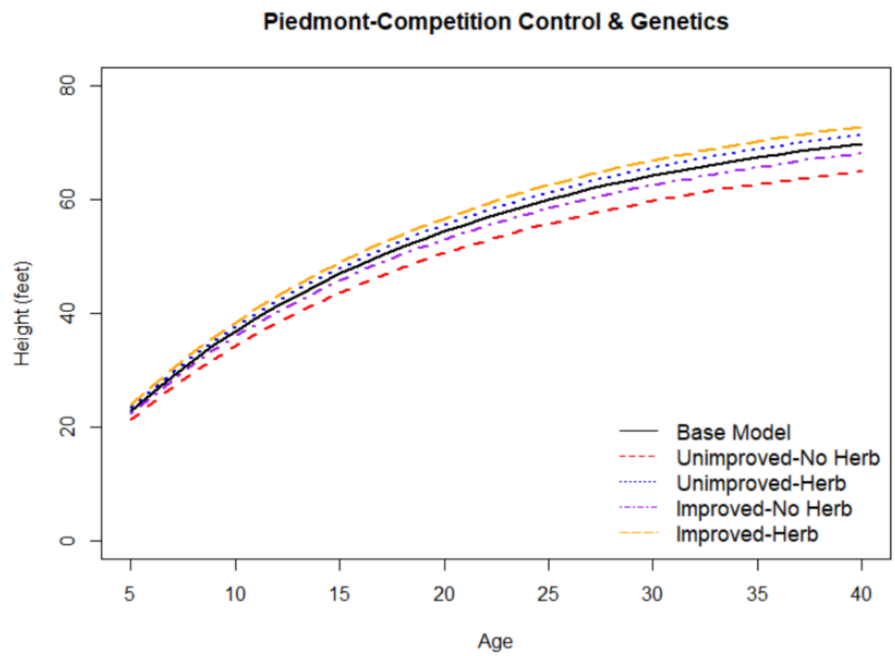


Figure 4.6 A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of unimproved genetics without competition control, unimproved genetics with competition control, improved genetics without competition control, and improved genetics with competition control were added to show the impact of the interaction of genetics and level of competition control on height.

Table 4.1).

Prior work from the authors showed that the bulk-lot mixed group and the single family blocks were not significantly different so for analysis purposes the bulk-lot mixed and single family blocks were considered to be one “improved” genetic category to allow for dummy variable analysis. Competition control was also treated as a dummy variable where the levels were sustained competition control and no competition control.

Four Chapman-Richards style GADA models were fit in R (R Development Core Team 2020) for each region. The local parameter X was allowed to vary per each plot for all models. Model 1 was fit to the data with age as the only variable and serves as the base model for comparison. Model 2 included the dummy variable for sustained competition control or no competition control. Model 3 included the dummy variable for improved or unimproved genetics, and Model 4 included dummy variables for both competition control and genetics.

$$\overline{H}_{Dom} = e^{X}(1 - e^{Ab_2})^{b_3 + b_4 X^{-1}} \quad (1)$$

$$\overline{H}_{Dom} = e^{X} e^{Cb_5}(1 - e^{Ab_2})^{b_3 + b_4 X^{-1}} \quad (2)$$

$$\overline{H}_{Dom} = e^{X} e^{Gb_6}(1 - e^{Ab_2})^{b_3 + b_4 X^{-1}} \quad (3)$$

$$\overline{H}_{Dom} = e^{X} e^{Cb_5} e^{Gb_6}(1 - e^{Ab_2})^{b_3 + b_4 X^{-1}} \quad (4)$$

$\overline{H}_{Dom}$ is the average dominant and codominant height for each plot,

e is a mathematical constant,

X is the local parameter,

A is the age,

C is the competition control dummy variable (0, 1),

G is the level of genetics dummy variable (0, 1).

R^2, bias, and root mean squared error (RMSE) were calculated for each model and a likelihood-ratio test was performed for each model pair to evaluate goodness-of-fit and which model most adequately fit the data. For model validation the site index equation was derived and evaluated from ages 5 to 50 for fit. This was accomplished by first taking the natural logarithm of both sides of the equation and solving for X. Following the methods and assumptions of Trim et al. (2019), X was found to be:

$$X_0 = \frac{\left(ln(H_0) - Cb_5 - Gb_6 - b_3 ln(1 - e^{A_0 b_2})\right) + \sqrt{\left(ln(H_o) - Cb_5 - Gb_6 - b_3 ln(1 - e^{A_0 b_2})\right)^2 - 4b_4 ln(1 - e^{A_0 b_2})}}{2} \quad (5)$$

H_0 is site index (feet),

A_0 is index age (years).

Substituting X_0 into the original GADA formation and reducing the model, the final SI equation can be represented by:

$$H = H_0 \left(\frac{1 - e^{Ab_2}}{1 - e^{A_0 b_2}}\right)^{(b_3 + b_4 X_0^{-1})} \quad (6)$$

Results

The beta values from the fitting of Models 1-4 were reported in (Table 4.2). The R^2 for model 1 in the coastal plain was 97.92% and 98.98% in the piedmont, (Table 4.2). Model 2 included the variable for competition control, the R^2 improved slightly in both regions and became 98.15% in the coastal plain and 99.07% in the piedmont. Model 3 included the variable for level of genetic improvement, again slight improvements over Model 1 were seen, in the coastal plain the R^2 was 97.95% and 99.00% in the piedmont. Model 4 was fit with two variables, the level of genetic improvement and level of competition control. The R^2 in the coastal plain was 98.16% and 99.08% in the piedmont making it the model with the highest R^2 in both regions. In the piedmont, region Model 1 had the lowest standard deviation, 0.9898, and bias. In the coastal plain region Model 1 had the lowest standard deviation, 0.9792, and Model 2 had the lowest bias, -0.0069. All models in both regions had bias value that were near zero and all were negative indicating all model have a tendency to overpredict tree height.

Residuals for all models appear to be normally and randomly distributed and indicated a proper fit, Figure 4.2 and Figure 4.3. Some additional variation is present at larger predicted values at older ages versus the smaller predicted values at younger ages, however this is likely due to reduced sample size with increasing age and as installations were lost due to harvesting activity. In the piedmont Model 2, Model 3, and Model 4 had a significant likelihood ratio compared to Model 1, indicating that those three models all individually fit the data better than Model 1. Model 2 and Model 3 were then individually compared to Model 4, this time assuming they were the baseline since all three models were deemed improvements over Model 1. It was found that Model 4 in both instances had a statistically significant likelihood ratio test indicating the two parameter GADA model was the best fit to the data in the coastal plain. In the coastal plain, Model 2, Model 3, and Model 4 were significant when compared to Model 1. When Model 2 and Model 3 were compared to Model 4, Model 4 was only significant when compared to Model 2 indicating that in this region the presence or absence of competition control was a much more important driver for height growth than genetics.

A site index 60 curve at base age 25 years for Model 1 was plotted for both physiographic ranges, (Figure 4.4 - Figure 4.6). At age 25 the percent difference in height was calculated for the respective subgroups analyzed in models 2-4 and curves based on the percent increase or decrease were added to the Model 1 curves. As expected it can be seen that in both regions competition control and improved genetics resulted in a gain above the projected SI curve while the absence of competition control and unimproved genetics resulted in a percent decrease, (Figure 4.4and Figure 4.5). When the interaction of competition control and genetics were considered in both regions improved genetics with competition control resulted in the highest gains while unimproved genetics with no competition control resulted in the largest decrease. In the Piedmont improved genetics without competition control showed a small gain while unimproved genetics with competition control showed a slight percent decline below the SI curve, however in the coastal plain the opposite was found. The addition of competition control was what resulted in a percent gain while the absence resulted in a percent decrease, (Figure 4.6). All tables and figures have been converted to English units and can be found in Appendix C.

Discussion

A rotation-aged and region-wide PMRC study located in the piedmont and the coastal plain of the southeastern United States was evaluated to determine if the addition of genetic and competition control variables could improve the fit of a GADA site index function for loblolly pine. A variety of edaphic and climatic site conditions were inherently present in the data given the number of installations established throughout several states in each region. Results therefore are reflective of general trends for the specified regions however extrapolation to other regions or species should be done with caution as trends may change. Genetic improvement has continued beyond the families present in this study; however, results are supportive that by incorporating a variable for the level of genetic improvement into the GADA model will lead to a better fitting SI model. Genetics and competition control were the only variables included in this model, but additional silvicultural treatments such as fertilization could be added in a similar manner if appropriate data are available.

Conclusion

While the scope of this analysis is limited to a select grouping of first-generation open-pollinated loblolly pine families with one silvicultural variable, results are supportive that the addition of these variables to a GADA SI model will improve the fit for loblolly pine. Results indicate that if the level of genetic improvement and whether competition control was used on the site are known and incorporated into the SI model, a better fit can be achieved in both regions. In the coastal plain the likelihood ratio test did not find significance between Model 4 and Model 3; however, Model 4 has the lowest standard deviation of the four models and highest R^2. Caution should be used when extrapolating beyond the range of the original dataset, as it can result in illogical values. Additional silvicultural variables such as fertilization rates and timing were not included in these models as it was not a treatment built into this research study design, though it is possible the addition of further variables would continue to improve the model fit. Further work is needed in this area to capture additional silvicultural effects.

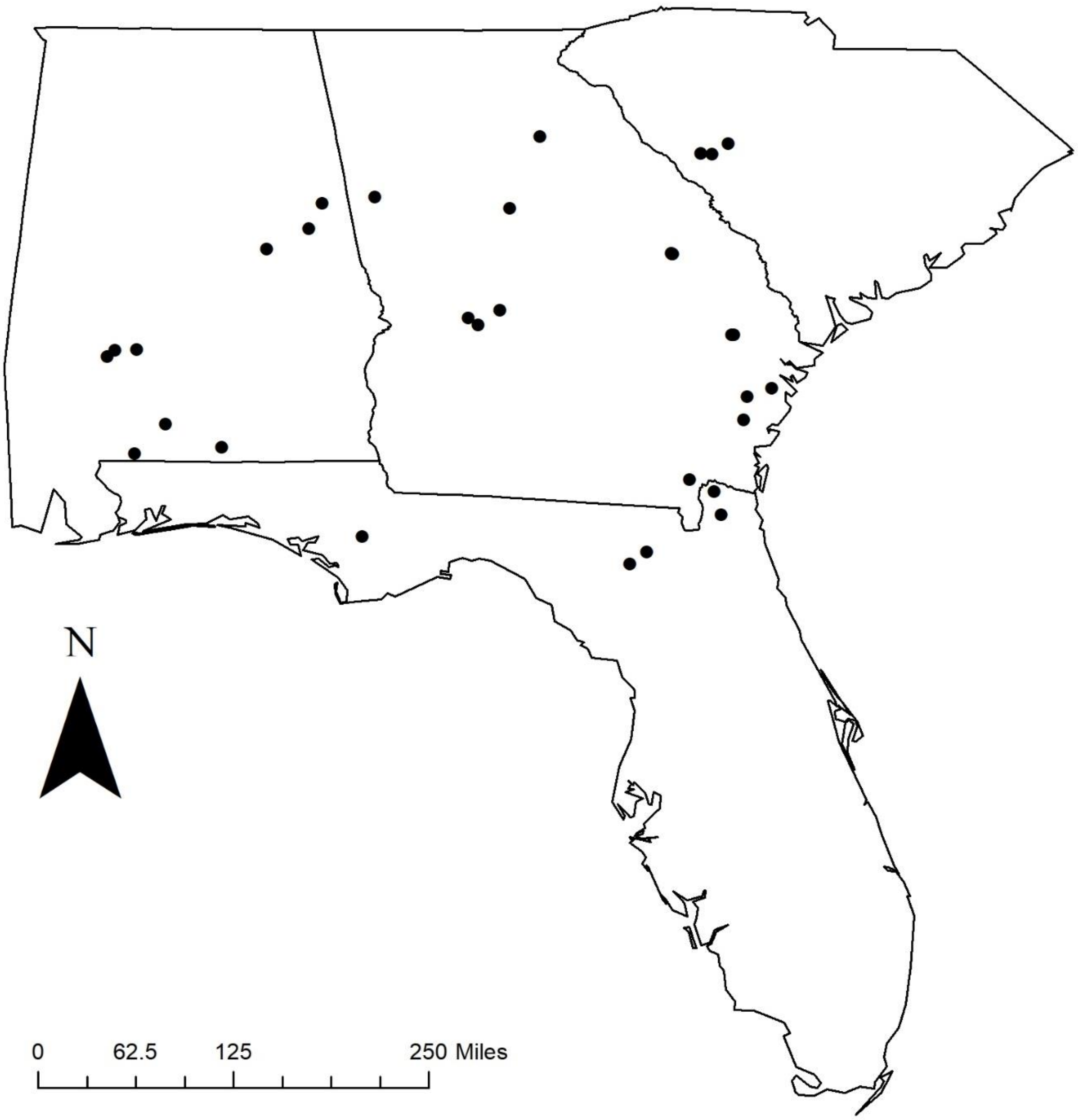


Figure 4.1. Map of PMRC HerbGen installation locations throughout the southeast US.

