AN INVESTIGATION OF THE EFFECTS OF GENETICS AND PLANTING DENSITY ON AGE 6 PERFORMANCE OF EIGHT DIVERSE LOBLOLLY PINE GENOTYPES WHEN GROWN ON TWO CONTRASTING SITES

by

DEREK S. DOUGHERTY

(Under the Direction of Michael Kane)

ABSTRACT

This study evaluated performance of eight enhanced loblolly pine (*Pinus taeda*) genotypes planted at two densities (388 and 518 TPA) on two contrasting sites, an upland site in Marion County, Georgia and a lowland, coastal site in Berkeley County, South Carolina. Genotypes evaluated included one high yielding open pollinated (OP) family, three elite control mass pollinated (CMP) crosses, two somatic embryogenesis (SE) clones and two rooted cutting (RC) clones. The study utilized a randomized complete block design with main plots of density split on genotype treatments. Treatment effects on mean DBH, height, DBH/HT ratio, site index, individual tree volume, per acre basal area, and per acre volume were evaluated. Genotype was by far the most impactful treatment at age 6. Planting the best performing genotype in the study as compared to the low end performer significantly (p-value = <0.001) increased the mean variables of DBH by 1.7 inches, height by 12 feet, basal area by 35 ft^2/acre, volume per tree by 1.0 ft^3, and per acre volume by 268 ft^3 by age 6. Choosing to operate on a SC coastal site versus a GA upland site significantly (p-value = <0.001) increased DBH by 0.3 inches, mean total height by 3.2 feet, volume per tree by 0.4 ft^3, basal area per acre by 7.4 ft^2, and volume per acre by 170 ft^3. At age 6, at a basal area of 51 ft^2 per acre on the SC site and 44 ft^2 per acre on the GA site, density was highly significant on DBH (0.3 inches greater at 388 TPA) and basal area (7.4 ft^2/acre greater at 518 TPA). Through 6 growing seasons, both site and genotype were highly significant (p-value < 0.001) on site index. No significant site x genotype or site x density interactions were observed. Growth and yield by product class was projected by product class and bare land value (BLV) was calculated for all treatments. Base model variables input into the FastLob growth and yield model included age 6 exhibited site index, basal area, and surviving trees per acres for both sites. Age 13 tree grading on the GA site empowered a grade-adjusted BLV comparison for that site. Site effects increased BLV by 11% going from the GA upland site to the SC coastal site. Genotype effects increased BLV by 57% going from commercial clone C40 to the highest ranking genotype. Clone AA93 and CMP M15 graded out at 52% and 29% pole percentage at age 13.

INDEX WORDS: loblolly pine, initial planting density, genotype, site index, control mass pollination, clone, level of tree improvement, bare land value, mean annual increment

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Purpose of Study

Loblolly pine (*Pinus taeda*) has been actively grown in commercial pine plantations in the southeast United States for investment and wood production purposes since the end of WWII. A large amount of research has been completed surrounding site selection, site manipulation, tree improvement, and growth culture during this time period. Up until 2006-2007, the vast majority of the pine seedlings deployed were from open pollinated families or mixes. Initial planting densities in the early plantation development era were high and have trended downward over the last two to three decades. Over the last decade, the availability and planting of seedlings from control mass pollinated crosses and selected varietals has increased. Driven by increased seedling costs, a focus on dimensional products versus pulpwood, and anticipated advanced stand dynamics and development, initial planting densities have trended downward. The purpose of this study is to report on the performance of a unique set of eight loblolly pine genotypes sourced from three levels of tree improvement (open pollination, control-mass pollination, and varietals) planted at two new comparative densities (388 and 518 TPA) on two contrasting sites (a South Carolina coastal lowland site and an inland, Georgia upland site), for the purpose of understanding how genotype, density, and site affect stand dynamics and investor yield and value. This study is unique in its use of field graded pole percentage being applied to calculated operational investor bare land values.

Dissertation Structure

A literature review concerning what is known and published in regards to the history and current status of tree improvement, site considerations and impacts, and initial density impacts is provided in Chapter 1. A detailed assessment of the performance of loblolly pine genotypes planted at two densities on two contrasting sites in regards to diameter at breast height (DBH; 4.5’ above the ground), total height (HT), mean tree volume, per-acre basal area, per-acre volume, and DBH/HT ratios is presented in Chapter 2. Chapter 3 addresses the historical use of site index as a productivity qualifier in plantation management and mean HT and exhibited site index (SI) results for the current study. Impacts of genotype, density and site on site index are discussed for the range of genotypes and densities operationally deployed on a high resource SC coastal site versus a lower resource GA upland site. Impacts of site, density, and genotype on investor return, expressed as bare land value (BLV), from growth projections based on age 6 per acre BA, exhibited SI, and actual trees per acre are evaluated in Chapter 4. Conclusions from the prior dissertation chapters are summarized in Chapter 5.

Literature Review

Forestry in the southeastern U.S. (13 States) is a significant business sector generating $230.6 billion, or over 2% of the regional economic output. There are about 200 million acres of privately owned land that support this industry. Southern forests represents only 27% of the forested land in the U.S. but produce 60% of the U.S.A. timber harvest volume (Wear and Greis, 2012). This harvest volume is 15% of the global industrial supply. It is estimated that there are about 39 million acres of planted forest in the South representing about 19% of the total timberland in the region (Wear and Greis, 2012). These plantations, produce about 40% of the annual harvested volume (Hernandez et al., 2016). Plantation acreage established per year has increased from about 500,000 acres in the mid-1950s to between 1.5 to 2.0 million acres currently. Much of the early pine plantations established were related to subsidy programs, including the Farm Bank Era plantings of the 1950's and 1960's and the Conservation Reserve Programs of the 1980's and 1990's. Today, most of the acres being planted are driven by the belief that growing forest products is a profitable business. There is still a great opportunity to increase forest production in the South by both increasing the acreage of plantation forest and also increasing the application of available and emerging forest management technology (Fox et al., 2007; Stanturf et al., 2003).

While planted acres have increased production, per-acre production has also increased dramatically (Fox et al., 2007; Stanturf et al., 2003). It is estimated that plantation production has doubled every rotation (25 years) for the period of 1950- 2015. Stanturf et al. (2003) suggest that in the 1920's mean annual increment was about one green-ton/acre/year and by 2003 mean annual increment on intensively managed plantations was near 8 green tons per acre/year. The adoption of many technologies has led to the increases in production. Vegetation competition control, forest nutritional management and accelerated tree improvement have been three of the main drivers of increased pine plantation production (Fox et al., 2007). Continued increases in atmospheric carbon dioxide have also been estimated to be increasing pine production potential (Baldwin et al., 2001; Valentine, 1997).

Loblolly Pine Tree Improvement Contributions to Increase Production

Loblolly pine tree improvement programs began on a large scale in the early 1950's with a mass selection of quality phenotypes from across the range of loblolly pine. The first large scale orchards established from these selections occurred in 1953 (Zobel, 1953). The first series of orchards were referred to as 1st generation orchards. Progeny testing was utilized to identify which of the wild high-quality phenotypic selections would transmit their apparent good traits (volume, height, straightness, fusiform rust resistance and the absence of forking) to their progeny. Fully rogued 1st generation orchards supplied seed that on average would increase volume production by 10-12% (Dougherty et al., 2010). However, some "elite" selections from the 1st generation of tree improvement could increase production by as much as 45%. A similar average production gain of 8-12% has been achieved for each subsequent generation of tree improvement (Dougherty et al., 2010). Testing of third and fourth cycle selections are now under way and fourth cycle orchards are being established (McKeand, 2017).

Tree improvement is now executed as a rolling front or cycles of testing. This approach permits bringing forward the best 1st and 2nd generation selections as well as forward selections made from the latest tree improvement breeding efforts. The rolling-front testing method coupled with earlier in-field selection which is being enabled by both improved testing and statistical methods has shortened the selection time from 8-10 years to 4-5 years. In addition, private large-scale seedling producers such as ArborGen and International Forest Company have greatly accelerated the development and testing of enhanced genetic material. These companies focus on production of high quality sawtimber elite genotypes using only the very best selections from tree improvement cooperatives and from their own internal tree improvement development programs. The result of working with small elite populations, using new technology such as control mass pollination (CMP) and clonal production (Varietals) and testing has greatly accelerated the production and availability of elite genetics to all forest landowners. Control mass pollinated produced seedlings (full-sib crosses) will exceed gains from open-pollinated (OP) selections (half-sib families) because of the exclusion of non-improved wild pollen (McKeand, 2017). Prior to 2005 only a few thousand acres were being planted with CMP or better genetics. Today, it is estimated that about 116 million CMP seedlings, representing 15% of seedlings, are produced per year (McKeand, 2017). The adoption rate for the past five years for CMP seedlings is estimated to be more than 10,000 acres/year. Attributes such as high yield, high stem quality, low fusiform rust infection, low forking and subsequent lower stand-level risk are driving their rapid adoption by forest landowners.

Genetic Deployment Options

A wide range of seedlings that represent different levels of tree improvement are now available for forest landowners to deploy on their lands. The different levels of tree improvement range from multiple cycles of conventionally improved OP, to CMP selections, to clonal selections derived from elite control-pollination crosses. Open-pollinated selections come from a known mother tree located in an improved orchard. Control mass pollinated selections come from an improved mother tree fertilized with improved pollen collected from a known father tree. A clone is an individual with superior traits that was selected from a controlled-cross. The selected clone is then scaled up using somatic embryogenesis or rooted cutting techniques.

Genotype Productivity Potential and Stem Trait Performance Values

Genotypes available today for regeneration represent a wide range in productivity potential, stem quality, disease resistance, and stand potential value (McKeand et al. 2006). Productivity increases are estimated to range from around 8-12% from the initial cycle of tree improvement to over 50% from the most advanced control-crosses and varietal seedlings (Dougherty et al. 2010). Stem quality traits that have been conventionally assessed by the tree improvement cooperatives include straightness, rust susceptibility, and forking. Additional traits of ramicorn branching, sinuosity, top and limb breakage, and branching characteristics among others are assessed outside of the cooperatives. Assessments are generally made in single-tree replicated progeny tests established at multiple locations, with measurement and analysis completed by age 4-5 years.

Crown Ideotypes of Advanced Genetic Options

The available genotypes for planting represent a broad range in crown ideotypes (Martin et al. 2001, Martin et al. 2005). Crown ideotypes may be classified as narrow, moderate or broad. These crown ideotypes are sometimes further classified as "crop" or "competition" ideotypes (Cannell 1978). A broad crown or competition ideotype would be the more conventional type which stereotypically holds large amounts of foliage to capture incoming sunlight and subsequently requires either many branches or larger individual branches to support the mass of foliage. Large heavily foliated "competition ideotypes" will tend to grow branches to greater lengths and quickly occupy whatever space is allocated as well as push-in to the neighboring tree crowns. In contrast, a 'crop' ideotype will allocate more of its growth resources into height, display less foliage, and therefore require either fewer branches or smaller branches, which result in less selfshading. These differences in crown structure suggest that each ideotype may need to be deployed at different stand densities to optimize growth and yield.

Stand Density and Genotype Impacts on Stem Diameter

The strong effects of stand density on diameter growth has long been recognized (Pienaar, et al., 1997). Carlson et al.(2009) observed significant loblolly pine diameter reductions due to stand density (363 TPA vs 726 TPA) by age 5 in a plantation growing at a site index (SI) trajectory of 71 feet at base age 25 years. With new loblolly pine genotypes growing at a site index of nearly 90 feet, Steiger (2013) observed significant reduction in diameter at breast height (DBH) from low to moderate density (218 TPA and 436 TPA) as early as age-3 and significant genotype x density interaction effects on DBH by age-4. Sabatia and Burkhart (2013) also observed significant genotype x density effects on DBH at age-8 for OP, CMP and clonal genotypes. They did not measure at early ages to be able to detect the age when this interaction first became significant. Clearly the increase in SI potential due to genetic and silvicultural improvements should be impacting initial planting density assignments if forest managers do not want to experience significant DBH growth reduction before the first planned thinning. The significant genotype x density effect on DBH growth also suggests that the optimum initial planting density assignment may be different for different genotypes.

Stand Density and Genotype Impacts on Height

Height has historically been assumed to not be affected by stand density (Pienaar and Shiver, 1984; Harms et al., 1994, 2000). There have been some reports of height growth being less when planted at low density versus being planted at high density (MacFarlane et al., 2000; Sharma et al., 2002). There have also been reports of initial slowed height growth at low densities and then observing a "cross-over" effect (Scott et al., 1998) as the stand develops and attains higher between-tree competition (Anton-Fernandez et al., 2011). Steiger (2013) for a wide range of genotypes-ideotypes found significant differences in height, by density, at ages 3-4. By age-5 there were significant genotype x density effects on height. Sabatia and Burkhart (2013) also observed significant genotype x density effects on height, diameter and height/diameter (DBH/HT) ratio at age-8 for a range of levels of tree improvement from OP, CMP and Clonal.

The most comprehensive report on the effects of initial planting density on height development of loblolly was done by Anton-Fernandez et al. (2011). This study spanned both coastal (two locations) and piedmont (2 locations) regions and had annual measures from age-1 to age-25 years for sixteen different planting configurations. Initial planting density ranged from a low of near 300 TPA to a high of 2725 TPA. The results showed that density effects on height began by age-6 and that they were maintained through age-25. The maximum impact of density on SI over the 25-year period was 13 feet. This magnitude of initial density impacts on SI led the authors to conclude that to have realistic estimates of future growth and yield that we should use different SI values for the same site depending on the initial planting density. The early rotation significant genotype x density effect as observed by Steiger (2013) and Sabatia and Burkhart (2013) complicate the issue of expected SI for a given site even more. Additional yield estimation complications may also be manifested if specific genotypes have differences in diameter and height distributions as would be expected for clones versus CMP versus OP. Clonal populations have no genetic diversity, CMP populations have reduced gene pools and OP selections represent a population with large genetic diversity. Further complications in yield estimation are also introduced if genotypes differ in their diameter/height ratios.

Stand Density and Genotype Impacts on Biomass Allocation by Tree Component

Total merchantable biomass gains are sought through faster growing genotype deployment. Another potential advantage for timber producers is made if a producer can grow timber in such a way that a higher percentage of the total biomass produced is focused in the merchantable stem as opposed to non-merchantable branches and foliage. Multiple destructive sampling studies have been conducted on studies with a density treatment (Burkes et al., 2003, Zhao et al., 2012, Subedi et. al., 2012; Adegbidi et al., 2005; Samuelson et al., 2004). Both Burkes et al. (2003) and Zhao et al. (2012) evaluated the impact of planting densities ranging from 300 to 1800 TPA in the Plantation Management Research Cooperative (PMRC) Culture x Density Studies. Burkes et al. (2003) evaluated the standing biomass and biomass partitioning in slash pine and loblolly pine plots in southern Georgia at 4 years of age and found that stand-level stem biomass increased with planting density and that higher stand densities allocated more biomass to stem production. For 12-year old loblolly pine plantation studies in the series in the Piedmont and Upper Coastal Plain, Zhao et al. (2012) found that planting density, up to 900 TPA, significantly affected stand-level above ground biomass accumulation and partitioning, but not above that level. Like Burkes et al. (2003) they found that increasing stand density decreased biomass allocation into branches as opposed to the stem wood component. Shelton (1984) evaluated above ground biomass accumulation and partitioning over 25 years of growth for loblolly pine stands established at 486, 777, and 1741 trees per acre. He found that differences in accumulation and allocation did not persist through age 25 years.

Loblolly Pine Genotype Impacts on Biomass Allocation by Tree Component

It is well established that loblolly pine genotype impacts above ground volume (McKeand, 2006). Tree improvement programs make comparisons annually using volume indices driven by diameter and height and assume that green weight differences and dry weight biomass differences are similar to the calculated volume index rankings. Destructive sampling studies which provide actual dry biomass comparisons across genotypes are rare due to both the work involved and the number of studies with a genotype treatment. Blazier et al. (2002) and Aspinwall et al. (2012) completed above ground destructive sampling in studies with a genetic component. Blazier et al. (2002) found that foliage per branch allocations differed between half-sib trees from different provenances, North Carolina Coastal vs Oklahoma-Arkansas stock, on a droughty site in Oklahoma. They did not find significant differences in either stem component or branch component percentages, rather just more foliage carried per branch on the eastern source material. Aspinwall et al. (2012) completed destructive sampling and analysis for 9 genotypes across 3 levels of tree improvement after 3 growing seasons in an operational pine plantation setting in Coastal North Carolina. They found differences in stem volume, percent stem wood, percent branch wood, and partitioning to fine roots. They also concluded that genotypic differences in stem volume were independent of genotypic differences in biomass partitioning.

Changes in biomass allocation that result in shifts in the DBH/HT ratio are important. In diameter distribution and individual tree growth and yield models the DBH/HT ratio is used to estimate heights and ultimately tree volume (Clutter et al., 1983; Avery and Burkhart 2002 and Lynch et al., 1999). Height and diameter relationships are also important considerations in making management decisions such as thinning or harvesting. DBH/HT is also a main driver for estimation of risk of stem breakage related to ice, snow or wind (Braggs et al., 2003). Genetic improvement may affect the DBH/HT ratio of a stand of trees. Andersson et al., 2007 and Kroon et al., 2008 found that for *Pinus sylvestris* selection for improved growth based on height growth resulted in trees with a lower DBH/HT ratio. For slash pine, genetically improved slash versus non-improved slash also showed a lower DBH/HT ratio. Steiger (2013) investigated the effects of loblolly pine genotypes grown at two stand densities (436 TPA and 218 TPA) on dominant height and DBH. Based on his data for six year-old loblolly genotypes ranging from broad crown OP to narrow crown clones both density and genotype affected the DBH/HT ratio. The impacts of the range in genotypes change the DBH/HT ratio from 14% to 21%; with the lowest DBH/HT being for narrow crown ideotypes grown at the higher density and the highest DBH/HT observed for the broad crown OP or CMP. The average effect of stand density (218 TPA vs 436 TPA) on the DBH/HT was for this ratio to decrease by about 18%. Thus, both the choice of genotype and the growing density will be important considerations in how a genotype is deployed to optimize a specific desired timber product.

The purpose of this study is to better define the interaction of site, genetics and initial planting density on tree growth, tree attributes, and expected stand yields. In addition, the effects of these main treatments on exhibited site index, stem defects, and pole percentage are evaluated, including their subsequent impact on investor bare land value (BLV).

Literature Cited

Adegbidi, H.G., Jokela, E., Comerford, N.B. 2005. Factors influencing production efficiency of intensively managed pine plantations in a 1-to-4-year-old chronosequence. Forest Ecology and Management 218 (1-3): 245-258.

Andersson, B., Elfving, B., Persson, T., Ericsson, T., Kroon, J. 2007. Characteristics and development of improve *Pinus sylvestris* in northern Sweden. Canadian Journal of Forest Research 37:84-92.

Anton-Fernandez, C.A., Burkhart, H.E., Strub, M., Amateis, R. 2011. Effects of initial spacing on height development of loblolly pine. Forest Science 57 (3): 533-545.

Aspinwall, M.J., King, J.S., McKeand, S.E. 2012. Productivity differences among loblolly pine genotypes are independent of individual tree biomass partitioning and growth efficiency. Trees 27 (3): 533-545.

Avery, T.E. and Burkhart, H. 2002. Forest Measurements, 5th ed., McGraw Hill, New York 456p.

Baldwin, V.C., Jr., Burkhart, H.E., Westfall, J.A., Peterson, K.D. 2001. Linking growth and yield and process models to estimate impact of environmental changes on growth of loblolly pine. Forest Science 47(1): 77-82.

Blazier, M.A., Hennessey, T.C., Lynch, T.B., Wittwer, R.F. 2002. Comparison of branch biomass relationships for North Carolina and Oklahoma/Arkansas loblolly pine seed sources growing in southeastern Oklahoma. Forest Ecology and Management 159(3): 241-248.

Braggs, D.C., Shelton, M.G. and Zeide, B. 2003. Impacts and management implications of ice storms on forests in the southern United States. Forest Ecology and Management 186: 99-123.

Burkes, E.C., Will, R.E., Barron-Gafford, G.A., Teskey, R.O., Shiver, B. 2003. Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. Forest Science 49 (2): 224-234.

Cannell, M.G.R. 1978. Improving per hectare forest productivity. Proc. Fifth North American Forest Biology Workshop p. 120-148. Univ. Florida School of Forest Resources and Conservation, Gainesville, FL.

Carlson, C.A., Fox, T.R., Creighton, J., Dougherty, P.M., Johnson, J. 2009. Nine-year growth responses to planting density manipulation and repeated early fertilization in a loblolly pine stand in the Virginia Piedmont. Southern Journal of Applied Forestry 33 (3): 109-114.

Clutter, J.L., Fortson, J.C., Pienaar, L.V., Brister, G.H., Bailey, R.L. 1983. Timber Management-A Quantitative Approach. John Wiley & Sons, Inc., New York. 333p.

Dougherty, D., Bryant, R., Burkhart, H., Dougherty, P., Jones, S., McKeand, S. 2010. Valuing tomorrow's loblolly pine plantations. Forest Landowner 69(1): 19-21.

Fox, T.R., Jokela, E.J., Allen, H.L. 2007. The development of pine plantation silviculture in the southern United States. Journal of Forestry 105(7): 337-344.

Harms, W.R., DeBell, D.S., Whitesell, C.D. 1994. Stand and tree characteristics and stockability of *Pinus taeda* plantations in Hawaii and South Carolina. Canadian Journal of Forest Research 24(3): 511-521.

Harms, W.R., Whitesell, C.D., Debell, D.S. 2000. Growth and development of loblolly pine in a spacing trial planted in Hawaii. Forest Ecology and Management 126(1): 13-34.

Hernandez, G.A., Harper, R.A., South, D.B. 2016. Tree planting in the South, 1925 to 2012. Tree Planters' Notes 59(2): 4-7.

Kroon, J., Andersson, B., and Mullin, T.J. 2008. Genetic variation in the diameter-height relationship in Scots pine (*Pinus sylvestris*). Canadian Journal of Forest Research 38: 1493-1503.

Lynch, T.B., Hitch, K.L., Huebschmann, M.M., Murphy, P.A. 1999. An individual-tree growth and yield prediction system for even-aged natural shortleaf pine forests. Southern Journal of Applied Forestry 23: 203-211.

MacFarlane, D.W., Green, E.J., Burkhart, H.E. 2000. Population density influence assessment and application of site index. Canadian Journal of Forest Research 30(9): 1472-1475.

Martin, T.A., Johnson, K.H. and White, T.L. 2001. Ideotype development in southern pines: rationale and strategies for overcoming scale-related obstacles. Forest Science 47(1): 21-28.

Martin, T.A., Dougherty, P.M., Topa, M.A., McKeand, S.E. 2005. Strategies and case studies for incorporating ecophysiology into southern pine tree improvement programs. Southern Journal of Applied Forestry 29: 70–79.

McKeand, S.E., Jokela, E.J., Huber, D.A., Byram, T.D., Allen, H.L., Li, B., and Mullin, T.J. 2006. 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.E. 2017. Making sense of the genetics market. Forest Landowner 76(5): 14-19.

Pienaar, L.V., Shiver, B.D. 1984. The effect of planting density on dominant height in unthinned slash pine plantations. Forest Science 30 (4) 1059-1066.

Pienaar, L.V., Shiver, B.D., Harrison, W.M. 1997. Growth Potential of Loblolly Pine Plantations in the Georgia Piedmont: A Spacing Study Example. Plantation Management Research Cooperative Technical Report 1997-1. Daniel B. Warnell School of Forest Resources, Athens, Georgia. 15p.

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

Samuelson L.J., Johnsen K., Stokes T. 2004. Production, allocation, and stemwood growth efficiency of *Pinus taeda* L. stands in response to six years of intensive management. Forest Ecology and Management 192(1): 59-70.

Scott, W.R., Meade, R.L., Hyink, D., Miller, R. 1998. Planting density and tree-size relations in coastal Douglas-fir. Can. J. For. Res. 28 (1):74-78.

Sharma, M., Burkhart, H.E., Amateis, R.L. 2002. Modeling the effect of density on the growth of loblolly pine trees. Southern Journal of Applied Forestry 26(3): 124-133.

Shelton, M.G. 1984. Effects of Initial Spacing of Loblolly Pine Plantations on Production and Nutrition Dynamics during the first 25 Years. PhD dissertation. Mississippi State University Starkeville, MS, 158p.

Stanturf, J.A., Kellison, R.C., Broerman, F.S., Jones, S.B. 2003. Productivity of southern pine plantations: Where are we and how did we get there. Journal of Forestry 101(3): 26-31.

Steiger, J.J. 2013. Impacts of Different Levels of Genetic Homogeneity on Juvenile Stem Characteristics and Potential Stand-level Value in Loblolly Pine. M.S. Thesis, North Carolina State University, Raleigh, NC, 82p.

Subedi, S., Kane, M., Zhao, D., Borders, B., Greene, D. 2012. Cultural intensity and planting density effects on aboveground biomass of 12-year-old loblolly pine trees in the Upper Coastal Plain and Piedmont of the southeastern United States. Forest Ecology and Management 267: 157–162.

Valentine, H.T. 1997. Height growth, site index, and carbon metabolism. Silva Fennica 31(3): 251-263.

Wear, D.N., Greis J.G. 2012. The Southern Forest Futures Project: Summary Report. General Technical Report SRS-168. USDA Forest Service Southern Research Station, Asheville, NC. 103 p.

Zhao, D., Kane, M., Borders, B., Subedi, S., Akers, M. 2012. Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the Southeastern United States. Canadian Journal of Forest Research 42: 111-122.

Zobel, B.J. 1953. Seed orchards for superior trees. Forest Farmer 13 (2): 10-12.

CHAPTER 2

A COMPARISON OF AGE SIX YIELD CHARACTERISTICS FOR EIGHT GENOTYPES OF LOBLOLLY PINE PLANTED AT TWO DENSITIES ON TWO SITES IN THE UPPER COASTAL PLAIN OF GEORGIA AND THE LOWER COASTAL PLAIN OF SOUTH CAROLINA[1]

[1] Dougherty, D.S., M.B. Kane, B.P. Bullock, R.F. Daniels, and J.A. Wright. To be submitted to Forest Ecology and Management

Abstract

Loblolly pine (*Pinus taeda*) was planted in 2005 on two contrasting sites, a Georgia (GA) upland Upper Coastal Plain site and a South Carolina (SC) Lower Coastal Plain site. Both sites were operationally site prepared and managed post-planting. Eight genotypes were planted at a low initial planting density (388 TPA) and a moderate density (518 TPA). The genotypes in the study included an open-pollinated (OP) entry, three control mass pollinated (CMP) entries, two somatic embryogenesis (SE) clones, and two rooted cutting (RC) clones. The study design was a randomized complete block design with split plots on the main treatment of initial planting density and three replications of each treatment at both sites. Diameter at breast height and total height measurements were completed for all plots at age 6. Genotype was by far the most impactful treatment at age 6. Planting the best performing genotype as compared to the worst performer significantly (p-value = <0.001) increased the mean variables of DBH by 1.7 inches, height by 12 feet, per-acre basal area by 35 ft^2, volume per tree by 1.0 ft^3, and per acre volume by 268 ft^3 by age 6. Choosing to operate on a SC coastal site versus a GA upland site significantly (p-value = <0.001) increased DBH by 0.3 inches, mean total height by 3.2 feet, volume per tree by 0.4 ft^3, basal area per acre by 7.4 ft^2, and volume per acre by 170 ft^3. At age 6, at a basal area of 51 ft^2 on the SC site and 44 ft^2 on the GA site, the density effect was highly significant on DBH (0.3 inch greater at 388 TPA) and basal area (7.4 ft^2 greater at 518 TPA). Density was not significant on height (p-value of 0.06) but was significant on per-acre volume (59 ft^3 at 518 TPA; p-value = 0.05 level). Clone AA93 and control cross M16 had significantly greater volume per acre than OP 03 that is used as a check in many loblolly pine genetic tests. Relative volume per acre across tree improvement levels was

as follows: RC clones > CMP crosses > OP O3 > SE clones. Across sites, RC clone AA93 and CMP M16 exhibited base age 25 site indices of 87 feet and 82 feet, respectively. At these operational growth rates, the lower initial planting density offset early DBH losses. Choice of fast growing genotypes like AA93 or M16 significantly affected height growth and may increase exhibited plantation age-25 site index performance.

Introduction

A wide range of genotypes that represent different levels of tree improvement is now available for forest landowners to deploy on their lands (McKeand, 2017). Different levels of tree improvement for loblolly pine range from conventional multiple-cycle improved open-pollinated genotypes (OP), to control mass pollinated (CMP), to clonal selections derived from elite control-pollination crosses. Open-pollinated selections come from a known mother tree located in an improved orchard. Control mass pollinated selections come from an improved mother tree fertilized with pollen collected from a known improved father. A clone is an individual with superior traits that was selected from a control-cross and propagated using somatic embryogenesis or rooted cutting techniques. These selections available for artificial regeneration represent a wide range in productivity potential, stem quality, disease resistance and stand value (McKeand, et al., 2006a. They also represent a broad range in crown ideotypes (Martin et al., 2001, 2005). These differences in crown structure suggest that each ideotype may need to be deployed at different stand densities to optimize growth and yield.

Establishment of new loblolly pine plantations with new genetic seedlings from advanced cycles of conventional tree improvement or increasing levels of tree improvement impact the rate of timber stand development in these new plantations (McKeand, 2006a). Advancing the growth trajectory of a loblolly pine plantation speeds up the effects of stand density on impacted variables. While operational growth trajectories are increasing, initial planting densities are decreasing (Lang et al., 2012). A couple of recently published studies incorporate both the increasing growth rates and the decreasing initial planting densities. Steiger et al. (2013), growing at an exhibited site index of 87 ft, observed a significant reduction in diameter from a low to a moderate density (218 TPA and 436 TPA) as early as age 3 and significant genotype x density interaction effects on DBH by age 4. Sabatia and Burkhart (2013) observed significant genotype x density effects on diameter at age 8 from their study growing at an average site index of 86 ft base age 25 years and planted at densities of 275 and 550 trees per acre. Both Steiger and Sabatia's studies included genetic treatment entries from a range of levels of tree improvement from elite OP, CMP and Clonal genotypes. Steiger completed annual measures from age 3 to age 6. Sabatia did not do measures prior to age 8 and thus couldn't conclude at what age the density impact on height was significant.

In contrast to diameter and basal area, height has been considered as the variable perhaps least affected by density (Pienaar et al., 1984 Harms et al., 2000). Reported results on the impact of density on height have been conflicting (Fernandez et al., 2011), with some reports of height growth being less at low density versus those planted at high density (MacFarlane et al., 2000, Sharma et al., 2002, Steiger, 2013) and other reports of decreases in height with increasing density. In their newer resource planting established in 2005, Steiger (2013) for a wide range of genotype-ideotypes found significant differences in height at ages 3 and 4. By age 5 there were significant genotype x density effects on height. Sabatia and Burkhart (2013) also observed significant genotype x density effects on height and height/diameter ratio at age 8. The inconsistencies in the reported density effects on height and the emerging thought that density may have greater than expected impacts on height growth prompted Fernandez et al. (2011) to complete a comprehensive report on some older resource plantings. Their study included two coastal and two piedmont locations with open pollinated seedling plantings and had annual measures from age 1 to age 25 years for sixteen different planting designs. Initial planting density ranged from a low of near 300 TPA to a high of 2725 TPA. They found that the density effects on height began by age 6 and were maintained through age 25, with a full impact on base age 25 year exhibited site index over the period to be as large as 13 feet.

With new genotype options empowering increasing growth trajectories and density having reported impacts on diameter, height, basal area and volume growth of young loblolly pine stands, it is important to work to further understand the effects of both genotype and lower or moderate planting densities on loblolly pine stand development so that proper deployment decisions are made regarding which genotypes to plant and at what initial planting density to deploy them to optimize specific target timber products.

The objectives of this study are to:

(1) Quantify the impacts of eight genotypes that represent a wide range in genetic diversity (two-rooted cutting derived clones, two somatic embryogenesis clones, three CMP and one OP selection) on the development of height, diameter at breast height (DBH), and the diameter/height (DBH/HT) ratio by age 6 years when grown at two initial planting densities (388 TPA and 518 TPA).

(2) Identify if the interactions of genotype x density impacts on height, DBH and DBH/HT ratio are significant by age 6.

(3) Determine the extent that age 6 genotype growth varies when grown in a Lower Coastal Plain poorly drained site versus an interior, well-drained upland site.

Methods

Site Description

This study consisted of two installations. The South Carolina installation is located in Berkeley County, South Carolina (33° 14.512 N, 80° 10.866 W) in the Lower Coastal Plain. The Georgia installation is located in Marion, County, Georgia (32° 17.596 W, 84° 26.513 W) in the Upper Coastal Plain. Both sites were previously occupied by loblolly pine plantations. The South Carolina (SC) site has somewhat poorly drained Lynchburg fine sandy loam, Meggett loam (poorly drained) and Seagate loamy sand (somewhat-poorly drained) soil series, a 220 day mean frost-free period and mean annual rainfall of 48.1 inches. Previous rotation SI on this soil complex averaged from 70-75 feet. The Georgia installation consists of a well-drained Orangeburg loamy sand soil series, a frost-free period of 230-260 days and an annual rainfall average of 49.8 inches. Previous rotation SI on this soil averaged from 62-65 feet. Soil characteristics are provided in Table 2.1 for both sites.

Table 2.1 NRCS* soil series and soil and site characteristics affecting productivity potential and site preparation activities for the SC and GA study installations

Site	Soil Series	Texture	Drainage Class	Depth to Water Table (inches)	Depth to Restriction (inches)	Slope (%)	pH	O.M. Content (%)
GA	Orangeburg	loamy sand	Well-drained	80"+	80"+	0-3%	4.5-6	1-2%
SC	Meggett	loam	Poorly-drained	0" to 12"	80"+	0-3%	3.5-5.5	6-8%
SC	Lynchburg	fine, sandly loam	Somewhat poorly	6" to 18"	80"+	0-3%	3.5-5.5	3-4%
SC	Seagate	loamy sand	Somewhat poorly	20" to 30"	80"+	0-3%	3.5-5.5	3-4%

*Information from NRCS Soil Survey (2018)

Climatic data include mean monthly precipitation (Figure 2.1) and mean monthly temperature (Figure 2.2) and were obtained from the National Centers for Environmental Information (www.ncdc.noaa.gov/cdo-web/search) (NOAA, 2018).

Plant Material Description:

Eight different genetic entries were used in this study (Table 2.2).

Table 2.2 Study genotype entries by production type, origin, and crown ideotype

Genotype	Production Type	Parent Origins	Crown Ideotype	Branch Size
AA93	Rooted Cutting Clone	South Carolina	Narrow	Small
AA32	Rooted Cutting Clone	South Carolina	Moderate	Small to Moderate
C40	Somatic Embryogenesis (SE) Clone	South Carolina	Narrow	Moderate
C36	Non-commercial SE Clone	South Carolina	Moderate	Small
M2	Control Pollinated	South Carolina	Moderate	Small to Moderate
M15	Control Pollinated	South Carolina	Moderate	Small
M16	Control Pollinated	South Carolina	Broad	Large
O3	Open Pollinated	South Carolina	Broad	Large

Genotype O3 is a widely planted and high-ranking volume producer that serves as an elite commercial check in many progeny and breeding test programs. Genotypes M2, M15, and M16 are control mass pollinated crosses (CMP) made from elite volume producing parents. Genotypes, C36 and C40 are somatic-embryogenesis-produced clones that were withdrawn from the commercial market since the time of planting. C36 SE clone was only a commercial clone for 1-year before rust and growth issues became evident. Alternatively, many acres of C40 have been planted across the southeastern United States. Genotypes AA93 and AA32 are high-yielding rooted cutting clones for which growth performance has been observed and published (Maier et al., 2012. 2013; Sabatia and Burkhart, 2013). Clonal genotypes were container stock. Control pollinated and OP genotypes were 1-0 bare-root stock.

Study Design

The study was installed as a randomized complete block with split plots. Main treatment plots were for density (388 or 518 trees per acre). Main plots were split for random genotype assignment. Each study installation contained three blocks (reps).

Genotypes were assigned at random to subplots within each density plot. Genotype plots were 0.22 acres in size. Measurements were made on all trees in a 0.12 acre interior measurement plot. This provided 60 potential measurement trees in the 518-TPA plots and 45 measurement trees in the 388-TPA density plots.

Study Establishment

The study was designed to test the performance of a range of genotypes under operational conditions. The SC site received a shear and bed treatment in the summer of 2004 and then chemical application in the fall of 2004 with a per-acre rate of 32 oz. of Chopper (2 lbs. imazapyr) and 1 quart of Garlon-4 (triclopyr). After hand planting in late 2004, the SC site received a spring herbaceous weed control treatment with 3 oz./acre of Oust (sulfometuron methyl).

The GA site received an upland bedding treatment followed by a fall chemical site preparation treatment of 16 oz./acre of Arsenal (4# imazapyr) plus 3 oz. Oust (sulfometuron methyl)/per acre. The GA site was hand planted in late 2004. A summer herbaceous weed control treatment of 3.75 oz./acre of Transline (clopyralid) and 2 oz. of SFM75 (sulfometuron methyl) was applied in a banded treatment along the row.

On both sites the between row spacing was 14 ft. For the 388 TPA treatment, the within row spacing was 8 ft between trees and for the 518 TPA treatment the within row spacing was 6 ft. No fertilizer or additional treatments were applied over the study period.

Measurements and Calculations

Trees were measured after the completion of the 6^{th} growing season. Survival status was assessed and DBH measured on all trees within the embedded measurement plots. DBH was measured with a steel diameter tape. Total heights were measured on every other tree using a Haglof Vertex hypsometer. The measured heights were used to estimate the non-measured trees using regression at the plot level. Individual tree volumes were calculated using the University of Georgia Plantation Management Research Cooperative (PMRC) equations by Harrison and Borders (1996). While the PMRC publication provides different equation parameters for the Upper and Lower Coastal Plains, the Lower Coastal Plain equation was used for both locations to avoid non-treatment effects. The equation and parameters are summarized here:

$$VOBm = 0.00145519 * DBH^{1.826051} H^{1.221965}$$

where VOB_m *= outside bark merchantable stem volume*
DBH = Diameter at breast height
H = total tree height

Survival, mean DBH, mean height, mean DBH/HT ratio, mean tree basal area, and mean tree volume were calculated for each plot. Basal area per acre and volume per acre were calculated by multiplying the plot values by the per acre expansion value.

The top half of the measured heights were considered to be the dominant and codominant heights for the plot. The mean of these trees were used along with age to estimate site index at base age 25 from the adapted Clutter and Lenhart (1968) site index table historically used on the operational land bases where the study installations were located.

Percent change for the tree and stand attributes between the sites and densities and among the genotypes examined was calculated to compare the relative impact of these factors. In all cases, the percent change was calculated as the difference between the poorest performing treatment and the best performing treatment divided by the performance of the poorest treatment (the base).

Statistical Analysis

A combined Analysis of Variance (ANOVA) was performed to examine differences between sites (Table 2.3). Within site ANOVA was performed for a split-plot design for each site using both SAS (SAS/STAT, 2017) and R statistical packages. Within an installation, ANOVA was used to test for block, density, genotype, and any interactive effects on survival, mean DBH, mean height, DBH/HT ratio, mean individual tree volume, mean tree basal area, basal area per acre and total volume per acre. The linear model used for was:

$$Y_{ijkl} = \mu + B_i + D_j + G_k + B_iD_j + B_iG_k + D_jG_k + \varepsilon_{ijkl}$$

Where Y_{ijkl} is the observed dependent variable; B_i is the effect of the *i*th block (*i* = 1-3); D_j is the effect of the *j*th density (318 or 518 TPA density); G_k is the effect of the *k*th genotype (k = 1-8); B_iD_j is the block by density effect; B_iG_k is the block by genotype effect; D_jG_k is the density by genotype effect; and ε_{ijkl} is the random error associated with the model and is assumed to be distributed N (O, σ^2). Proc Mixed was used for the analysis. Duncan's test was used for significant means comparison. The alpha level for assigning significance was 0.05.

Table 2.3 ANOVA table for the randomized complete block with split plot design with genotype assigned randomly inside the split plots, three blocks per installation, and 'across site' analysis for two sites, including a GA upland site and a SC lowland site.

Source	Df
Analysis for each site	
Block	2
Planting density	1
Error	2
Subtotal	5
Genotype	7
Stocking * Genotype	7
Error	28
Subtotal	47
Analysis across sites	
Site	1
Site * planting density	1
Error	2

Results

Environmental Trends

The trends in monthly precipitation for the SC coastal site and the GA upland site are illustrated in Figure 2.1. Both locations had above normal and well distributed rainfall in the year of establishment (2005). Two years, 2007 and 2010, were drought years at the GA upland site. All six years at the SC coastal site had well-distributed rainfall.

The average monthly air temperature trends are illustrated in Figure 2.2. The monthly patterns in air temperature are similar for the two sites. However, temperature averaged over 80 degrees F in the summer of the two drought years at the GA upland site. Clearly the GA upland site had less rainfall and higher evaporative demand than the SC coastal site.

Figure 2.1 Monthly precipitation trends for the SC coastal and GA upland sites for the 2005-2010 period.

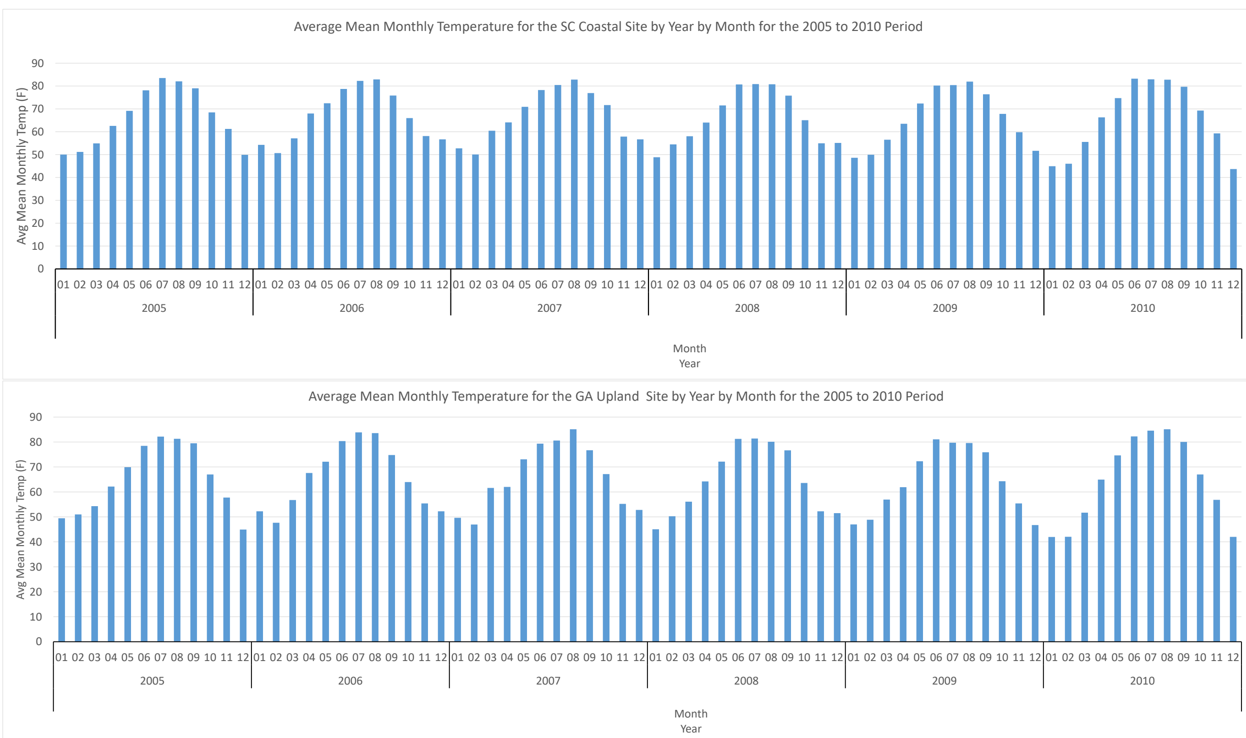

Figure 2.2 Average monthly temperature trends for the SC coastal and GA upland sites for the 2005-2010 period.

Tested Effects Significance on Tree and Stand Attributes

The significance of the impacts of site, initial planting density, and genotype on factors of survival, mean DBH, mean height, mean DBH/HT ratio, mean volume/tree, mean basal area/acre, mean volume/acre and site index is summarized in Table 2.4. Site effects were significant on all variables. Genotype was significant on all variables except survival. Initial planting density was significant on all factors except survival, mean height, and site index with mean height and site index having a p-value of 0.06. No interactions were significant.

Table 2.4 P-values of tested effects of site, genotype, and initial planting density and their interactions on survival, mean DBH, mean height, mean DBH/HT ratio, mean Vol./tree, mean basal area/acre, mean volume/acre, and site index. Bold values are significant at alpha = 0.05.

Effect	Survival	Mean DBH	Mean Height	Mean DBH/HT	Vol./Tree	Basal Area/acre	Vol./Acre	Site Index
Site	**0.026**	**0.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Genotype	0.0759	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Site*Genotype	0.381	0.5188	0.4808	0.8889	0.3025	0.4059	0.3667	0.5338
Density	0.4551	**<.0001**	0.0605	**<.0001**	**<.0001**	<.0001	0.0048	0.0668
Site*Density	0.3967	0.7524	0.7586	0.7815	0.8825	0.1609	0.1849	0.8078
Genotype*Density	0.8979	0.7025	0.7961	0.3914	0.4631	0.3406	0.4683	0.8301
Site*Genotype*Density	0.6975	0.8108	0.9464	0.7988	0.6803	0.8769	0.8634	0.9603

Survival

There were no statistical differences in age 6 survival for genotype, density, block, or any of the evaluated interactions (Table 2.4). Site was significant at p-value = 0.026. Survival was greater than or equal to 90% for all genotype-density plantings except for clone C40 and M15 (88% in the high-density GA planting) (Table 2.5). Survival on the SC site (95%) was significantly greater than on the GA site (93%). Survival by genotype across sites range from 91.5% for C40 to 96% for AA93.

Table 2.5 Average survival and standard error (SE) by treatment and by site for eight genotypes planted at and two planting densities (388 and 518 TPA) on two locations (Berkeley County, SC and Marion County, GA). Across density means followed by the same letters do not differ significantly from each other.

Site	Genotype	Across Densities Mean	SE	518 TPA Mean	SE	388 TPA Mean	SE
SC Coastal	AA32	0.96a	0.00	0.96	0.01	0.96	0.01
SC Coastal	AA93	0.96a	0.02	0.97	0.01	0.95	0.03
SC Coastal	C36	0.91b	0.02	0.91	0.04	0.91	0.02
SC Coastal	C40	0.94ab	0.02	0.94	0.01	0.93	0.03
SC Coastal	M15	0.94ab	0.03	0.94	0.04	0.93	0.04
SC Coastal	M16	0.97a	0.01	0.97	0.01	0.97	0.03
SC Coastal	M2	0.95ab	0.02	0.97	0.02	0.93	0.03
SC Coastal	O3	0.97a	0.01	0.99	0.01	0.96	0.01
SC Coastal	Average	0.95a	0.02	0.96	0.02	0.94	0.03
GA Upland	AA32	0.95a	0.01	0.97	0.01	0.93	0.01
GA Upland	AA93	0.96a	0.01	0.97	0.02	0.96	0.01
GA Upland	C36	0.93ab	0.01	0.94	0.02	0.91	0.01
GA Upland	C40	0.89b	0.03	0.88	0.02	0.90	0.06
GA Upland	M15	0.91ab	0.02	0.88	0.01	0.94	0.01
GA Upland	M16	0.92ab	0.02	0.92	0.03	0.92	0.05
GA Upland	M2	0.95a	0.02	0.94	0.03	0.96	0.01
GA Upland	O3	0.93ab	0.02	0.94	0.02	0.91	0.02
GA Upland	Average	0.93b	0.02	0.93	0.02	0.93	0.02
Across Sites	Average	0.94	0.02	0.94	0.02	0.94	0.02

Mean DBH

Mean DBH differed statistically by site, genotype and density (Table 2.4). There were no significant differences due to any of the interactions evaluated. Average genotype DBH by initial planting density (High=518 TPA and Low= 388 TPA) and across planting densities is shown for each site (SC or GA) for each genotype in Table 2.6. Average DBH across all genotype-density combinations was 4.7 inches at the South Carolina coastal site and 4.4 inches at the Georgia upland site. This significant difference in average age 6 DBH represents a 6.8% difference.

Table 2.6 Average age 6 DBH (inches) observed for eight genotypes planted at two initial planting densities (388 TPA and 518 TPA) and at two locations (Berkeley County, SC & Marion County, GA). Genotype averages across densities at each site are also given. Across density and across site means followed by the same letter do not differ significantly.

		Across Densities		518 TPA		388 TPA	
Site	Genotype	Mean	SE	Mean	SE	Mean	SE
SC Coastal	AA32	4.64a	0.13	4.45	0.15	4.84	0.15
SC Coastal	AA93	4.79a	0.07	4.67	0.05	4.91	0.09
SC Coastal	C36	3.5b	0.18	3.37	0.29	3.63	0.24
SC Coastal	C40	4.63a	0.2	4.21	0.05	5.04	0.13
SC Coastal	M15	5.06a	0.17	4.80	0.09	5.31	0.27
SC Coastal	M16	4.98a	0.12	4.87	0.21	5.10	0.14
SC Coastal	M2	4.91a	0.25	4.55	0.18	5.28	0.37
SC Coastal	O3	4.67a	0.13	4.60	0.20	4.73	0.20
SC Coastal	Average	4.65a	0.16	4.44b	0.15	4.86a	0.20
GA Upland	AA32	4.54ab	0.13	4.28	0.10	4.80	0.10
GA Upland	AA93	4.53ab	0.16	4.26	0.19	4.81	0.09
GA Upland	C36	3.29d	0.17	3.10	0.28	3.47	0.16
GA Upland	C40	3.99c	0.15	3.76	0.21	4.23	0.12
GA Upland	M15	4.79ab	0.12	4.53	0.07	5.05	0.06
GA Upland	M16	4.89a	0.08	4.76	0.10	5.02	0.10
GA Upland	M2	4.64ab	0.13	4.41	0.17	4.87	0.05
GA Upland	O3	4.43bc	0.18	4.18	0.30	4.68	0.13
GA Upland	Average	4.39b	0.14	4.16b	0.18	4.62a	0.10
Across Sites	Average	4.52	0.15	4.30	0.17	4.74	0.15

Mean DBH by genotype across sites and densities ranged from 3.4 inches for CF36 to 4.9 for M15 and M16. CF40 had the second smallest mean DBH (4.3 inches) (Figure 2.3).

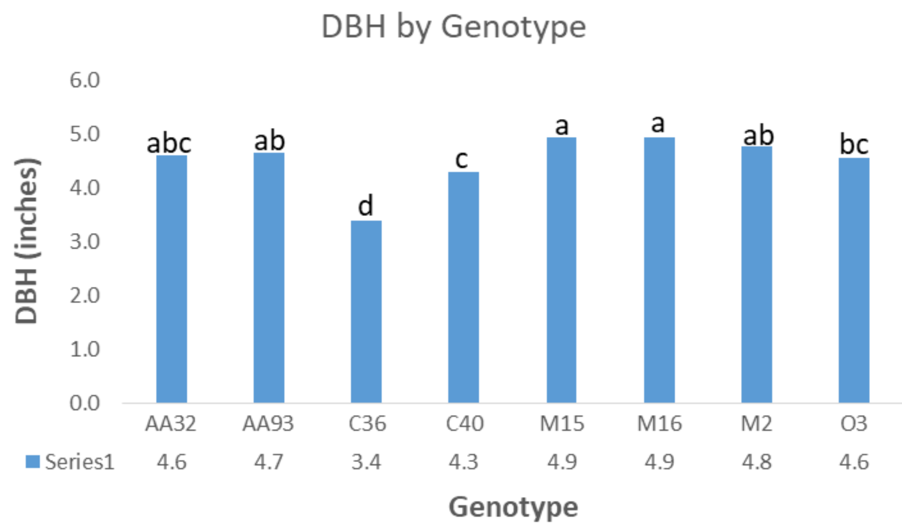

Figure 2.3: Average age 6 DBH's determined for eight genotypes grown at two densities at a South Carolina coastal site located in Berkeley County and a Georgia upland site located in Marion County. Across site DBH means followed by the same letter do not differ significantly from each other.

At the SC site, the order from largest to smallest DBH by genotype for the high density plantings was: (1) M16 (2) M15 (3) clone AA93 (4) OP3 (5) clone AA-32=M2 (6) clone CF40 and (7) clone CF36 (Table 2.6). The order was similar in the low-density planting with M15 and M16 and clone AA93 having the largest DBH's and clone CF36 having the lowest DBH. The maximum DBH difference between genotypes at SC was 1.5 inches in the high- density planting and 1.7 inches in the low-density planting. Genotype selection for planting could represent a reduction of up to 13% DBH by age 6 on the SC coastal site.

At the GA upland site, the order from largest to smallest DBH in the high-density planting was (1) M16 (2) M15 (3) M2 (4) clones AA93=clone AA32 (5) OP3 (6) clone CF40 and (7) clone CF36 (Table 2.6). The DBH ranking was almost identical to that observed in the GA low density plantings: (1) M15 (2) M16 (3) M2 (4) clone AA32=clone

AA93 (5) OP3 (6) clone CF40 and (7) clone CF36 (Table 2.7). The range in DBH between all genotypes grown on the GA upland site in the 518 TPA regime was 1.7 inches. For the commercial genotypes (excluding CF36) the range in DBH was 1.0 inches. The range in DBH between all genotypes grown in the GA upland 388 TPA regime was 1.6 inches while that of the more commercial genotypes was 0.9 inches. The choice of genotype impact was as great as 23% increase in age 6 DBH for the commercial genotype pool considered in this study.

Mean DBH was 4.3 inches for the 518 TPA density and 4.7 inches for the 388 TPA density (Table 2.6). Average age 6 DBH for trees grown in the 518 TPA regime at the SC coastal site was 4.5 inches. The average DBH for trees growing in the 388 TPA regime was 4.8 inches, resulting in a difference of 0.3 inches (6.7%).

At the GA upland site, the average DBH in the 518 TPA regime at age 6 was 4.3 inches. The average DBH in the 388 TPA regime was 4.7 inches, a difference of 0.4 inch due to the choice of initial planting density. The decrease in average DBH indicates that a reduction of about 8.5% in DBH resulted from increasing the planting density by 130 TPA.

The DBH similarities in genotype across sites and densities and the statistical analysis (Table 2.4) both point to no genetics x site x density interaction for DBH development through age 6. For all eight genotypes a reduction occurred in mean DBH when initial planting density increased from 388 TPA to 518 TPA. The same trend was observed at both the SC coastal site and the GA upland site. However, the average across genotype difference in age 6 DBH between trees in the low-density planting and the high-density planting was 0.38 inches at the SC site and 0.46 inches at the Georgia upland site. By age 6 the effect of increasing initial planting density on average DBH was more impactful than the difference due to growing a stand on a SC coastal site versus a GA inland site. The effect of increasing initial planting density from 388 TPA to 518 TPA was greater on the GA upland site than on the SC lowland site.

Mean Height

Site and genotype effects on height were highly significant (Table 2.4). No interactions were significant. Mean height by site, density and genotype treatment are shown in Table 2.7.

Table 2.7 Mean Age 6 height (feet) for eight genotypes grown at two planting densities (High = 518 TPA and Low = 388 TPA) on a SC coastal site and a GA upland site. Genotype and site means followed by the same letters do not differ significantly from each other.

		Across Densities		518 TPA		388 TPA	
Site	Genotype	Mean	SE	Mean	SE	Mean	SE
SC Coastal	AA32	29.6b	0.8	29.0	1.2	30.1	1.3
SC Coastal	AA93	32.4a	0.4	32.2	0.3	32.5	0.8
SC Coastal	C36	20.2d	1.0	20.1	2.0	20.3	1.2
SC Coastal	C40	26.8c	0.7	25.5	0.4	28.1	0.7
SC Coastal	M15	28.4bc	0.9	28.3	0.7	28.6	1.8
SC Coastal	M16	28.4bc	0.5	28.4	1.2	28.4	0.4
SC Coastal	M2	29.0bc	0.9	28.2	1.3	29.7	1.2
SC Coastal	O3	27.0c	0.8	27.5	1.3	26.5	1.1
SC Coastal	Average	27.7a	0.8	27.4a	1.0	28.0a	1.1
GA Upland	AA32	26.8ab	0.7	26.0	1.3	27.6	0.6
GA Upland	AA93	28.7a	0.9	27.6	1.6	29.8	0.6
GA Upland	C36	17.9e	0.9	17.6	1.8	18.1	0.8
GA Upland	C40	21.3d	0.7	20.7	1.4	21.8	0.3
GA Upland	M15	24.9bc	0.3	24.9	0.6	24.9	0.2
GA Upland	M16	26.1bc	0.3	26.5	0.4	25.7	0.3
GA Upland	M2	25.9bc	0.8	25.1	1.5	26.6	0.7
GA Upland	O3	24.3c	0.9	23.8	1.9	24.8	0.0
GA Upland	Average	24.5b	0.7	24.0a	1.3	24.9a	0.4
Across Site	Average	26.1	0.7	25.7	1.2	26.5	0.8

Average height across genotypes and initial planting densities was 27.7 feet for the SC coastal site and 24.5 feet for the Georgia upland site (Table 2.7). Mean height by genotype across sites and densities ranged from 19.0 feet for C36 to 30.5 feet for AA93 (Figure 2.4).

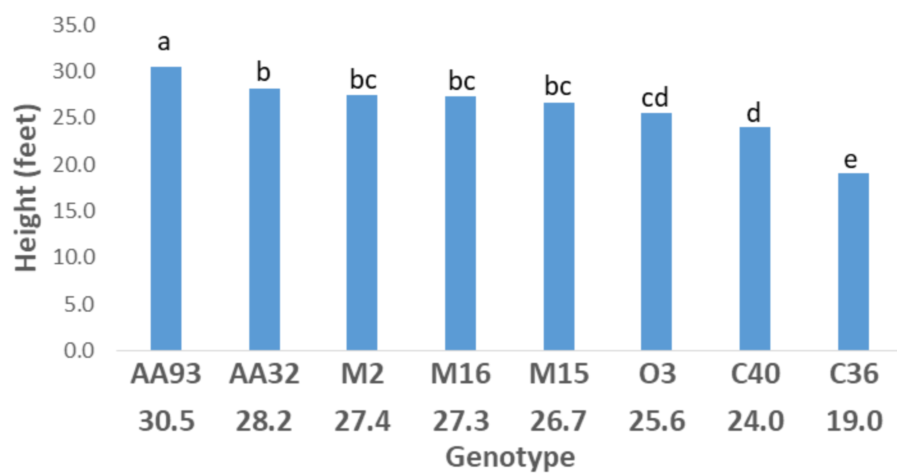

Figure 2.4: Average six-year total heights determined for eight genotypes grown at a South Carolina Coastal site located in Berkeley County and a Georgia upland site located in Marion County. Genotype means followed by the same letters do not differ significantly from each other.

At the SC coastal site, the range in heights across genotypes in the high-density planting was from 20.1 to 32.2 feet; a difference of 12.1 feet. The range in heights across genotypes in the low-density plantings was 20.3 to 32.5 feet; a difference of 12.2 feet. Clone AA93 was significantly taller than all other genotypes except AA32 and M2. Clone AA32, M2, M16 and M15 had significantly greater heights than CF40. All genotypes had a greater height than clone CF36. These differences represent a considerable separation in the age 6 average height performance among genotypes.

On the GA upland site, the range in heights averaged across the eight genotypes planted at 518 TPA was from 17.6 feet to 27.6 feet; a difference of 10 feet. The range in heights for the same eight genotypes planted at 388 TPA at the GA upland site was from 18.1 to 29.8; a difference of 11.7 feet.

Trends in average age 6 height for each level of tree improvement are apparent. In the SC coastal site when grown at 518 TPA the trend was RC-clones (30.6 feet) > CMP crosses (28.3 feet) >OP elite (27.4 feet) > CF40 (25.5 feet). When grown at 388 TPA at the SC coastal site, the ranking was: RC-clones (31.3 feet) > CMP crosses (28.9 feet) >CF40 (28.1 feet) > OP elite (26.5 feet).

At the GA upland site, the trends in average height across the levels of tree improvement deployed at 518 TPA was: RC-clones (26.8 feet) > CMP crosses (25.5 feet) > OP elite (23.8 feet) > CF40 (20.7 feet). When deployed at the low density of 388 TPA the tree improvement level ranking was: RC-clones (28.7 feet) > CMP crosses (28.6 feet) > OP elite (24.8 feet) > CF40 (21.8 feet).

The genotype rankings at each site and across initial planting densities were very consistent; with the RC-clones being first, CMP crosses second and then either the OP elite entry or the C40 SE-clone being next.

The effects of initial planting density on age 6 height had a p-value of 0.06, with mean height slightly greater for the 388 TPA (26.4 feet) that the 518 TPA density (25.7 feet). At the SC-coastal site, the average age 6 height was 27.4 feet for trees in the 518 TPA and 28.0 feet for trees grown in the 388 TPA treatment. At the GA upland site trees in the 518 TPA treatment average 24.0 feet while those in the 388 TPA treatment averaged 24.9 feet. The effects of initial planting density on height was not as strong or as consistent as on DBH. For heights, at age 6 some genotypes (O3, M16, & M15) had heights that were equal or slightly greater at the high initial planting density.

Average Diameter to Height Ratio (DBH/HT)

Site, genotype and density effects on DBH/HT were highly significant (Table 2.4). No interactions were significant. The average age-6 DBH/HT ratios are shown in Table 2.8. The SC coastal site trees had a significantly lower average DBH/HT ratio (0.168) than the average (0.174) observed for the GA upland site (Table 2.8). The SC coastal site produces trees that have smaller average DBH at a given height than the trees on the GA upland site.

Table 2.8 Mean Age 6 DBH/HT for eight genotypes grown at two planting densities (High=518TPA and Low=388 TPA) on a SC Coastal site and a GA upland site. The units are DBH in inches over height in feet. Genotype means or within-site density means with the same letters do not differ significantly from each other.