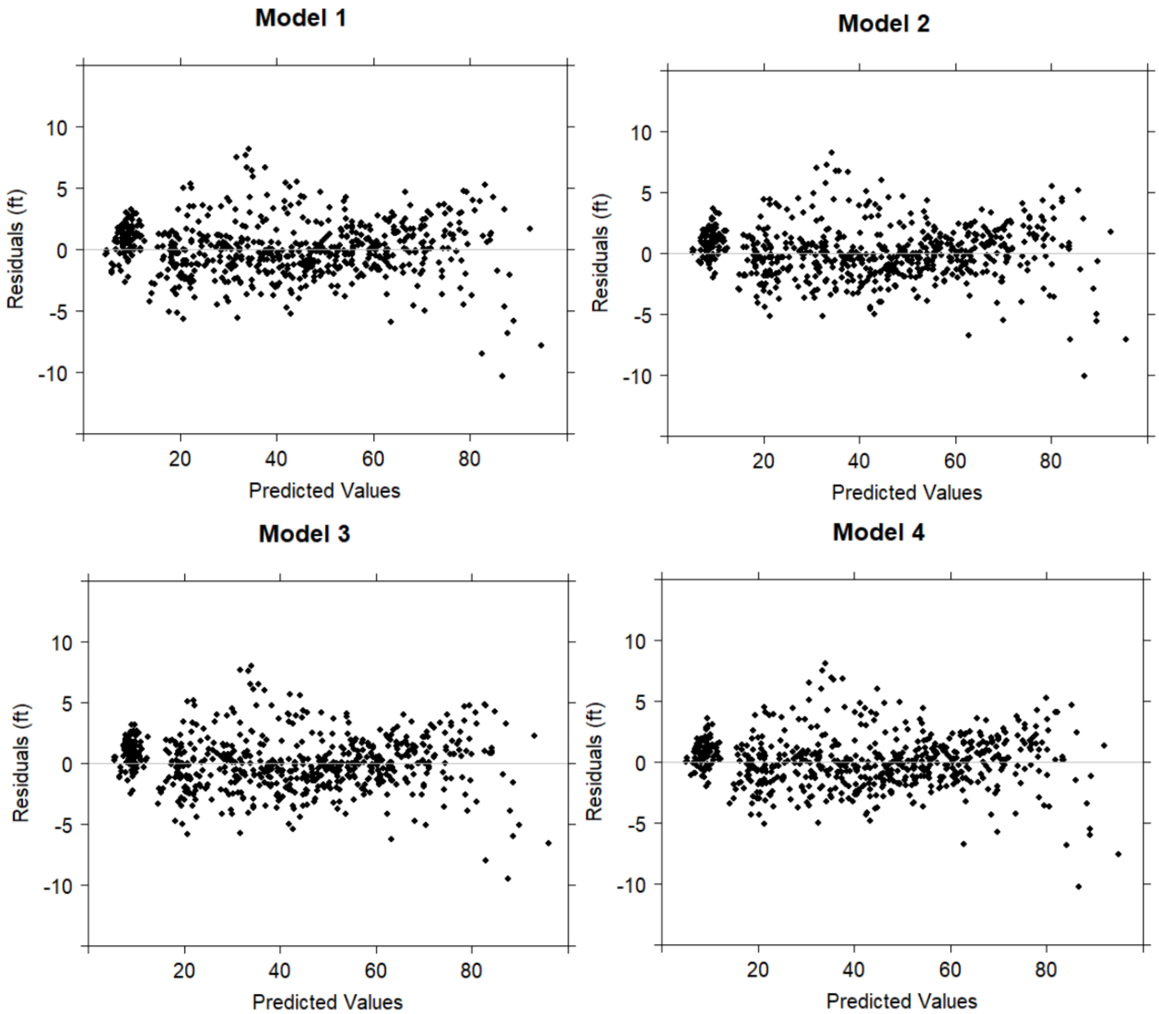


Figure 4.2 Residuals for piedmont GADA models 1-4. Model 1 is the base model fit with age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

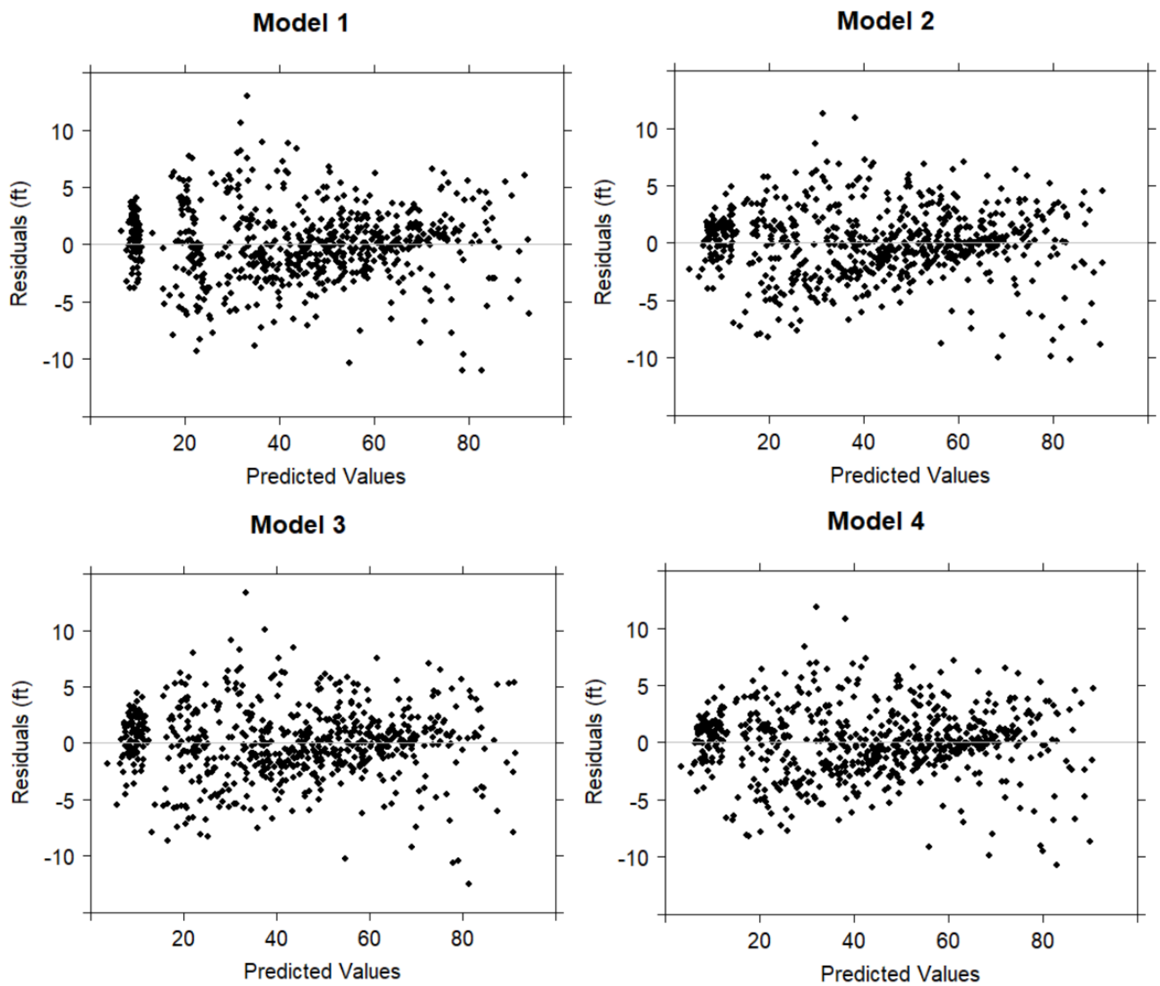


Figure 4.3 Residuals for coastal plain GADA models 1-4. Model 1 is the base model fit with age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

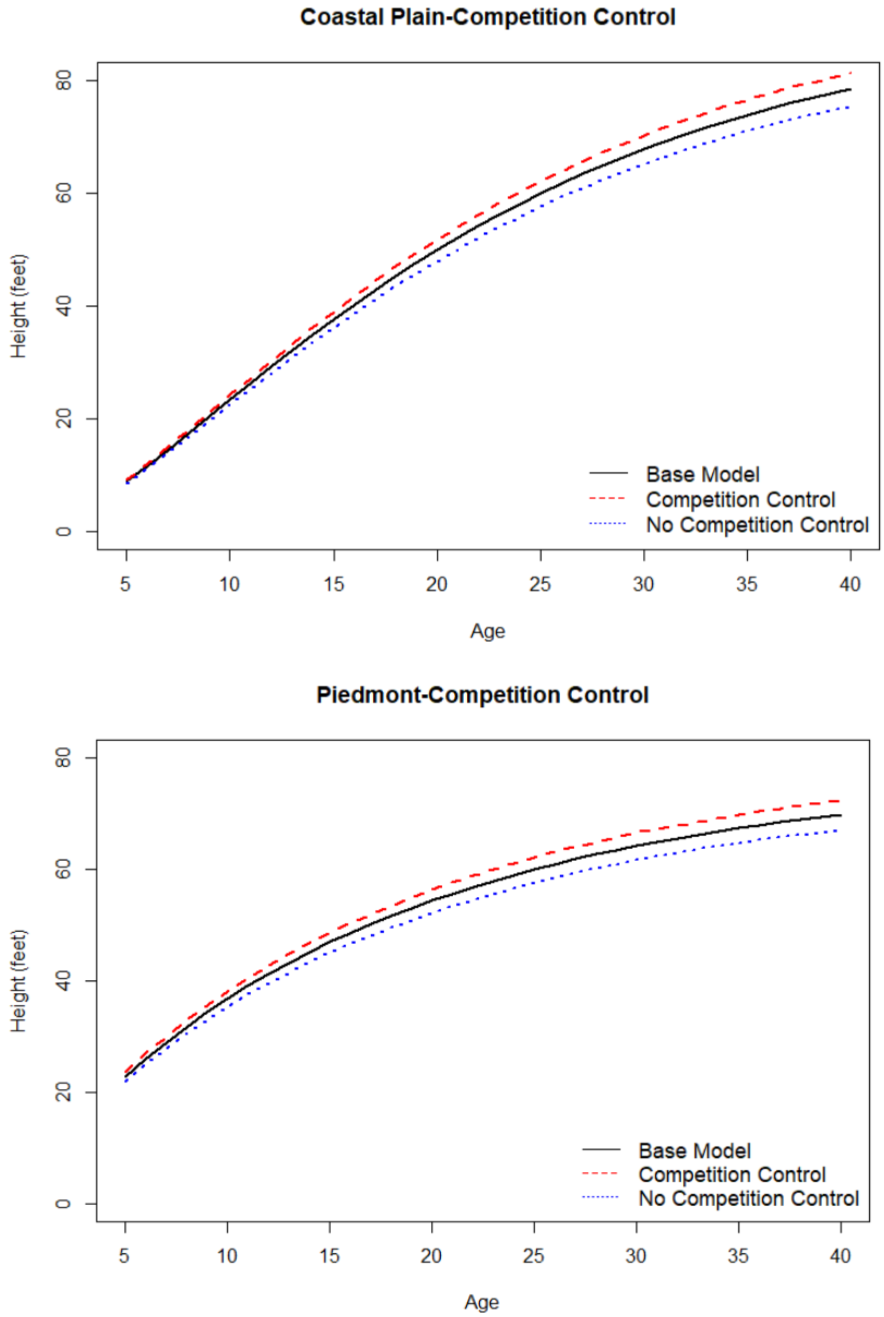


Figure 4.4. A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of competition control and no competition control were added to show the impact of competition control on height.

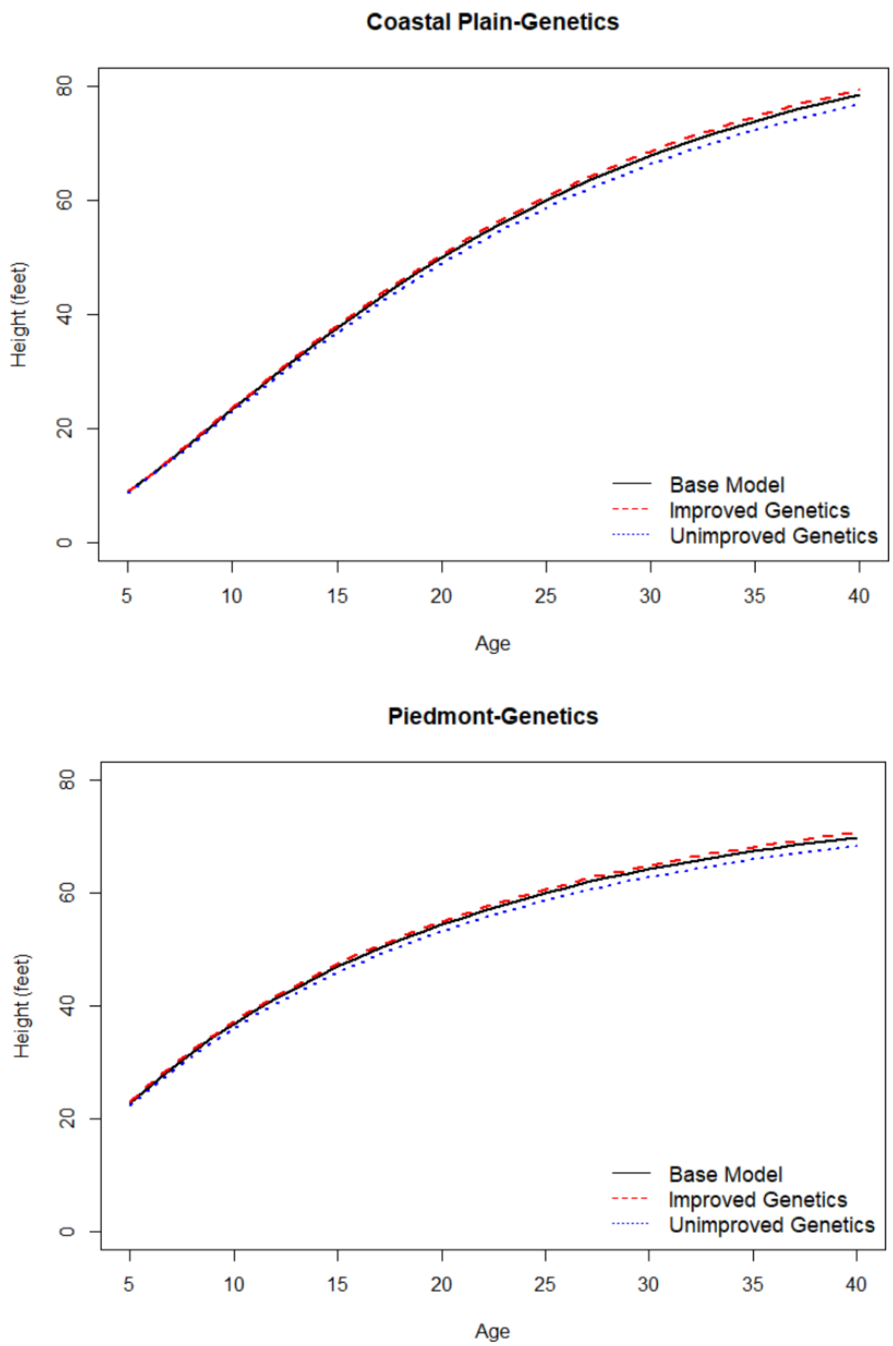


Figure 4.5 A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of unimproved genetics and improved genetics were added to show the impact of genetics on height.

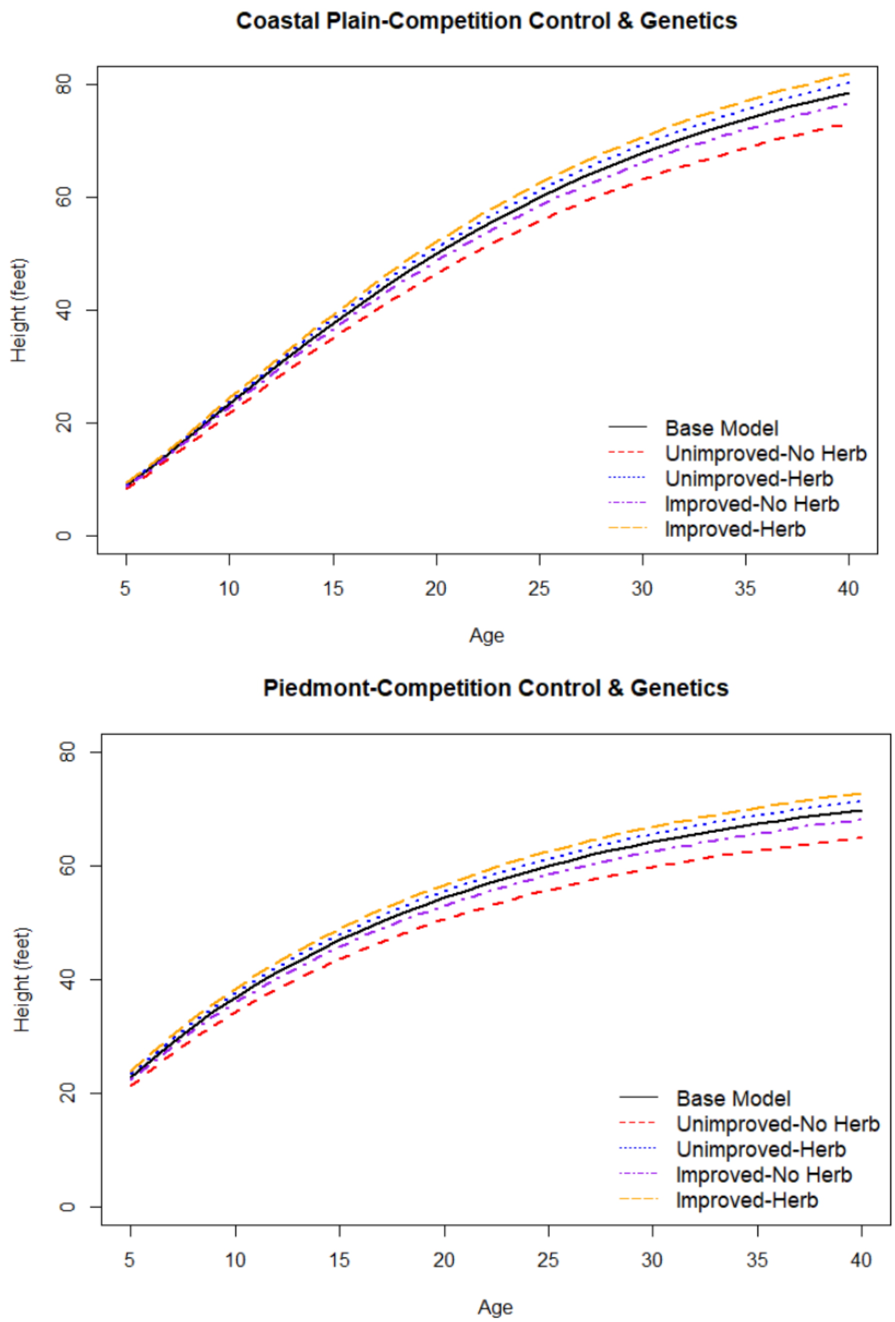


Figure 4.6 A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of unimproved genetics without competition control, unimproved genetics with competition control, improved genetics without competition control, and improved genetics with competition control were added to show the impact of the interaction of genetics and level of competition control on height.

Table 4.1. Number of PMRC HerbGen installations, plots within installations, and trees within plots present in each region at each age.

	Coastal Plain			Piedmont		
Age	**Installation**	**Plot**	**Tree**	**Installation**	**Plot**	**Tree**
3	16	128	5,636	15	118	5,312
6	16	128	5,291	15	118	4,987
9	16	128	16,125	15	118	15,452
12	16	128	15,635	15	113	14,457
15	16	127	15,214	15	113	16,891
18	14	103	11,880	15	111	12,732
21	11	81	8,828	10	79	8,237
25	9	65	6,350	7	55	5,174
30	6	42	3,651	4	32	2,407

Table 4.2. Model parameters for Model 1-4 for both the piedmont and coastal plain regions. Model 1 is the base model fit with and age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

	b_2	b_3	b_4	b_5	b_6	$RMSE$	R^2	Bias
Piedmont								
Model 1	-0.0531	-0.3307	7.6506	--	--	0.7992	0.9898	-0.0310
Model 2	-0.0512	1.1023	2.3267	-6.0927	--	0.7547	0.9907	-0.0569
Model 3	-0.0530	1.2857	0.0976	--	-5.0319	0.7909	0.9900	-0.0445
Model 4	-0.0543	1.126	8.7342	-22.8576	-6.7524	0.7456	0.9909	-0.0398
Coastal Plain								
Model 1	-0.0612	2.6754	-6.2267	--	--	1.1503	0.9792	-0.0433
Model 2	-0.0621	1.0001	7.7798	-12.8971	--	1.0914	0.9815	-0.0003
Model 3	-0.0617	1.1662	4.8047	--	-15.2962	1.1411	0.9796	-0.0138
Model 4	-0.0611	0.9920	18.0769	-32.6037	-2.3158	1.0890	0.9816	-0.0048

Table 4.3 Likelihood ratio test for each model comparison in both regions. An * denotes a significant value at $\alpha = 0.05$. Model 1 is the base model fit with age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

Model comparison	Likelihood ratio
Piedmont	
Model 1 & Model 2	57.03*
Model 1 & Model 3	10.65*
Model 1 & Model 4	68.75*
Model 2 & Model 4	58.10*
Model 3 & Model 4	11.72*
Coastal Plain	
Model 1 & Model 2	80.13*
Model 1 & Model 3	12.51*
Model 1 & Model 4	82.36*
Model 2 & Model 4	69.85*
Model 3 & Model 4	2.23

CHAPTER 5

DISCUSSION

Having an operational baseline of comparison will only grow in importance as genetic improvement continues in loblolly pine plantations, especially now that unimproved stock is no longer commercially planted or available. Expected improvement gains are reported as a percent increase over unimproved stock, however if unimproved stock is no longer planted this comparison loses relevance for foresters and land managers. The proposal put forward in this research is that a well performing first-generation open-pollinated loblolly pine family that is still commonly planted would be a more meaningful operational comparison for current and future forest plantations.

Rotation aged results of research block plots are becoming available, allowing for the opportunity to obtain a greater understanding of the impacts of genetic improvement, silviculture, and their interactions on stand development and productivity. These results can inform forestland owners and managers if observed early gains are reflective how the stands continue to develop over time and if those gains carry on through rotation to increase growth and final yield. Decisions on which genetic selections to move forward to the next breeding cycle and which silvicultural management techniques to continue using have been limited to primarily progeny tests and mid rotation results respectively. This research explored first-generation open-pollinated loblolly pine families in the coastal plain and piedmont regions of the southeastern United States with the objective of addressing some of these problems.

A system of equations was developed in Chapter 2 in which the estimated 25^{th} and 97^{th} dbh percentiles could be used to predict the shape and scale parameters of a two-parameter Weibull distribution to reliably estimate stand diameter distributions in loblolly pine over ages 3-30. The 25^{th} and 97^{th} percentiles could be estimated as a function of basal area per hectare, trees per hectare, and age. Quadratic mean diameter is also needed to estimate the shape parameter of the Weibull distribution. Height-diameter relationships were also modeled to allow predicting of individual tree volume via a combined variable equation. Height was modeled as a function of management intensity, site index, trees per hectare, and diameter at breast height. If prior stand management is not known the height can still be estimated via a traditional height-diameter relationship.

Projections for growth and yield are often developed from young stands. Few studies look beyond mid-rotation due to the length of time it takes for stands to mature. By the time a stand matures to rotation age the next generation of genetic improvement is available, as improvement occurs many families become no longer commercially available if early results are not promising. Some high performing families do however remain commercially available. Chapter 3 analyzed a rotation age study in which the effects of a still commonly operationally planted first-generation open-pollinated (OP) improved genetic loblolly pine OP 7-56, competition control, and their interaction were evaluated not only at each measurement age, but also across time. Diameter at breast height, average dominant height, trees per acre, basal area per acre, merchantable volume, and total volume were the variables of interest as indicators of stand growth and yield. It was found that competition control and genetics were significant across time for nearly every model and that interactions were present over time. For total volume per acre and merchantable volume per acre in the piedmont physiographic region a greater than additive effect was found at rotation age when stands with improved genetics and competition control were compared to stands of unimproved genetic stock with no competition control. It was noted that for plots in this study without competition control there was a lot of competition pressure from woody vegetation present, indicating that to see the full impact of genetic improvement, appropriate silvicultural management should be practiced to support those improved trees through rotation.

Site index is the most commonly used indicator of site quality and production potential in forestry. Site index (SI) is the average height of the dominant and codominant trees at a specified reference age, age 25 in the case of southern pine plantations. Chapter 4 evaluated if the addition of parameters for level of genetics and competition control could improve the predictive ability of a generalized algebraic difference approach (GADA) SI model. A Chapman Richards style GADA SI model was fit to rotation aged data in the coastal plain and piedmont regions. It was found that in both the coastal plain and piedmont regions the addition of a parameter for genetic improvement or for competition control significantly improved the model, however a model with both competition control and genetics improvement parameters performed the best and was recommended to use if the data were available. This leads to an improvement in SI estimation for a given tract, improving the forestland owners and managers knowledge of site productivity and aiding in decision making.

The research presented in Chapters 2 – 4 aims to improve the understanding of how first-generation open-pollinated stands of loblolly pine developed over time and if early expected growth gains were maintained through rotation age. The data represent a variety of site conditions across a large geographic region in the southeastern U.S. and is representative of general trends across the regions. Caution should be used when extrapolating beyond the coastal plain and piedmont regions of the southern United States and trends may vary in different geographical regions.

Future research is needed to expand the Chapter 2 benchmark study to also characterize relationships for OP 7-56 in the Western Gulf region. At the time of writing, single family research block plots meeting the criteria for inclusion in that region were not known to the authors. Chapter's 3 and 4 only considered two levels of genetics and two levels of competition control. Additional levels of genetic improvement, competition control, or silvicultural management techniques such as fertilization and pest control have the potential to impact the results significantly. As rotation aged data becomes available for more recently deployed improved genetic stands, re-evaluating these results will be necessary to determine how future genetic improvement and more intensive silvicultural management practices are interacting.

Due to its fast growth and ability to grow tall and straight loblolly pine will continue to be a highly important species commercially in the southeastern United States. This work aims to improve knowledge for forestland owners and managers. A better understanding of how improved genetic selections and intensive silviculture interacts, not just at a snap shot in time early in the stands rotation, but through time to a harvestable age will allow for better management decisions to be made. With better management decisions comes a more efficient use of resources and improved valuation of future stands.

REFERENCES

Arabatzis, A.A. and Burkhart, H.E. 1992. An evaluation of sampling methods and model forms for estimating height-diameter relationships in loblolly-pine plantations. *Forest Science*, **38** (1), 192-198.

Bailey, R.L. and Clutter, J.L. 1974. Base-age invariant polymorphic site curves. *Forest Science*, **20** (2), 155-159.

Bailey, R.L. and Dell, T. 1973. Quantifying diameter distributions with the Weibull function. *Forest Science*, **19** (2), 97-104.

Balmer, W.E. and Little, N.G. 1978. Site preparation methods. Proceedings: A Symposium on Principles of Maintaining Productivity on Prepared Sites, edited by T. Tippen, 60-64.

Bennett, F.A. 1968. Multiple product yield estimates for unthinned slash pine plantations, pulpwood, sawtimber, gum. USDA Forest Service. Southeast Forest Experimental Station, Asheville, NC., 21 p.