		Across Densities		518 TPA		388 TPA	
Site	Genotype	Mean	SE	Mean	SE	Mean	SE
SC Coastal	AA32	0.16b	0.00	0.15	0.00	0.16	0.00
SC Coastal	AA93	0.15b	0.00	0.14	0.00	0.15	0.00
SC Coastal	C36	0.17a	0.00	0.16	0.00	0.18	0.00
SC Coastal	C40	0.17a	0.00	0.16	0.00	0.18	0.00
SC Coastal	M15	0.18a	0.00	0.17	0.00	0.18	0.00
SC Coastal	M16	0.17a	0.00	0.17	0.00	0.18	0.00
SC Coastal	M2	0.17a	0.01	0.16	0.00	0.18	0.01
SC Coastal	O3	0.17a	0.00	0.17	0.00	0.18	0.00
SC Coastal	Average	0.17b	0.00	0.16b	0.00	0.17a	0.00
GA Upland	AA32	0.17c	0.00	0.16	0.01	0.17	0.00
GA Upland	AA93	0.16d	0.00	0.15	0.00	0.16	0.00
GA Upland	C36	0.18ab	0.00	0.17	0.00	0.19	0.01
GA Upland	C40	0.19ab	0.00	0.18	0.00	0.19	0.00
GA Upland	M15	0.19ab	0.00	0.18	0.00	0.2	0.00
GA Upland	M16	0.19ab	0.00	0.18	0.00	0.19	0.00
GA Upland	M2	0.18bc	0.00	0.18	0.00	0.18	0.01
GA Upland	O3	0.18abc	0.00	0.17	0.00	0.19	0.00
GA Upland	Average	0.18a	0.00	0.17b	0.00	0.19a	0.00
Across Sites	Average	0.17	0.00	0.17	0.00	0.18	0.00

All genotypes had a significant greater DBH/HT across sites and densities than clone AA93 which is a true “crop” ideotype (Figure 2.5). Genotypes M15, M16, CF40, and OP3 which are broad crown, “competitor” ideotypes had higher DBH/HT ratios than either AA32 or AA93. Genotypes M2 and AA32 are moderate crown and their DBH/HT ratio ranks between the broad crown competitor ideotypes and AA93 a “crop” ideotype.

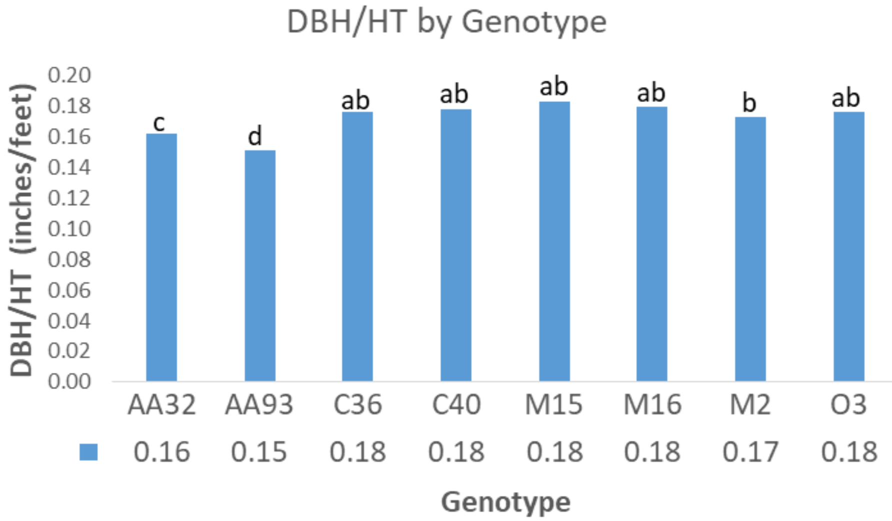

Figure 2.5. Average six-year DBH/HT ratios determined for eight genotypes grown at a South Carolina Coastal site located in Berkeley County and a Georgia upland site located in Marion County when grown at two planting densities (518 TPA and 388 TPA). Genotype means with same letters do not differ significantly from each other.

On the SC coastal site, DBH/HT ratios ranged from 0.15 to 0.18 across genotypes for the low-density plots and 0.14 to 0.17 for the high-density plots. On the GA site, the low- density plots had a range in genotype DBH/HT ratio of 0.16 to 0.20 as compared with a range of 0.15 to 0.18 on the high-density plots on the same site. All genotypes DBH/HT ratios were lower at a given site in the high-density plots than in the low-density plots; except genotype M2 on the GA site which was 0.18 in both growing densities (Table 2.8).

On both the SC coastal and the GA upland sites the average age 6 trend in the DBH/HT ratio is to decrease as initial planting density is increased from 388 TPA to 518 TPA (Table 2.8). On the SC coastal site the average D/HT ratio was 0.16 in the 518 TPA regime and 0.17 for the trees in the 388 TPA regime. The same average DBH/HT trend was observed for the GA upland site. At the GA upland site average DBH/HT of trees in the 518 TPA regime was 0.17 and the average for trees in the 388 TPA regime was 0.18.

At both locations this suggests that DBH (Table 2.6) is being suppressed more by planting density than height is being impacted by density (Table 2.7).

Individual Tree Volume

Site, genotype and density effects on individual tree volume were highly significant. No interactions were significant (Table 2.4).

Table 2.9 Mean Age-6 individual tree volumes (cubic feet) for eight genotypes grown at two densities (388 TPA and 518 TPA) on a SC coastal site and a GA upland. Across density means followed by the same letters do not differ significantly from each other.

		Across Densities		518 TPA		388 TPA	
Site	Genotype	Mean	SE	Mean	SE	Mean	SE
SC Coastal	AA32	1.64a	0.12	1.50	0.15	1.78	0.17
SC Coastal	AA93	1.85a	0.07	1.76	0.06	1.94	0.12
SC Coastal	C36	0.67b	0.08	0.64	0.13	0.71	0.11
SC Coastal	C40	1.5a	0.14	1.20	0.04	1.8	0.07
SC Coastal	M15	1.83a	0.15	1.65	0.09	2.01	0.27
SC Coastal	M16	1.78a	0.09	1.71	0.16	1.84	0.11
SC Coastal	M2	1.79a	0.19	1.53	0.15	2.05	0.29
SC Coastal	O3	1.47a	0.10	1.46	0.14	1.48	0.18
SC Coastal	Average	1.57a	0.12	1.43b	0.12	1.70a	0.17
GA Upland	AA32	1.35ab	0.1	1.17	0.12	1.53	0.08
GA Upland	AA93	1.44ab	0.13	1.23	0.17	1.65	0.09
GA Upland	C36	0.50d	0.06	0.45	0.11	0.55	0.06
GA Upland	C40	0.85c	0.08	0.75	0.13	0.95	0.06
GA Upland	M15	1.36ab	0.07	1.23	0.05	1.50	0.06
GA Upland	M16	1.49a	0.05	1.44	0.08	1.53	0.06
GA Upland	M2	1.35ab	0.11	1.19	0.16	1.51	0.06
GA Upland	O3	1.17b	0.11	1.03	0.19	1.31	0.07
GA Upland	Average	1.19b	0.09	1.06b	0.13	1.32a	0.07
Across Sites	Average	1.38	0.10	1.25	0.12	1.51	0.12

The average individual tree volume for the SC coastal site was 1.6 cubic feet as compared to the GA upland site with 1.2 cubic feet. This represents a 33% difference in individual tree average volume between the SC and GA sites by age 6.

The trends in genotype age 6 individual tree volumes across sites and densities are shown in Figure 2.6. Genotype volume performance rankings are similar at both installations.

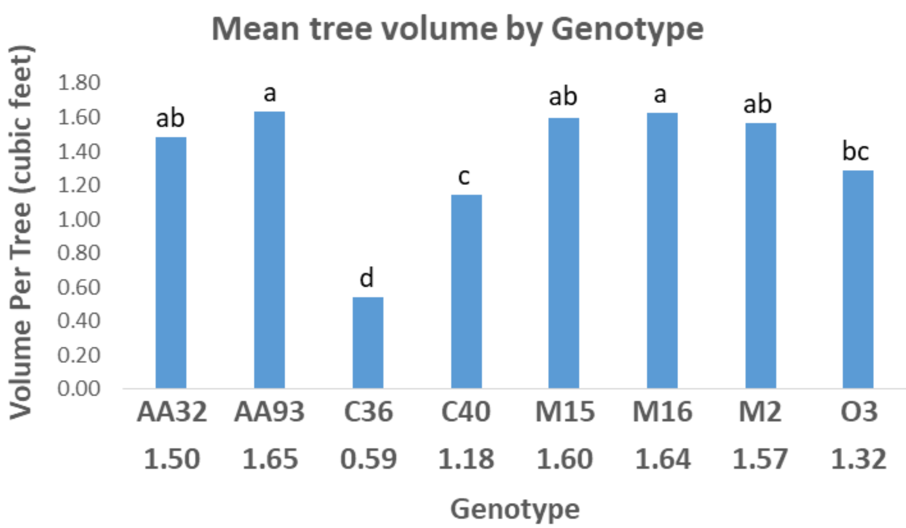

Figure 2.6. Average six mean individual tree volumes determined for eight genotypes grown at a South Carolina Coastal site located in Berkeley County and a Georgia upland site located in Marion County. Genotype means with the same letters do not differ significantly from each other.

At the SC coastal site, age 6 average individual tree volumes range from 0.6 cubic feet for SE-clone CF36 to 1.8 cubic feet (RC-clone AA-93) when grown at 518 TPA (Table 2.9). When grown at 388 TPA, individual tree volumes ranged from 0.7 cubic feet (CF36) to 1.9 cubic feet or a difference of 1.2 feet due to genotype selection (Table 2.9). These differences in individual tree volume represent a 171% difference in individual tree volume at age 6 due to the choice of genetics deployed. The order from largest to smallest average individual tree volume by level of tree improvement when grown at 518 TPA at the SC site was: RC-clones (1.6 cubic feet) = CMP crosses (1.6 cubic feet) > O3 elite (1.5 cubic feet) > C40 (1.2 cubic feet). The order from largest to smallest individual tree volume when deployed in the 388 TPA regime was: RC-clones (1.9 cubic feet) =CMP crosses (1.9 cubic feet) >C40 = OP elite (1.5 cubic feet) (Table 2.12).

On the GA upland site, age 6 average individual tree volumes ranged from 0.4 cubic feet for CF36 to 1.4 cubic feet (M16) at 518 TPA (Table 2.9). At 388 TPA, the range in average individual tree volume was from 0.5 cubic feet for CF36 clone to 1.5 for CMP cross M16. The ranking by level of tree improvement at the GA site for the low-density planting regime was RC-clones (1.6 cubic feet) > CMP crosses (1.5 cubic feet) > OP3 elite (1.3 cubic feet) > CF40 clone (1.0 cubic feet). The ranking by level of tree improvement when ordered from largest to smallest age 6 individual tree volume when grown at 518 TPA was: CMP crosses (1.3 cubic feet) > RC-clones (1.2 cubic feet) > O3 elite OP (1.0 cubic feet) > CF40 clone (0.7 cubic feet). At the GA upland site genotypes M16, AA93, M15, AA32, M2, and O3 were not statistically different from each other in individual tree volume. Clones CF40 and CF36 were significantly less in individual tree volume than genotypes M16, AA93, M15, AA32, M2, O3 (Figure 2.6).

Tree volume averaged 1.51 cubic feet for the 388 TPA density and 1.25 cubic feet for the 518 TPA density. At the SC coastal site, average across-genotype individual tree volume was 1.4 cubic feet for trees grown at 518 TPA and 1.7 cubic feet for trees grown at 388 TPA (Table 2.13). This difference represents a 21% increase in age 6 individual stem volume from reducing initial planting densities from 518 TPA to 388 TPA.

At the GA upland site, average individual tree volume at 388 TPA was 1.3 cubic feet and 1.1 at 518 TPA. This represents an 18% decrease in individual tree volume when trees are grown at 518 TPA versus 388 TPA. The reduction in individual tree volume from growing at 388 TPA versus 518 TPA was 3% less at the GA upland lower resource site than was observed at the SC coastal site.

Making the poorest choice in genotypes (CF36) and growing it at high initial planting density versus choosing the best individual volume producing genotype (M2 or M15) and growing it in the low initial planting regime (318 TPA) at SC results in a difference of average age 6 individual tree volume of 1.4 cubic feet per tree. This would represent a 233 percent fall-down in age 6 individual tree volume. Making the poorest choice in genotypes (CF36) and growing it at high initial planting density versus choosing the best individual volume producing genotype (M16) results in a difference of average age 6 individual tree volume of 1.0 cubic feet. This would represent a fall-down in potential individual tree volume of 222 percent.

<u>Per-Acre Basal Area</u>

Site, genotype and density effects on basal area were highly significant (Table 2.4). No interactions were significant.

Table 2.10 Mean age 6 per acre basal areas (ft^2) for eight genotypes at two densities (Low=388 TPA, High=518 TPA) on a SC coastal site and a GA upland site. Across density means followed by the same letters do not differ significantly from each other.

		Across Densities		518 TPA		388 TPA	
Site	Genotype	Mean (ft^2)	SE (ft^2)	Mean (ft^2)	SE (ft^2)	Mean (ft^2)	SE (ft^2)
SC Coastal	AA32	51.0ab	2.5	54.3	3.4	47.6	2.9
SC Coastal	AA93	53.5ab	2.9	59.0	1.1	47.9	3.3
SC Coastal	C36	28.9c	3.0	31.3	5.2	26.6	3.7
SC Coastal	C40	49.8b	1.7	48.7	1.1	50.9	3.4
SC Coastal	M15	59.4a	3.8	62.7	4.6	56.1	6.3
SC Coastal	M16	60.1a	4.0	66.3	5.3	53.9	3.5
SC Coastal	M2	56.3ab	3.2	57.8	3.3	54.8	6.0
SC Coastal	O3	52.6ab	3.9	59.7	3.9	45.5	3.1
SC Coastal	Average	51.4a	3.1	55.0b	3.5	47.9a	4.0
GA Upland	AA32	47.1ab	1.6	49.3	1.8	45.0	2.3
GA Upland	AA93	47.1ab	2.1	48.6	3.8	45.7	2.3
GA Upland	C36	25.2d	2.3	26.4	4.6	23.9	2.2
GA Upland	C40	34.8c	1.5	35.5	3.1	34.2	0.7
GA Upland	M15	50.6ab	1.1	50.5	1.1	50.7	2.1
GA Upland	M16	53.4a	2.3	58.3	0.8	48.5	0.9
GA Upland	M2	49.3ab	2.1	51.2	4.2	47.5	0.7
GA Upland	O3	44.4b	3.1	46.5	6.3	42.2	1.4
GA Upland	Average	44.0b	2.0	45.8a	3.2	42.2a	1.6
Across Site	Average	47.7	2.6	50.4	3.4	45.0	2.8

The overall average age 6 basal area/acre for the SC Coastal site was 51.4 ft^2/ac (Table 2.10). The overall average age 6 basal area for the GA upland site was 44.0 ft^2/ac. Basal area periodic annual increment for the six-year period from establishment has been 8.6 ft^2/ac/yr for the SC coastal site and 7.7 ft^2/ac/yr for the GA upland site. This represents about a 12% higher age 6 BA/acre/year increment at the SC coastal site versus the GA upland site.

Genotype was highly significant factor affecting basal area/acre (Table 2.14, Figure 2.7). Basal area per acre by genotype across sites and densities ranged from 27 ft^2/ac for CF36 to 56.7 ft^2/ac for M16.

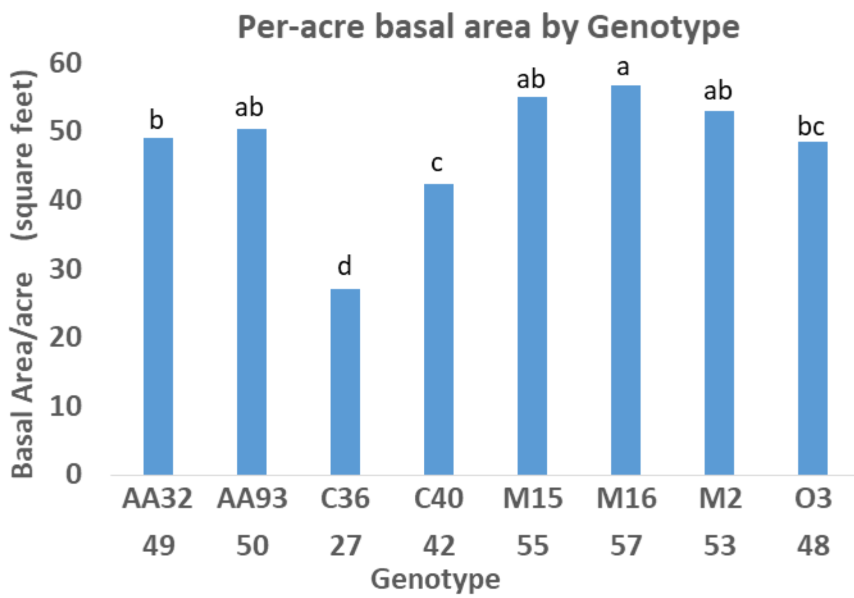

Figure 2.7 Average age 6 mean per acre basal area determined for eight genotypes grown at two densities on a South Carolina Coastal site located in Berkeley County and a Georgia upland site located in Marion County. Genotype means with the same letters do not differ significantly from each other.

On the GA upland site, the range in genotype BA in the 518 TPA regime was from a low of 26.4 ft^2/ac (C36) to a high of 58.3 ft^2/ac (M16); a difference of 32 ft^2/ac. The range in genotype BA observed for the 388 TPA regime was from a low of 23.9 ft^2/ac (C36) to a high of 50.7 ft^2/ac (M15); a difference between genotypes of 26.8 ft^2/ac. For the commercial genotypes (dropping C36), the range in genotype BA was from 16.1 ft^2/ac (388 TPA) to 22.7 ft^2/ac (518 TPA). Genotype M16 had the highest absolute value for BA (58.3 ft^2/ac) but was not significantly different than the BA observed for genotypes M15, M2, AA32, and AA93 (Figure 2.7, Table 2.15). All CMP genotypes and rooted cutting clones had significantly more per-acre BA at age 6 than the somatic embryogenesis clones. Genotype CF36 was the poorest BA performer.

On the SC coastal site, the range in genotype BA observed for the 518 TPA regime was from a low of 31.3 ft^2/ac (CF36) to a high of 66.3 ft^2/ac (M16); a range of 35 ft^2/ac. The range in genotype BA observed for the 388 TPA regime for the 388 TPA regime was from a low of 26.6 ft^2/ac to a high of 54.8 ft^2/ac (M2) representing a difference of 28.2 ft^2/ac. If only the commercial genotypes are considered (less C36), the between genotype difference in BA for the high-density regime was 17.5 ft^2/ac and for the low-density regimes was 9.5 ft^2. At the SC coastal site, genotypes M15 and M16 had the highest absolute values for BA; 60.1 ft^2/acre and 59.4 ft^2/acre. However, they were not significantly different from the average BA observed for AA93, O3 or AA32 (Figure 2.7). All CMP and rooted cutting clones were significantly higher in BA than C36.

Average across-genotype age 6 basal area observed for the SC coastal site was 55 feet in the 518 TPA density regime and 47.9 ft^2/ac in the 388 TPA regime (Table 2.10). This difference of 7.1 ft^2/ac represents 15% more basal area development in the high-density regime than in the low-density regime and is significant at the alpha 0.05 level (Table 2.4).

Average across-genotype age 6 basal area observed at the GA upland site was 45.8 ft^2/ac for the high density planting regime and 42.2 ft^2/ac for the low-density regime (Table 2.10). The observed difference of 3.6 ft^2/acre between the BA of trees in the 518 TPA regime and the 388 TPA regime is only 8.5% less and is not statistically significant. The effects of initial planting density on BA at age 6 have been more impactful at the SC coastal site than at the GA upland site.

The effect of “genotype choice” on age 6 BA (28-32 ft^2/ac at 518 TPA) is much greater than the choice of planting at 518 TPA versus 388 TPA (5-7 ft^2/ac) or planting 518 TPA on a SC coastal vs a GA upland site (4.4 ft^2/ac). However, collectively all three factors, site, initial trees per acre, and genotype, are important factors that should influence the decision of how many established trees/acre to target for. For instance, if one knows they will first thin at a height of 45 ft and a BA of 140 ft^2/acre, then a genotype specific equation which estimates basal area as a function of SI and TPA would be helpful in determining the number of TPA to plant using that genotype.

Per-Acre Volume

Site, genotype and initial planting density were all significant factors affecting average age 6 volume per acre (Table 2.4). No interactions tested were significant.

The average overall volume per acre was 645 ft^3/ac on the SC coastal site and 476 ft^3/ac on the GA upland site (Table 2.11). This site level difference of 170 ft^3/ac on the SC coastal site represents about 36 percent more standing age 6 total stem volume at the SC coastal site. The greater standing volume at the SC coastal site is driven by having a 0.3 inch greater age 6 DBH, 7.4 ft^2/ac greater BA, 3.2 feet greater average height and two percent higher survival than the GA upland site.

Table 2.11 Average Age 6 per-acre volume (ft^3) for eight genotypes grown at two densities on a SC coastal site and a GA upland site. Across density means followed by the same letters do not differ significantly from each other.

		Across Densities		518 TPA		388 TPA	
Site	Genotype	Mean (ft^3)	SE (ft^3)	Mean (ft^3)	SE (ft^3)	Mean (ft^3)	SE (ft^3)
SC Coastal	AA32	679ab	45	714	69	643	64
SC Coastal	AA93	775a	47	857	25	693	62
SC Coastal	C36	268c	37	293	67	243	43
SC Coastal	C40	598b	26	564	14	631	46
SC Coastal	M15	743a	63	782	72	704	114
SC Coastal	M16	753a	57	834	84	671	51
SC Coastal	M2	723ab	51	740	68	707	90
SC Coastal	O3	624ab	59	721	71	527	57
SC Coastal	Average	645a	48	688a	59	602a	66
GA Upland	AA32	549ab	29	563	52	536	37
GA Upland	AA93	592a	39	592	76	592	40
GA Upland	C36	200d	27	211	54	189	23
GA Upland	C40	322c	22	325	50	320	3
GA Upland	M15	534ab	14	541	18	528	24
GA Upland	M16	592a	31	658	19	525	6
GA Upland	M2	548ab	36	556	76	540	26
GA Upland	O3	466b	44	486	94	447	13
GA Upland	Average	475b	30	491a	55	460a	22
Across Site	Average	560	39	590	57	531	44

Volume per acre by genotype across sites and densities ranged from 324 ft^3/ac for C36 to 683 ft^3/ac for AA93 (Figure 2.8).

For the SC coastal site, Vol/Ac across densities ranged from a low of 267.9 ft^3/ac (C36) to a high of 774.7 ft^3/Ac (AA93). This difference in average standing volume represents a 189 percent potential impact due to choice of genotype. If only the commercial genotypes are considered, the range in average age 6 standing volume is from 597.7 ft^3/Ac (C40) to 774.7 ft^3 (AA93). This represents a potential gain in standing volume of about 30 percent due to genotype. The main significant differences in standing volume were between the high yielding rooted cutting clones and CMP crosses versus the SE clones (C40 and C36) (Figure 2.8).

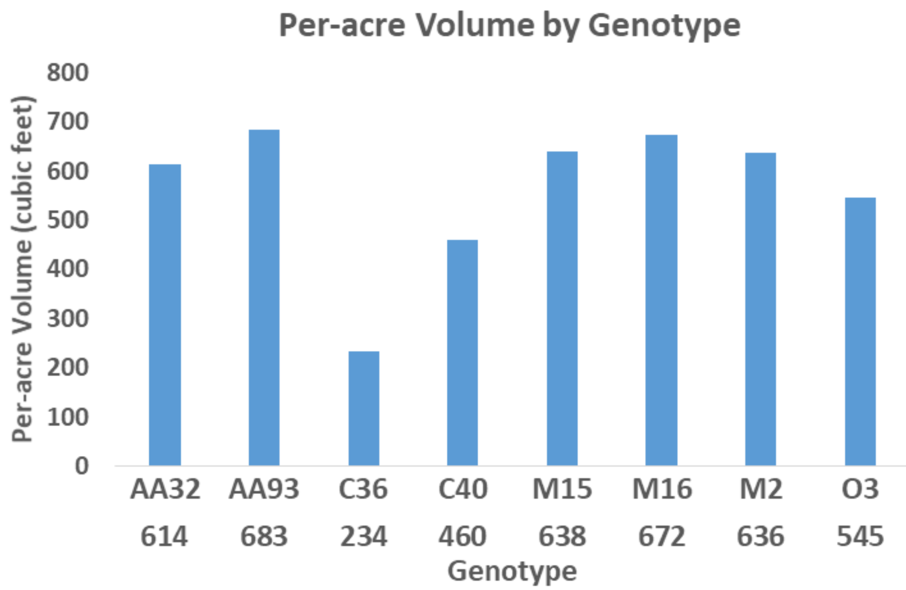

Figure 2.8 Average age 6 mean per-acre volume determined for eight genotypes grown at two densities (388 TPA and 518 TPA) on a South Carolina Coastal site located in Berkeley County and a Georgia upland site located in Marion County. Genotype means with the same letters do not differ significantly from each other.

In the high density plots, volume per acre estimates ranged from 592 (AA93) to 200 ft^3 (CF36) across the eight genotypes. The low density plot range was very similar, at 592 ft^3 (AA93) to 189 ft^3 (C36), with the only intermediate rank change being in some slight shift among the three MCP entries and AA32. At the tree improvement level, in the high density plots: RC-Clones (571 ft^3/ac)>MCP (558 ft^3/ac)>OP (466 ft^3/ac)>SE-Clones (261 ft^3/ac). In the low density plots, the ranking and magnitude were similar: RC-Clones (564 ft^3/ac)>MCP (531 ft^3/ac)>OP (465 ft^3/ac)>SE-Clones (254 ft^3/ac). In this operational example, moving from planting C36 to deploying AA93, would result in an increase in volume per acre of 196% in the high density plots, and 213% in the low density plots. If only considering the commercial genotypes, moving from use of C40 to AA93 would provide a volume per acre increase of 84% in the high density plots and 85% in the low density plots.

The average across genotype standing volume in the two initial planting density regimes deployed on the SC coastal site was 688 ft^3/ac (518 TPA) and 602 ft^3/ac (388 TPA). The average difference in standing volume between the two density regimes is 86 ft^3/ac. This represents 14% more standing volume in the 518 TPA regime versus that determined for the 388 TPA regime. This difference is largely driven by site differences in average DBH (Table 2.5) and HT (Table 2.7). Average survival was about two percent less for trees in the 388 TPA regime (Table 2.5).

At the GA upland site, the average across-genotype standing volume was 491 ft^3/ac and 460 ft^3/ac in the 518 TPA and 388 TPA regimes respectively. The 32 ft^3/ac less standing volume in the 388 TPA regime represents only a 7 percent less standing volume than was observed for the high-density treatment. Average survival was 93 percent in both density regimes so the difference in standing volume is a function of differences in height and DBH. The density effect on standing volume was about twice as great on the high resource SC coastal site as it was on the low resource GA upland site.

Effect Summary

The treatment effects are summarized in Table 2.12. Genotype had a greater effect than density or site for all variables compared in this study. Density had a greater percent impact than site on DBH and per-acre basal area. Site had a bigger impact than density on height, DBH/HT ratio, volume/tree and volume per acre.

Table 2.12 Maximum difference between observed or calculated age 6 means of loblolly pine DBH, Height, DBH/HT ratio, Basal Area, Volume/Tree and Volume per acre due to genotype, site and planting density. Differences are expressed as the absolute difference and as a percentage of maximum change.

	DBH		Height		DBH/HT Ratio		Basal Area/Acre		Volume/Tree		Volume/Acre	
Treatment	Inches	Percent	Feet	Percent	in/feet	Percent	Ft^2/acre	Percent	Ft^3	Percent	Ft^3/acre	Percent
Site	0.3	7	3.2	13	0.01	8	9	12	0.4	33	70	36
Genotype	1.7	21	12	60	0.05	33	35	112	1	233	268	189
Density	0.4	9	0.6	2	0.01	6	7	15	0.3	21	86	14

Discussion

The results for this study for a wide range of genotypes, levels of tree improvement (TI), and site conditions (coastal vs upland) strongly support no significant genetics by environment (GXE) interaction with regards to growth. No genotype by site or genotype x density interactions were detected for any of the measured parameters. This is consistent with the report of McKeand et al. (2006b) where they concluded that with most genotypes and most silviculture regimes, there would be little GXE, and interactions would not be an issue. These reports contrast with the significant genetics x site interaction reported for slash and loblolly pine by Roth et al. (2010) who attribute the significant differences in the interactions of genetics x site and genetics x silviculture intensity to the range of genotypes deployed and the range of site types evaluated. Neither our study, nor McKeand et al. (2006a) nor Roth et al. (2010) found a significant genotype x density interaction. In contrast, Steiger (2013) found a significant genotype x density interaction.

This study investigated the effects of site, initial planting density and genotype on early loblolly stand growth and development under operational conditions. The choice of site to operate on is an important consideration as illustrated by the potential productivity maps of Sampson and Allen (1999). In this study the productivity and growth of eight genotypes planted at two densities on an upland site in Marion County, GA was contrasted with that observed at a coastal site in Berkeley County, SC. Site preparation and herbaceous weed control treatments were applied at the same level of intensity at both locations and the exact same genetics were used at both locations.

The study allows a comparison of site effects driven mostly by inherent soil and experienced weather conditions. The sites received near normal annual precipitation that was well distributed during their establishment year. This likely contributed to the excellent survival observed at both locations. Average survival at the GA upland site and the SC coastal site was 93% and was 95%, respectively. However, over the six-year study period the GA site experienced summer months with less than three inches of rainfall whereas the SC coastal site had no years with low summer monthly rainfall. Monthly rainfall patterns were also different for the two locations. At the GA location the lowest monthly rainfall occurs in the fall of the year. At the SC coastal site often the lowest rainfall was in the early spring months.

The observed patterns in average monthly temperature were similar for both sites (Figure 2.2). However, at the GA site three of the six years had average monthly summer temperatures greater than 80 degrees F while no average summer monthly temperatures greater than 80 degrees F were observed at the SC coastal site. The higher average monthly temperatures at the GA upland site were coupled with the lower rainfall periods. This combination of high temperature, higher evaporative demand and lower water availability would be expected to lead to higher maintenance respiration cost, lower net photosynthesis and ultimately lower growth potential (Albaugh et al., 2004). The average reported frost-free period at the GA location is 230 days and 220 days at the SC coastal site. Winter and spring temperatures are slightly lower at the GA site than at the SC site. These observed differences in soil and environmental conditions were reflected in height, diameter and volume performance of the genetics employed on these two sites.

Modeled current annual increment (CAI) productivity potential at the areas including these two sites was approximately 425 and 500 cubic ft/ac/year for the GA and SC sites (Sampson and Allen 1999) respectively, or 18% greater at the SC site. These estimates were based on having four units of leaf area. Perdue et al. (2017) modeled mean annual increment (MAI) operational differences at 9.7 and 11.1 tons/ac/year for the GA and SC sites respectively, or 14% greater at SC. Their regime assumed operationally intensive management of a plantation established at 550 trees per acres and grown to age 14 without thinning. Average age 6 ft^3/ac volumes at the GA and SC sites are 476 and 645 respectively, with 36% greater volume present on the SC site. The difference in percentage is greater than modeled, but the results represent a unique six year span during the early part of the rotation.

Comparable Studies

Established in 2005, the current study provides an early look at the performance and potential impact of controlled cross and clonal genotypes as compared to elite open pollinated seedling material developed over the period from 1955 to 2005. Additional loblolly pine studies (Sabatia et al., 2013; Steiger, 2013) have been documented in the last five years that include 1) a genotype treatment covering the three levels of tree improvement, 2) an initial planting density treatment within the low to moderate range, and 3) exhibited growth trajectories in the upper end of today's operational range. These studies are particularly pertinent to compare with the results of the current study. Site, numbers of genotypes, and initial planting density are summarized for comparison in Table 2.13.

Table 2.13 Study treatment descriptions for four similar studies with advanced genotypes at two densities and high growth trajectories. The studies include installations located in Georgia, N. Carolina, and S. Carolina, each with two contrasting initial planting densities and four to ten genotypes across three levels of tree improvement.

Investigator	Study Location	Number of Genotypes	Level of Tree Improvement	Low Density	High Density	Age of Measures
Dougherty	Marion Co., GA	8	1 OP, 3 CMP, 4 Clones	388	518	6
Dougherty	Berkeley Co., SC	8	1 OP, 3 CMP, 4 Clones	388	518	6
Steiger[1]	Onslow Co., NC	10	4 OP[3], 3 CMP, 3 Clones	218	435	6
Sabatia[2]	Berkeley Co., SC	4	1 OP, 1 CMP, 2 Clones	275	550	8

[1] Steiger, 2013; [2] Sabatia 2013; [3] One OP entry was a seed orchard mix

All four study sites have genotype entries covering the three levels of tree improvement (Table 2.13). The Steiger site clonal entries are all SE clones. The Sabatia site includes only elite rooted-cutting clones. The current study sites include both the SE and rooted-cutting clonal entries. All genotypes planted on these four sites contain coastal SC source material, with many of the genotypes in common or having similar pedigree. The Sabatia site has four genotypes, all in common with the current study, including AA93, AA32, O3, and M2. The current study sites and the Steiger site share an SE clone and O3 in common.

Site characteristics for the four sites are summarized in Table 2.14. The soils on the three coastal sites (current GA coastal site, Steiger, and Sabatia) all have potential for high productivity. The GA upland soil that is located inland has moderate productivity potential. The site preparation on the current study's GA upland site and the SC coastal site was operationally intensive and high quality. The site preparation on the Sabatia study site was also high quality and some additional fertilization and herbicide treatments were completed. The Steiger site received heavy mechanical site preparation and chemical site preparation. In contrast, the Steiger site received added fertilization and weed control treatments compared to our more operational study care. The Steiger mechanical site preparation was more variable in regards to bed quality as compared to the current study sites and that of the Sabatia. The soils on the Sabatia site and the current study's SC coastal site are very similar (Table 2.14). These two sites are located in near proximity to each other. The soils on the Steiger site are muck based, higher in organic matter, and located at higher latitude just off the NC coast.

Table 2.14 Soil and site description information for four study installations located in Georgia, N. Carolina, and S. Carolina, each with two contrasting initial planting densities and four to ten genotypes across three levels of tree improvement.

Investigator	Study Location	Site Type	Slope Position	Soil Texture	Soil Drainage	Productivity Potential
Dougherty	Marion Co., GA	Inland	Upland	Loamy sand	Well drained	Moderate
Dougherty	Berkeley Co., SC	Coastal	Lowland	Loam and loamy sand	V. Poorly	V. High
Steiger[1]	Onslow., NC	Coastal	Lowland	Mucky loam	V. Poorly	V. High
Sabatia[2]	Summerville, SC	Coastal	Lowland	Loamy sand over clay	Somewhat poorly	V. High

[1] Steiger, 2013; [2] Sabatia 2013

For discussion and comparison purposes, Tables 2.15 – 2.19 and Tables 2.21 and 2.22 provide the measured and summarized impact of genotype on survival, DBH, height, site index, per-acre basal area, and per-acre volume from the current study and the Steiger and Sabatia study sites.

Site Effects

The average age 6 site growth advantage of the SC over the GA site, across genotypes and planting densities was 3.2 feet in height (13%); 0.3 inches in DBH (7%); 0.38 ft^3/tree in individual tree volume (33%); 7.4 ft^2/ac in BA (17%) and 169.7 cubic ft/ac in standing volume (36%). A height difference of 3.2 feet at age 6 represents an exhibited SI (base age 25 years) difference of about 5 feet. Borders and Bailey (2001) observed a difference of 10 feet in exhibited SI by age 8-9 years between a GA Piedmont (Eatonton, GA powerline site; SI 83 across treatments with 604 TPA) and a GA coastal site (Waycross, GA wet site; SI 93 ft with 677 TPA) when both received intensive herbicide and fertilization treatments. The potential productivity model of Sampson and Allen (1999) provides climate driven estimates of 375 cubic feet MAI for Eatonton, GA and 475 cubic ft/ac MAI for Waycross GA (mean annual increment difference of about 100 cubic ft/ac/year). Using the Fastlob growth and yield model (Amateis, et al., 2001), planting 550 TPA on a 15 year rotation requires a site index of 90 ft base age 25 to attain an MAI of 375 ft3/ac/yr. With the same TPA, a SI of 98 ft will produce a MAI of 475 Ft^3/ac/yr. In this case study, a foot of site index improvement equates to a MAI production increase of around 12.5 ft^3/ac/year. In comparison to our GA upland and SC coastal sites, the Sampson and Allen (1999) margin is closer to 75 ft^3/ac/year, which would equate to a site index difference of 6 ft across sites. The actual measured mean height difference is 3.2 ft and the predicted SI difference is 5.2 ft (Clutter and Lenhart, 1968) based on age 6 heights. This reconciles well and this study provides a good example of geographic or site differences in productivity potential.

Average site difference in DBH was only 0.3 inches at the end of six growing seasons. This represents a 7% larger average tree DBH at the SC site. Height growth differed more (13%) than DBH growth (7%). There was a significant change in the DBH/HT ratio between sites. Trees at the GA site tend to be shorter for a given DBH. This has implications for growth and yield modeling as well as resistance to ice and snow loading (Bragg et al., 2002; Pile et al., 2016). Site effects have also been reported to influence the DBH/HT ratio and taper (Amateis and Burkhart, 1987a). The general trend is for more inland, continental, lower resource sites to have greater DBH/HT ratios. This presumably results because height growth is more sensitive to resource limitations than diameter growth. Estimates of the impacts of site on the DBH/HT ratio are often confounded with genetics because the same genotypes are not utilized on inland vs coastal sites. This was not the case in this study where both study sites shared the same genotypes.

The site effects on per acre basal area, individual tree volume, and volume per acre were significant. Individual tree volume, basal area per acre, and volume per acre on the SC site increased over the GA site by 33%, 17% and 36% respectively. These results provide a good estimate of the effects of geographical location on early stand development and strongly suggest that early differences in stand performance are important and significantly impact the rate of stand development.

Genotype Effects and Considerations

Genotype was highly significant on all evaluated variables except survival. Through six growing seasons, genotype had a bigger impact on all variables than either site or density (Table 2.12). No genotype interactions were significant.

On our operational-based study, the average survival was 93% on both sites (Table 2.5). Genotype impacted survival by 6% (Table 2.15). This number could have been impacted by the varying stock type of the OP and CMP entries as compared to the container stock type of the clonal seedlings. The Steiger and Sabatia studies had even higher survival, 97 and 98%, respectively, with similar or lessened impact among genotypes at 6% and 2% respectively. These studies may have been impacted by stock type differences as well. Site preparation and post plant care was slightly more intensive on the Steiger and Sabatia studies. In general, all genotypes in the four studies showed high survival. In summary, no genotype impact on survival was shown for the populations tested which were of SC coastal origin.

Table 2.15 Comparison of mean survival measures on four loblolly pine genotype x density study sites in GA, SC, and NC. Sabatia data is age 8. All other measurement data is based on age 6 measures

	Survival (percentage)									
	Low Density					High Density				
Study	Min.	Max.	Ave.	Diff.	% Change[3]	Min.	Max.	Ave.	Diff.	% Change[3]
Steiger[1] --- Onslow Co., NC	94	99	96	5	5%	93	99	97	6	6%
Dougherty - Marion Co., GA	91	96	93	5	5%	88	97	93	9	11%
Dougherty - Berkeley Co., SC	91	97	94	6	6%	91	99	96	8	8%
Sabatia[2] - Berkeley Co., SC	98	99	99	1	1%	95	99	97	4	4%

[1]Steiger, 2013

[2]Sabatia, 2013

[3]Calculated as the difference between the minimum and maximum values

In the current study, the choice of genotype impacted realized age 6 DBH by 1.7 inches or 47% (Table 2.16). This impact of genotype choice was larger on DBH than site (6.8%) or density (8.5%) (Table 2.12). The DBH impact is major as it primarily drives both volume production (as compared to height and taper) and product class distribution. In the Steiger study, DBH ranged by 2.3 inches at age 6 based on genotype for the 10 entries. This represented a 53% gain by the best performing genotype as compared to the worst performing genotype. This is 7% greater impact as compared to our study. In Sabatia's study, with four genotypes present, DBH only ranged by 0.4 inches, or a 7% gain due to genotype. The four genotypes in Sabatia's study are all fast growers with strong allocation to diameter growth, thus this lessened impact is not surprising.

Table 2.16 Comparison of mean DBH measures on four loblolly pine genotype x density study sites in GA, SC, and NC. Sabatia data is age 8, all other measurement data is based on age 6 measures.

	DBH (inches)									
	Low Density					High Density				
Study	Min.	Max.	Ave.	Diff.	% Change [3]	Min.	Max.	Ave.	Diff.	% Change [3]
Steiger[1] --- Onslow Co., NC	4.3	6.6	5.8	2.3	53%	3.7	5.6	4.9	1.9	51%
Dougherty - Marion Co., GA	3.5	5.1	4.6	1.6	46%	3.1	4.8	4.2	1.7	55%
Dougherty - Berkeley Co., SC	3.6	5.3	4.8	1.7	47%	3.4	4.9	4.5	1.5	44%
Sabatia[2] - Berkeley Co., SC	6.7	6.9	6.8	0.2	3%	5.4	5.9	5.7	0.5	9%

[1]Steiger, 2013

[2]Sabatia, 2013

[3]Calculated as the difference between the minimum and maximum values divided by the minimum

For the current study, the genotype impact on age 6 height (61%; Table 2.17) is 4.6 times greater than the impact of site (13%) and 30 times greater than the impact of density (2%). This suggests that genotype selection impacts on site index and early stand height, important for adjacency certification guidelines, are substantial. The studies of Steiger and Sabatia confirm this with respective impacts on height of 56% and 29%, respectively (Table 2.22). Ten genotypes on Steiger, eight genotypes of the GA site, eight genotypes of the SC site, and four genotypes on Sabatia provided respective height changes due to genotype of 10.8, 10.9, 12.2, and 9.7 feet by age 6 to 8 years (Table 2.17). The subsequent magnitude of change on expected SI base age 25 height was 15, 18, 21, and 13 (Table 2.18). If 3 feet of site index affects rotation length volume by approximately 10%, then the volume impact associated with this height and site index change would be 43% to 70%. This is a major impact in merchantable volume due simply to genotype selection.

On both the GA site and the SC site, the site index was higher in the 388 densities plantings as compared to the higher 518-TPA density plots. Here, the 388 TPA density allocates enough resources for added height growth while maintaining and balancing pressure to occupy the site. On the higher resource Steiger study site, the site index was higher in the high density (435 TPA; 88 ft SI) as compared to the very low density (218-TPA; SI 86 ft) plots. Here the 218 TPA density is so low that there is either a need to allocate resources into occupying the space or lessened need to compete for light with height, a lessened inherent genotype allocation into height, or some combination that causes a decrease in SI going from the 435 TPA to 218 TPA density. In Sabatia's SC coastal site, there is a balance between spacing, site occupation needs, competitive light demands, and inherent genotype height allocation and the site index is the same (SI 86 ft) at both the 275 TPA and the 550 TPA densities though 8 years of growth. Older density studies generally show a maximum height response in the 350-460 TPA range (Pienaar et al., 1997). The current study's low density treatment at 388-TPA falls in this range. The low density treatments of Steiger (218 TPA) and Sabatia (275 TPA) fall well below this range.

Table 2.17 Comparison of the impact of genotype on mean height on four loblolly pine genotype x density studies in GA, SC, and NC. The Sabatia data is from age 8 measures, all other data is from age 6 measures.

	Mean Total Height (feet)									
	Low Density					High Density				
Study	Min.	Max.	Ave.	Diff.	% Change[3]	Min.	Max.	Ave.	Diff.	% Change[3]
Steiger[1] --- Onslow Co., NC	19	29	27	10	53%	20	31	28	11	55%
Dougherty - Marion Co., GA	18	30	25	12	67%	18	28	24	10	56%
Dougherty - Berkeley Co., SC	20	32	28	12	60%	20	32	27	12	60%
Sabatia[2] - Berkeley Co., SC	34	43	38	9	26%	34	43	38	9	26%

[1]Steiger, 2013

[2]Sabatia, 2013

[3]Calculated as the difference between the minimum and maximum values divided by the minimum

Table 2.18 Comparison of the impact of genotype on base age 25 site index on four loblolly pine genotype x density studies in GA, SC, and NC. The Sabatia data is based on age 8 measures. All other data is from age 6 measures.

	Site Index[4] (in feet)									
	Low Density					High Density				
Study	Min.	Max.	Ave.	Diff.	% Change[3]	Min.	Max.	Ave.	Diff.	% Change[3]
Steiger[1] --- Onslow Co., NC	76	90	86	14	18%	76	92	88	16	21%
Dougherty - Marion Co., GA	66	86	78	20	30%	65	82.47	77	17.5	27%
Dougherty - Berkeley Co., SC	70	90	83	20	29%	69	89.91	82	20.9	30%
Sabatia[2] - Berkeley Co., SC	79	92	86	13	16%	79	92	86	13	16%

[1]Steiger, 2013

[2]Sabatia, 2013

[3]Calculated as the difference between the minimum and maximum values divided by the minimum

[4]Base age 25 calculated using adapted Clutter and Lenhart(1968)

The DBH/HT ratio can be interpreted as the amount of DBH growth (inches) expected with a foot of height growth. The DBH/HT ratio has implications on yield, quality, product class, risk, and management. The biology behind it is driven by competition for light and site resources. A shade intolerant species like loblolly pine will allocate to height to compete for needed light (de Campos, 2016). Height growth is required to establish crown length. Density and site resources are known to affect height growth (Valentine et al., 2011). Density determines crown width and site resources determine crown thickness or leaf area along the crown length (Vose and Allen, 1988). Crown leaf area directly affects diameter growth (Valentine et al., 2012). Crown length directly affects cross-sectional diameter growth below the crown (Valentine et al., 2012). Individual branches and tree branching patterns affect the stem diameter growth within the crown (Kidombo and Dean, 2017). The choice of genotype heavily impacted realized onsite height growth in the current study (Table 2.9) and branching characteristics (Martin et al., 2001). Together, genotype inherent height allocations and actual allocated site resources (site plus density) affect diameter growth and subsequently the DBH/HT ratio, and potentially taper. Age 6 DBH/HT ratio in the current study is driven largely by the choice of genotype (24%) as compared to site (8%) or density (6%) (Table 2.12). In both the Steiger and Sabatia's studies the genotype impact on DBH/HT ratio at ages 6 and 8 years, respectively, was also 24% (Table 2.19).

Table 2.19 Comparison of genotype impact on DBH/HT ratio on four loblolly pine genotype x density studies in GA, SC, and NC. Sabatia data is based on age 8 measures. All other study data is from age 6 measures.

	DBH/HT Ratio[4]									
	Low Density					High Density				
Study	Min.	Max.	Ave.	Diff.	% Change[3]	Min.	Max.	Ave.	Diff.	% Change[3]
Steiger[1] --- Onslow Co., NC	0.183	0.231	0.213	0.048	26%	0.153	0.186	0.173	0.033	22%
Dougherty - Marion Co., GA	0.160	0.200	0.180	0.040	25%	0.150	0.180	0.170	0.030	20%
Dougherty - Berkeley Co., SC	0.150	0.180	0.170	0.030	20%	0.140	0.170	0.155	0.030	21%
Sabatia[2] - Berkeley Co., SC	0.158	0.201	0.179	0.043	27%	0.136	0.165	0.151	0.029	21%

[1]Steiger, 2013

[2]Sabatia, 2013

[3]Calculated as the difference between the minimum and maximum values divided by the minimum

[4]DBH in inches divided by total height in feet

The DBH/HT ratio can impact 1) actual volume formula functioning, 2) differences in expected volume from some conventional growth and yield volume estimates, and 3) potential for stem breakage, pre-and-post-thinning. Volume equations generally utilizing DBH and height variables are used to estimate individual tree volumes and scaled per-acre cubic foot volumes. These two variables do a good job of estimating volume from open pollinated seedling populations of loblolly pine (Wood, 2009). The other variable that would effect this accuracy is stem taper. Buford and Burkhart (1987) found no differences in stem taper among improved open pollinated genotypes and unimproved genotypes. Wood (2009) found differences in stem taper between somatic embryogenesis (SE) clones and their parent populations in 8-year old trees, but concluded that Amateis and Burkhart

(1987b) equations utilizing DBH and HT alone, without taper, correctly estimated stem volume.

Differences in Girard form class (FC) are well established, understood, and commonly applied when dealing with mature wood inventories and sales. Common form classes (FC) used for loblolly pine range from FC 78 for second growth forests to FC 82 for old growth pine. With each point of FC equating to a 3% increase in board foot volume (Scribner Scale), a 12% potential impact on lumber volume (Ashley, 1999) is implied. Thus, we know that taper has impact on mature stand value, beyond what is captured by DBH and height variables alone. The FC difference associated with age (second growth vs. old growth) is due to the slowing or ending of height growth, changes in live crown length, and time where the tree crown is fixing carbohydrates and wood continues to be laid down on an already established stem length. Maximum additions to stem diameter occur at the base of the live crown (Labyak and Schumacher, 1954) and are associated with local branch leaf area (Kidombo and Dean, 2017). The question remains whether genotype can impact stem taper at maturity for a newer resource of faster growing trees and adapting management.

While the lower log has been of primary interest due to its heavy weighting on total tree volume, as growth trajectories increase, depending on markets we may see multiple-log height trees in shorter rotations, where the upper logs and their taper impact total volume, i.e. tree height growth may continue allowing FC to increase due to fixing of the live crown length. In the current study, the amount of DBH growth for a given foot of height growth was impacted by genotype to the extent that the DBH growth added differed by up to 24% at age 6. Varying gene combinations may create crosses or clones that have a different DBH/HT ratio and crown ideotype such that taper varies enough to be impactful.

Beyond the volume estimation impact question, the DBH/HT impact on tree risk is clearly important. The impact on tree value, regardless of taper, is clear as well. The average range in DBH/HT ratio among genotypes in the low density plots across studies was 0.04 and for the high density plots was 0.03 (Table 2.19). There is a clear pattern of decreasing DBH/HT ratio with increasing density. Density is managed by controlling the initial trees per acre and by thinning timing and intensity. Based on this study and those of Steiger's and Sabatia's, early rotation DBH/HT can be managed through genotype and density decisions. The impact of differences of DBH/HT ratio as the height of a tree increases if density impacts are offset or averted by initial TPA and early thinning timing decisions and actions are illustrated in Table 2.20. In this example, contrasting a genotype with a DBH/HT ratio of 0.12 with that of a genotype with a DBH/HT ratio of 0.16 provides an increase in DBH of 1.2 inches at 30 feet, 2.4 inches at 60 feet, and 3.2 inches at 80 feet in height. Even with just a minor 0.02 difference in DBH/HT the impact on DBH is 0.6, 1.2 and 1.8 inches at those same heights, respectively. These differences would impact resistance to breakage in wind or ice events. These differences either empower greater wood volume, lessen time to reach a higher valued product class, or produce more wood in a higher valued product class. The magnitude of even the smallest diameter addition range (0.6 inches to 1.8 inches) is substantial, especially if it is gained through genotype decisions verses density decisions. The assumption of greater value due to increased diameter assumes that the stem volume is not offset by taper differences and that the added

DBH does not come at the expense of decreased wood quality from larger branches. With the introduction of narrow-crowned ideotypes, this is now conceivable.

Table 2.20 Predicted DBH in inches at a given height with a genotype specific DBH/HT ratio.

	Height (feet)						
DBH/HT	30	40	50	60	70	80	90
0.12	3.6	4.8	6	7.2	8.4	9.6	10.8
0.13	3.9	5.2	6.5	7.8	9.1	10.4	11.7
0.14	4.2	5.6	7	8.4	9.8	11.2	12.6
0.15	4.5	6	7.5	9	10.5	12	13.5
0.16	4.8	6.4	8	9.6	11.2	12.8	14.4
0.17	5.1	6.8	8.5	10.2	11.9	13.6	15.3
0.18	5.4	7.2	9	10.8	12.6	14.4	16.2

For the current study, the genotype impact on age 6 per-acre basal area (112%) was 9-fold that of site (12%) and 7.5-fold that of density (15%) (Table 2.12). In comparison, the impact of genotype on Steiger's study was 132% and on Sabatia's study was 17% (Table 2.21). As per-acre basal area is driven largely by DBH, survival, and initial planting density, Sabatia's decreased impact was due largely to the narrowed genotype selection and their common focus of DBH growth. Steiger's impact on DBH confirms the impact of genotype when provided high levels of available resources and a range of loblolly pine genotypes and resulting ideotypes. The magnitude of basal area range in Steiger's, the GA site, the SC site and the Sabatia site studies were 32.3, 28.2, 32.2, and 12.9 ft^2/ac, respectively. If annual basal area increment near the time of thinning is in the 8-10 ft^2/ac/yr. range, these differences would impact thinning age and mid-rotation cash flow by 1 to 4 years due to genotype alone. This has major impacts to planning schedules and cash flow timing for institutional timber investors.

Table 2.21 Per-acre basal area on four study sites with two planting densities and genotype entries crossing three levels of genetic improvement. The sites are located in GA, SC, and NC.

	Basal Area/Acre (ft^2/acre)									
	Low Density					High Density				
Study	Min.	Max.	Ave.	Diff.	% Change[3]	Min.	Max.	Ave.	Diff.	% Change[3]
Steiger[1] --- Onslow Co., NC	20.4	50.6	39.5	30.2	148%	29.7	64.1	56.1	34.4	116%
Dougherty - Marion Co., GA	23.9	48.4	42.2	24.5	103%	26.4	58.3	45.8	31.8	120%
Dougherty - Berkeley Co., SC	26.6	56.1	47.9	29.5	111%	31.3	66.3	55.0	35	112%
Sabatia[2] - Berkeley Co., SC	66	70.7	68.7	4.70	7%	83.1	103.4	94.5	20.3	24%

[1]Steiger, 2013

[2]Sabatia, 2013

[3]Calculated as the difference between the minimum and maximum values divided by the minimum

For the current study, the difference in planting the lowest yielding genotype and the highest yielding of the eight genotypes was 268 ft^3/ac, an improvement of 189% in per acre volume. This was 13.5 times the impact of density (14%) and 5.3 times the impact of site (36%) (Table 2.12). In Steiger's study, the comparable impact from the least to best of ten genotypes was 293% (Table 2.22). For Sabatia's study, the comparable impact was 53%, again lessened in difference due to the inclusion of only four elite volume producing genotypes.

Table 2.22 Comparison of standing cubic foot volume/acre on four loblolly pine study sites with two planting densities and genotype entries including three levels of genetic improvement. The sites are located in GA, SC, and NC. All were reported from age 6 measures excepting Sabatia measures completed at age 8 years.

	Volume/acre (ft^3/acre)									
	Low Density					High Density				
Study	Min.	Max.	Ave.	Diff.	% Change[3]	Min.	Max.	Ave.	Diff.	% Change[3]
Steiger[1] --- Onslow Co., NC	154	585	451	431	279%	241	977	691	736	306%
Dougherty - Marion Co., GA	189	592	460	403	213%	211	592	491	381	180%
Dougherty - Berkeley Co., SC	243	704	602	461	190%	293	857	688	564	192%
Sabatia[2] - Berkeley Co., SC	940	1336	1118	395	42%	1230	2007	1588	777	63%

[1]Steiger, 2013

[2]Sabatia, 2013

[3]Calculated as the difference between the minimum and maximum values divided by the minimum

Planting Density Effects

Both the 388 TPA and 518 TPA planting densities are practical regimes to consider today. The lower initial TPA regime would utilize genotypes that have good genetic control over branch size development. A lower density regime is also desirable on low-resource supplying sites due to minerology and/or low organic matter content. The 518 TPA regime is good for genotypes that need between tree competition to control branch size development and is a good choice in areas where both a good pulpwood and sawtimber market exists and an early commercial thinning is assured to be possible. Average survival in the 388 TPA regime was 93% (361 TPA) and 96% (373 TPA) at the GA and SC sites, respectively. Average survival in the 518 TPA regime was 94% (485 TPA) and 96% (498 TPA) at the GA and SC sites respectively. Thus, observed differences in tree growth and stand development at the GA site is due to an actual difference of 124 TPA and a difference of 125 TPA at the SC site. There were no site x density effects on survival or any growth measure at either site.

With a p-value of 0.06, the main effect of density age 6 height was not significant at the alpha 0.05 level. No significant difference in pine height due to initial planting density is consistent with the studies of Pienaar and Shiver (1984) and Harms et al. (1994, 2000). Carlson et al. (2009) observed a similar lack of response (summarized at age 9) on a slower growth trajectory SI 71 feet loblolly pine site in Virginia planted at 363 and 726 TPA. Sharma et al. (2002) reported significant density effects on height after age-9 (average SI 66 feet; spacings ranging from 303 to 2722 TPA). Land et al. (2004) reported significant density impacts on height at age 5 on a SI 77 ft site in east central Mississippi planted at 435, 680, and 1,742 trees per acre. Some long-term spacing trials demonstrate site index reductions due to higher planting densities, such as Pienaar and Shiver (1993). The most conclusive series of spacing studies was conducted by Anton-Fernandez (2011). They observed over a 22-year period that on both piedmont and coastal sites for spacings ranging from 303 to 2,723 trees per acre that higher densities reduced SI by as much as 14 feet and density effects on dominant height were significant at age 7. This was for stands that ranged in SI from 61 feet to 75 feet. At both the GA and SC sites the trees in this study were growing at higher average exhibited SI ranges, 65 feet to 84 feet and 69 feet to 90 feet respectively. Steiger (2013) reported significant density effects on height by age 5 at a North Carolina (NC) coastal site with some of the most elite genotypes available today. In the Steiger (2013) study the narrower crown clones with strong apical dominance were taller in their low-density plantings (218 TPA). The trend toward significant height reduction with increased density beginning early in the rotation on high site trajectory stands such as those reported in this study and in the study of Steiger (2013) suggests that an early thinning will be needed if height (and SI) losses are to be avoided. In general, these results indicate that initial planting density choice when using enhanced genotypes and more intensive silviculture is a more important consideration than it has been in the past and should consider the potential growth trajectory and the particular genotype growth allocation characteristics.

While height was just beginning to be impacted by initial planting density, considerable reduction in average DBH had occurred by age 6 on both sites. The average reduction in DBH at the GA upland site was 0.4 inches or 9% due to increasing the planting density from 388 TPA to 518 TPA. At the SC coastal site, the reduction in age 6 DBH was 0.3 inches or 7%. The threshold basal area at which DBH began to decline could not be determined from this study. However, Steiger (2013) using similar genotypes growing at a similar exhibited SI (>90 feet) observed diameter reductions for trees growing at 218 and 436 TPA to occur by age 3. Carlson et al. (2009) found significant differences in average DBH between trees planted at 363 TPA and 726 TPA to occur by age 5 on an exhibited SI 71 feet site. The basal area at age 5 in the 726 TPA planting was about 25 square feet per acre. Early DBH growth loss is significant. Steiger (2013) observed a density effect reduction of about 0.6 inches by age 5. Zhao et al (2011) reported significant density effects on DBH as early as age-8. By age-12 their observed difference in DBH of trees grown at 300 TPA versus 600 TPA was nearly 2.0 inches. DBH growth is very sensitive to initial planting density.

As growth potential increases and stand development accelerates even further through continued improvement in genetics and silviculture technology, considerable adjustments in the initial TPA decisions will need to be made. Even with current technology, the potential DBH losses before thinning are very significant. For instance, a DBH reduction of 1 inch by the first thinning could easily mean that an additional two years may be required to attain a defined sawtimber DBH specification. Pienaar et al. (1997) reported age 14 mean DBH for a planting density range of from 200 TPA to 1000 TPA for an exhibited SI 81 site. The loss in mean DBH from 200 to 400 TPA was 1.7 inches and from 400 to 600 TPA was 1.2 inches. Assuming an after-thinning DBH increment of 0.5 inches/year, it would require an additional 3.4 years for the thinned 400 TPA stand to reach the size of the trees in the 200 TPA at age 14. For the thinned 600 TPA stand it would take an additional 2.4 years to attain the same size as the age 14 400 TPA stand.

Initial planting density effects on the DBH/HT ratio were also already significant in this study by age 6. This results because of the sensitivity of DBH growth to increasing stand density. Height was not significantly affected by stand density by age 6 at an alpha level of 0.05, but had a p-value of 0.07. While the two planting densities utilized in this study resulted in only a 6% difference in the DBH/HT by age 6, it is to be expected that over the rotation this factor would have the largest impact on the DBH/HT ratio. This results because the effects of planting density increase with age (Carlson et al. 2009). Using the report of Pienaar et al. (1997) that provides DBH and HT measures for trees growing at 200, 400 and 600 TPA from age-5-year to age-14 to calculate the trend in the DBH/HT ratio with age demonstrates the age x density interaction. At 200 TPA the DBH/HT ratio decreased from 0.22 to 0.20. While for trees in the 600 TPA regime the DBH/HT ratio decreased from 0.19 to 0.14. The important message from this study is that there are three major factors that must be considered to produce the optimum DBH/HT ratio that results in trees without too much taper or trees that have a low DBH/HT ratio and would be vulnerable to breakage or blowdown after thinning. For example, planting a genotype like clone AA93 that has an inherent low DBH/HT ratio (Table 2.11) at a high stand density on a high resource coastal site will create a stand that would have to be handled carefully at the time of thinning.

Increasing the initial planting density from 388 TPA to 518 TPA increased the rate of basal area per acre development on both the SC coastal and the GA upland site and the site by density interaction was not significant. However, the 7.1 square feet/acre increase (17%) in BA development due to increasing the planting density at the SC coastal site was greater than that observed on the lower-resource GA upland site. At the GA upland site, the differences between densities in BA was only 3.6 square feet/acre and was not statistically significant. The smaller difference in BA production observed at the GA upland low resource site may imply that with more TPA basal area response to planting density increases on low resource sites is more limited by site resources. Resource depletion and slowed growth is supported by the study of Barron-Gafford et al. (2003) that showed a trend of decreasing foliar and stem nitrogen as stand density was increased. This finding has important implications for optimizing genetic deployment decisions.

Standing volume per acre integrates the effects of density on growth parameters (height and diameter) and survival. In this study average survival was almost equal for both planting densities. The difference in age 6 standing volume between the moderate-density planting (518 TPA) and the low-density planting (388 TPA) at the SC coastal site was 85.6 cubic feet/acre and was 31.8 cubic feet/acre at the GA upland site. Early rotation production increases by planting more TPA are reported in most spacing studies. The smaller difference on the GA upland low resource site suggests that resource limitations had influenced tree growth in the higher density planting more than in the lower density planting. At the SC coastal site, the average early rotation periodic annual increment (PAI) through age 6 was 115 cubic feet/acre/year and 100 cubic feet/acre/year for the high and low-density regimes, respectively. At the GA upland site, the average PAI was 82 cubic feet/acre/year and 77 cubic feet/acre/year, respectively, for the high and low-density regimes. The early rotation density effects were a 14.3% reduction in annual stem volume production on the SC coastal site and only a 7.0% reduction at the GA upland low-resource site.