Bettinger, P., Boston, K., Siry, J.P. and Grebner, D.L. 2016. *Forest management and planning*. Academic press.

Borders, B.E., Zhoao, D., Wang, M. and Kane, M. 2014. Growth and yield models for second/third rotation Loblolly pine plantations in the Piedmont/Upper Coastal Plain and Lower Coastal Plain of the Southeastern U.S. *Plantation Management Research Cooperative Technical Report 2014-1*. Athens, GA.

Buford, M. and Burkhart, H.E. 1987. Genetic-improvement effects on growth and yield of loblolly-pine plantations. *Forest Science*, **33** (3), 707-724.

Bullock, B.P. and Burkhart, H.E. 2005. Juvenile diameter distributions of loblolly pine characterized by the two-parameter Weibull function. *New Forests*, **29** (3), 244.

Burkhart, H., Avery, T. and Bullock, B.P. 2019. *Forest Measurements*. 6th edn. Waveland Press, Inc.

Burkhart, H.E. and Tomé, M. 2012. *Modeling forest trees and stands*. Springer Science & Business Media.

Burns, R.M. and Honkala, B.H. 1990. Silvics of North America Volume 1 *Agriculture Handbook 654*. USDA.

Carlson, C.A., Fox, T.R., Burkhart, H.E., Allen, H.L. and Albaugh, T.J. 2009. Accuracy of subsampling for height measurements in loblolly pine plots. *Southern Journal of Applied Forestry*, **33** (3), 145-149.

Cieszewski, C.J. 2002. Comparing fixed-and variable-base-age site equations having single versus multiple asymptotes. *Forest Science*, **48** (1), 7-23.

Cieszewski, C.J. and Bailey, R. 2000. Generalized algebraic difference approach: theory based derivation of dynamic site equations with polymorphism and variable asymptotes. *Forest Science*, **46** (1), 116-126.

Cunningham, K., Barry, J.E. and Walkingstick, T. 2008. Managing loblolly pine stands--from A to Z. University of Arkansas Division of Agriculture. University of Arkansas Cooperative Extension Service Printing Services, 6 p.

Diéguez-Aranda, U., Burkhart, H.E. and Amateis, R.L. 2006. Dynamic Site Model for Loblolly Pine (Pinus taeda L.) Plantations in the United States. *Forest Science*, **52** (3), 262-272.

Dorman, K.W. and Zobel, B.J. 1973. Genetics of loblolly pine. USDA Forest Service. Washington, DC., 21 p.

Egbäck, S., Bullock, B.P., Isik, F. and McKeand, S.E. 2015. Height-diameter relationships for different genetic planting stock of loblolly pine at age 6. *Forest Science*, **61** (3), 424-428.

Farmer, S. 2017. Switchgrass in Pine Plantations. *Southern Research Station Communications*. USDA. Southern Research Station.

Fox, T., Morris, L. and Maimone, R. 1989. The impact of windrowing on the productivity of a rotation age loblolly pine plantation. Proceedings of the Fifth Biennial Southern Silviculture Research Conference, New Orleans, LA. USDA Forest Service Genteral Technical Report No. SO-74, 133-140.

Fox, T.R., Jokela, E.J. and Allen, H.L. 2007. The development of pine plantation silviculture in the Southern United States. *Journal of Forestry*, **105** (7), 337-347.

Friedman, S.T. and Adams, W.T. 1985. Estimation of gene flow into two seed orchards of loblolly pine (Pinus taeda L.). *Theoretical and Applied Genetics*, **69** (5), 609-615.

Geyer, W.A. and Lynch, K.D. 1987. Use of Site Index as a Forestry Management Tool. *Transactions of the Kansas Academy of Science (1903-)*, **90** (1/2), 46-51.

Hamilton, R. 2019. Forest soils and site index. *Woodland Owner Notes*. NC State University. NC State Extension.

Jokela, E.J., Martin, T.A. and Vogel, J.G. 2010. Twenty-five years of intensive forest management with southern pines: important lessons learned. *Journal of Forestry*, **108** (7), 338-347.

Lantz, C.W. and Kraus, J.F. 1987. A guide to southern pine seed sources. *Gen. Tech. Rep. SE-43. Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 34 p.*, **43**.

Lowery, R.F. and Gjerstad, D.H. 1991. Chemical and mechanical site preparation. In *Forest regeneration manual*, Springer, pp. 251-261.

Martin, S.W. and Shiver, B.D. 2002. Impacts of vegetation control, genetic improvement and their interaction on loblolly pine growth in the Southern United States - Age 12 results. *Southern Journal of Applied Forestry*, **26** (1), 37-42.

Massey Jr., F.J. 1951. The Kolmogorov-Smirnov test for goodness of fit. *Journal of the American statistical Association*, **46** (253), 68-78.

McKeand, S. 2019a. The evolution of a seedling market for genetically improved loblolly pine in the southern United States. *Journal of Forestry*, **117** (3), 293-301.

McKeand, S., Abt, R., Allen, H., Li, B. and Catts, G. 2006a. What are the best loblolly pine genotypes worth to landowners? *Journal of Forestry*, **104** (7), 352-358.

McKeand, S., Jokela, E., Huber, D., Byram, T., Allen, H., Li, B. and Mullin, T. 2006b. Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. *Forest Ecology and Management*, **227** (1-2), 178-184.

McKeand, S., Mullin, T., Byram, T. and White, T. 2003. Deployment of genetically improved loblolly and slash pines in the South. *Journal of Forestry*, **101** (3), 32-37.

McKeand, S.E. 1988. Optimum age for family selection for growth in genetic tests of loblolly pine. *Forest Science*, **34** (2), 400-411.

McKeand, S.E. 2019b. The Evolution of a Seedling Market for Genetically Improved Loblolly Pine in the Southern United States. *Journal of Forestry*, **117** (3), 293-301.

Mehtatalo, L., de-Miguel, S. and Gregoire, T.G. 2015. Modeling height-diameter curves for prediction. *Canadian Journal of Forest Research*, **45** (7), 826-837.

Miguel, E.P., Machado, S.D., Figueiredo, A. and Arce, J.E. 2010. Using the Weibull function for prognosis of yield by diameter class in Eucalyptus urophylla stands. *Cerne*, **16** (1), 94-104.

Miller, J.H., Zutter, B.R., Zedaker, S.M., Edwards, M.B. and Newbold, R.A. 2003. Growth and yield relative to competition for loblolly pine plantations to midrotation—a southeastern United States regional study. *Southern Journal of Applied Forestry*, **27** (4), 237-252.

NCSU Cooperative Tree Improvement Program. 2018. Introduction to the PRS. http://www.treeimprovement.org/2018).

Pienaar, L., Burgan, T. and Rheney, J. 1987. Stem volume, taper and weight equations for site-prepared loblolly pine plantations. *Plantation Management Research Cooperative Technical Report 1987-1*. University of Georgia.

R Development Core Team. 2020. The Comprehensive R Archive Network. https://cran.r-project.org/index.html.

Reynolds, M.R., Burk, T.E. and Huang, W.C. 1988. Goodness-of-fit tests and model selection procedures for diameter distribution models. *Forest Science*, **34** (2), 373-399.

Rubilar, R.A., Allen, H.L., Fox, T.R., Cook, R.L., Albaugh, T.J. and Campoe, O.C. 2018. Advances in Silviculture of Intensively Managed Plantations. *Current Forestry Reports*, **4** (1), 23-34.

Sabatia, C. and Burkhart, H. 2013a. Height and diameter relationships and distributions in loblolly pine stands of enhanced genetic material. *Forest Science*, **59** (3), 278-289.

Sabatia, C. and Burkhart, H. 2013b. Modeling height development of loblolly pine genetic varieties. *Forest Science*, **59** (3), 267-277.

Schabenberger, O. and Pierce, F.J. 2001. *Contemporary statistical models for the plant and soil sciences*. CRC press.

Schmidtling, R.C. 2001. Southern Pine Seed Sources. USFS. Southern Research Station, 25 p.

Seltman, H. 2018. Experimental Design for Behavioral and Social Sciences. College of Humanities and Social Sciences at Carnegie Mellon University.

Sharma, M., Amateis, R.L. and Burkhart, H.E. 2002. Top height definition and its effect on site index determination in thinned and unthinned loblolly pine plantations. *Forest Ecology and Management*, **168** (1-3), 163-175.

Sherrill, J.R., Bullock, B.P., Mullin, T.J., McKeand, S.E. and Purnell, R.C. 2011. Total and merchantable stem volume equations for midrotation loblolly pine (Pinus taeda L.). *Southern Journal of Applied Forestry*, **35** (3), 105-108.

Squillace, A. 1989. Tree improvement accomplishments in the South. 20th Southern Forest Tree Improvement Conference, 26-30.

Tippin, T. 1978. Proceedings: a Symposium on Principles of Maintaining Productivity on Prepared Sites Southern Forest Experiment Station.

Todd, D., Pait, J. and Hodges, J. 1995. The impact and value of tree improvement in the South. 23rd Southern Forest Tree Improvement Conference, 7-15.

Trim, K.R., Coble, D.W., Weng, Y., Stovall, J.P. and Hung, I.K. 2019. A New Site Index Model for Intensively Managed Loblolly Pine (Pinus taeda) Plantations in the West Gulf Coastal Plain. *Forest Science*.

Vitousek, P.M. and Matson, P.A. 1985. Intensive harvesting and site preparation decrease soil nitrogen availability in young plantations. *Southern Journal of Applied Forestry*, **9** (2), 120-125.

Wells, O.O. and Wakeley, P.C. 1966. Geographic Variation in Survival, Growth, and Fusiform-Rust Infection of Planted Loblolly Pine. *Forest Science*, **12** (suppl_2), a0001-z0001.

Xiang, B., Li, B.L. and McKeand, S. 2003. Genetic gain and selection efficiency of loblolly pine in three geographic regions. *Forest Science*, **49** (2), 196-208.

Zobel, B. and Talbert, J. 1984. *Applied forest tree improvement*. John Wiley & Sons.

APPENDIX A

CHAPTER 2: ENGLISH UNITS

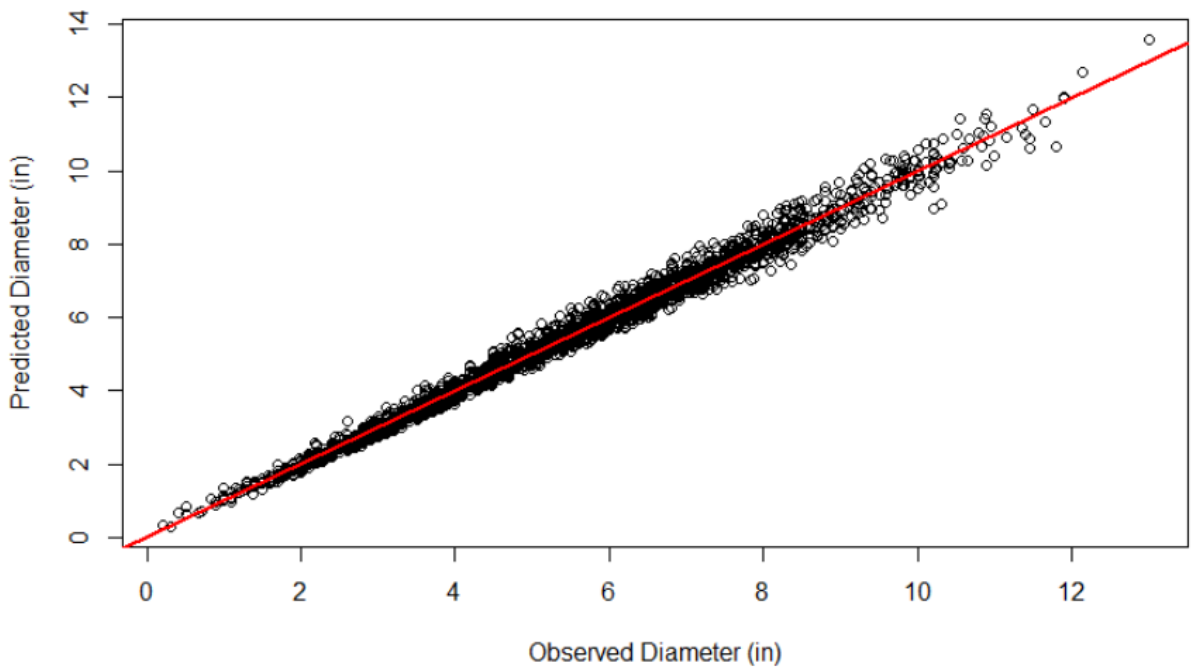


Figure A.1. Predicted vs. observed data points for the 25th DBH percentile (in) for all plots (Equation 1). A 1:1 relationship is indicated by the red line.