Conclusion

This study allowed comparison of the relative impacts of site, density, and genotype in fast growing operationally managed plantations at age 6. At this stage of growth, resource availability per tree is relatively good, but declining annually as the overall per acre site occupancy increases and competition for resources increases. Review of the literature shows that without thinning, density and site effects will likely increase and decrease the positive impacts of the best genotypes. However, up to age 6, genotype has been the primary factor of impact on DBH, height, basal area, and volume growth. If available resources are managed through fertilization and early thinning, significant effect of genotype and its impact on volume should continue. Also note that a poor choice of genotype can decrease growth below average and offset a productive site, proper density decision, or quality silviculture.

The low to moderate density range of the subject study and the comparable studies (218 to 550 TPA collectively) allow adequate per-tree resource allocation to facilitate early growth trajectories of SI in the upper 80 ft to lower 90 ft range (base age 25 years). Managing in this lower density range that prevents valuable diameter loss, and at higher realized growth trajectories that allow for the combination of high volumes of larger dimensional lumber, can lead to higher per acre timber value potential. Decisions to plant the best genotypes and manage at densities in the 300-500 TPA range are often made based on growth and yield model runs. Currently, most growth and yield models are not genotype specific. This is obviously a major limitation to decision making. Similarly, site index is not generally adapted for lower densities (i.e. 300-500 TPA compared to 600 to 750 TPA or higher). Correctly adapting these two points of impact into available growth and yield models could be of great value to more accurately evaluating the new resource genotypes into regimes utilizing lower to moderate initial planting densities.

Literature Cited

Albaugh, T.J., Allen, H.L., Dougherty, P.M., Johnsen, K.H. 2004. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. Forest Ecology and Management 192: 3-19

Amateis, R.L., Burkhart, H.E. 1987a. Tree volume and taper of loblolly pine varies by stand origin. Southern Journal of Applied Forestry 11:185-189

Amateis, R.L., Burkhart, H.E. 1987b. Cubic-foot volume equations for loblolly pine trees in cutover, site-prepared plantations. Southern Journal of Applied Forestry 11:190-192

Amateis, R.L., Burkhart, H.E., Allen, H.L., Montes, C. 2001. FastLob (A stand-level growth and yield model for fertilized and thinned loblolly pine plantations). University of Virginia Polytechnical Institute

Anton-Fernandez, C., Burkhart, H.E., Strub, M., Amateis, R. 2011. Effects of initial spacing on height development of loblolly pine. Forest Science 57 (3), pp 533-545.

Ashley, B.S. 1999. Reference Handbook for Service Foresters. US Department of Agriculture Forest Service, NA-FR-15

Barron-Gafford, G.A., Will, R.E., Burkes, E.C., Shiver, B., and Teskey, R.O. 2003. Nutrient concentrations and contents, and their relation to stem growth, of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. Forest Science 49(2):291–300.

Borders, B.E., Bailey, R.L. 2001. Loblolly pine-pushing the limits of growth. Southern Journal of Applied Forestry 25: 69–74

Bragg, D.C., Shelton, M.G., Heitzman, E. 2002. Silvicultural lessons from the December 2000 ice storms. P. 1– 6 in Proc. of 2002 Arkansas Forest Resources Center Arkansas Forestry Symposium, Walkingstick, T., R. Kluender, and T. Riley (eds.). University of Arkansas Cooperative Extensive Service, Little Rock, AR

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

Carlson, C.A., Fox, T.R., Creighton, J., Dougherty, P.M., Johnson, J. 2009. Nine-year growth responses to planting density manipulation and repeated early fertilization in a loblolly pine stand in the Virginia Piedmont. Southern Journal of Applied Forestry 33 (3): 109-114

Clutter, J.L., and Lenhart, J.D. 1968. Site index curves for old-field loblolly pine plantations in the Georgia Piedmont. Georgia Forest Resource Council Rep. 22 -Series 1.4 p.

de Campos Franci, L., Pereira, L., Machado, R.S., Haddad, C.R., Martins, F.R. 2016. Strategies of a light-demanding emergent tree to thrive in a neotropical seasonal forest with alternating light or water shortage. Braz. J. Bot: 39: 207. https://doi.org/10.1007/s40415-015-0211-5

Harms, W.R., Whitesell, C.D., Debell, D.S. 2000. Growth and development of loblolly pine in a spacing trial planted in Hawaii. Forest Ecology and Management 126(1): 13-34

Harms, W.R., DeBell, D.S., Whitesell, C.D 1994. Stand and tree characteristics and stockability in a spacing trial planted in Hawaii and South Carolina. Canadian Journal of Forest Research 24(3):511-521

Harrison, W.M, Borders, B.E. 1997. Yield Prediction and Growth Projection for Site Prepared Loblolly Pine Plantations in the Carolinas, Georgia, Alabama and Florida. PMRC Technical Report 1996-1. Daniel B. Warnell School of Forest Resources, Athens, Georgia. 59p.

Kidombo, S.D., Dean, T.J. 2017. Growth of tree diameter and stem taper as affected by reduced leaf area on selected branch whorls. Canadian Journal of Forest Research Online pp. 1-7

Labyak, L.F., Schumacher, F.X. 1954. The contribution of its branches to the main-stem growth of loblolly pine. Journal of Forestry 52 (5):333-337.

Land, S.B, Roberts Jr., S.D., Duzan Jr., H.W. 2004. Genetic and spacing effects on loblolly pine plantation development through age 17. Proceedings of the 12th Biennial Southern Silvicultural Research Conference. General Technical Report SRS-71. 594 p.

Lang, A., Baker, S. Mendell, B. 2012. Forest Management Practices of Private Timberland Investors and Managers in the US South. Forest Resource Association Technical Report 16-R-17.

MacFarlane, D.W., Green, E.J., Burkhart, H.E. 2000. Population density influence assessment and application of site index. Canadian Journal of Forest Research 30(9): 1472-1475.

Maier, C.A., Johnsen, K.H., Dougherty, P.M., McInnis, D., Anderson, P., Patterson, S. 2012. Effect of harvest residue management on tree productivity and carbon pools during early stand development in a loblolly pine plantation. Forest Science 58 (5): p430-445.

Maier, C.A., Johnsen, K.H., Dougherty, P., Albaugh, T., Patterson, S. 2013. Ecophysiological difference in tree carbon gain and water use for two fast growing loblolly pine ideotypes that differ in carbon allocation. American Geophysical Union, Fall 2013 Meeting Proceedings, Abstract #B21E-07.

Martin, T.A., K.H. Johnson and T.L. White. 2001. Ideotype development in southern pines: rationale and strategies for overcoming scale-related obstacles. Forest Science 47(1): 21-28.

Martin, T.A., Dougherty, P.M., Topa, M.A., McKeand, S.E. 2005. Strategies and case studies for incorporating ecophysiology into southern pine tree improvement programs. Southern Journal of Applied Forestry 29: 70–76.

McKeand, S.E. 2017. Making sense of the genetics market. Forest Landowners, September/October: pp 14-19.

McKeand, S.E., Abt, R.C., Allen, H.L., Li, B., Catts, G.P. 2006a. What are the best loblolly pine genotypes worth to landowners. Journal of Forestry October/November 2006. Pp 352-358.

McKeand, S.E., Jokela, E.J., Huber, D.A., Byram, T.D., Allen, H.L., Lee, L.B., Mullin, T.J. 2006b. Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. Forest Ecology and Management. 227: 178-184

NOAA. 2018. National Centers for Environmental Information. Climate data online websearch. www.ncdc.noaa/cdo-web/search.

Perdue, J.H., Stanturf, J.A., Young, T.M., Huang, X., Dougherty, D.S., Pigott, M.P., Guo, Z. 2017. Profitability potential for Pinus taeda L. (loblolly pine) short-rotation bioenergy plantings in the southern USA. Forest Policy and Economics Vol. 83:146-155

Pienaar, L.V., Shiver, B.D. 1993 Early results from an old-field loblolly pin spacing study in the Georgia Piedmont with competition control. Southern Journal of Applied Forestry 17(4):193-196

Pienaar, L.V., Shiver, B.D. 1984 The effect of planting density on dominant height in unthinned slash pine plantations. Forest Science 30(4):1059-1066

Pienaar, L.V., Shiver, B.D., Harrison, W.M. 1997. Growth Potential of Loblolly Pine Plantations in the Georgia Piedmont: A Spacing Study Example. PMRC Technical Report 1997-1. Daniel B. Warnell School of Forest Resources, Athens, Georgia. 15p.

Pile, L.S., Maier, C.A., Wang, G.G., Yu, Dapao. 2016. Responses of two genetically superior loblolly pine clonal ideotypes to a severe ice storm. Forest Ecology and Management, Volume 360, pages 213-220.

Roth, B.E., Jokela, E.J., Martin, T.A., Huber, D.A., White, T.L. 2010. Family by environment interactions for loblolly and slash pine plantations in the Southeastern United States. Proceedings of the 14th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-121. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station, pg. 35-41

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

Sampson, D.A., Allen, H.L. 1999. Regional influences of soil available water, climate, and leaf area index on simulated loblolly pine productivity. Forest Ecology and Management. 124: 1–12.

SAS INSTUTE INC. 2000-2004. *SAS 9.2 Help and Documentation.* SAS Institute. Cary, NC.

Scott, W.R., Meade, R.L., Hyink, D., Miller, R. 1998. Planting density and tree-size relations in coastal Douglas-fir. Canadian Journal of Forest Research 28 (1):74-78.

Sharma, M., Burkhart, H.E., Amateis, R.L. 2002. Modeling the effect of density on the growth of loblolly pine trees. Southern Journal of Applied Forestry 26(3):124-133.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at the following link: https://websoilsurvey.sc.egov.usda.gov/. Accessed January 2018.

Steiger, J. J. 2013. Impacts of Different Levels of Genetic Homogeneity on Juvenile Stem Characteristics and Potential Stand-level Value in Loblolly Pine. North Carolina State University Thesis. 82p.

Valentine, H.T., Makela, A., Green, E.J., Amateis, R.L., Makinen, H., Ducey, M.L. 2012. Models relating stem growth to crown length dynamics: application to loblolly pine and Norway spruce. Trees 26:469-478

Vose, J.M., Allen, H.L., 1988. Leaf area, stem wood growth, and nutrition relationships in loblolly pine. Forest Science 34:547-563

Wood, E.R. 2009. Clonal Variation of Stem Taper in Loblolly Pine. North Carolina State University Thesis. 131p.

Zhao, D., Kane, M., Borders, B. 2011. Growth responses to planting density and management intensity in loblolly pine plantations in the southeastern USA Lower Coastal Plain. Annals of Forest Science, 68 (3), pp.625-635.

CHAPTER 3

EVALUATION OF AGE 6 EXHIBITED SITE INDEX FOR EIGHT GENOTYPES OF LOBLOLLY PINE GROWN AT TWO STAND DENSITIES ON A SOUTH CAROLINA COASTAL SITE AND A GEORGIA UPLAND SITE[2]

[2] Dougherty, D.S., M.B. Kane, B.P. Bullock, R.F. Daniels, and J.A. Wright. To be submitted to Forest Ecology and Management

Abstract

Loblolly pine plantation growth trajectory is quantified by base age 25 site index (SI). Site index, the mean height of the dominant and co-dominant trees, at base age 25 is used to project expected volumes and subsequent values to be received from future loblolly pine plantation harvests. This study evaluated the effects of site, genotype, and initial planting density on SI using a randomized complete block design with main plots split on density. Study installations included a high resource South Carolina (SC) coastal site and a lower resource, inland Georgia (GA) upland site. Two initial planting densities included a low 388 tree per acre (TPA) and a moderate 518 TPA density. Eight genotypes were evaluated including one open pollinated (OP) family, three control mass pollinated crosses (CMP), two somatic embryogenesis (SE) clones, and two rooted cutting (RC) clones. Through 6 growing seasons, both site and genotype were highly significant (p-value < 0.001) on SI. Planting density had a p-value = 0.06. No significant site x genotype or site x density interactions were observed. Mean base age 25 year site index was 6 ft higher on the SC coastal site (83 ft) than the GA upland site (77 ft). Genotype had the largest impact on age 6 estimated SI. At the SC site, SI ranged from 69 ft to 90 ft for the eight genotypes. At the GA site, SI ranged from 65 ft to 84 ft for the same genotypes. Genotype exhibited SI ranking was similar at both sites. Operational SI from pine plantations established in the 1970’s and 1980’s averaged in the low 70 ft to low 60 ft range for the Southeast U.S. coastal and inland regions, respectively. Driven by availability of enhanced genotype seedlings, operational exhibited SI’s are now occurring in the 80 ft to 100 ft range. This study demonstrates the effect of choice of genetics and site on realized SI.

Introduction

Site index (SI) is the most commonly used index of productivity potential for managed loblolly pine plantations growing in the Southeast USA. Its wide acceptance and use in predicting stand productivity has resulted because of the belief that height growth is independent of stand density and when coupled with measures of stand density and basal area, it can be utilized in growth and yield models to make estimates of expected yields. However, recent studies indicate that stand density may be reducing dominant height earlier in the rotation to a greater extent than was previously thought (Harms et al., 1994; Anton-Fernandez et al., 2011). This earlier interaction of height with stand density could result from more rapid stand development as growth rates are increased through improved silviculture techniques and improved genetics, fundamental changes in the inherent growth allocation patterns of the genotypes being selected for breeding and deployment (Sabatia and Burkhart, 2013; Staudhammer et al., 2009) and from site improvements due to weather, atmospheric and edaphic changes that occur from one rotation to another.

Skovsgaard and Vanclay (2008) published a detailed review on the development and use of SI as an index of stand productivity potential. They report that SI has an edaphic (soil), physical (climatic-atmosphere) and plant species component. In addition to these factors, management intensity and effectiveness will have a significant effect on the actual achieved SI and stand production. Skovsgaards and Vanclay's (2008) definition of forest productivity as the production that can be realized at a certain site with a given genotype and a specific management regime moves us closer to where we are today. This definition recognizes that tree improvement and new seedling production techniques (CMP and Clonal seedling production) have greatly expanded the range of genetic seedling quality that timber growers can choose to deploy on their sites (McKeand, 2017). It does not fully recognize the impact that rotation-to-rotation changes in atmospheric, weather and edaphic (forest floor and mineral fraction) conditions may have on future growth potential.

Today we expect the next rotation to almost double in production from the previous rotation based on the historical trend in production in Southeast USA managed loblolly pine plantations (Stanturf et al., 2003; Fox et al., 2007). A doubling of production from rotation to rotation implies that SI of a given site has changed significantly from rotation to rotation. Under this type of production change history, using the measured SI from a previous rotation has little value in predicting next rotation yields. To estimate production potential for the next rotation would require (1) adjusting the observed previous rotation SI based on technology, atmospheric and management intensity and efficiency changes that drive SI that will be implemented or occur over the next rotation or (2) waiting to obtain a reliable estimate of exhibited SI for the new stand or (3) using weather data averages along with atmospheric predictions (CO2, VPD) in physiological models such as 3-PG (Landsburg and Waring, 1997) to make estimates of potential production for a given site and then using a fall-down approach (Dougherty, 2015) to adjust the estimated potential production down based on soil conditions, planned silvicultural treatments, genetic quality choice, and expected management effectiveness. Examples of this latter approach to estimating potential production are reflected in the potential productivity maps of Sampson and Allen (1999) produced using 3-PG calibrated for loblolly pine. To adjust for expected changes in SI we must know which components of SI are "fixed" and which vary with time. In addition, the magnitude of change associated with the varying components must be understood. Some of the driving variables outlined in Table 3.1 can change from one managed forest rotation to the next.

Table 3.1 Factors potentially impacting a change in exhibited site index over time in loblolly pine plantations in the U.S. South

SI Driving Variable	Change	Impacts	Reference
Atmospheric	2 ppm/year of CO_2 50 ppm/25 yr rotation	0.28 ft/yr. increase in SI 7 ft/rotation	Baldwin et al. 2001 Valentine 1997
Fertilization Carryover	30-40 lbs. P/acre	Variable depending on Site prep. treatments	Everett and Palm-Leiss, 2009
Forest floor buildup and release	200-400 lbs. N/acre, 20 P/acre, etc.	225 lbs. elemental N=extra 10 ft SI	Kiser and Fox, 2012 Maier et al., 2012
Understory biomass		Green tons/ac=3ft SI increase	Subedi et al., 2014
Genetic Gain	20% volume gain	0.4 ft/BVvol gain	Stanturf et al., 2003
Other Silv. Improv.	10% volume gain	4.0 ft of SI	Fox et al., 2007

Based on these considerations, it is clear that rather than viewing site or genetics as being homogeneous and stable we must view SI as a very dynamic indicator of productivity potential. The main objectives of this article are (1) to investigate the interaction of initial planting density on height and exhibited site index early in the rotation (2) to better quantify the differences in production potential of an upland site versus a more mesic coastal site and (3) explore the magnitude that choice of genetics to deploy can have on the production potential (exhibited SI) on an upland versus an Atlantic coastal site.

Methods

Study Site Description

This study consisted of two installations. The South Carolina installation is located in Berkeley County, South Carolina (33° 14.512 N, 80° 10.866 W). This site is located in the Lower Coastal Plain and the climate is impacted by the proximity to the Atlantic Ocean. The Georgia installation is located in Marion, County, Georgia (32° 17.596 W, 84° 26.513 W). This is an Upper Coastal Plain site, located well inland from the Atlantic Gulf Coastal climate influence (typically subject more to a continental effect in dry summer periods). Past site use, typical climate, descriptive soil information, genotype plant material, and site preparation and post-plant care systems are described in detail in the 'Methods' section of Chapter 2.

Study Design

The study was installed as a randomized complete block with split plots. Main treatment plots are for density (388 or 518 trees per acre). Main plots were split for random genotype assignment. Each study installation contained three blocks (replications). The eight genotypes were assigned at random to subplots within each density plot. Genotype split plots were 0.22 acres in size. Measurement in both densities was made on all trees in a 0.12 acre interior measurement plot resulting in 60 measurement trees in the 518 tree/acre density and 45 potential measurement trees in the 388 trees per acre density.

Measurements and Calculations

Trees were measured after the completion of the 6^{th} growing season. Survival status was assessed and diameter at breast height (DBH) measured on all trees within the embedded measurement plots. Total heights were measured to the nearest foot on every other tree using a Haglof Vertex hypsometer. The measured heights were used to estimate the non-measured trees using regression at the plot level. The top 50% of the measured height trees were considered to be the dominant and codominant heights for the plot. The mean height of these trees were used along with age to estimate site index at base age 25 for each plot from the site index table adapted from Clutter and Lenhart (1968). These tables have been used operationally with this land base.

Statistical Analysis

The study design is a randomized complete block with split plots with two sites, eight genotypes and two planting densities. The ANOVA table is shown in Table 3.2.

Table 3.2 ANOVA table for the randomized complete block design with splits on the density treatment, genotype assigned randomly inside the split plots, 3 blocks per installation, and 'across forest' analysis for two installations, including a GA upland site and a SC lowland site.

Source	Df
Analysis for each site	
Block (3)	2
Stocking (2)	1
Error	2
Subtotal	5
Genotype(8)	7
Stocking * Genotype	7
Error	28
Subtotal	47
Analysis Across site	
Forest	1
Error	2
Subtotal	5
Forest*Stocking	1
Error	2

A combined analysis of variance was performed to look for differences between sites. Within site analysis of variance was performed for a split-plot design for each individual forest. Both SAS (SAS/STAT, 2017) and R statistical packages were used for analysis. Within an installation, ANOVA was used to test for block, density, genotype, and any interactive effects on site index. The linear model used for was:

$$Y_{ijkl} = \mu + B_i + D_j + G_k + B_iD_j + B_iG_k + D_jG_k + \varepsilon_{ijkl}$$

where Y_{ijkl} is the mean height and estimated site index; B_i is the effect of the *i*th block (*I* = 1-3); D_j is the effect of the *j*th density (318 or 518 TPA density); G_k is the effect of the *k*th genotype (k = 1-8); B_iD_j is the block by density effect; B_iG_k is the block by genotype effect; D_jG_k is the density by genotype effect; and ε_{ijkl} is the random error associated with the model and is assumed to be distributed N (O, σ^2). Proc Mixed was used for the analysis. Duncan's test was used for significant means comparison. The alpha level for assigning significance was 0.05.

Results

Precipitation and temperature trends for the period of the study are provided in the 'Results' section of Chapter 2.

Total Height

Site and genotype effects are significant on total height at age 6 (Table 3.3). Initial planting density effects had a p-value of 0.06. No interactions were significant. Results for these effects are discussed in detail in Chapter 2.

Table 3.3 ANOVA summary for total height and site index (SI) across sites (SC lowland and GA upland sites) for main treatments and interactions. Statistically significant values are bolded.

Effect	Height Pr > F	SI Pr > F
Site	**<.0001**	**<.0001**
Genotype	**<.0001**	**<.0001**
Site*Genotype	0.4808	0.5338
Density	0.0605	0.0668
Site*Density	0.7586	0.8078
Genotype*Density	0.7961	0.8301
Site*Genotype*Density	0.9464	0.9603

Trends in average total height for each of the eight genotypes at the SC coastal and the GA upland sites are shown in Figure 3.3. The same ranking in height was observed at both sites.

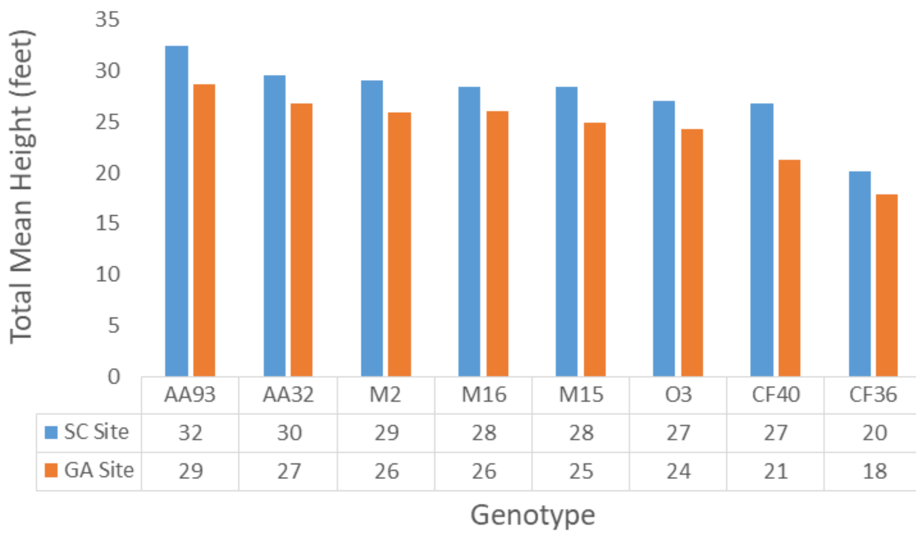

Figure 3.1 Mean age 6 total height for eight genotypes planted at two densities on a SC lowland site and a GA upland site. Bars with totally unique letter are significantly different at the alpha .05 level.

Site (GA upland versus SC coastal) effects on total height were significant (Table 3.3). The across genotype and density average total height was 27.7 feet for the SC Coastal site and 24.5 feet for the GA upland site. Height increased 3.2 feet or 13% by age 6 moving from the GA site to the SC site. The SC site had a greater total height at age 6 for all genotypes (Figure 3.1) than was observed at the GA upland site. No genetics x site interaction was significant.

Genotype effects on total height were also highly significant at both sites (Table 3.2). Age 6 heights across densities ranged from 32.4 feet for Clone AA93 to 20.1 feet for clone CF36 at the SC site. Mean age 6 heights across densities ranged from 28.7 feet for clone AA93 to 17.9 feet for CF36 at the GA site. Total mean height contrast across sites (Figure 3.2) indicates that AA93 performed better than any other genotype. Clone AA32 performed similarly to the full-sib genotypes but significantly better than O3 the open pollinated elite genotype.

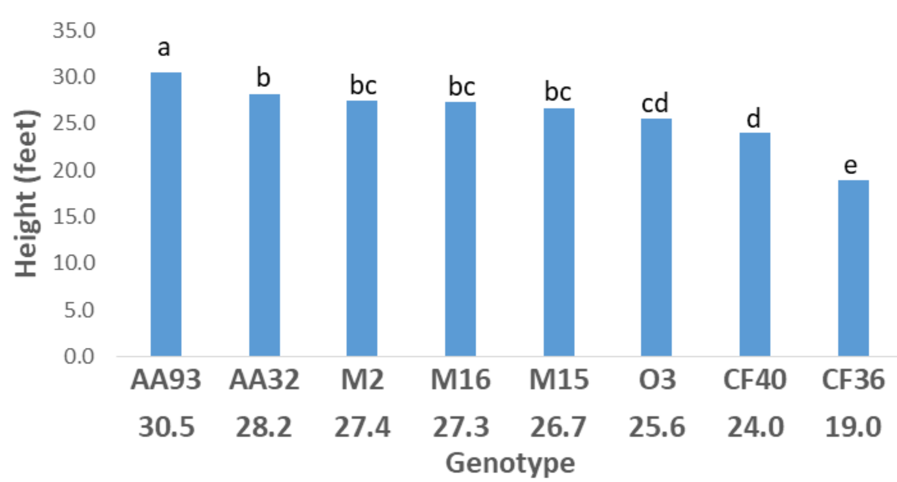

Figure 3.2 Summary of loblolly pine genotype mean height for eight genotypes. Genotype means with the same letters do not differ significantly from each other. .

All the RC clones and CMP crosses performed better than the O3 genotype and the SE clones. Genotype CF36 performed poorer than any other genotype.

Exhibited Site Index (SI)

Site and genotype effects were significant for exhibited SI. The density treatment had a p-value of 0.06. No interactions were significant.

Trends in exhibited SI at age 6 by genotype and site are shown in Figure 3.3. Exhibited SI trends are similar to the trends observed for total height as would be expected because exhibited SI was derived from total height and age.

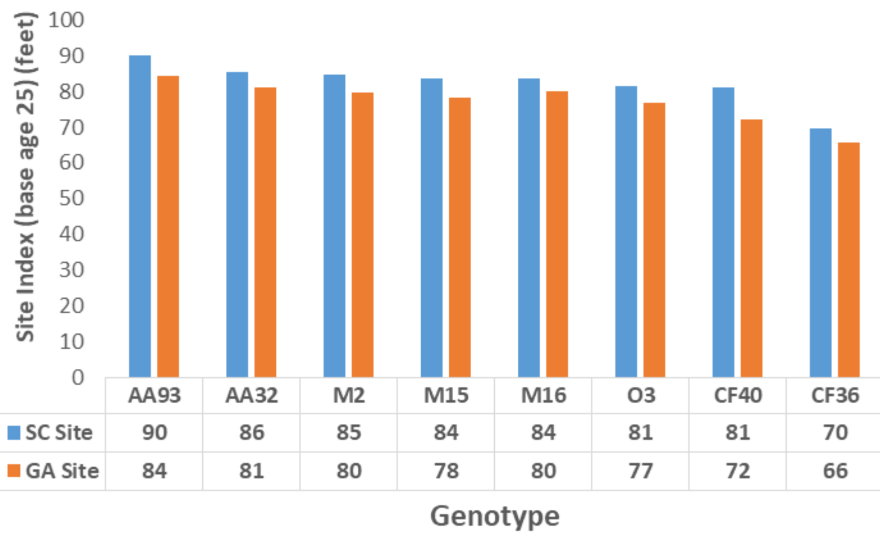

Figure 3.3 Mean age 6 exhibited site index (base age 25) by site and genotype for the SC lowland and GA upland sites

Exhibited SI at the SC site across densities ranged from 70 feet to 90 feet; a range of 20 feet. The mean for SI at the SC site was 83 feet. Exhibited SI at the GA site across densities ranged from 65 feet to 84 feet; a range of 19 feet. The mean SI at the GA site was 77 feet. Estimated age 6 SI on the SC site was 6 feet higher than that of the GA site.

All genotypes in the study, except CF36, have been widely used in the Southeast US breeding programs and sold commercially for operational use. The range in exhibited SI determined for the commercial genotypes grown at the SC coastal site was from 81 feet (C40) to 90 feet (RCAA93); a range of 9 feet. The range in exhibited SI for the commercial genotypes grown at the GA upland site was 72 feet (C40) to 84 feet (AA93); a range of 12 feet. The mean commercial genotype site indices at the SC and GA site were 85 feet and 79 feet, respectively.

Mean site index by genotype across sites and densities ranged from 68 feet (C36) to 87 feet (AA93) (Figure 3.4).

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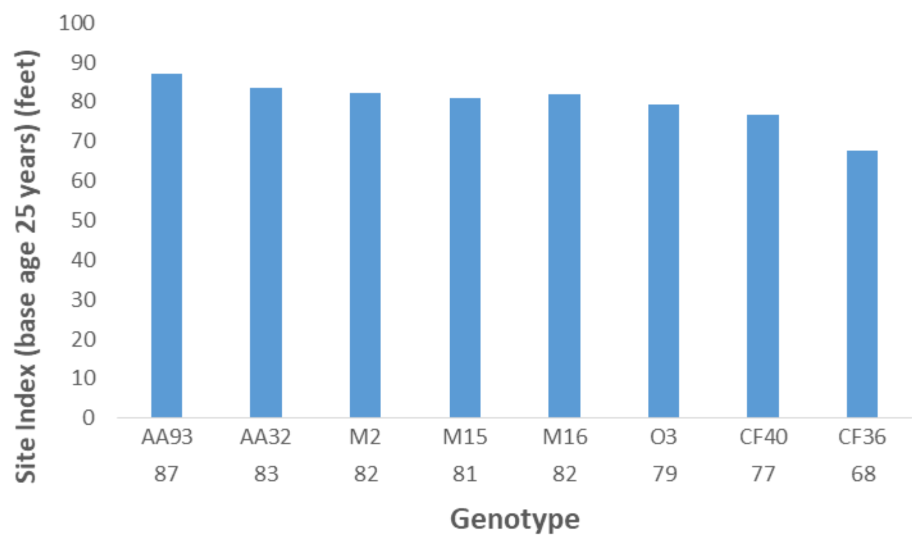

Figure 3.4 Summary of SI means across sites and densities by genotype.

<u>Variation in Site Index</u>

The standard error of site index by genotypes for each site across densities in presented in Table 3.4.

Table 3.4 Calculated mean site indices (base age 25 years; Clutter and Lenhart, 1968) and standard errors for age 6 for eight loblolly pine genotypes planted at two densities at a SC coastal and GA upland site.

Site	Genotype	Site Index (feet)	Std. Error (feet)
SC Coastal	AA93	90	0.66
SC Coastal	AA32	86	1.35
SC Coastal	M2	85	1.42
SC Coastal	M15	84	1.46
SC Coastal	M16	84	0.89
SC Coastal	O3	82	1.28
SC Coastal	C40	72	1.16
SC Coastal	C36	69	2.15
GA-Upland	AA93	84	1.41
GA-Upland	AA32	81	1.19
GA-Upland	M16	80	0.49
GA-Upland	M2	80	1.39
GA-Upland	M15	78	0.46
GA-Upland	O3	77	1.54
GA-Upland	C40	72	1.28
GA-Upland	C36	65	1.79

At the SC coastal site the range in the standard error of the means observed for the eight genotypes ranged from 0.66 feet for RC AA93 to 2.15 feet for SE clone C36. The range in standard errors observed for exhibited SI for the GA upland site was from 0.46 feet for controlled cross M15 to 1.79 feet for clone C36. At the SC coastal site, the average standard error for the RC clones, CMP, O3 and SE clone genotypes was 1.0, 1.23, 1.30 and 1.65 feet, respectively. At the GA upland site, the average standard error in exhibited SI for the RC clones, CMP, O3 and SE clones was 1.30, 0.76, 1.50, 1.53 feet, respectively. In general, the CMP and RC clones were the least variable genotypes and the SE clones the most variable genotypes. However, the variation in exhibited SI at both locations was low for all genotypes.

Discussion

The effects of genetics, initial planting density and site type on age 6 exhibited SI were investigated on two diverse sites (SC Coastal poorly drained soil and an upland, inland, well-drained soil in west central Georgia) and at two planting densities (388 and 518 TPA). Both sites were pine plantation cutover sites and operationally prepared with similar chemical and mechanical treatments. Both sites were not fertilized and were operationally treated for herbaceous weed control. The study permitted an evaluation of the impacts of site, initial planting density and a range of genetic selections on age 6 exhibited SI.

<u>Site Effects</u>

The average previous rotation operational realized SI for the SC coastal area is about 74 feet based on work by Clutter et al., (1984). An average previous rotation operation achieved site index for the GA upper coastal plain area was about 62 feet based on reports by Pienaar and Rheney (1994). This would represent about a previous-rotation 12 foot expected difference in exhibited SI between a coastal SC site and a GA upland site. Historically, the genotypes deployed on the GA upland site would have been different from those deployed on a SC coastal site. Site preparation would also have been different with coastal poorly drained sites being bedded and upland sites being flat planted. Thus, some of the 12 feet difference based on previous estimates of the difference in SI for interior upland sites vs coastal sites were confounded with genetic and site preparation intensity differences. In this study the average (across density and genotypes) age 6 exhibited SI was 83 feet for the SC coastal site and 77 feet for the GA upland site; an average difference of 6 ft. Genetics, site preparation and management intensity were the same on both sites.

Thus, the 6 feet advantage observed for the SC site most likely is driven by a more favorable water balance and nutrient supplying regime of the SC coastal site.

The range in average exhibited SI differences across the two sites and densities for genotypes that varied in levels of tree improvement from OP, CMP, RC clones and SE clones were 4.4, 4.4, 5.2 and 6.8 feet, respectively. No significant site x genetics or site x density effects were observed. These results suggest no significant genetic x environment (GxE) effect occurs over a wide range of levels of genetic improvements when deployed on GA upland versus coastal SC site conditions. This is consistent with other reports (McKeand et al., 2006a).

Site differences represented two diverse locations and site resource supplying capacities. The reviews of Fox et al. (2007) and Stanturf et al. (2003) of the changes in site productivity illustrate the magnitude that technology improvements and on-going changes in weather regimes and atmospheric conditions (CO_2, rainfall, evaporative demand and temperature) have had on average plantation production. Stanturf et al. (2003) suggest we moved from 6 Gtons/ac to now 8 Gtons/ac and are moving toward achieving 10 Gtons/ac. Using the Timberland Decision Support Model (Texas Forest Service, 2017) with 454 TPA planted a SI 75 ft site would produce a mean annual increment (MAI) of 6 green tons per acre (Gtons/ac), a SI 85 would produce a MAI of 8 Gtons/ac and a SI 95 would produce a MAI of 10 Gtons/ac. Based on the results of this study, the assessments of Fox et al. (2007) and Stanturf et al. (2003) of the trends in productivity seem correct. At the region-wide scale it is hard to disaggregate the factors that are driving these site productivity changes; clearly genetic advancements, nutrition management and weed control are significant technology factors. The age 3 height results of Subedi et al. (2014)

from an investigation of rotation-to-rotation changes on a Florida spodosol suggest that the untreated controls have increased in productivity by as much as a 31 feet in exhibited SI. The untreated controls received no herbicide or fertilizer in the initial rotation and where planted with first generation loblolly pine planting stock. For the second rotation establishment, these plots were mulched, double-pass bedded, and planted over in the same location with an improved loblolly pine family in December 2009. While too early for conclusive growth trajectory conclusions, something major has changed rotation over rotation. This would be due to improved genetics (OP to CMP), changes in the physical and chemical site properties due to previous rotation activities, (no fertilizer or major weed control), improved bed quality and subsequent weed control, and or improved weather or atmospheric conditions. For the retreated vs non-retreated fertilized plots, through age-3 there was no change in exhibited SI, implying that there is significant nutrient carryover from the previous rotation. Subedi et al. (2014) results are preliminary but do serve to indicate that the changes being brought about by a rotation of intensive pine plantation management and changes occurring in the atmosphere-weather component of SI are large and must be considered in predicting expected next rotation SI.

Stand Density Effects

No significant effects (alpha 0.05) of initial planting density (318 TPA vs 518 TPA) on age 6 total height or exhibited SI were observed in this study. However, the planting density effect had a p-value of 0.07. An analysis of 22-year height data from a long-term, multi-site spacing study (plot densities ranging from 300 TPA to 2,272 TPA) encompassing the coastal plain and piedmont regions of VA and NC, USA found that height growth impacts due to density first occurred at approximately age 6 at a basal area of near 60 ft^2/ac

(Anton-Fernandez et al., 2011; Amateis and Burkhart, 2012). Carlson et al. (2009) observed a similar result as in our study on a SI 71 density study where height was significantly affected by density at age 9 but had not affected total height enough to be biologically meaningful yet. Carlson et al. (2009) conclusion was that the density effect on height would continue to increase. Anton-Fernandez et al. (2011) observed a significant density suppression at age 6 and that the density height suppression continued through age 25 with major impacts on final height. Their final conclusion was, "After variations in site quality through mixed-effects modelling approach were accounted for, these trials in loblolly pine exhibited differences in SI originating from differences in initial planting densities of approximately 4m (13 feet) between the closest spacing (2,272 TPA) and the widest spacing (303 TPA). This finding means that if forest managers want to have realistic estimates of future growth and yield they should use different SI values for the same site depending on the initial planting density in loblolly pine plantations in the southeastern United States. One cannot compare the site productivity of two sites by simply comparing the observed height; the effect of density on dominant height development and thus, on SI should be included, especially if close spacings are involved."

The combination of planting at moderate to high densities, using elite genetic seedlings can greatly accelerate the onset of growth-limiting density that suppresses height and basal area growth. A good example of this was the study of Steiger (2013) that deployed a range of elite OP, CMP and Clonal genotypes. By age 6 a basal area of 74 ft^2/ac was attained by the most rapid growing genotype planted at 436 TPA. While no significant age 6 reduction in height were shown for trees growing at 436 TPA versus those growing at 218 TPA on that very high resource supplying site, the rapid stand development potential of the fast growing genotype at even a moderate density is well demonstrated.

There is some evidence that the ideotype must also be considered when assessing the potential effects of planting density on height suppression. Staudhammer et al. (2009) identified loblolly and slash crop ideotypes that did not experience the same level of between tree competition as broader crown competitor ideotypes. This is similar to the results report by Sabatia and Burkhart (2013) where narrow crown clones did not experience the same height suppression as broader crown OP and CMP as DBH or basal area increased.

Understanding when and to what extent height growth is affected by density is important to growth and yield modeling efforts if yield estimates are to be made with improving accuracy and if proper up-front planting density prescriptions are to be made. To predict next rotation expected SI one must consider the impacts of genetic choice, previous site effects on resource carryover and site improvements, and on-going changes in weather and atmospheric regimes. Significant adjustments in initial planting densities and consideration of the best ideotype genetics to deploy will be required to avoid excess early rotation crop tree diameter loss, SI loss and early density related mortality. The effects of site index and initial planting density on the age that a stand may become impacted by SI loss due to between tree competition and interactions, assuming that the threshold for height loss occurs at a BA of 60 ft^2/ac, is illustrated in Table 3.5.

Table 3.5 Projected average age[1] in years at which basal area attains 60 ft^2/ac for a range of 300 trees per acre to 600 trees per acre and a range of site indices from 70 feet to 100 feet for planted loblolly pine.

	Planting Density (TPA)			
$SI_{25\ year}$ (Feet)	**300 TPA**	**400 TPA**	**500 TPA**	**600 TPA**
70	10.0	9.0	8.5	8.0
80	9.0	8.0	7.5	6.5
90	8.0	7.0	6.5	6.3
100	7.0	6.5	6.0	5.5

[1]Age projected using Timberland Decision Support System (Texas Forest Service, 2017)

This simulation indicates that a previous SI-70 rotation site that was planted with 600 TPA would have the same level of basal area at age-8 as a current SI 90 stand would have if the initial planting density was 300 TPA. This should send a strong signal to landowners about the need to recognize how the changes in SI potential that are occurring should affect stand development and planned intermediate rotation management decisions. Adjusting initial planting density, deployment of less competitive crop ideotypes, considering different deployment options, planned earlier thinning options or no-thin low-density plantings for small-moderate size sawlog production are all viable considerations. A thorough understanding of the characteristics of the genotype being deployed will be essential for making the needed initial planting densities and deployment system.

Genotype Effects

The "choice of genetics" had a major effect on height growth and thus exhibited SI at age 6 at both test sites. The range in exhibited SI across genotypes at the SC coastal site was from 69 feet to 90 feet or a difference of 21 feet of site index. For the GA upland site, the observed range in exhibited SI averaged across planting density was from 65 feet to 84 feet; a difference of 19. Thus, the impact of choice of genotype to plant would be about the same for the SC coastal or the GA upland site, for the population examined.

Sabatia and Burkhart (2013) reported age 8 results for a density by genotype study in Berkeley County, SC. Their study utilized some of the same RC clones (AA93 and AA32), O3 and one of the CMP (M2) included in this study. No SE clones were included in their study. Based on the range of age 8 heights reported by Sabatia and Burkhart (2013) it was possible to estimated exhibited SI for their study. Their average exhibited SI across genotypes and planting densities was 89 feet. Their observed range in exhibited SI across the deployed genotypes was 13 feet. This is similar to the range in commercial genotype exhibited SI of 10 feet in the current study for the SC coastal site. Steiger (2013) observed a range in exhibited SI for a group of genotypes that spanned a wide range of levels of tree improvement; OP, CMP and SE clones. The study included O3 and two of the SE clones that were in this study. Reported age 6 exhibited SI in the Steiger (2013) study ranged from 71 feet to 98 feet; a range of 27 feet. However, if the noncommercial clone in his study was not considered, the range in commercial genotype exhibited site index at age 6 was 10 feet. It is interesting to compare the "choice-of-genotype" effect on exhibited SI with that observed for a study that utilized previous rotation first and second-generation OP families. Svensson et al. (1999) studied the growth trends of twelve OP families on a coastal NC site. He assessed average height from age 4 to 11. Using their height data, it was possible to estimate exhibited SI from age 4 to age 11 for each genotype deployed. Several important contrasts can be made with our study:

1. The average exhibited SI observed by Svensson et al. (1999) at age 11, across genotypes, was 72 feet; typical of previous coastal rotation expected SI.
2. The range in their 12 genotypes exhibited SI at age 11 was from 68 feet to 76 feet; a difference in 8 feet of exhibited SI related to "choice-of-genotype". This is a smaller range in exhibited SI than was observed for the commercial genetics that were deployed in the current study. This would be expected because a much broader range of levels of tree improvement (OP to Clones) were included in the current study instead of just OP selections.
3. The genetic correlations of juvenile (age 4) heights were high and stable. They observe no changes in ranks of families over the 7 year period. Interestingly determined average exhibited SI at age 4 was the same as determined at age 11 site index.

One of the higher yielding families in the Svennson study is family 8-103. This strong 1st generation loblolly pine family represents about a 9% improvement in volume over unimproved loblolly pine. For comparison, the mid-point breeding value for volume of the parents of CF36 and CF40 in the current study would provide estimates of 28% and 22% volume gain, respectively. Compare this to an open pollinated family used in the current study, O3, which represent a 47% improvement in volume over the same common unimproved loblolly pine check lot. Family 8-103 and its 9% volume increase is representative of some of the lower end loblolly pine seedlings still being sold in the Southeast U.S. market for planting on private landowner land. O3, planted in the current study would still out rank the majority of open pollinated pine seedlings sold in the Southeast US today. Current study CMP entries M2, M15, and M16 and clones AA93 and

AA32 all had higher mean per acre volumes (Table 2.11) than O3 which ranks high in the NCSU breeding cooperative testing program. These comparisons speak to the strength of performance of the genotype entries in the current study and help demonstrate the range of genotype volume performance available today.

Based on the results of the current study and others, it is obvious that selection of the best genotype and ideotype for deployment is of major importance. Selection, purchase, and deployment of an inefficient or maladapted genotype such as C36, or marginal production genotype like C40, or planting of a lower volume breeding value family like 8-103, could substantially decrease exhibited site index and volume production potential and offset potential gains from investments in quality site preparation and tending treatments. In contrast, deployment of a highly efficient genotype such as AA93, AA32 or good CMP provides maximum leverage from the site preparation and seedling after-plant care investments.

The two SE-clones entries in this study had the lowest heights and predicted site indices and were lower than the O3 industry standard ‘check’ used in this study. In contrast, the RC-clones had the highest overall heights. The CMP material showed improvement over the strong OP industry standard ‘check’, O3, used in the current study. These rankings suggest that individual genotype selection and its inherent production potential and traits are more important than the method of propagule production or improvement. However, with that said and excluding the SE-clones, genotypes with increasing level of genetic improvement (RC>CMP>OP) exhibited higher site indices.

In addition, based on the estimates of the “site improvement” being brought about by increased atmospheric carbon dioxide (8 feet/25 yr. rotation; Baldwin et al., 2001) and the impacts of “carry-over” influences from organic matter buildup (residues, forest floor or understory vegetation) and nutrients from previous rotation fertilization (Subedi et al., 2014) the combined atmospheric and soil system change effect most likely are a much larger influence on site potential than the site differences we observed between a GA upland site and a SC coastal site.

Stand density effects on height in the current study had a p-value of 0.06 level, just above the alpha of 0.05, but age 6 basal area per acre was slightly below the 60 ft^2/acre level reported to impact height. The average BA on the GA upland and SC coastal was 47.7 and 51.0 ft^2/acre, respectively. This is not quite to the BA threshold that Anton-Fernandez et al. (2011) and Amateis and Burkhart (2012) of 58 ft^2/acre where they observed significant density related height reductions. Results of their studies do suggest that density effects on achieved SI are large (up to 13 feet reduction in final SI) and must be considered in estimating next rotation expected SI. Based on the results of Sabatia and Burkhart (2013) and Staudhammer et al. (2009) the choice of ideotype will also be important in determining the effects of planting density on achieved SI.

These considerations for estimating next rotation expected SI suggest the need for land managers to:

1) Retain the information on the level of genetics deployed in the previous rotation; genetic selection and established breeding value for volume and height. This provides a basis for estimating what level of genetics you are moving from and moving to.

2) Retain the SI achieved in the past rotation. This can also serve as an index of the amount of organic matter that may be potentially left in the system at the end of the rotation.
3) Provide an estimate of nutrient input carry-over and the cumulative levels of nutrients applied to the previous rotation—
4) Quantify the end-of-rotation understory is that can be utilized as a latent nutrient pool for the next rotation.

We have moved from a time when plantation SI in the 50-60 feet range was the expectation to now where many stands are approaching and exceeding exhibited SI of near or over 90-100 ft in 25 years. Studies like the across-rotation yield comparisons being conducted on the University of Florida IMPAC (Subedi et al., 2014) site will be of great value in helping to partition out where these growth gains are coming from. Additional, well designed, rotation-to-rotation or multi-rotation studies that retain the old treatments and add new levels of genetics are much needed. New approaches to modelling and predicting potential SI are also much needed. These must include the driving factors that were summarized in this study.

Conclusion

The results of this study and the series of studies reviewed for this article clearly demonstrate that all of the components of SI (genetics, soil system chemical and physical properties, and atmospheric-weather regimes) are perhaps more dynamic than has historically been recognized. This study's results showed that age 6 exhibited SI range at two locations (SC coastal and an interior GA-upland) could be as much as 19-20 ft depending only on the "choice of genotype" to deploy. These observations were for operational establishment regimes that did not include any fertilization. The genetic choices in the current study did not span the full range of commercial genetic qualities that are commercially available so the genetic impact we found must be considered as conservative. A major conclusion from this study is that the "genetic choice" impact must be an input into any up-front investment planning much more than it is being done so today. This study just examined "genetic choice" impacts on productivity potential but similar ranges of benefits in stem quality improvements and in risk management opportunities will also be greatly affected.

This study did provide a good estimate of the differences in productivity potential of a resource-rich SC coastal site versus a central west Georgia upland well-drained lower resource supplying capacity site. The average "Site" difference of 6 feet in exhibited SI is significant but considerable less impactful than the "choice of genetics" consideration. Site may also be less impactful than increases in atmospheric carbon dioxide (Baldwin et al., 2001) and impacts of "carry-over" organic matter and nutrients (Subedi et al., 2014).

Choosing the right initial planting density and ideotype will be important to optimize the volumes of the defined timber product needed for specific market zones. Results of other studies do suggest that density effects on achieved SI are large and the choice of ideotype will also be important in determining the effects of planting density on achieved SI.

To manage stand density effects on SI landowners must recognize the influence that increasing the SI from a SI of 70-75 to 90-100 will have on stand development rate, loss of crop tree diameter and the age when density-related mortality may begin. To estimate the expected next rotation SI, forest landowners need to consider the following factors: geographical location, soil characteristics, and long term weather regimes; impact of changes in carbon dioxide and weather regimes; and influence of “choice of genetics”; physical and chemical “carry-over”; deployment method, initial planting density and choice of ideotype.

This study has also identified the need to better understand the actual factors that are driving the production increase that has and are occurring in the US Southeast. Additional, well designed, rotation-to-rotation or multi-rotation studies that retain the old treatments and add new levels of genetics are much needed. New approaches to modelling and predicting potential SI are also much needed.

Literature Cited

Amateis, R.L., Burkhart, H.E. 2012. Rotation-age results from a loblolly pine spacing trial. Southern Journal of Applied Forestry 36(1): 11-17.

Anton-Fernandez, G., Burkhart, H.E., Strub, M., and R.L. Amateis. 2011. Effects of initial spacing on height development of loblolly pine. Forest Science 57: 201-2011.

Baldwin, V.C. Jr., Burkhart, H.E., Westfall, J.A., Peterson, K.D. 2001. Linking growth and yield and process models to estimate impact of environmental changes on growth of loblolly pine. Forest Science 47(1): 77-82.

Carlson, C.A., Fox, T.R., Creighton, J., Dougherty, P.M., Johnson, J. 2009. Nine-year growth responses to planting density manipulation and repeated early fertilization in a loblolly pine stand in the Virginia Piedmont. Southern Journal of Applied Forestry 33(3): 109-114

Clutter, J.L., Lenhart, J.D. 1968. Site Index Curves for Old-field Loblolly Pine Plantations in the Georgia Piedmont. Georgia Forest Research Council Rep. 22 -Series 1.4 p.

Clutter, J.L., Harms, W.R., Brister, G.H. and Rheney, J.W. 1984. Stand structure and yields of site prepared loblolly pine plantations in the lower coastal plain of the Carolinas, Georgia and north Florida. Gen. Tech. Rep. SE-27. Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 173p.

Dougherty, D.S., Modeling the New Southern Forest Resource. 2015 Forest Insight East Meeting, Valdosta, GA., October 28, 2015.

Everett, C.J., Palm-Leis. 2009. Availability of residual phosphorus fertilizer for loblolly pine. Forest Ecology and Management 258: 2207-2213.

Fox, T., Jokela, E., Allen, H. 2007. The development of pine plantation silviculture in the southern United States. Journal of Forestry. 105(7): 337-347.

Harms, W.R., DeBell, D.S., Whitesell, C.D 1994. Stand and tree characteristics and stockability in a spacing trial planted in Hawaii and South Carolina. Canadian Journal of Forest Research 24(3):511-521

Kiser, C.L., Fox, T.R. 2012. Release of nitrogen and phosphorus from loblolly pine forest floor in a post-harvest climate. Soil Science Society of America Journal 76: 2278-2288.

Landsberg, J.J., Waring, R.H. 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance, and partitioning. Forest Ecology and Management 95:209-228.

Maier, C.A., Johnsen, K.H., Dougherty, P., McInnis, D., Anderson, P., Patterson, S. 2012. Effect of harvest revenue management on tree productivity and carbon pools during early stand development in a loblolly pine plantation. Forest Science 58(5): 430-445

McKeand, S.E. 2017. Making sense of the genetics market. Forest Landowners, September/October: pp 14-19.

McKeand, S.E., Jokela, E.J., Huber, D.A., Byram, T.D., Allen, H.L., Li, B., Mullin, T.J. 2006. Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. Forest Ecology and Management 227: 178-184

Pienaar, L.V and Rheney, J.W. 1994. Growth Potential of Loblolly in the Georgia Piedmont. University of Georgia, Plantation Management Research Cooperative. Warnell School of Forest Resources. Plantation Management Research Cooperative Report 1994-1. 15 pp.

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

Sampson, D.A., Allen, H.L. 1999. Regional influences of soil available water-holding capacity and climate, and leaf area index on simulated loblolly pine productivity. Forest Ecology and Management 124(1): 1-12.

SAS Institute. 2011. The SAS systems for Windows. Release 9.2, SAS Inst., Cary, NC

Skovsgaard, J.P. and Vanclay, J.K. 2008. Forest site productivity: A review of the evolution of dendrometric concepts for even-aged stands. Forestry. Vol. 81, No. 1

Stanturf, J.A., Kellison, R.C., Broerman, F.S., Jones, S.B. 2003. Productivity of southern pine plantations: Where are we and how did we get there. Journal of Forestry. 101:26-31.

Staudhammer C.L., Jokela, E.J., and Martin, T.A. 2009. Competition dynamics in pure-versus mixed-family stands of loblolly and slash pine in the southeastern United States. Canadian Journal of Forest Research 39: 396-409.

Steiger, J.J. 2013. Impacts of Different Levels of Genetic Homogeneity on Juvenile Stem Characteristics and Potential Stand-level Value in Loblolly Pine. North Carolina State University Thesis. 82p.

Subedi, P., Jokela, E.J., Vogel, J.G. and Martin, T.A. 2014. Inter-rotational effects of fertilization and weed control on juvenile loblolly pine productivity and nutrient dynamics. 12th North American Forest Soils Conference Proceedings. 16 pp.

Svensson, J.C., McKeand, S.E., Allen, H.L., and Campbell, R.G.1999. Genetic variation in height and volume of loblolly pine open-pollinated families during canopy closure. Silvae Genetica 48(3-4): 204-208.

Texas Forest Service. 2017. Timberland Decision Support System. Texas A & M University. http://tfsfrd.tamu.edu/tdss

USDA Forest Service. Southeastern Forest Experimentation Station. GTR SE-27. 173pp.

Valentine, H.T. 1997. Height growth, site index, and carbon metabolism. Silva Fennica 31(3): 251-263.

CHAPTER 4

AN AGE 6 EVALUATION OF THE IMPACT OF SITE RESOURCES, INITIAL PLANTING DENSITY AND GENOTYPE DEPLOYMENT ON MEAN ANNUAL INCREMENT AND BARE LAND VALUE FOR EIGHT LOBLOLLY PINE GENOTYPES PLANTED AT TWO DENSITIES ON SITES IN THE UPPER COASTAL PLAIN OF GEORGIA AND THE LOWER COASTAL PLAIN OF SOUTH CAROLINA[3]

[3] Dougherty, D.S., M.B. Kane, B.P. Bullock, R.F. Daniels, and J.A. Wright. To be submitted to Journal of Forest Economics

Abstract

Bare land value (BLV) was calculated for eight genotypes planted at two densities (388 and 518 trees per acre ---TPA) on a GA upland site in Marion Co., GA and a SC coastal site in Berkeley Co., SC. Genotype entries included two somatic embryogenesis (SE) clones, two rooted-cutting (RC) clones, three control mass pollinated (CMP) crosses, and one open-pollinated (OP) family. BLV was calculated for two cases, including a base case (for both sites) and a grade-adjusted case (GA site only). Tonnage estimates by product class were projected using the Fastlob growth and yield model. Variables defining the stands to be projected included age 6 exhibited site index (SI), basal area (BA) and surviving TPA. A 5% discount rate was used for the analysis. Stumpage rates were based on Timber Mart South pricing reports for the two areas. Site and genotype effects were significant on BLV in both case studies. Density and all interaction effects were not significant. In the base case, BLV increased by 57% from the lowest returning commercial genotype (C40) to the highest (AA93). Grades were completed on the GA upland site after the 13th growing season. All calculated BLV's decreased when the grades were applied as compared to the SI, BA and TPA supported runs alone. Two genotypes, clone AA93 and CMP M15, had graded pole percentages tallied at 52% and 29% respectively on the lower resource upland site. Mean annual increment ranged from 4.6 to 7.3 tons/acre/year due to genotype selection, representing a 59% impact. Site effects increased BLV by 11% moving from operating on a GA upland site to a SC coastal site. Mean annual increment increased by 0.8 tons/acre/year going from a GA upland site to the SC coastal site.

Introduction

Recently published forest resource statistics estimate the acreage of planted yellow pine in the US South to cover 40 million acres (Oswalt et al, 2018). The majority of this plantation area is loblolly pine (*Pinus taeda*). The pine volume from this plantation resource is estimated at 58 billion cubic feet, which is 49% of the overall estimated southeastern US pine volume (Oswalt et al., 2018). Accurate estimates of the acreage and volume of this resource are needed for questions of mill and market supply and sustainability. Many factors impact southeastern US softwood timber supply. Two primary factors include: 1) the rate of establishment of pine plantations and 2) the subsequent annual growth rate of those newly planted pine stands. Both of these factors are influenced by the investment return potential anticipated from plantation pine growing technology at the time of establishment.

Potential pine plantation growth rates have doubled every 20 years since the 1970's (Stanturf, 2003; Fox et al., 2007). Southeastern US site production potential for loblolly pine (ft^3/acre) based on climatic variables has been published by Sampson and Allen (1999). The Sampson and Allen data assumed high levels of resource availability and a subsequent leaf area index (LAI) of four units. Sampson and Allen showed current annual increment (CAI) production potential, generally ranging from 350-550 ft^3/acre/year across the Southeast US. Assuming 55 lbs/cubic feet, this equates to CAI rates of 9.7 to 15.1 tons/acre/year. Southeastern US site operational dry weight production potential for loblolly pine for purposeful biomass plantations based on climatic variables and soil texture and slope position has been published by Perdue et al. (2017). Perdue et al. (2017) estimate the operationally intensive productivity potential for purposeful, non-thinned biomass rotations (14 year length) in dry tons. Converted to green tons (Gtons), their estimates range from 4.8 to 18.2 Gtons/ac/yr, with mean productions rates of 8.8 Gtons/ac/yr on an upland sand, 9.6 Gtons/ae/yr on an upland sandy loam, and 11.8 Gtons/ac/yr on a lowland clay site.

Factors that affect the growth rate of new pine plantations include site quality, establishment technology, and management systems (Fox et al., 2007). Establishment technology includes site preparation systems, seedling allocation, and the number of seedlings to plant per acre. A great deal of progress has been made in the understanding of how to prepare a site for loblolly pine growth in regards to nutrition needs, water management, and competition control (Fox et al., 2007). In 2007, Fox et al. concluded that "Implementing site-specific, integrated management regimes that incorporate the genetic gains available from tree improvement along with silvicultural practices that optimize resource availability throughout the rotation is key to enhancing productivity of southern pine plantations." That period, 2006-2007, coincided with the widespread launch of two new commercial levels of tree improvement genotypes. These two new levels of genotype improvement result from the implementation of large scale production of control mass pollinated (CMP) and clonal propagation processes. Collectively, these new genotypes, along with the most elite 2nd generation open pollinated seedlings, represent a new level of genetic potential made available to leverage the sites and proven pine management culture of the southern US. In 1999, Li et al. estimated that if only the best OP families were planted, volume gains from 26-35% were possible. In 2004, Jansson and Li showed potential full sib cross volume gains of over 50%. Thirteen years later, and with continued development through controlled cross breeding and varietal testing, forward progress continues.

As growth trajectories are increasing and loblolly pine tree improvement programs move forward, the question of how many seedlings to plant per acre continues to be evaluated for the new resource of genotypes. The general trend has been for the number of planted trees per acre to drop from historical planting spacings and rates of 9 ft x 7 ft or 10 ft x 6 ft (around 726 TPA) or greater to a current average of 592 TPA (Lang et. al, 2012). Landowners with sawtimber focus generally plant 435 to 605 TPA, with a much lesser number of landowners planting 303 to 400 TPA.

Landowners have multiple options for land use and financial returns are a key driver for the land use decision. The same factors that affect timber growth rate, coupled with forest product markets and associated stumpage prices and economic and environmental risks, impact whether a landowner commits land to timber production and at what level of management intensity. Private landowners and institutional investment managers have major investments in southeastern US pine plantations due to a history of investment success through this land use (Yin and Sedjo, 2001). Continued use of the pine plantation investment vehicle is dependent on the ability to produce a strong return. Primary criteria used for land use decisions include net present value (NPV), bare land value (BLV) and associated internal rate of return (IRR). A slump in pine sawtimber demand and subsequent drops in pine sawtimber stumpage prices over the period from 2007 to 2017 have greatly decreased the average returns from pine plantation harvests and investments. Investors applying pine plantation timber growing technologies work to offset stumpage pine price declines with added per-acre volume production.

The purpose of this paper is to evaluate a group of 'new resource' genotypes planted under operation intensity in 2005 as part of an Enhanced Genetics by Density Study that was established at two contrasting sites and two low to moderate densities (388 and 518 TPA). This group of genotypes includes entries from all three levels of tree improvement, including open pollinated seedlings, mass-control pollinated seedlings, and clonally propagated seedlings (both through rooted-cuttings and somatic embryogenesis, SE). The focus of the paper is to evaluate the effects of site, genotype and density on growth rates and investor BLV.

Methods

Site Description:

This study consisted of two installations. The South Carolina installation is located in Berkeley County, South Carolina (33° 14.512 N, 80° 10.866 W) which can be found in the Lower Coastal Plain and the climate is impacted by the proximity to the Atlantic Ocean. The Georgia installation is located in Marion, County, Georgia (32° 17.596 W, 84° 26.513 W). This is an Upper Coastal Plain site, located well inland from the Atlantic Gulf Coastal climate influence (typically subject more to a continental effect in dry summer periods). Past site use, typical climate, descriptive soil information, genotype plant material, and site preparation and post-plant care systems are described in detail in the 'Methods' section of Chapter 2.

Study Design

The study was installed as a randomized complete block with split plots on genetics. Main treatment plots are for density (388 or 518 trees per acre). Main plots were split for random genotype assignment. Each study installation contained three blocks (replications). Genotypes were assigned at random to subplots within each density plot. Genotype split plots were 0.22 acres in size. Measurement in both densities was made on all trees in a 0.12 acre interior measurement plot resulting in 60 measurement trees in the 518 tree/acre density and 45 potential measurement trees in the 388 trees per acre density.