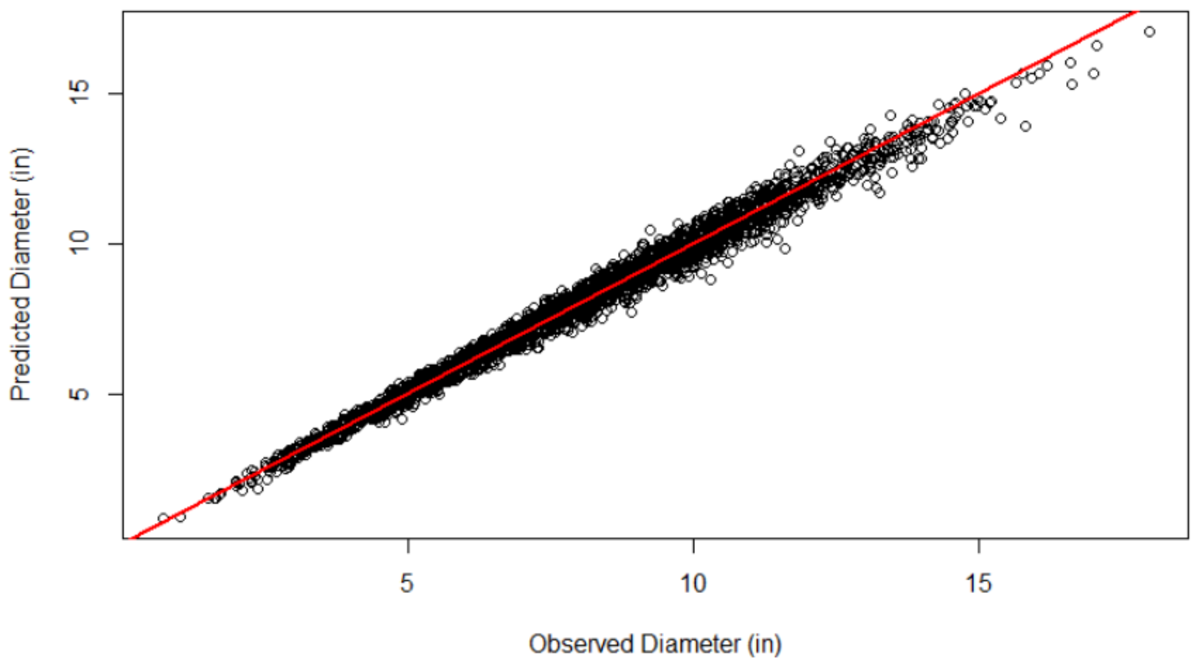


Figure A.2. Predicted vs observed data points for the 97th DBH percentile for all plots (Equation 2). A 1:1 relationship is indicated by the red line.

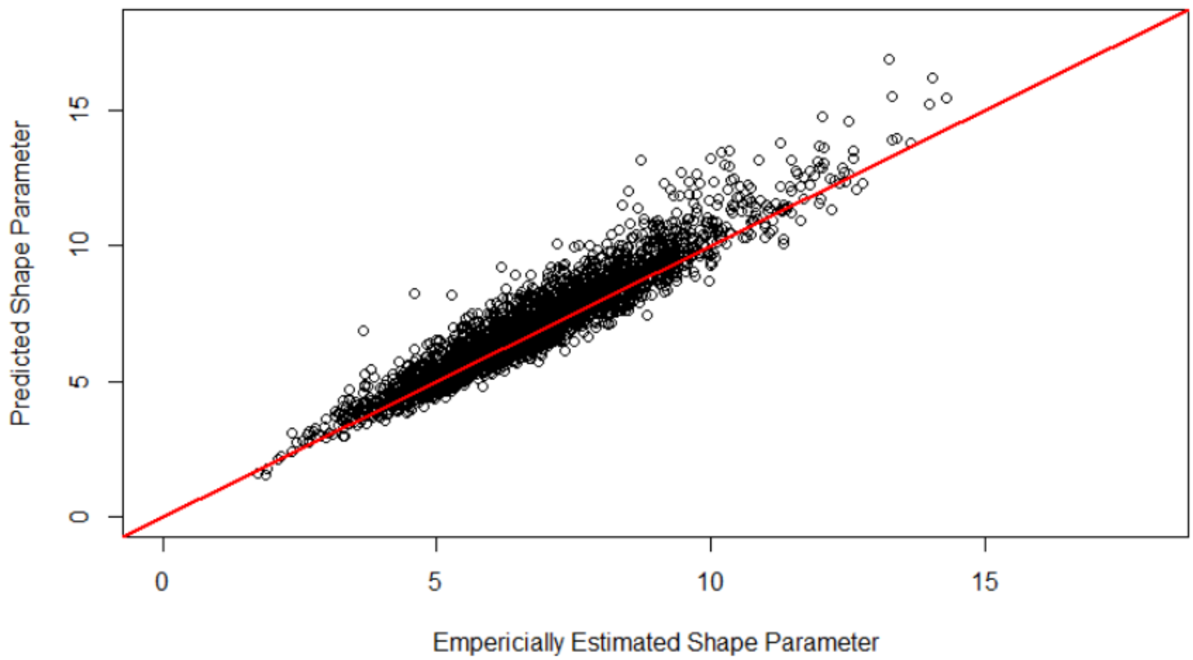


Figure A.3. Predicted shape parameter (in) vs. empirically estimated shape parameter (in) for two-parameter Weibull distribution for all plots (Equation 5). A 1:1 relationship is indicated by the red line.

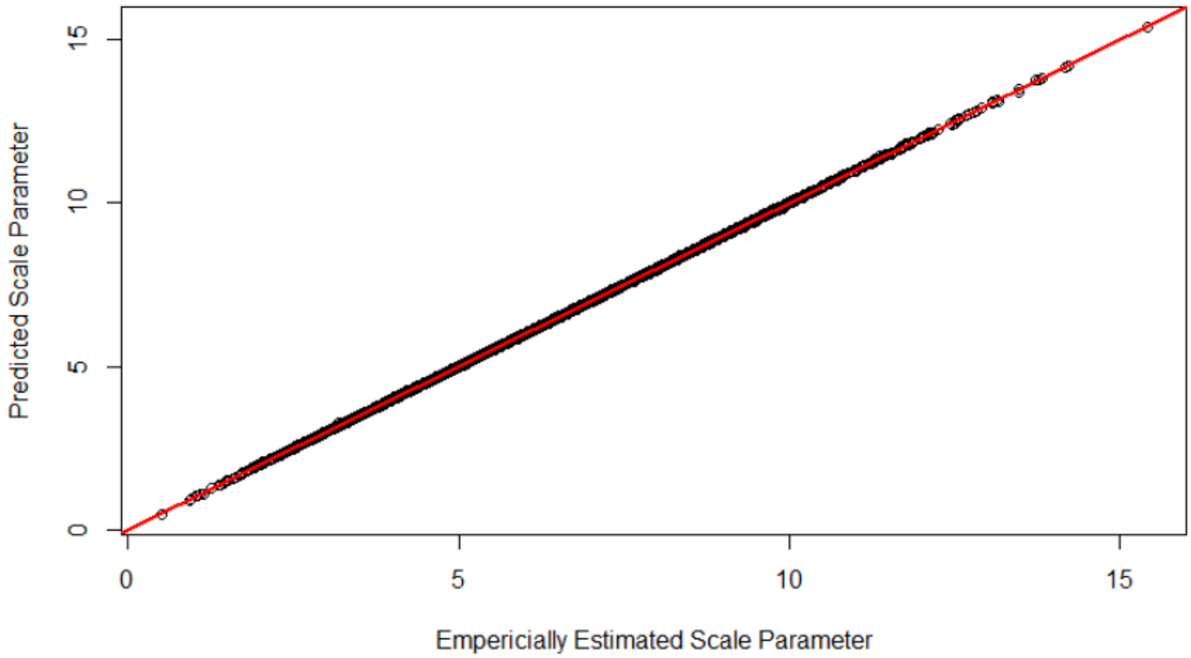


Figure A.4. Predicted scale parameter (in) vs. empirically estimated scale parameter (in) for the two parameter Weibull distribution for all plots (Equation 6). A 1:1 relationship is indicated by the red line.

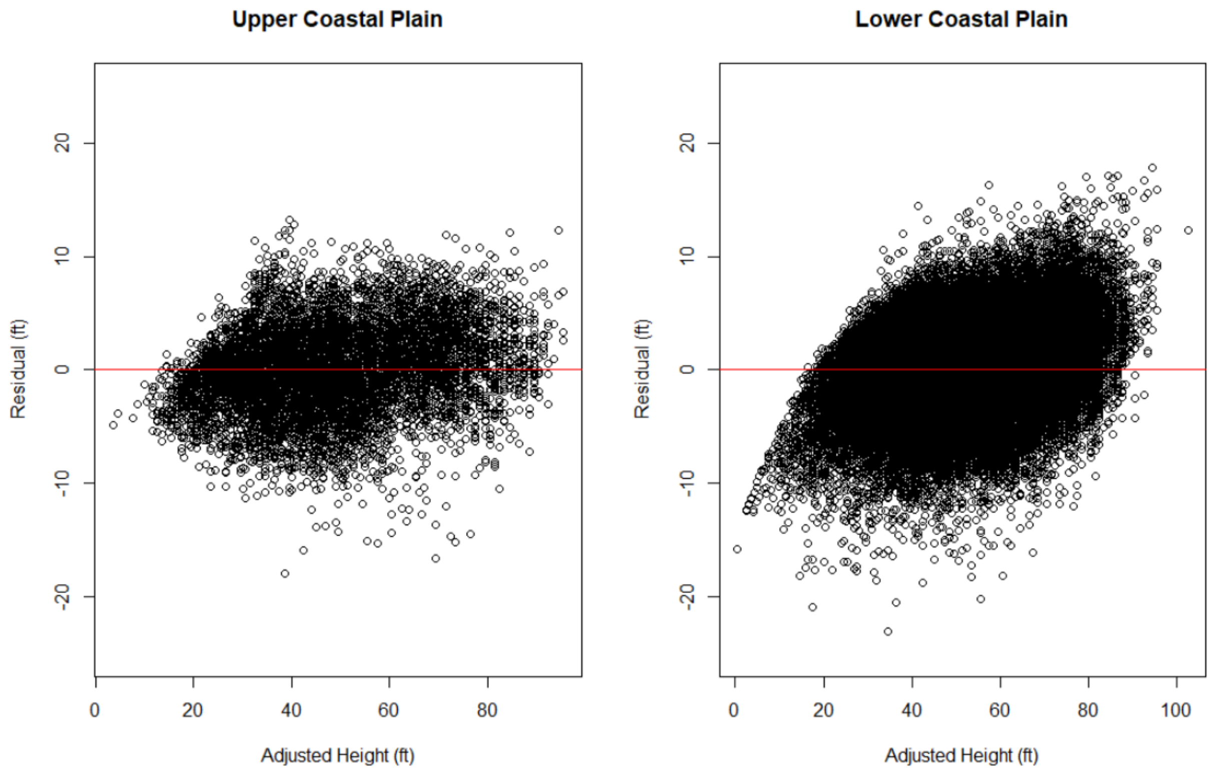


Figure A.5. Residual plot for Equation 5 by height for all plots.

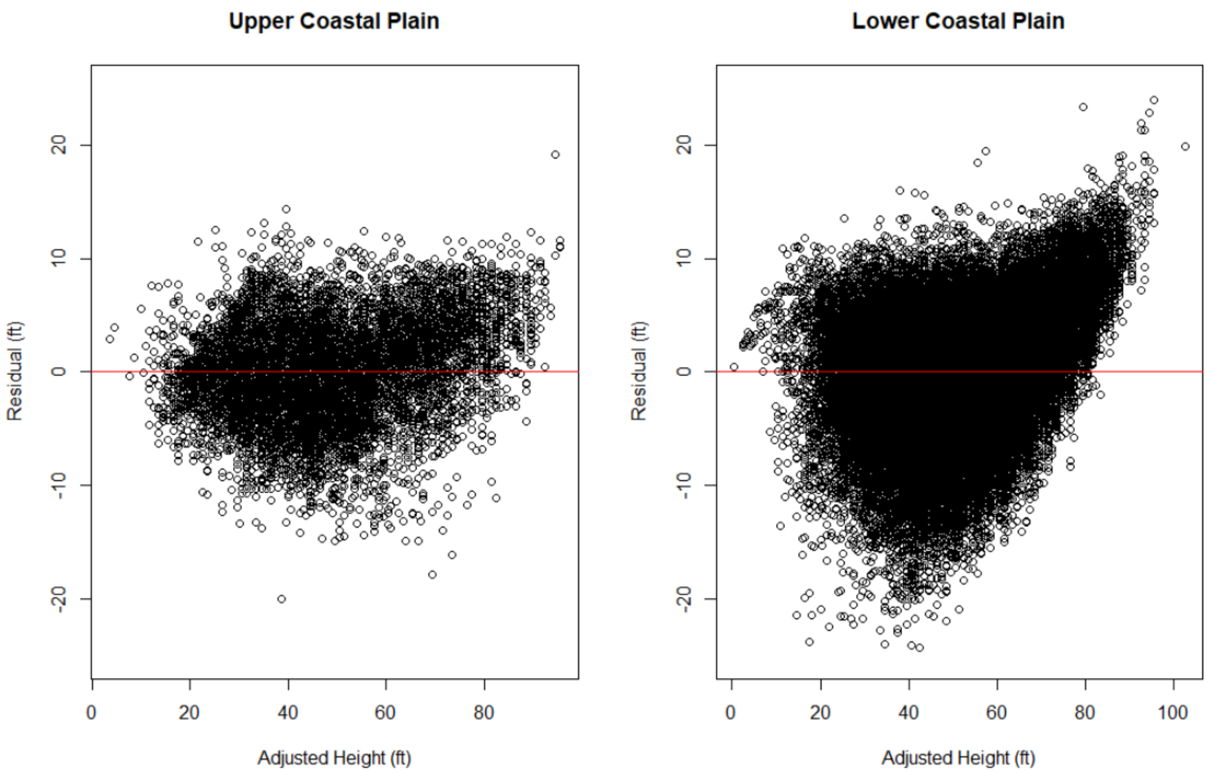


Figure A.6. Residual plot for Equation 6 by height for all plots.