Study Establishment

The study was designed to test the performance of a range of genotypes under operational conditions. The SC site received a shear and bed treatment in the summer of 2004 and then chemical application in the fall of 2004 with a per-acre rate of 32 oz of Chopper (2# imazapyr) and 1 quart of Garlon-4 (triclopyr). After hand planting in late 2004, the SC site received a spring herbaceous weed control treatment with 3 oz/acre of Oust (sulfometuron methyl). The between row spacing on both sites was 14 ft. For the 388-TPA treatment, the within row spacing was 8 ft between trees and for the 518-TPA treatment the within row spacing was 6 ft.

The GA site received an upland bedding treatment followed by a fall chemical site preparation treatment of 16 oz/acre of Arsenal (4# imazapyr) plus 3 oz Oust (sulfometuron methyl)/per acre. The GA site was hand planted in late 2004. A summer herbaceous weed control treatment of 3.75 oz/acre of Transline (clopyralid) and 2 oz of SFM75 (sulfometuron methyl) was applied in a banded treatment along the row. No fertilizer or additional treatments were applied over the study period. This series of site treatments represented the operational regime assigned to each site.

Measurements, Projections and Calculations

Trees were measured after the completion of the 6th growing season. Survival status was assessed and diameter at breast height (DBH) measured on all trees within the embedded measurement plots. Diameters were measured with a steel diameter tape. Total heights were measured on every other tree. Tree heights were measured with a Haglof Vertex hypsometer. The measured heights were used to estimate the non-measured tree heights using regression at the plot level. Survival, mean DBH, mean height, and mean tree basal area were calculated for each plot. Basal area per acre was calculated by multiplying the plot values by the per acre expansion value.

Age 6 measured surviving trees per acre, dominant and co-dominant heights and calculated site index base age 25, and plot-level basal area were used to project rotation-length volumes by product class. The top half of the measured heights were considered to be the dominant and codominant heights for the plot. The mean of these trees were used along with age to estimate site index at base age 25 from the adapted Lenhart and Clutter site index table historically used on the operational land bases where the study installations were located. Plot level basal area was scaled to per acre by multiplying by 8.33 (scale up factor; measurement plot size of .12 acres).

The FastLob DSS growth and yield model (Amateis et al., 2001) was used for projecting harvest timings and thinning and final harvest volumes by product class. A one-thin rotation was modeled with the thinning completed when the dominant height reached 50 ft. The residual thinning target was to thin back to 180 trees per acre. The final harvest clear-cut age was determined when the dominant height reached 85 ft. While the initial planting densities were 388 and 518 trees per acre, in order to represent the true operationally planted genotype impacts, actual age 6 surviving trees per acre were input. The primary outputs of interest for comparison were 1) thinning age, 2) thinning volume, 3) clearcut age, 4) mean annual increment (tons/acre/year) and 5) bare land value (BLV).

For the MAI calculation, the thinning removals were added to the final harvest removals and that sum was divided by the rotation age. Bare land value was calculated using the following formula:

$$BLV = FV/(1+i)^{\wedge(n-1)}$$

Where FV = the sum of all cash flows compounded to the final harvest age

i = discount rate
n = clearcut harvest age

Merchantable product classes and specifications applied are provided in Table 4.1.

Table 4.1 Forest market products, specifications, and stumpage prices for merchantable pine products projected from growth of eight genotypes at two densities growing on the SC and GA sites.

	Specifications		Stumpage
Pine Product	Min. DBH	S.E.D	Price
Pulpwood	3.5"	2"	$11
Chip-n-saw	8.5"	6"	$19
Sawtimber	12.5"	7"	$26

For the BLV calculations, stumpage prices used were 4th quarter, Timber-Mart South (2017) (TMS) reported market price means for the GA transition region (between TMS GA region 1 and 2) and the SC coastal region (TMS SC Region 2) in 2017. Stumpage pricing for both regions was very similar for the period (Table 4.1). For the BLV calculations, activity costs and seedling costs were assigned at market rates for the regions in 2017-18 (Table 4.2). Both the SC site and the GA site had mechanical site preparation treatments. These costs were assigned at $95/pass, with the GA site having a one-pass upland ripping/small bed treatment ($95/acre) and the SC lowland site having a two-pass shear and bed treatment ($190/acre). Herbicide application costs were assigned at $85/acre for chemical site preparation and $25/acre for herbaceous weed control for both the SC and GA sites. Seedling prices were assigned at $85/M, $230/M, and $350/M for open-pollinated elite, control-mass-pollinated elite, and varietal seedling stock respectively (ArborGen, 2017). Total per-acre site preparation costs (mechanical and chemical site preparation plus herbaceous weed control) were $205 and $300 for the GA and SC sites, respectively. Annual management fees and taxes were assumed to be offset by hunt lease revenues and thus cancelled out from the BLV calculation. All activity, stumpage, and seedling prices were assumed to be real, i.e. no inflation or appreciation. A discount rate of 5% was used for the analysis.

Table 4.2 Summary of management activity costs for the SC and GA sites. The SC site received a 2-pass mechanical treatment while the GA site received a 1-pass treatment. All other activities costs were equal.

Management Activity	Cost
Mechanical Site Preparation	$95/pass
Chemical Site Preparation	$85/acre
Herbaceous Weed Control	$25/acre
Planting Labor Costs	$0.07/seedling
Seedling Purchase:	
Open pollinated	$60/M
Control-mass-pollinated	$200/M
Varietal	$400/M

Georgia Upland Site Defects, Stem Quality Grades, and Grade-Adjusted BLV Calculation

To more fully integrate the effects of the genotype, site and initial planting density treatments on projected returns, a grade-adjusted BLV was calculated for the GA site. To facilitate this base vs. grade-adjusted comparison, the study trees on the GA site were graded at age 13, prior to thinning, in regards to stem quality and suitability for both sawtimber and pole markets. The SC coastal site had been thinned and thus pre-thin grades were not available for comparison. The stem quality grades from the Georgia upland site were used to adjust the base case product volumes projected from FastLob. Sawtimber

(ST) volumes were adjusted to reflect only those stems that would be utilized as quality ST. In addition, the proportion of quality sawtimber that was graded as satisfactory for pole production was moved from ST to pole quality volume and valued at $45.00/ton.

During the grading, each individual surviving tree was given a stem quality grade (SQG) score from 1 to 5. The grade specifications are summarized in Table 4.3. A #1 grade was assigned when the tree had no or only minor operational defects and would be sorted out as a sawtimber quality stem. An elite group of stems were further sorted out of the Grade #1 trees as pole quality trees. A pole quality tree required near-perfect straightness, below-average branch size, and average or low taper. Grade #2 trees would still make quality sawtimber but had some defects. A primary degrade pushing a tree towards a #2 call was sweep in the stem, generally a deviation of 1-3 inches from vertical over a 16 foot run. A #3 grade was tallied for trees with rough branching (large knots, steep angle, etc.) or multiple defects, i.e. big branches and sweep. A #4 grade was applied to trees with sawtimber potential in the butt log, but with some defect, generally a fork or broken top or large branch, limiting the tree to only pulpwood production above the defect. A #5 call described a tree with no sawtimber or pole potential, i.e. pulpwood only.

Table 4.3 Stem quality grade descriptions for grading completed at age 13 on eight genotypes planted at two densities under operational management at an upland site in Marion County, GA

Grade	Description
1	Stem quality is without major defects that would prevent utilization for sawtimber production
2	Stem has 1 or 2 minor defects but would still be utilized for sawing quality lumber
3	Stem quality is rough due to sweep, bad branching, or other defects, and would make low-grade lumber
4	Lower stem quality is good, but upper portions are only usable for pulpwood.
5	Tree has a major defect(s) and can be utilized for pulpwood production only

The primary defects causing trees to be graded as low quality sawtimber or pulpwood-only included stem rust galls, forks, crook, suppression, and severe broken tops. The count of these defects on living trees were tallied and summed, and a defect percentage was calculated by defect type for each plot.

The GA site grades were applied to the GA site plot level growth and yield run product class breakdowns. Grades #3, #4, and #5, collectively the lowest quality trees, were used to shift a genotype and density specific percentage of the modeled sawtimber tonnage down to the pulpwood class. This was completed at the plot-level. It was assumed that ½ of the lower quality trees would be removed at the time of thinning through the 'operator-select' thinning contractors and thus only 50% of the defect percentage was discounted from the projected sawtimber and CNS product class volumes. The discounted wood tonnage was transferred to the pine pulpwood class.

For the pole quality grade adjustment, this shift of a portion of the product class volumes upward into the pole product class was not made to the CNS product class (for small poles) or pulpwood class, but rather was only applied to the sawtimber size product class. This shift thus only allows for large pole inclusion and impact on BLV. It was conservatively assumed that only 50% of the pole quality trees would be correctly sorted out by the logging contractor or absorbed by the pole market, which is one of the more volatile forest product markets in the southeastern US.

Statistical Analysis

A combined Analysis of Variance (ANOVA) was performed to examine differences between sites. Within site, ANOVA was performed for a split-plot design for each site using both SAS (SAS/STAT, 2017) and R statistical packages. Within an installation, ANOVA was used to test for block, density, genotype, and any interactive effects on thinning age, thinning removal volume, clearcut age, clearcut volume, MAI, stem defects, stem grades and BLV. The linear model used was:

$$Y_{ijkl} = \mu + B_i + D_j + G_k + B_iD_j + B_iG_k + D_jG_k + \varepsilon_{ijkl}$$

Where Y_{ijkl} is the observed dependent variable; B_i is the effect of the *i*th block (i = 1-3); D_j is the effect of the *j*th density (318 or 518 TPA density); G_k is the effect of the *k*th genotype (k = 1-8); B_iD_j is the block by density effect; B_iG_k is the block by genotype effect; D_jG_k is the density by genotype effect; and ε_{ijkl} is the random error associated with the model and is assumed to be distributed N (O, σ^2). Proc Mixed was used for the analysis. Duncan's test was used for significant means comparison. For comparisons of the defect or other percentages, the means were normalized prior to analysis. The alpha level for all calculations was 0.05.

Results

Environmental Trends

Precipitation and temperature trends for the period through age 6 are provided in the 'Results' section of Chapter 2.

Growth and Yield Projections

A summary of the means from the growth and yield projections are provided in Table. 4.4.

Table 4.4 Means summary for growth and yield projections completed using age 6 measured data from a SC coastal site and a GA upland site planted with eight genotypes at two planting densities (388 TPA and 518 TPA). BA is per-acre basal area in ft^2/acre. Tons is merchantable green tons per acre.

			Age 6 Status			Thinning		Clear-cut					Rotation		
Site	DEN	GEN	SI	TPA	BA	Age	Tons	Age	PP	CNS	ST	Tons	Tons	MAI	BLV
GA	518	AA32	80	483	49.3	12	33.2	29	20.4	41.4	87.3	149.0	182.2	6.4	$591.71
GA	518	AA93	82	483	48.6	12	33.7	27	22.2	46.0	76.6	144.8	178.5	6.6	$625.59
GA	518	CF36	65	469	26.4	18	31.9	40	16.5	32.3	99.3	148.1	180.0	4.5	$196.38
GA	518	CF40	71	439	35.5	16	31.1	35	17.3	34.0	98.8	150.1	181.1	5.2	$349.33
GA	518	M15	78	439	50.5	13	33.6	30	18.7	37.1	98.5	154.2	187.8	6.3	$698.18
GA	518	M16	81	458	58.3	12	35.3	28	19.2	38.3	98.3	155.8	191.2	6.8	$798.93
GA	518	M2	79	469	51.2	13	35.2	30	19.4	39.1	91.9	150.5	185.7	6.3	$681.96
GA	518	O3	76	469	46.5	14	34.9	31	19.0	38.1	93.0	150.2	185.1	5.9	$691.67
GA	**HIGH Means**		**77**	**464**	**45.8**	**14**	**33.6**	**31**	**19.1**	**38.3**	**93.0**	**150.3**	**183.9**	**5.9**	**$579.22**
GA	388	AA32	83	350	45.0	12	22.5	27	19.8	34.9	91.8	146.5	169.0	6.3	$659.34
GA	388	AA93	86	358	45.7	11	23.2	25	21.7	41.7	84.0	147.5	170.6	6.9	$764.82
GA	388	CF36	66	342	23.9	17	20.5	39	16.0	25.4	107.0	148.4	168.9	4.3	$235.57
GA	388	CF40	73	339	34.2	15	21.2	34	16.6	28.2	107.1	151.9	173.1	5.1	$410.98
GA	388	M15	78	353	50.7	13	25.2	30	16.5	29.6	115.9	162.0	187.2	6.3	$755.91
GA	388	M16	79	344	48.5	13	24.0	31	17.7	30.4	106.3	154.3	178.4	5.8	$657.25
GA	388	M2	81	358	47.5	13	25.0	28	18.6	34.6	102.2	155.4	180.4	6.4	$758.83
GA	388	O3	78	342	42.2	13	21.9	30	17.8	30.7	103.7	152.1	174.0	5.8	$709.74
GA	**Low Means**		**78**	**348**	**42.2**	**13**	**22.9**	**30**	**18.1**	**31.9**	**102.2**	**152.3**	**175.2**	**5.8**	**$619.05**
GA	**Overall Total**		**77**	**406**	**44.0**	**14**	**28.3**	**31**	**18.6**	**35.1**	**97.6**	**151.3**	**179.6**	**5.8**	**$599.14**

			Age 6 Status			Thinning		Clear-cut					Rotation		
Site	DEN	GEN	SI	TPA	BA	Age	Tons	Age	PP	CNS	ST	Tons	Tons	MAI	BLV
SC	518	AA32	85	478	54.3	12	35.1	26	22.5	46.7	78.3	147.5	182.7	7.1	$613.90
SC	518	AA93	90	486	59.0	10	34.8	23	25.0	52.7	70.4	148.1	182.9	8.1	$755.28
SC	518	CF36	69	453	31.3	16	30.2	37	17.6	34.7	94.4	146.7	177.0	4.8	$177.85
SC	518	CF40	79	472	48.7	13	34.3	29	19.2	38.4	95.9	153.5	187.8	6.4	$504.46
SC	518	M15	84	472	62.7	12	37.1	26	20.5	41.6	92.7	154.8	191.9	7.4	$792.67
SC	518	M16	84	486	66.3	12	39.1	26	20.3	40.9	96.2	157.3	196.4	7.5	$816.26
SC	518	M2	83	483	57.8	12	35.6	27	21.2	43.3	88.1	152.6	188.2	7.1	$732.00
SC	518	O3	82	494	59.7	12	37.2	27	20.6	41.9	89.8	152.3	189.5	6.9	$787.16
SC	**HIGH Means**		**82**	**478**	**55.0**	**12**	**35.4**	**28**	**20.9**	**42.5**	**88.2**	**151.6**	**187.0**	**6.8**	**$647.45**
SC	388	AA32	87	361	47.6	11	22.5	24	21.5	43.9	90.0	155.4	177.9	7.3	$746.39
SC	388	AA93	90	355	47.9	10	23.5	23	24.0	46.5	79.7	150.2	173.7	7.7	$781.66
SC	388	CF36	70	342	26.6	16	20.1	36	17.3	27.7	95.8	140.7	160.8	4.4	$179.34
SC	388	CF40	83	350	50.9	12	23.9	26	19.2	35.9	102.1	157.3	181.2	6.9	$685.56
SC	388	M15	84	347	56.1	12	25.2	26	19.2	33.6	102.7	155.4	180.6	6.9	$791.67
SC	388	M16	84	364	53.9	12	26.1	26	19.2	35.8	102.5	157.5	183.6	7.0	$781.72
SC	388	M2	86	347	54.8	11	24.5	25	20.1	35.8	96.5	152.4	176.9	7.1	$800.36
SC	388	O3	81	358	45.5	13	24.6	28	18.8	35.0	98.1	152.0	176.6	6.3	$702.23
SC	**Low Means**		**83**	**353**	**47.9**	**12**	**23.8**	**27**	**19.9**	**36.8**	**95.9**	**152.6**	**176.4**	**6.6**	**$683.62**
SC Means			**82**	**415**	**51.4**	**12**	**29.6**	**27**	**20.4**	**39.7**	**92.1**	**152.1**	**181.7**	**6.7**	**$665.53**
Grand Means			**80**	**411**	**47.7**	**13**	**28.9**	**29**	**19.5**	**37.4**	**94.8**	**151.7**	**180.7**	**6.2**	**$632.33**

Significance of tested treatments

The treatment factors and their significance (alpha = 0.05) related to the impact of site, initial planting density, and genotype on thinning age, thinning volume, clear-cut age, MAI, and BLV are shown in Table 4.5. Site and genotype were highly significant on all response measures excepting thinning volume. No difference in thinning volume due to site or genotype was expected due to the thinning trigger being based on achieving a target height of 50 feet. With this thinning trigger, site and genotype effects would be expressed in shifts in the age of thinning. Initial planting density was significant for thinning volume. No interactions were significant.

Table 4.5 p-values of tested effects of site, genotype, and initial planting density and their interactions on Thin Age, Thin Volume, Clearcut Age, Clearcut Volume, MAI, and BLV. Bolded values are significant at alpha = 0.05.

Effect	Thin Age	Thin Volume	Clearcut Age	Clearcut Volume	MAI	BLV
Site	**<.0001**	**0.0141**	**<0.001**	0.4945	**<0.001**	**<0.001**
Genotype	**<.0001**	**<0.0001**	**<.0001**	**<0.0001**	**<0.001**	**<0.0001**
Site x Genotype	0.2225	0.4895	0.5643	0.4843	0.4575	0.4050
Density	0.1396	**<0.001**	0.1453	0.2169	0.1687	0.1184
Site x Density	0.6197	0.3801	0.9633	0.6996	0.8784	0.9394
Genotype x Density	0.9141	0.8947	0.7759	0.8559	0.6381	0.3759
Site x Genotype x Density	0.8482	0.9729	0.9095	0.6492	0.8874	0.8665

Thinning Age

Both site and genotype were highly significant in determining thinning age. The average thinning age across all treatments was 13 years (Table 4.4). Mean thinning age on the SC site was 12 years versus 14 years on the GA site.

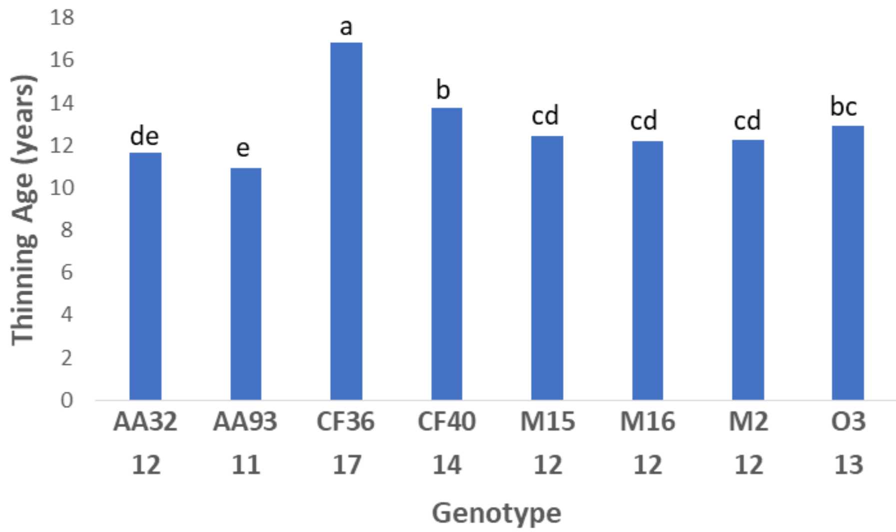

Figure 4.1 Projected thinning age at dominant/codominant height of 50 ft for eight genotypes grown at two densities (388 TPA and 518 TPA) on a SC coastal site and a GA upland site. Genotype means with the same letters do not differ significantly from each other.

Averaged across sites and densities, thinning age ranged from age 11 to age 17 (Figure 4.1) for the genotypes. At the SC site, the order for thinning readiness (rate at reaching the 50 ft height threshold) was AA93 (10 years) < AA32 (11 years) < M2 = M15 = M16 = O3 = C40 (12 years) < C36 (16 years) (Table 4.4). At the lower resource GA site, thinning age ranged from age 12 to 18 years. The order of thinning age was AA93=AA32 (12 years) < M2 = M15 = M16 (13 years) < O3 (14 years) < C40 (15 years) < C36 (18 years) (Table 4.4).

Thinning Volume

Only the initial planting density treatment was significant on thinning volume removals (Table 4.5; Figure 4.2). There were no significant interactions. The overall average was 29 tons. The low-density plots averaged 23 tons/acre removed compared to the high density plot removal average of 35 tons/acre. Planting 518 TPA versus 388 TPA resulted in an average removal of 12 tons/ac more at the first thin. No significant thinning volume effects due to genotype or site were expected because by definition stands were grown to the same trigger thinning height.

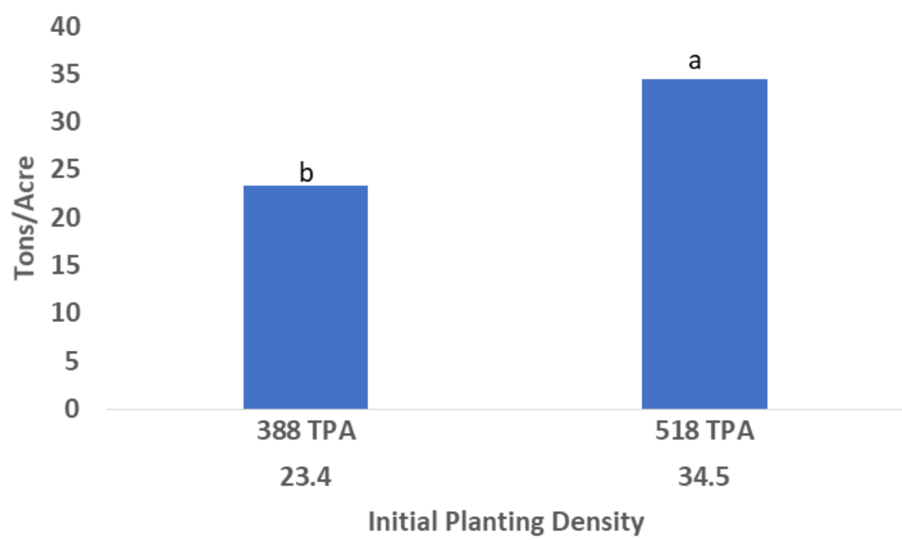

Figure 4.2 Average across site and across genotype projected thinning removal tons for two initial planting densities of eight genotypes on a SC coastal site and a GA upland site. Initial planting density means with different letters are significantly different from each other.

Clearcut Age

Site and genotype were significant on clearcut age (Table 4.5). Initial planting density was not a significant factor in determining clearcut age. No interactions were significant.

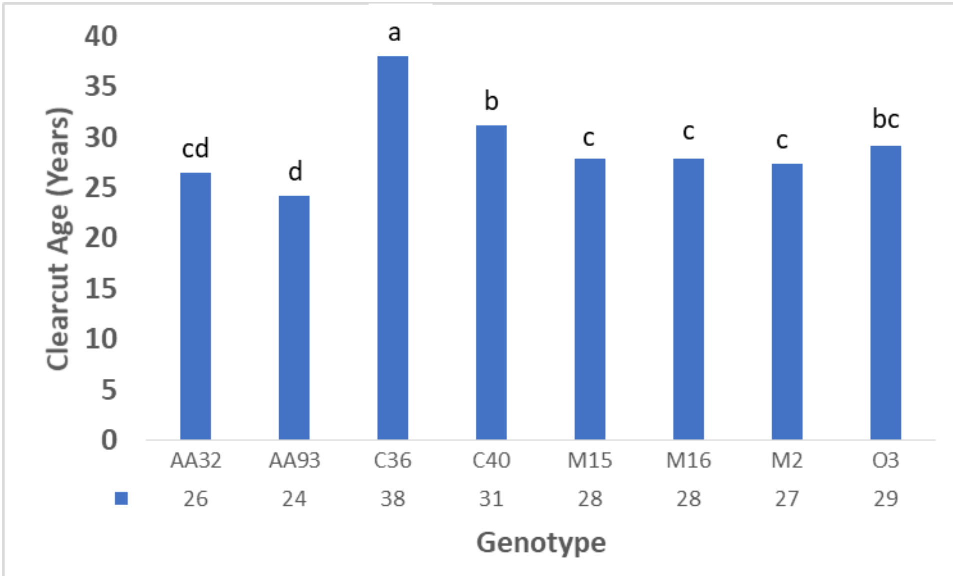

Figure 4.3 Clearcut age at 85 ft for eight genotypes grown at two densities (388 TPA and 518 TPA) on a SC coastal site and a GA upland site. Genotype means with the same letters do not differ significantly from each other.

The mean clearcut age across sites was 29 years; averaging 27 years at the SC site and 31 years at the GA site. Choice of site impacted clear-cut age by four years (13% reduction in investment period).

Across sites and densities, mean clearcut age by genotype ranged from age 24 (clone AA93) to age 38 (clone C36) (Figure 4.3). The selection of planting clone AA93 versus clone 36 decreased the investment period by 37%. Excluding non-commercial clone C36, the selection of planting clone AA93 versus commercial clone C40 decreased the investment period by 23%.

At the SC site, clearcut age ranged from 23 to 37 years (Table 4.4). The ranking was as follows: AA93 (age 23) < AA32 (age 25) < M2=M15=M16 (age 26) < O3=C40 (age 28) < C36 (age 37) (Table 4.4). The ranking was similar at the GA upland site, but with a little more differentiation: AA93 (age 26) < AA32 (age 28) < M2=M16 (age 29) < M15 (age 30) < O3 (age 31) < C40 (age 35) and C36 (age 40).

Clearcut Volume

Clearcut volume and product tonnage distributions are shown in Table 4.4. No significant difference comparisons were made because thinning and clearcut triggers were based on stands attaining a "trigger" height, resulting in fairly similar expected standing volumes for all treatments but occurring at different ages. Differences in production due to assigned treatments are better evaluated by comparing their effects on MAI.

Mean Annual Increment (MAI)

Production differences over the rotation due to site, genotype, and initial planting density were evaluated by comparing the MAI of stands grown to a final height of 85 feet and then clearcut (Table 4.4). Site and genotype were significant on MAI (Table 4.5). No interactions were significant.

MAI averaged 6.4 tons/acre/year across both sites (Table 4.4; Figure 4.4). The SC coastal site averaged 6.8 tons/acre/year vs. 6.0 tons/acre/year of production on the GA upland site. This difference represents a 13.3% increase in annual weight production rate gained from growing timber on a SC coastal site versus a GA upland site.

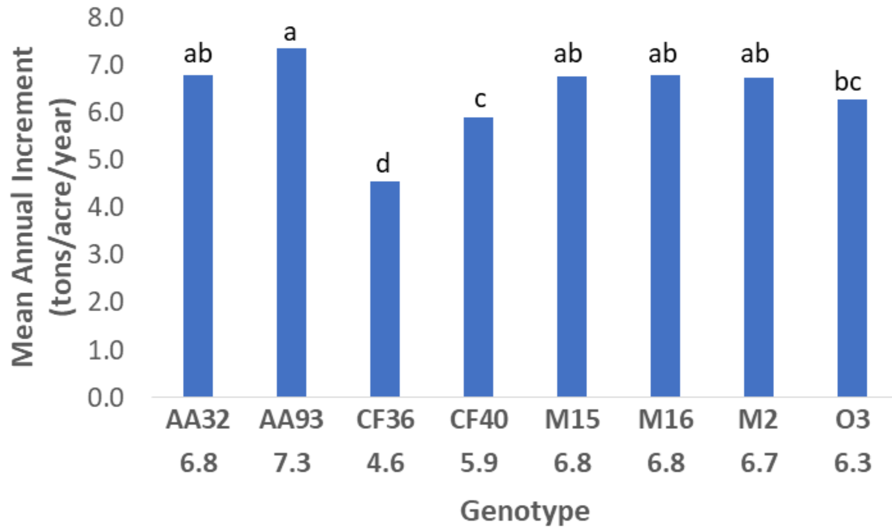

Figure 4.4 Projected mean annual increments for eight genotypes grown at two densities (388 TPA and 518 TPA) on a SC coastal site and a GA upland site. Genotype means with the same letters do not differ significantly from each other.

Across sites and densities, genotype specific MAI ranged from a low of 4.6 tons/acre/year (C36) to a high of 7.3 tons/acre/year (AA93). AA93's production rate was significantly greater than O3 (6.3 tons/acre/year), C40 (5.9 tons/acre/year) and C36 (4.6 tons/acre/year). AA32, M2, M15, and M16 had similar production rates to each other, all between 6.7 and 6.8 tons/acre/year. Planting AA93 versus C36 increased production by 63%. Planting AA93 versus commercial clone C40 increased production by 24%.

On the GA upland site, genotype impacts resulted in a range of average (across density) MAI from a low of 4.9 Gton/ac/yr for C36 to a high of 6.8 Gtons/ac/yr for AA93. This represents a 39% difference in MAI production on the GA site due to genotype selection.

On the SC site the mean MAI ranged from 4.7 Gtons/ac/yr (C36) to a high of 7.9 Gtons/ac/yr (AA93). This difference in MAI due to choice of genetics is 68%.

Bare Land Value (BLV)

Calculated BLV's for the different treatment plots at both sites are shown in Table 4.4. Site and genotype effects were highly significant on BLV (Table 4.5). No interactions were significant.

The GA upland site mean BLV ($599) was lower than the SC coastal site mean BLV ($666) (Table 4.4). This represents an 11.2% increase in BLV over the GA site. The BLV rank in genotypes across sites and densities was M16 ($764) > M15 ($760) > M2 ($743) > AA93 ($732) > O3 ($723) > AA32 ($653) > C40 ($488) > C36 ($197) (Figure 4.5). The BLV for M16 ($764) was significantly greater than that of all other genotypes. The BLVs for C40 and C36 were significantly less than the BLVs for the other six genotypes. The range of BLV across the genotypes was $567/acre, representing a 288% increase in BLV going from non-commercial clone C36 to M16. Comparing the BLV's of M16 and commercial clone C40 shows an increase of 57% in BLV.

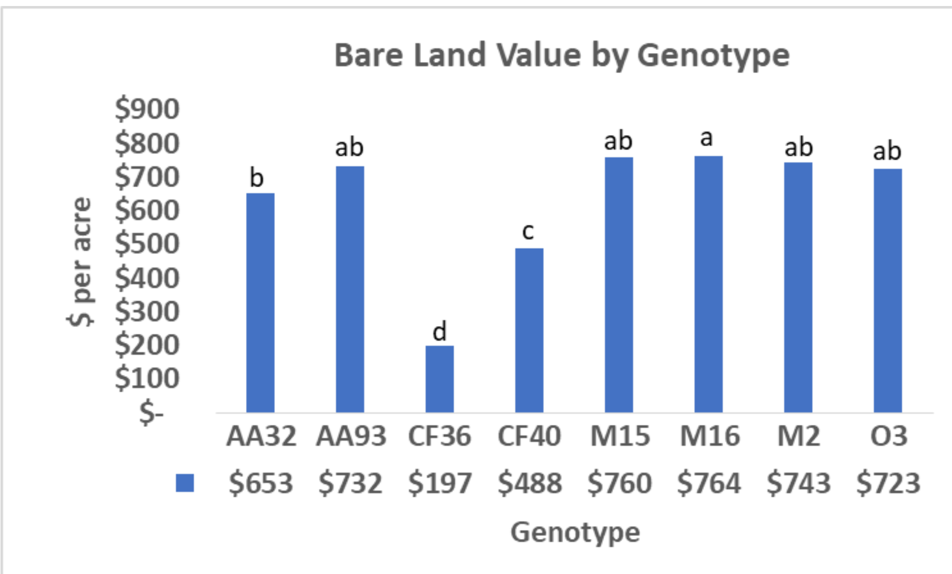

Figure 4.5 Bare land values (BLV) for eight genotypes planted at two densities under operational management at a coastal site in Berkeley County, SC and an upland site in Marion County, GA. Genotype means with the same letters do not differ significantly from each other.

Tree Improvement (TI) Level BLV Comparisons

At the TI-level, site and genotype are significant on BLV with p-values of 0.0195 and <0.001 respectively. Density is not significant (p-value of 0.1768) and no interactions are significant. CMP ($725), OP ($701), and RC-clones ($660) BLV's are not significantly different. The SE-clones BLV ($298) is significantly lower than all other TI-levels (Figure 4.6).

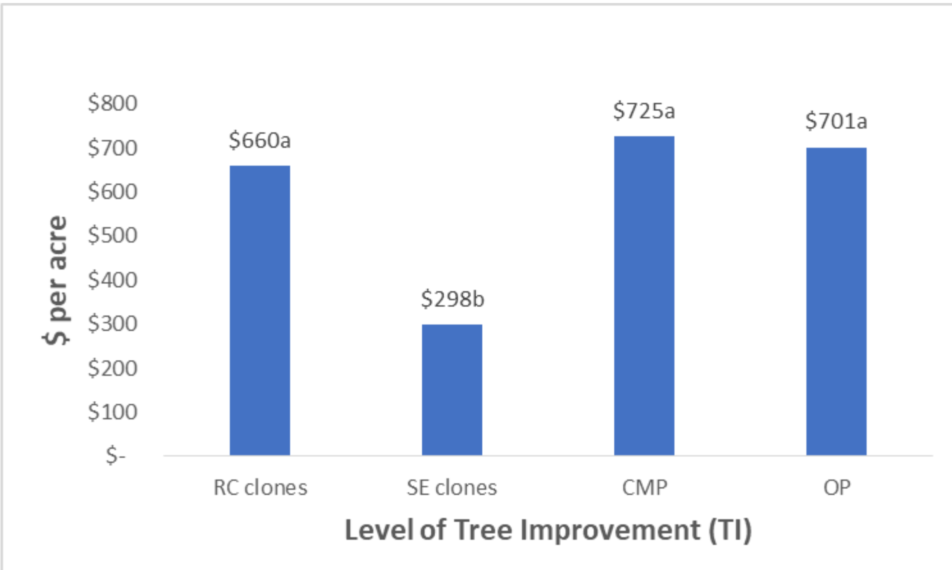

Figure 4.6 Bare land values (BLV) for trees from levels of tree improvement grown at two densities with eight total genotypes (2 rooted cutting clones; 2 somatic embryogenesis clones; 3 control mass pollinated (CMP) crosses; and one open pollinated (OP) family) on a GA upland site in Marion County. Means followed by the same letters do not differ significantly from each other.

GA Upland Site Defects and Observed Stem Grades

Stem grades and defects were assessed for the GA upland treatment plots after the completion of the 13th growing season. The ANOVA analysis of significance is shown in Table 4.6.

Table 4.6 Analysis of Variance results for mean stem quality grade (SQG) and stem quality defects including fusiform rust, forking, crook, suppression, and broken tops for eight genotypes at two initial planting densities grown under operational culture at an upland site in Marion County, GA. Bolded P-values are statistically significant at an alpha of 0.05.

Effect	Rust	Fork	Crook	Suppression	Broken Top	WTG
Block	0.9497	0.3875	0.3757	0.4752	0.3652	0.8507
Genotype	**<0.0001**	**<0.0001**	0.659	0.0694	0.4687	**<0.0001**
Density	0.0646	**0.0348**	0.325	0.2500	0.1655	0.0571
Genotype x Density	0.6439	0.2563	0.3845	0.1545	0.2814	0.9595

Genotype effects were significant on rust incidence, forking incidence, and mean whole tree grade. Density effects were significant on forking. Block was not significant. There were no significant interactions. Mean stem defects are summarized for the eight genotypes in Table 4.7.

Table 4.7 Age-13 stem defects for eight genotypes planted at two densities on an upland site in Marion County, Georgia with operationally intensive establishment. Means followed by the same letter are not significantly different from each other.

Genotype	Rust	Fork	Suppression	Crook	Broken Top
A32	0% c	3% c	1% a	1% a	0% a
A93	2% c	0% c	0% a	0% a	1% a
C36	59% a	2% c	5% a	0% a	0% a
C40	0% c	3% bc	4% a	1% a	0% a
M15	14% bc	7% abc	2% a	0% a	2% a
M16	26% b	10% ab	2% a	1% a	1% a
M2	18% b	6% abc	1% a	1% a	0% a
O3	18% b	11% a	1% a	2% a	1% a
Averages	17%	5%	2%	1%	1%

The most frequent stem defects were stem rust (Cronartium quercuum f. sp. Fusiforme) and forking (Table 4.7). Stem rust incidence on living stems averaged 17% at the GA upland site. The three commercial clones (AA93, AA32, and C40) reduced rust to

3% or less. Clone C36 and CMP cross M16 had 59% and 26% stem rust infection. Stem rust infection averaged 18% and 19% for the OP and CMP genotypes.

Forking is the second most frequent stem defect observed at the GA site (Table 4.7). Forking in the clone genotypes ranged from zero (AA93) to 3% (AA32 and C40). OP3 had the highest forking incidence (11%). The three CMP genotypes averaged 7% forking collectively, with M16 having the highest forking of that level of tree improvement at 10%.

<u>Stem Grades Observed at The GA Upland Site:</u>

Genotype effects on stem quality grade (SQG) were significant. Density and genotype by density were not significant. Mean SQG by genotype is shown in Figure 4.7.

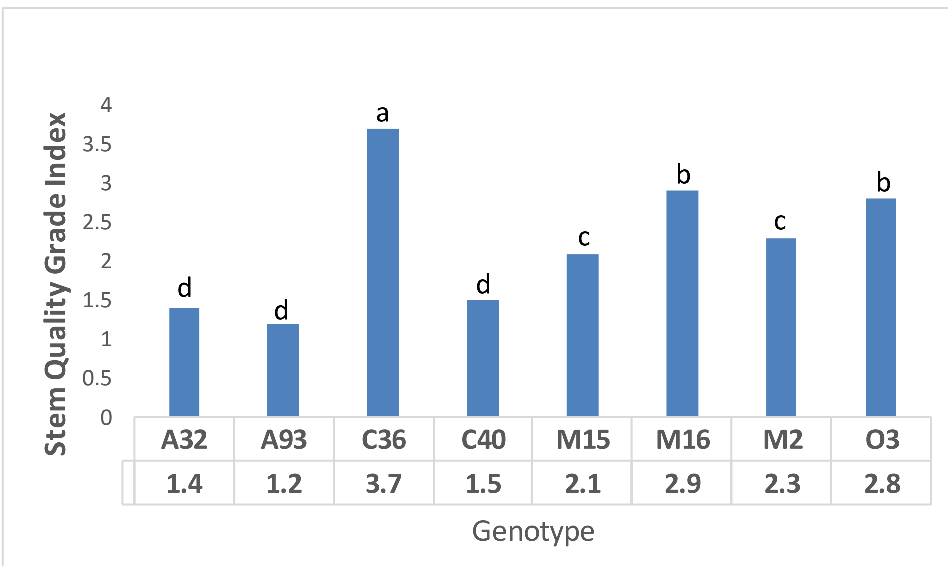

Figure 4.7 Age 13 mean stem quality index (SQI) for eight genotypes planted at two densities managed under an operational regime on an upland site in Marion County, GA. Genotype means with the same letters do not differ significantly from each other.

Stem quality index on the GA upland site ranged from 1.2 to 3.7 (Figure 4.7). The order from highest grade to least was as follows: AA93 (1.2) > AA32 (1.4) > C40 (1.5) >

M15 (2.1) > M2 (2.3) > O3 (2.8) > M16 (2.9) > C36 (3.7). The stem quality of clones AA93, AA32, and C40 was significantly better than that of all other genotypes. Crosses M15 and M2 were significantly better than M16, O3, and C36.

An average of 75% of the stems in the 518 TPA regime were graded as quality ST (Grades #1 and #2) as compared to 67% of stems in the 388 TPA regime, a difference of 8%.

Genotype had a large impact on the percent of quality stems. In the 518 TPA regime, the range in percent quality stems for commercial genotypes was 57.8% (M16) to 98.7% (AA93) (Table 4.8). In the 388 TPA regime, the percentage of quality ST stems for commercial genotypes ranged from 47% (M16) to 94.8% (AA93).

Table 4.8 Age 13 stem quality grades and product use quality summary for eight genotypes planted at two densities on a GA upland site in Marion County, GA.

			Grade						Quality	
Genotype	**Density**	**Survival**	**Poles**	**#1**	**#2**	**#3**	**#4**	**#5**	**Dimensional**	**Pulpwood**
A32	518 TPA	96.7%	29.2%	42.5%	20.3%	2.9%	1.7%	3.4%	92.0%	8.0%
A93	518 TPA	91.7%	59.6%	29.5%	9.6%	0.0%	0.0%	1.3%	98.7%	1.3%
C36	518 TPA	81.7%	9.4%	19.6%	7.5%	1.4%	0.7%	61.4%	36.5%	63.5%
C40	518 TPA	81.1%	21.3%	59.8%	15.0%	0.0%	1.3%	2.7%	96.0%	4.0%
M15	518 TPA	83.9%	28.5%	31.9%	13.8%	1.3%	4.6%	19.8%	74.2%	25.8%
M16	518 TPA	84.4%	12.9%	23.9%	20.9%	7.8%	1.9%	32.5%	57.8%	42.2%
M2	518 TPA	89.4%	25.6%	32.0%	16.4%	4.1%	0.6%	21.3%	73.9%	26.1%
O3	518 TPA	88.3%	9.3%	30.0%	28.0%	3.4%	4.0%	25.3%	67.3%	32.7%
Means	**518 TPA**	**87.2%**	**24.5%**	**33.6%**	**16.4%**	**2.6%**	**1.9%**	**21.0%**	**74.5%**	**25.5%**
A32	388 TPA	92.6%	22.6%	47.2%	24.5%	0.8%	2.4%	2.5%	94.3%	5.7%
A93	388 TPA	94.8%	43.9%	40.6%	10.3%	0.0%	0.0%	5.2%	94.8%	5.2%
C36	388 TPA	80.7%	6.5%	19.6%	2.6%	0.0%	0.9%	70.4%	28.7%	71.3%
C40	388 TPA	87.4%	15.3%	50.5%	12.8%	9.9%	4.3%	7.2%	78.6%	21.4%
M15	388 TPA	88.1%	29.4%	31.2%	12.6%	3.3%	4.2%	19.3%	73.1%	26.9%
M16	388 TPA	83.0%	8.9%	23.0%	15.2%	7.2%	4.5%	41.3%	47.0%	53.0%
M2	388 TPA	87.4%	22.3%	27.4%	17.0%	3.8%	3.8%	25.7%	66.7%	33.3%
O3	388 TPA	88.9%	6.6%	25.1%	18.5%	12.9%	4.6%	32.4%	50.1%	49.9%
Means	**388 TPA**	**87.9%**	**19.4%**	**33.1%**	**14.2%**	**4.7%**	**3.1%**	**25.5%**	**66.7%**	**33.3%**
Grand Means		**87.5%**	**21.9%**	**33.4%**	**15.3%**	**3.7%**	**2.5%**	**23.2%**	**70.6%**	**29.4%**

In addition to the percent quality stems, the percentage of pole quality stems was evaluated. The across genotype average percent poles in the 518 TPA regime was 24.5%. For the 388 TPA regime the average percent pole quality stems was 19.4% or 5.1% less than that observed for the 518 TPA regime. Specific genotype effects on pole quality ranged from a low of 9.3% (O3) to a high of 59.6% (AA93) in the 518 TPA regime and from 6.6% (O3) to a high of 43.9% (AA93) in the 388 TPA regime.

GA Upland Site Grade-Adjusted BLV's

For the GA upland site, the stem grades were applied to adjust the projected clearcut forest product tonnage estimates, including an upward adjustment of sawtimber volume for pole quality percentages and a downward adjustment for pulp quality percentages. Comparing the means for these grade-adjusted calculated BLVs, genotype was highly significant at p-value = <0.0001. No additional main treatments or interactions were significant

The grade-adjusted BLV's are shown in Figure 4.8. The rank of the grade-adjusted BLV's from greatest to least was AA93 ($621) > M15 ($573) > M2 ($536) > AA32 ($494) > M16 ($472) > O3 ($466) > C40 ($259) > C36 ($14). AA93's BLV was statistically similar to that of M15 and M2 but greater than all other genotypes. SE clones C40 and C36 BLV's were lower than all other genotypes.

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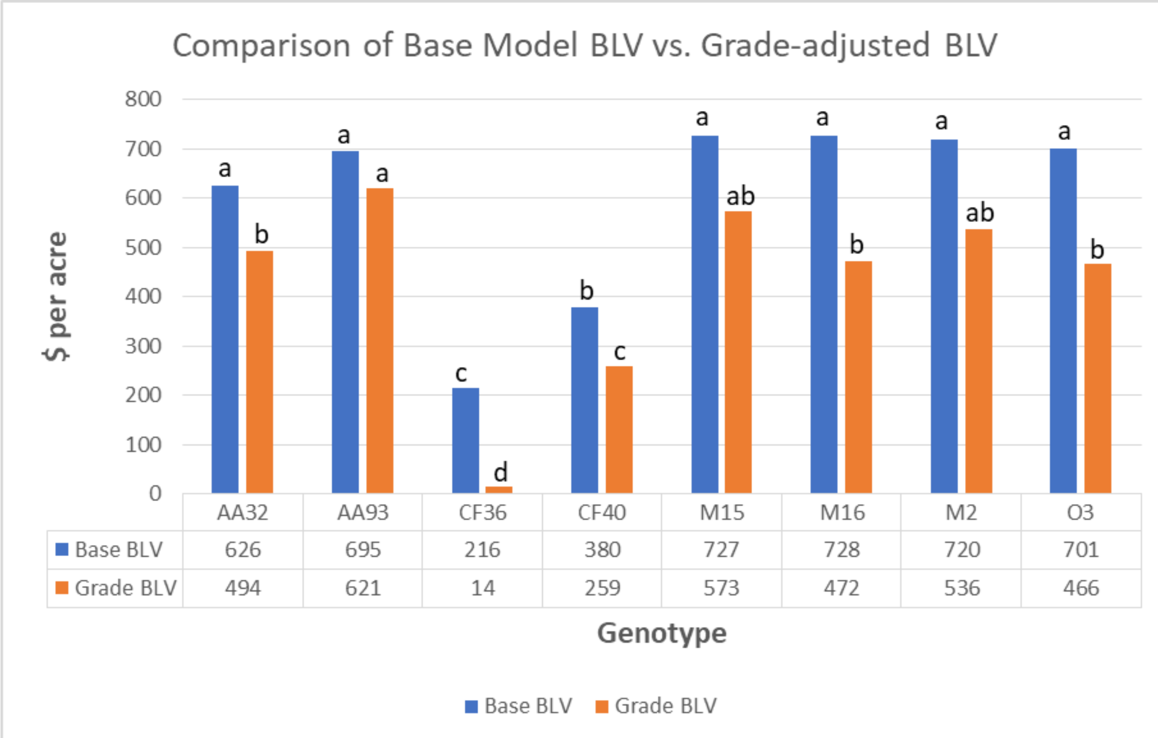

Figure 4.8 Comparison of base model BLV and Grade-adjusted BLVs for eight genotypes planted at two densities on a GA upland site in Marion County. Genotype means within comparison case with the same letters do not differ significantly from each other.

Main effects were evaluated for impact on Grade-adjusted BLV for the four levels of tree improvement. Genotype was significant at p-value = > 0.001. Density and block were not significant and no interactions were significant.

The BLV's are shown in Figure 4.9. The grade-adjusted BLV rank from highest to lowest was RC Clones ($557) > CMP ($527) > OP ($466) > SE ($136). The SE clones BLV is significantly lower than all other genotypes. The other levels are not significantly different.

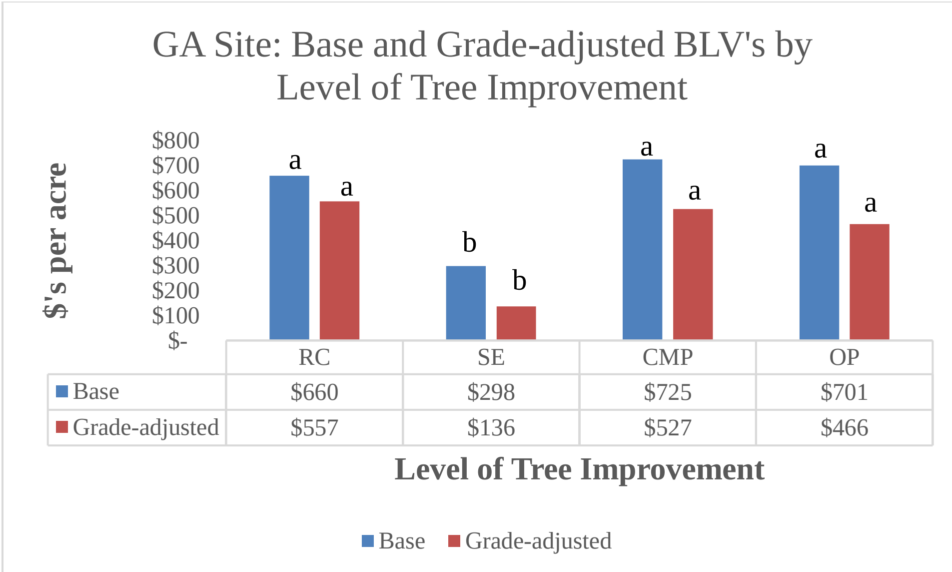

Figure 4.9 Mean BLV's for levels of tree improvement including rooted cutting clones, somatic embryogenesis clones, control mass-pollinated cross, and open pollinated family entries planted on a GA upland site in Marion County. Means within BLV comparison case with the same letters do not differ significantly from each other.

Discussion

This study provides a strong operational case study for comparing the impacts of site, genotype and density on investor returns in GA and SC. Investors must make decisions on the front end of the investment, at the time of land purchase and plantation establishment that, with the exception of some mid-rotation adjustment options, will result in a product class mix that matures in an unknown future market. While future markets are unknown, some rules of finance are known and can be managed. These rules include the time value of money impacts, i.e. upfront investment magnitudes, mid-rotation and final harvest magnitudes, and downstream cash flow timings all have a large impact on the investment returns eventually realized.

Assuming hunting lease payments are offset by taxes and management costs, the primary incomes from a pine plantation come at the time of thinnings and the final harvest.

Shortening either or both periods between the cost of establishment and the cash flow, assuming strong positive flows at the time, can help improve returns. In this operational case study, choice of investment site was statistically significant on both thinning age and clearcut age. Operating on a GA upland site versus a SC coastal site delayed thinning by one year and delayed the final harvest returns by two years. This delay can result in decreased return but also allows increased exposure to environmental risk and delayed deployment of new plantation and genetic technologies. Density did not have an effect on thinning or clearcut age. This was partly due to the limited difference in density between the two treatments (only 130 TPA), 388 TPA vs 518 TPA, but also due in large part to the defined thinning trigger being set as height versus diameter driven basal area. While foresters often use rules for a thinning trigger to include a threshold of 120 to 140 square feet of basal are per acre, many traditional sawtimber markets in the southeast US require a taller tree before they will consider a plantation commercial for thinning. In our case study we used a dominant height of 50 ft, which would be an average height of 45 ft to 47 ft in general, as our trigger to initiate the thinning. We used a dominant height of 85 ft to initiate the final clearcut harvest. For most sawtimber producing regions in the southeastern US, and for the higher growth trajectory stands evaluated, this is a very realistic end-of-regime target.

Harvest timing was most affected by the genotype treatment. Clone AA93 reached the designated thinning height by age 10 on the SC coastal site and age 12 on the GA upland site (Table 4.4). In comparison, OP3 required an additional two years to reach feasible thinning height on both sites, and SE clone C36 required six additional years. This is a major delay in cash flow timing on both counts. For clearcut timing, clone AA93 reached the 85-foot threshold in 23 and 26 years on the SC and GA sites respectively (Table 4.4). Clone AA93 allocates growth into height (Table 2.7) and has a different DBH/HT ratio (Table 2.8) and this impacts harvest timing and subsequently BLV. In contrast, OP3 requires 28 to 31 years on both sites respectively. This delay represents a 19% to 22% increase in exposure to environmental risks and the time value of money influence. The full range of genotype influence on clearcut harvest in this study, was a delay of 14 years (C36) averaged across both sites, or a negative delay of 57%.

In our study, the residual post-thinning target was set at 180 trees per acres, with a goal of leaving the best quality trees and thinning 'from below' or removing the culls. This target number represents a number of trees that can be carried to final harvest in a reasonable time period while still pushing the majority of the trees into the higher valued product classes (Table 4.4). Thinning volume was not significantly affected by genotype or site in this study. Thinning volume was affected by initial planting density (and subsequent survival), with more trees and significantly more pulpwood tonnage removed in the high density plots at the time of the first thinning. The low density plot thinning removed only 23.4 tons while the high density plot produced a more efficient 34.5 tons/acre (Figure 4.2).

Mean annual increment is a function of growth potential and site occupancy, as well as silvicultural management quality and genetic leverage (Fox et al., 2007). In our projection study, the initial planting density spread of 130 trees was not significant on MAI. The choice of operating on a SC coastal site versus a GA upland site had a positive impact of adding 0.8 tons/acre/year of growth (moving from 6.0 to 6.8 tons/acre/year). The choice of genotype had a much larger impact. Planting the highest yielding genotype, AA93 at

MAI of 7.3 tons/acre/year, versus the lowest yielding genotype, C36 with an MAI of 4.6 tons/acre/year, increased MAI by 2.7 tons per acre per year. This contrast, expressed over even a 25 year rotation, equates to 67.5 tons of merchantable wood in an equal rotation.

Investors make a choice on planting density and seedlings up front and the differences in allocated resources per tree and genetic leverage play out over the rotation. In the scenarios in this study, initial planting density is not significant on BLV, while genotype is highly significant. Without including the grade and defect information in the BLV calculation, through the estimated downgrading of products, M16 ranks out as the genotype with the highest BLV and therefore would generally be the purchase and deployment selection of choice. In this base comparison without the grades incorporated the conclusion is that the RC clones do not increase growth enough to justify their increase upfront cost. While their exhibited site indices (Table 3.4) are higher, their decreased basal areas driven by lesser diameter allocation per unit of height growth (Table 2.8) do not produce enough additional gains to justify the added investment.

In contrast, when the grades are injected into the calculation and have their effect on product class distribution, AA93's BLV exceeds that of M16 (Figure 4.8). Similarly, within the CMP grouping, M15's BLV exceeds that of M16. The impact of stem grades change the ranking of the individual genotypes.

Seedling deployment decision is currently often made and volume and value response is often modeled at the level of tree improvement. BLV comparisons from this study highlight the importance of estimating yields, grades and subsequent product class distribution and BLV at the genotype level. Comparison of the TI-level group mean BLV's in Figure 4.9 would suggest that RC clones and advanced control crosses have no statistically significant value over conventional OP tree improvement. Alternatively, deployment of the best ranking CMP cross (M15) in this study significantly increases investor return as compared to family O3 deployment.

Conclusions

Calculation of BLV for the different site, density, and genotype treatment options allows a comparison of the culminating effects of these important rotation decision points. It incorporates genotype attributes (growth potential, DBH/HT ratio impacts on BA and DBH, and survival trends), site characteristics (soil type, silvicultural needs, temperature and precipitation trends), initial planting densities, and market rates (for seedlings, site preparation and management costs, forest product stumpage rates) and estimates the magnitude of impact and ranks the economic impact of the treatments and treatment combinations for a potential investor.

In this study genotype has the largest effect on BLV. The choice of genotype impacted BLV by 57% for the commercial options, as compared to site impacts of 11% and density impacts that were non-significant at the 130-TPA spread and under the rotation length and management assumptions in the scenarios considered here.

The genotype grading on the GA upland site demonstrates the potential for high pole production with lobolly pine using unique ideotypes (Table 2.2) like rooted cutting clone AA93 (52% poles) and CMP M15 (29% poles). Clone AA93 has small branching characteristics, a larger DBH/HT ratio, and strong straightness. Clone AA93 moved from a BLV ranking of 5th in the base case scenario to a grade-adjusted ranking of #1.

The site and genotype were significant on level of tree improvement BLV ranking but this was highly impacted by the poor performance of clone C36 and limited performance of C40. The SE clones were poor (C36) to average (C40) performers in this economic evaluation study. The RC-clones were some of the best to moderate performers. All CMP were strong in regards to BLV and showed consistent improvement in investor return as compared to a strong industry check represent in open pollinated O3.

Literature Cited

Amateis, R.L., Burkhart, H.E., Allen, H.L., Montes, C. 2001. FastLob (A stand-level growth and yield model for fertilized and thinned loblolly pine plantations).

ArborGen. 2017. www.arborgen.com

Fox, T.R., Jokela, E.J., Allen, H.L. 2007. The development of pine plantation silviculture in the southern United States. Journal of Forestry. 105 (7): 337-334.

Jansson, G., Li, B. 2004. Genetic gains of full-sib families from disconnected diallels in loblolly pine. Silvae Genet. 53:60-64.

Lang, A., Baker, S. Mendell, B. 2012. Forest Management Practices of Private Timberland Investors and Managers in the US South. Forest Resource Association Technical Report 16-R-17.

Li, B., McKeand, S.E., Weir, R.J. 1999. Tree improvement and sustainable forestry --- impact of two cycles of loblolly pine breeding in the U.S.A. For. Genet. 6:229-234.

Oswalt, S.N., Miles, P.D., Pugh, S.A., Smith, W.B. 2018. Forest Resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-XXX. Washington, DC: US Department of Agriculture, Forest Service, Washington Office.

Perdue, J.H., Stanturf, J.A., Young, T.M., Huang, X., Dougherty, D.S., Pigott, M.P., Guo, Z. 2017. Profitability potential for Pinus taeda L. (loblolly pine) short-rotation bioenergy plantings in the southern USA. Forest Policy and Economics. 83:146-155

Sampson, D.A., Allen, H.L. 1999. Regional influences of soil available water, climate, and leaf area index on simulated loblolly pine productivity. Forest Ecology and Management. 124: 1–12.

SAS Institute. 2011. The SAS systems for Windows. Release 9.2, SAS Inst., Cary, NC.

Stanturf, J.A., Kellison, R.C., Broerman, F.S., Jones, S.B. 2003. Productivity of southern pine plantations: Where are we and how did we get there. Journal of Forestry. 101: 26-31.

Timber-Mart South. 2017. GA Stumpage Prices Quarterly. 2nd Quarter 2017. Athens, GA 30608, www.TimberMart-South.com

Yin, R., Sedjo, R.A. 2001. Is this the age of intensive management: A study of loblolly pine of Georgia's Piedmont. Journal of Forestry 99(12): 10- 17.

CHAPTER 5

OVERALL CONCLUSIONS AND RECOMMENDATIONS FROM AGE-6 COMPARISON OF TREE GROWTH AND EARLY STAND DEVELOPMENT OF EIGHT GENOTYPES GROWN AT TWO STAND DENSITIES ON TWO DIVERSE SITES

This study summarized the effects of genetic deployment of eight genotype at two low to moderate planting densities (388 vs 518 TPA) on a low-resource Georgia upland site and a contrasting high-resource South Carolina lower Coastal Plain site. This study was unique in that it is installed on a fully operational platform, including genetic selections, site preparation and year-1 protection treatments that were being deployed on the land base in 2005. This operation platform allows direct application to real world operational conditions being implemented today. High survival across both sites also contributed to non-confounded comparisons of site, planting density and genotypes.

Site, GA upland versus SC coastal, impacts tree growth and early stand development in two major ways. By age 6, the SC coastal site produced a 12% average increase in basal area and a 6 foot increase in exhibited site index (SI) over that observed for the GA upland site. The added site preparation cost for this increase in growth was $95/acre.

Increasing the planting density from 388 to 518 TPA did not significantly affect exhibited SI by age 6. Density impacts on height (HT) and SI had a p-value of 0.06.

Increased planting density increased mean per-acre basal area by an average of 7 ft^2/ac across sites through 6 growing seasons. Density influences at the SC coastal site were greater (9 ft^2) than at the GA upland site (4 ft^2).

Genotype is the treatment that had the largest impact on early rotation stand development in this study. The relative impacts of genotype are the same at both sites and at both planting densities. There was not a genetic x site or a genetic x density significant interaction on any of the measured performance traits. Genotype did result in age 6 exhibited SI differing by 19 feet on the GA upland site and 21 feet on the SC coastal site. This accelerated growth trajectory results in a range of age 6 basal areas spanning from 28.9 to 60.1 ft^2/acre at the SC site and a range of 25.2 to 50.6 ft^2/acre at the GA upland site. The combined effects of 21 feet difference in exhibited SI and a difference of 25-31 ft2/ac in age 6 basal area should be expected to create large differences in age of thinning, age of clearcut, volume and product yields and stem wood characteristics. Stands with a high age 6 basal area and advanced exhibited SI may incur severe reductions in diameter growth and crown loss before they attain a height or age that they are acceptable for thinning in some markets. It is important for operational managers to make good estimates of potential exhibited SI for new plantation prescribed genotype and planting density systems to avoid advanced stand trajectory management issues.

Genotype selection significantly affected the DBH/HT ratio of study trees. Changing DBH/HT ratios affect estimated per-acre basal area and projected volumes in growth and yield modeling. These ratios may also affect tree strength and bending.

Genotype selection significantly affects stem defects. Stem defects that downgrade production from sawtimber to pulpwood negatively impact and may significantly change the bare land value (BLV) rank of genotypes. Quality dimensional lumber grade percentage ranged from a high of 98.7% dimensional stems for the AA93 518-TPA plots to a low of 28.7% for the C36 388-TPA plots. Alternatively, genotypes with strong straightness, small branching, and average or low taper may increase the investment value of an operational stand by creating high-valued pole-class material. The high density AA93 plots on the GA upland site graded out at a mean of 59.6% pole quality compared to a low grade of 6.5% poles for the C36 388-TPA treatment combination. Genotype impacts are currently not captured well in existing growth and yield models. This limitation must be overcome.

In this study, BLV was evaluated for a base case where age 6 BA, exhibited SI, and surviving trees per acre affected future yields and value. The SC coastal site mean BLV ($666/acre) was 11.2% higher than the GA upland site mean BLV of $599/acre. In the base modeling case, BLV at a 5% discount rate ranged from $197/acre for clone 36 to $764/acre for CMP M16. A grade-adjusted case was applied and compared to the base case. BLV in the grade-adjusted case ranged from $14/acre for C36 to $621/acre for AA93. The grade-adjusted case lowered the BLV of all genotypes options. The applications of the grades changed the BLV rank of the genotypes.

Comparison of level of tree improvement (TI) alone did not significantly affect the calculated BLV's in the Base Case or the Grade-adjusted Case. Investors must look within the levels of tree improvement and select genotypes with high yield potential and quality stem grade characteristics to maximize BLV.