Table A.1. Study methods of each of the five trials in this study.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Year Planted	1996	2007	1987	2001, 2003, 2005	1987
Planting TPA	300, 600, 900, 1200, 1500, 1800	435, 726	681	388, 454, 518	750
Ages of data collection	2, 4, 6, 8, 10, 12, 15, 16, 17, 18, 21	2, 4, 6, 8	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 23, 25, 27, 29	4, 5, 7, 8, 9, 10, 11, 13, 15	3, 6, 9, 12, 15, 18, 21, 25
Site Preparation	Bed + chemical	Chemical	Operational site prep	(1) shear and bed + chemical (2) bed + chemical (3) drummed and bedded (4) shear and chop	Applied by cooperator prior to planting. (1) Lower Coastal Plain: primarily bedding (2) Upper Coastal Plain: ranged from chop and burn to shear, rake, and disc
Fertilization	(1) Operational application of competition control and fertilizer (2) Intensive application: annual application of competition control, and additional fertilization in first two growing seasons	Applied first growing season	(1) Control: no treatments (2) Fertilization: Yearly application for entire length of study, additional mid-summer treatment applied first two growing seasons (3) Herbicide: complete vegetation control for entire length of study (4) Fertilization and herbicide - combination of the fertilization and herbicide treatments	None	None
Competition Control		Herbaceous weed control applied first two growing seasons		(1) None (2) Applied first growing season	(1) None (2) Complete control of all competing vegetation: spraying in first three growing seasons and targeted application as needed yearly after

Table A.2. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 1[1]. The number of plots decreases over time due to mortality events, thinning activity or harvesting activity.

		DBH 25th quantile (in)			DBH 97th quantile (in)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
4	201	2.59	0.50	4.80	3.83	2.00	6.27	1.74	6.15	14.04	1.15	3.16	5.39
6	192	3.81	1.80	6.90	5.44	3.49	8.48	2.36	6.88	13.26	2.42	4.53	7.57
8	192	4.54	2.40	8.10	6.50	4.37	10.06	3.50	6.86	12.19	3.24	5.42	8.85
10	180	5.14	2.90	9.20	7.43	5.09	12.26	3.50	6.76	12.25	3.95	6.22	10.54
12	168	5.60	3.00	10.33	8.20	5.40	14.02	3.45	6.65	12.52	4.17	6.81	11.78
15	155	6.39	3.48	10.80	9.46	6.30	15.82	3.62	6.72	13.98	4.88	7.88	12.68
16	46	6.61	3.80	10.20	9.93	7.14	13.60	4.14	6.23	9.43	5.32	7.92	11.75
17	44	7.14	3.80	10.10	10.66	7.41	13.82	3.80	6.73	12.65	5.39	8.53	12.11
18	153	7.03	3.83	12.15	10.52	7.11	17.02	3.52	6.45	14.29	5.48	8.75	14.22
21	128	7.87	4.40	13.00	11.74	7.97	17.99	3.55	6.42	11.55	6.11	9.71	15.41

[1] Across all ages, n=1258 plots.

Table A.3. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 2[1]

		DBH 25th quantile (in)			DBH 97th quantile (in)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
2	6	2.58	2.30	2.80	3.60	3.30	3.92	6.53	7.25	8.78	2.82	3.07	3.31
4	6	4.57	4.00	5.40	6.09	5.42	6.58	7.22	8.30	9.74	4.71	5.24	5.90
6	6	5.60	4.80	6.50	7.54	6.86	8.26	7.17	8.37	10.35	5.78	6.42	7.23
8	6	6.24	5.25	7.20	8.52	7.56	9.30	6.57	7.86	9.67	6.40	7.22	8.13

[1] Across all ages, n=24 plots.

Table A.4. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 3[1]. The number of plots increased from age 3 to age 4 as the trees reached heights over 4.5ft. After age 11 the plot number gradually decreases over time due thinning and harvesting.

		DBH 25th quantile (in)			DBH 97th quantile (in)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
4	66	2.38	0.40	4.20	3.50	1.60	5.56	1.91	6.14	12.60	0.94	2.87	4.77
5	66	3.35	1.00	5.00	4.71	2.80	6.57	2.35	7.08	13.31	1.81	3.95	5.52
6	66	4.05	1.70	5.50	5.59	3.70	6.96	3.05	7.45	13.65	2.61	4.73	6.02
7	66	4.61	2.20	5.90	6.35	4.09	7.70	3.41	7.63	13.39	3.12	5.38	6.71
8	66	5.03	2.57	6.40	6.89	4.50	8.47	3.69	7.65	13.32	3.58	5.85	7.42
9	66	5.38	3.00	6.98	7.42	5.00	9.28	3.68	7.53	12.08	3.95	6.27	8.09
10	66	5.66	3.30	7.60	7.85	5.30	10.37	3.81	7.52	12.34	4.22	6.62	8.95
11	66	5.87	3.50	7.90	8.25	5.69	11.07	3.85	7.34	11.30	4.50	6.91	9.46
12	62	6.09	3.85	8.30	8.61	5.90	11.73	4.24	7.10	10.36	4.79	7.21	9.96
13	62	6.28	3.95	8.40	8.94	6.10	11.90	4.09	7.00	10.00	5.02	7.47	10.20
14	62	6.46	4.05	8.80	9.24	6.40	12.57	4.24	6.91	9.69	5.19	7.69	10.75
15	62	6.62	4.05	8.98	9.54	6.70	13.06	4.13	6.86	9.29	5.40	7.91	10.98
16	62	6.78	4.15	9.25	9.85	6.80	13.48	4.16	6.73	9.26	5.50	8.15	11.28
17	58	7.00	4.22	9.30	10.21	7.11	13.95	3.97	6.61	9.02	5.69	8.43	11.55
18	58	7.15	4.30	9.90	10.46	7.22	14.33	3.87	6.60	9.55	5.86	8.63	11.76
19	54	7.37	4.33	10.00	10.83	7.51	14.46	3.73	6.47	9.40	5.97	8.90	12.00
20	54	7.46	4.43	10.25	11.03	7.70	14.55	3.68	6.39	9.38	6.10	9.04	12.09
21	38	7.46	4.50	10.57	11.13	7.70	14.81	3.66	6.21	9.01	6.16	9.10	12.17
23	38	7.65	4.70	11.00	11.62	8.42	14.98	3.44	6.01	9.04	6.52	9.44	12.55
25	8	8.08	4.72	10.93	12.24	9.00	15.66	3.29	6.13	8.77	6.90	9.96	13.15
27	12	9.24	8.07	11.45	13.42	11.29	16.61	5.78	6.58	8.50	9.50	11.18	13.77
29	8	9.64	8.35	11.80	13.79	11.80	17.08	5.88	6.78	8.50	9.88	11.58	14.18

[1] Across all ages, n=1120 plots.

Table A.5. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 4[1]. The plots that are included in this study had different measurement schedules, so n varies over time based on data collection.

		DBH 25th quantile (in)			DBH 97th quantile (in)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
5	9	3.50	2.60	4.10	5.04	4.30	5.52	3.28	6.33	8.30	3.75	4.20	4.71
7	10	4.67	2.70	6.48	6.22	4.41	8.50	4.92	7.95	10.64	3.56	5.35	7.25
8	6	5.73	4.83	6.60	8.07	7.43	8.87	4.05	6.77	9.06	6.47	6.79	7.32
9	7	5.88	5.45	6.40	7.86	7.56	8.26	7.17	8.27	10.04	6.44	6.77	7.14
10	4	7.06	6.55	7.75	9.43	8.90	10.19	6.36	7.92	9.46	7.75	8.05	8.68
11	12	6.13	5.00	7.07	8.32	7.07	9.70	4.18	7.71	11.46	6.05	7.15	8.00
13	15	6.89	5.85	8.40	9.14	8.34	11.10	6.06	8.44	11.81	7.03	7.92	9.49
15	5	6.69	6.00	7.45	8.97	8.57	9.45	6.81	7.86	9.14	7.24	7.69	8.26

[1] Across all ages, n=77 plots.

Table A.6. Empirical summary statistics for the two-parameter Weibull distribution for research Trial 5[1].

		DBH 25th quantile (in)			DBH 97th quantile (in)			Shape Parameter			Scale Parameter		
Age	**n**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
6	7	3.20	1.80	4.50	4.80	3.17	6.49	4.33	6.22	8.41	2.75	4.12	5.16
9	7	4.27	3.20	5.52	6.37	4.93	7.98	4.96	6.11	7.93	4.29	5.42	6.42
12	7	4.98	4.00	6.20	7.53	6.12	9.44	5.17	6.11	7.47	5.48	6.32	7.23
15	7	5.47	4.50	6.70	8.52	7.00	10.61	4.63	6.11	7.17	6.39	7.01	7.92
18	7	5.81	4.80	7.00	9.25	7.60	11.52	4.49	6.11	7.63	6.94	7.54	8.43
21	6	6.33	5.50	7.30	10.20	9.39	12.35	4.59	6.11	7.41	7.63	8.11	8.90
25	6	7.04	6.20	7.78	11.08	10.10	13.38	4.48	6.11	6.80	8.21	8.78	9.45

[1] Across all ages, n=54 plots.

Table A.7. Coefficients of presented equations. Region appropriate coefficients are given for Equations 5, 6, and 7.

			UCP			LCP		
	Equation 1	Equation 2	Equation 5	Equation 6	Equation 7	Equation 5	Equation 6	Equation 7
$\hat{\beta}_1$	2.7302	2.3889	9.4613	5.0204	4.6977	16.2544	4.8995	4.3738
$\hat{\beta}_2$	0.5985	0.4025	-1.2869	0.0706	-5.8556	-1.4138	0.0831	-3.0282
$\hat{\beta}_3$	-0.0100	0.1273	2.2736	-8.6086	--	1.2518	-6.6552	--
$\hat{\beta}_4$	--	--	4.4879	-3.5173	--	4.1357	-3.1066	--
$\hat{\beta}_5$	--	--	0.0073	--	--	0.0091	--	--
$\hat{\beta}_6$	--	--	0.1402	--	--	0.1879	--	--
$\hat{\beta}_7$	--	--	-12.1834	--	--	-12.1953	--	--
$\hat{\beta}_8$	--	--	-4.2814	--	--	-3.9828	--	--

Table A.8. Practical application of the system of equations presented for a hypothetical stand in the upper coastal plain where SI=80, TPA=650, A=20, BA=200, and MI=moderate. The respective equations were used to predict the height in meters of a tree in each D-class. The predicted Weibull distribution parameters were used to estimate the D-class distribution. Volume per hectare estimates were based on each of the three different height equations and one common individual tree volume equation.

		Height (ft)				Volume (ft^3/ac)		
D-class	**D-class Distribution**	**Equation 5**	**Equation 6**	**Equation 7**		**Using Ht Equation 5**	**Using Ht Equation 6**	**Using Ht Equation 7**
3	0.92%	35.5	33.6	20.1		5.76	5.52	3.79
4	3.18%	45.2	43.5	29.9		39.68	38.35	27.69
5	8.03%	53.0	51.1	38.5		174.64	168.77	129.80
6	15.68%	59.2	56.8	45.8		535.76	514.89	419.23
7	23.34%	64.2	61.4	52.0		1162.29	1112.96	947.35
8	24.77%	68.3	65.1	57.3		1701.09	1622.94	1432.46
9	16.73%	71.7	68.1	61.7		1519.16	1444.01	1310.41
10	6.13%	74.6	70.7	65.6		712.66	675.84	627.67
11	0.99%	77.0	72.8	68.9		143.42	135.67	128.47
	99.77%[1]				**Total**	**5994.46**	**5718.93**	**5026.87**

[1] Due to small proportions in D-classes less than 3 in and greater than 11 in, total does not equal 100%.

APPENDIX B

CHAPTER 3: METRIC UNTIS

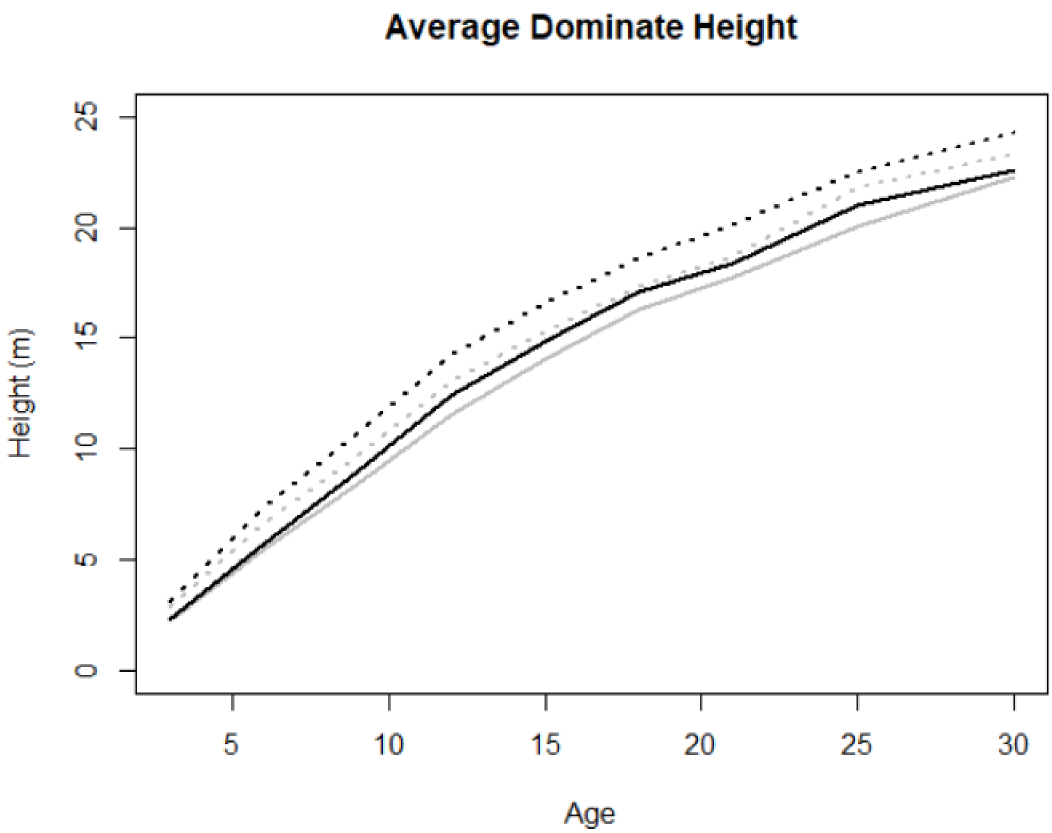


Figure B.1. Least squares means for average dominant height across time in the PMRC HerbGen coastal plain installations.

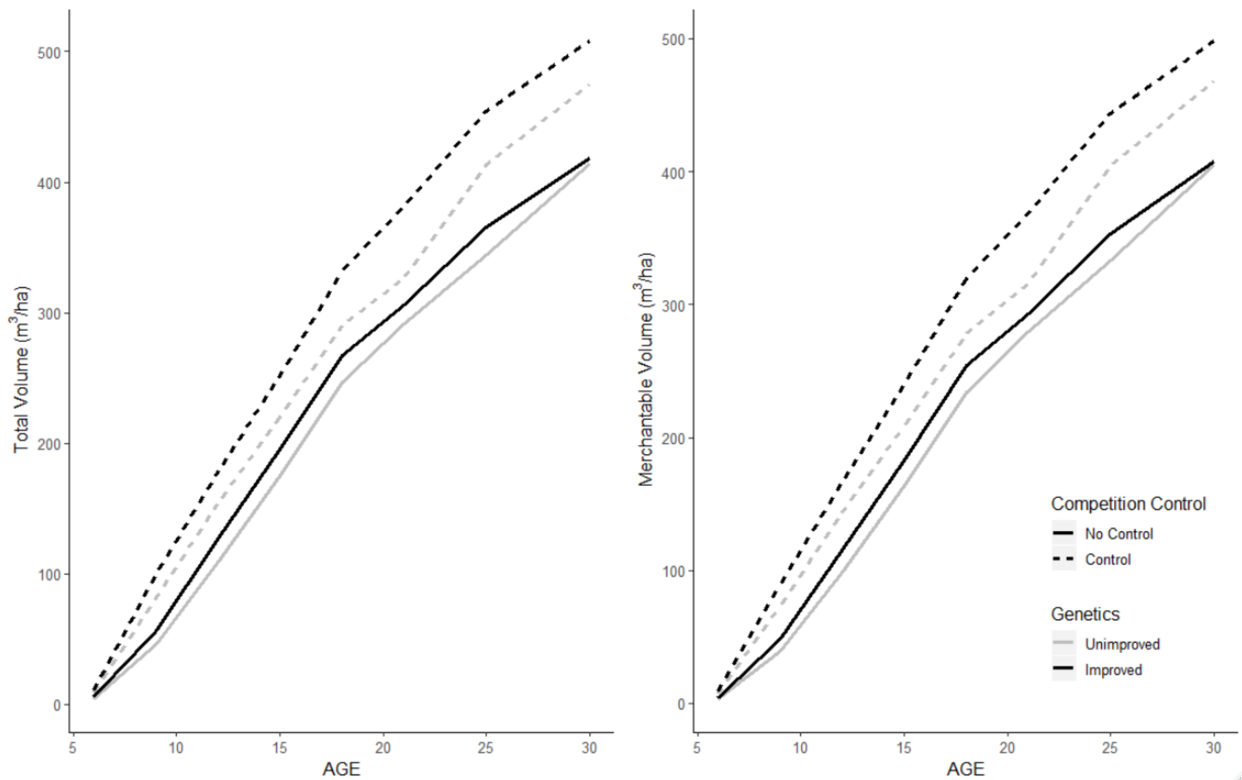


Figure B.2. Least square means for total volume per hectare and merchantable volume per hectare over time for the PMRC HerbGen installations in the coastal plain.

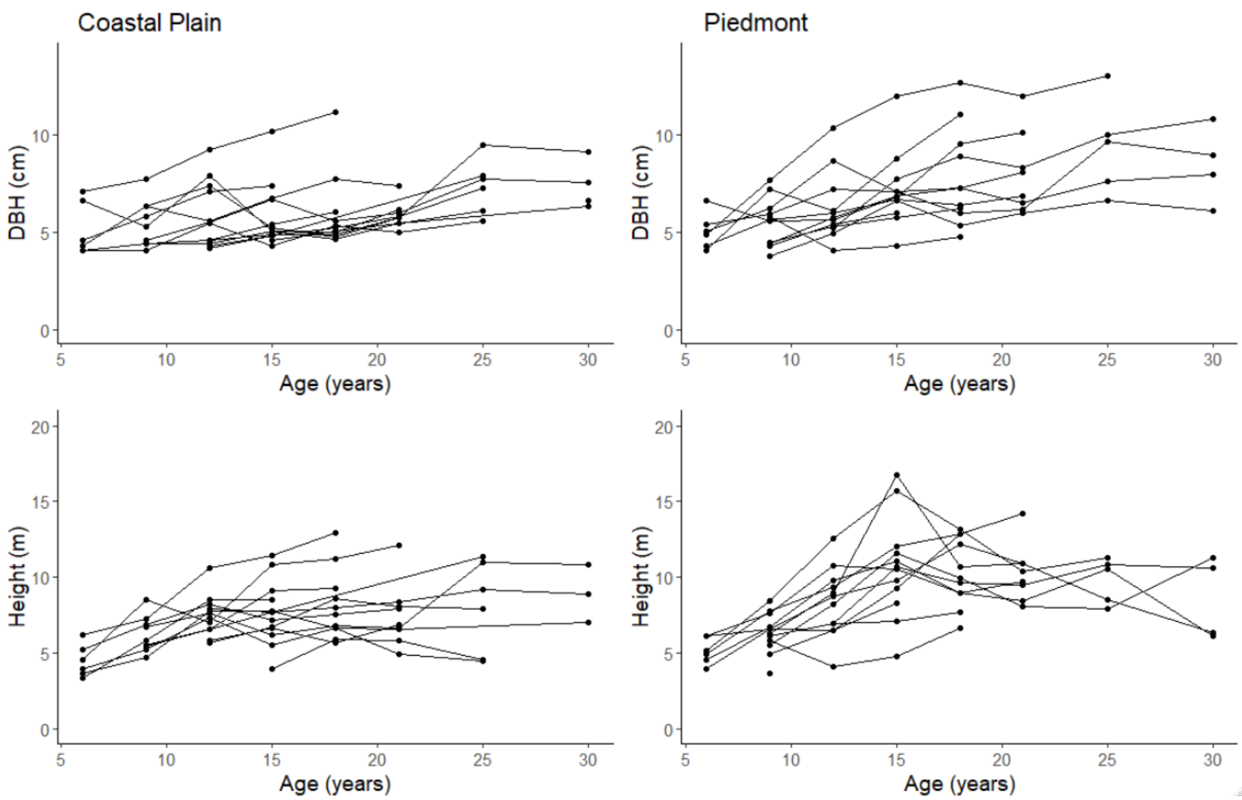


Figure B.3. Overall PMRC HerbGen installation averages across time for large woody competition in plots that did not receive competition control. Large woody competition was defined as any unplanted woody species, broadleaf or evergreen, that had a minimum dbh of 3.8cm.

APPENDIX C

CHAPTER 4: METRIC UNITS

Table C.1. Model parameters for Model 1-4 for both the piedmont and coastal plain regions. Model 1 is the base model fit with and age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

	b_2	b_3	b_4	b_5	b_6	$RMSE$	R^2	Bias
Piedmont								
Model 1	-0.0531	-0.3307	7.6506	--	--	0.7992	0.9898	-0.0063
Model 2	-0.0512	1.1023	2.3267	-6.0927	--	0.7547	0.9907	-0.0154
Model 3	-0.0530	1.2857	0.0976	--	-5.0319	0.7909	0.9900	-0.0219
Model 4	-0.0543	1.1260	8.7342	-22.8576	-6.7524	0.7456	0.9909	-0.0124
Coastal Plain								
Model 1	-0.0605	1.6010	-0.9672	--	--	-0.0435	0.9792	-0.0104
Model 2	-0.0617	0.9316	4.6546	-5.6248	--	-0.0954	0.9815	-0.0008
Model 3	-0.0456	1.0070	1.1660	--	-1.7770	-0.0269	0.9796	-0.0117
Model 4	-0.0606	0.9307	21.3752	-25.9916	-8.0641	1.2811	0.9816	0.9519

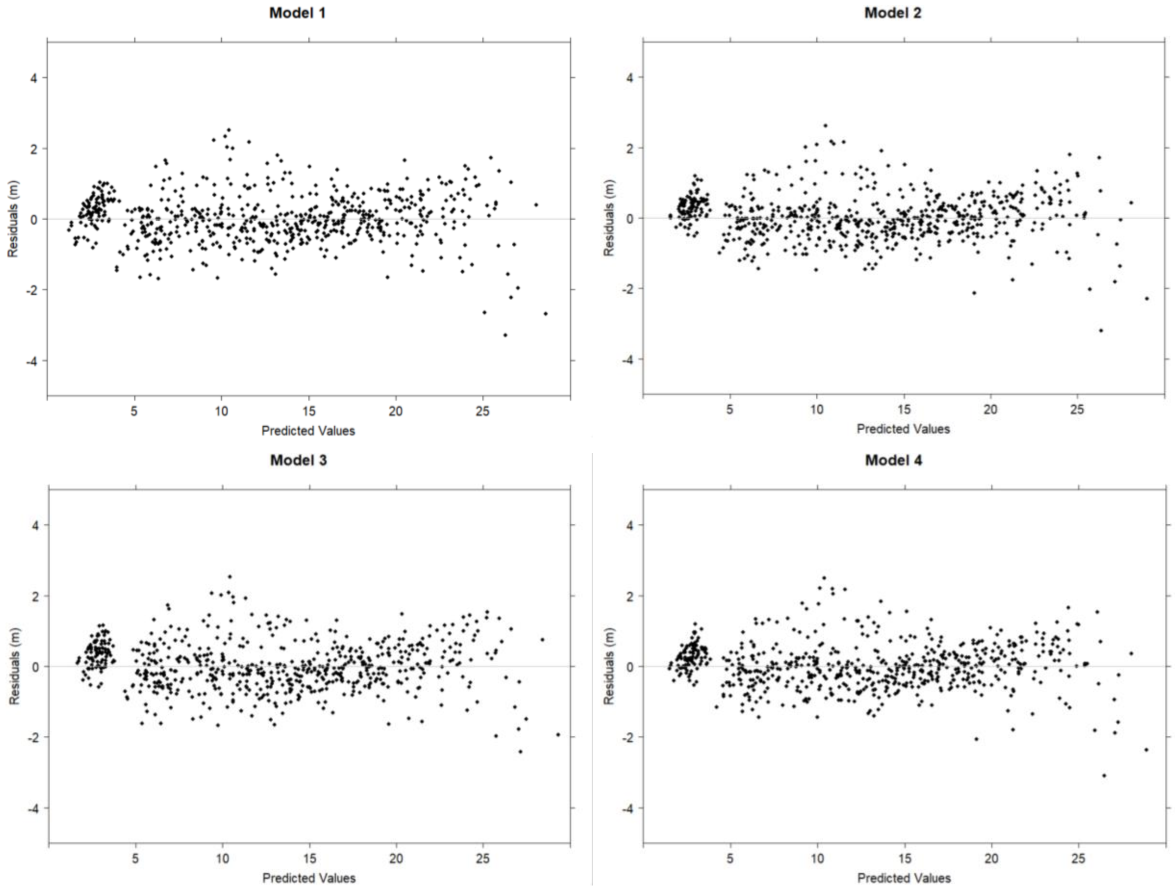


Figure C.1. Residuals for piedmont GADA models 1-4. Model 1 is the base model fit with age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.

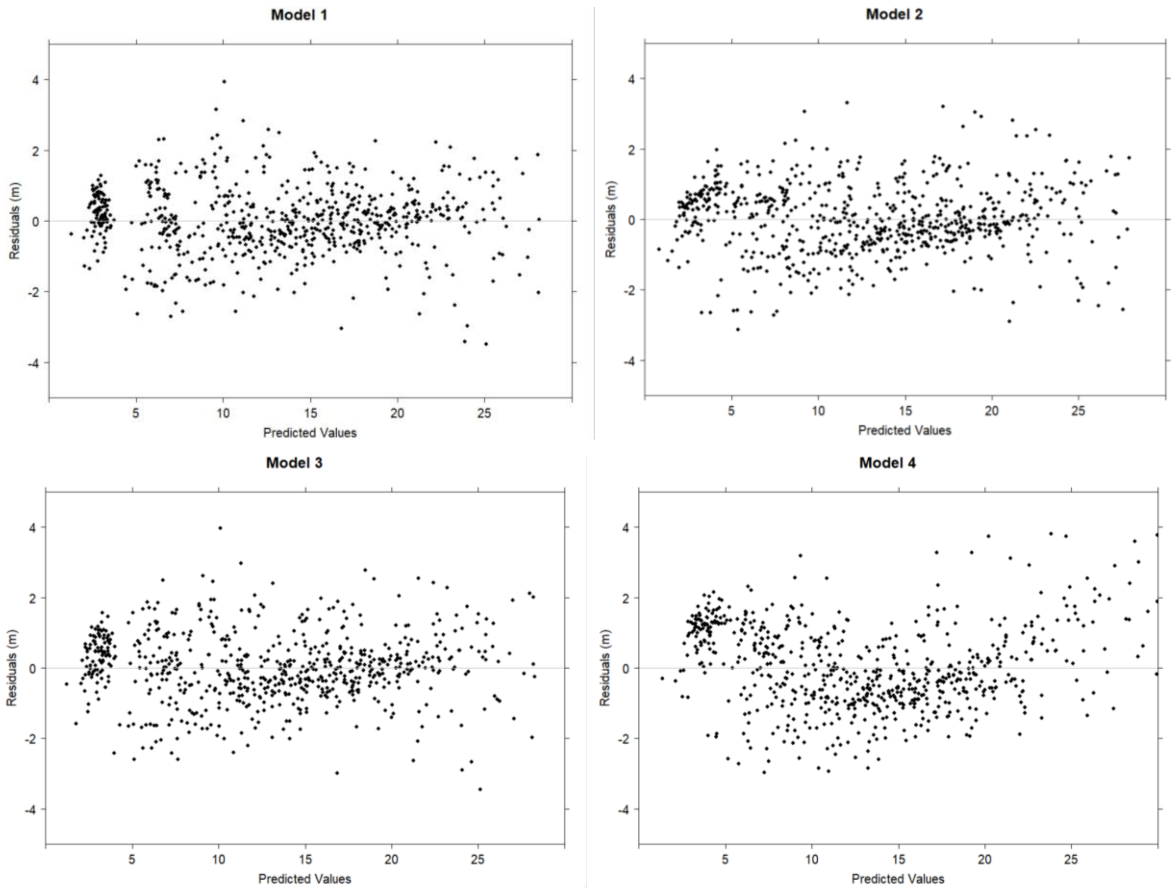
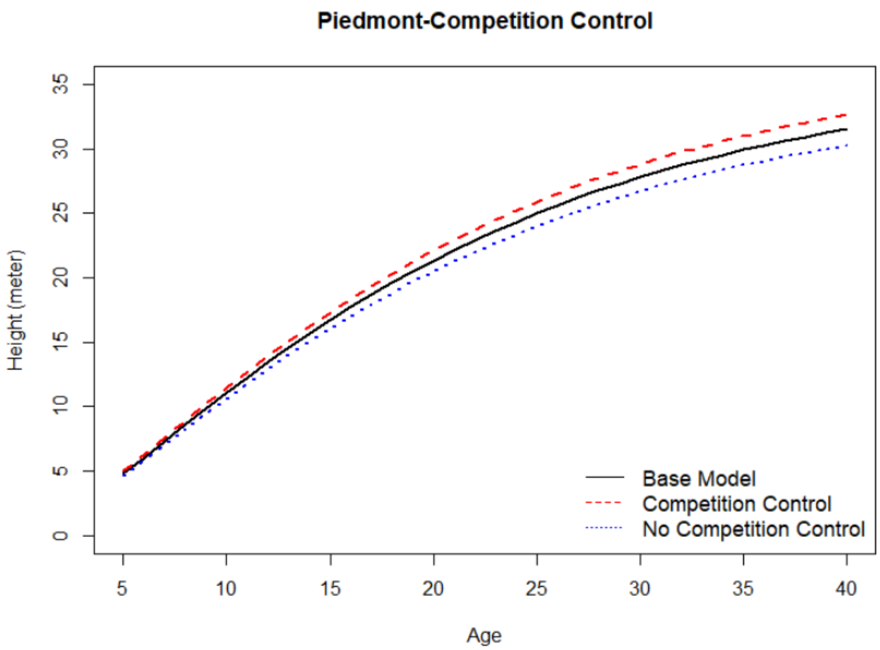


Figure C.2. Residuals for coastal plain GADA models 1-4. Model 1 is the base model fit with age. Model 2 was fit using a competition control variable. Model 3 was fit using a level of genetic improvement variable. Model 4 was fit using both a competition control variable and a level of genetic improvement variable.



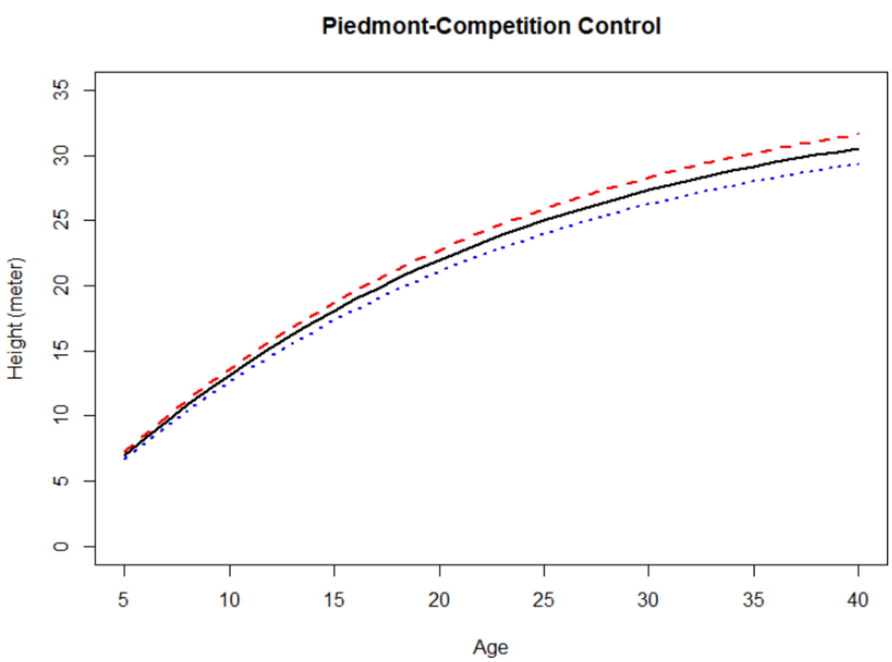
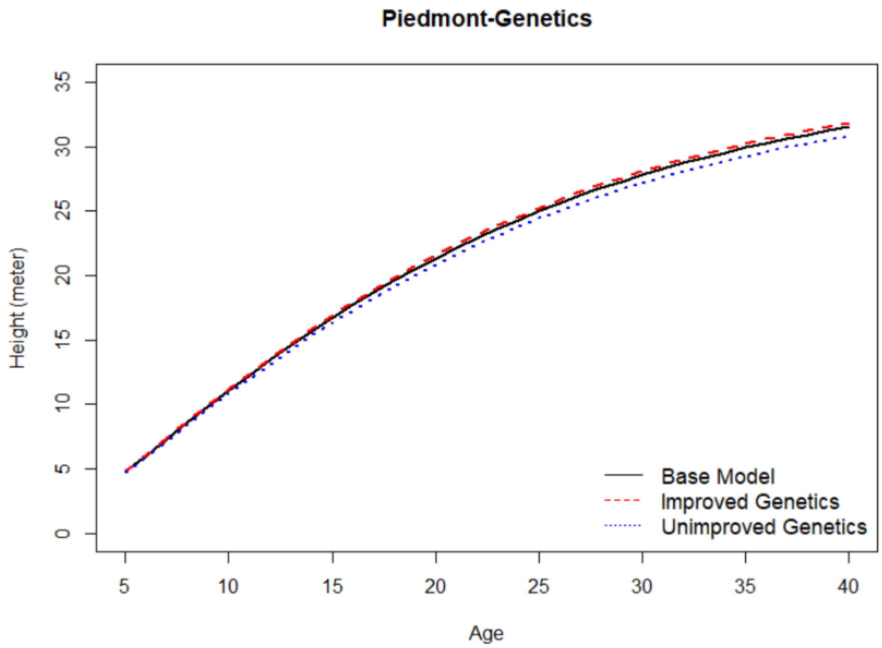


Figure C.3. A SI 25 baseline model was generated for both regions. The percent difference from mean for the groupings of competition control and no competition control were added to show the impact of competition control on height.



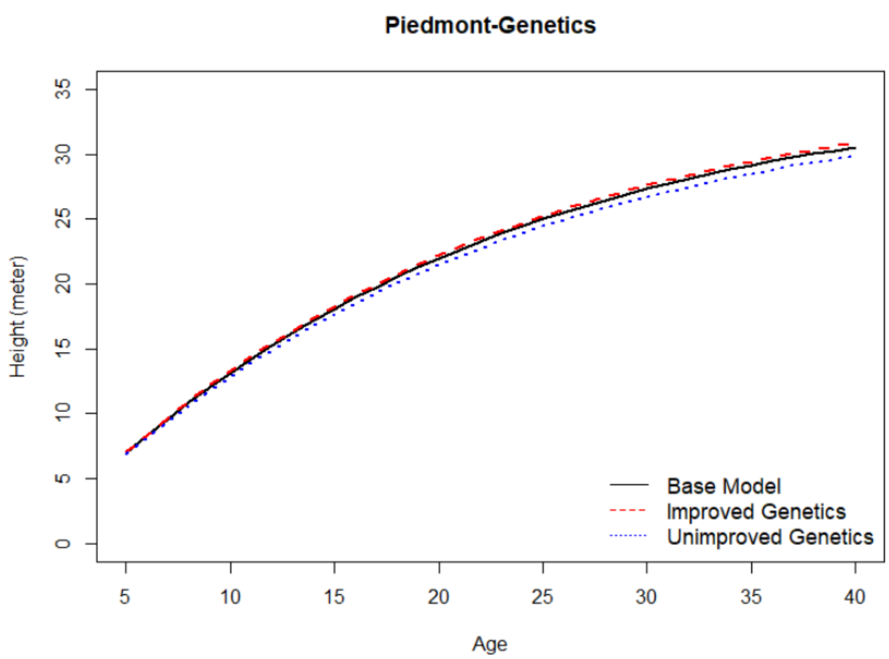
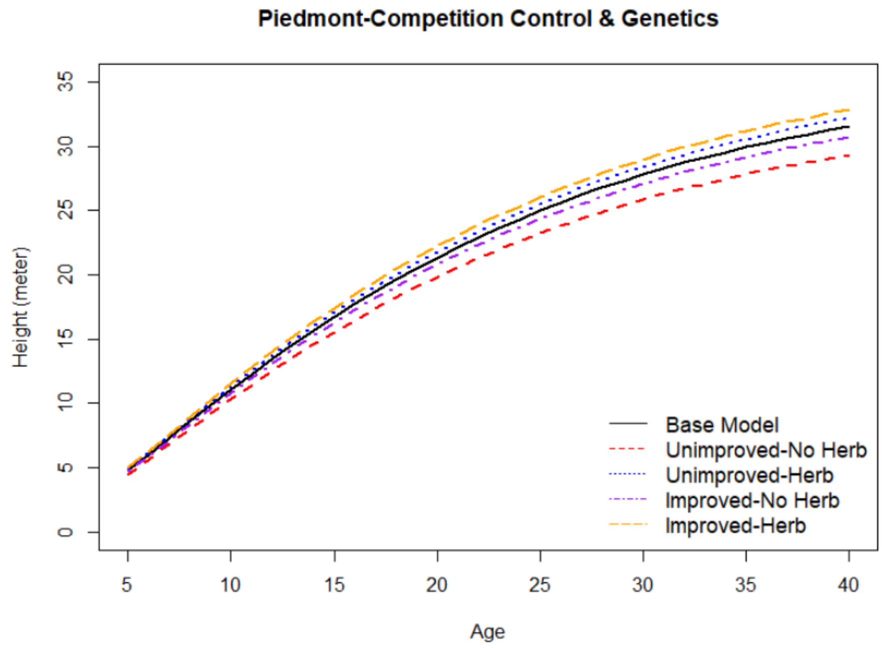


Figure C.4. A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of unimproved genetics and improved genetics were added to show the impact of genetics on height.



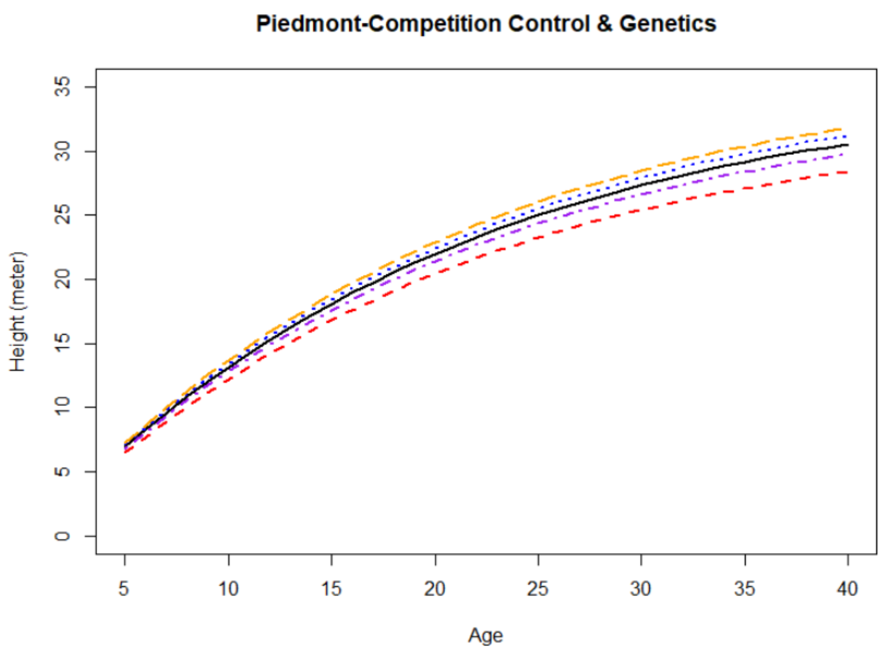


Figure C.5. A SI 60 baseline model was generated for both regions. The percent difference from mean for the groupings of unimproved genetics without competition control, unimproved genetics with competition control, improved genetics without competition control, and improved genetics with competition control were added to show the impact of the interaction of genetics and level of competition control on height.