ABSTRACT

ASPINWALL, MICHAEL JOSEPH. Relating Breast-Height Wood Properties to Whole-Stem Wood Properties in Loblolly Pine (Under the direction of Drs. Li and McKeand).

Prediction models describing the relationship between breast-height wood properties (wood density, α-cellulose content, and lignin content) and whole-stem wood properties were developed for juvenile and mature loblolly pine. Both genetic and environmental effects were examined when predicting whole-stem wood properties in juvenile loblolly pine. Also, the relationship between juvenile, transition, and mature wood properties and whole-stem wood properties were analyzed in both juvenile and mature loblolly pine. The juvenile trees used in this study were made up of 24 trees; 4 clones, 3 ramets per clone, replicated over two sites. The mature trees sampled in this study were 20 unrelated 20-year-old trees.

For juvenile loblolly pine, significant differences in all growth and wood property traits, excluding breast-height transition wood lignin content, breast-height juvenile α-cellulose content, and breast-height transition wood α-cellulose content were found between sites. At the Florida and Alabama sites, mean breast-height wood density values were 479.75 ± 8.27 and 424.37 ± 7.23 kg/m³, respectively. Across both sites, mean breast-height wood density values were 450.86 ± 7.96 kg/m³. Mean whole-stem values were 383.66 ± 4.29 and 429.27 ± 7.74 kg/m³ at the Alabama and Florida sites respectively. At the Alabama site, mean breast-height α-cellulose content was 42.12 ± .23%, while mean breast-height α-cellulose content at the Florida site was 42.94 ± .21%. Mean whole-stem α-cellulose content at the Florida site was 41.89 ± .18% and mean whole-stem α-cellulose content at the Alabama site was 41.25 ± .22%. Also, at the Florida and Alabama sites mean breast-height lignin content values were 27.10 ± .17% and 28.22 ± .22%, respectively. Calculated mean whole-stem lignin content was 27.21 ± .15% at the Florida site and 28.59 ± .13% at the

Alabama site. No significant clonal differences were found for any trait except breast-height juvenile wood α-cellulose content and height. Both linear and polynomial models were developed for describing the relationship between breast-height wood properties and whole-stem wood properties. Coefficients of determination for wood density ranged from 0.72 to 0.92 when data from both sites were combined. Across sites, coefficients of determination ranged from 0.43 to 0.73 for α-cellulose and 0.58 to 0.82 for lignin content. Correlations between breast-height wood properties and whole-stem wood properties were high and ranged from 0.84 to 0.92. Significant correlations were also found between breast-height juvenile and transition wood properties and whole-stem wood properties. However, the best predictor of whole-stem wood properties proved to be the entire breast-height pith to bark sample.

For mature loblolly pine, both linear models were developed that described the relationship between breast-height wood properties and whole-stem wood properties. In mature loblolly pine, mean breast-height wood density was 455.25 ± 4.15 $kg/m^3$and mean whole-stem wood density values was 414.52 ± 4.18 kg/m^3. Mean breast-height α-cellulose yield was 41.1 ± .22 % and mean whole-stem α-cellulose yield was 40.77 ± .20 %. Mean breast-height lignin content was 27.94 ± .14 % while mean whole-stem lignin content was 28.41 ± .12 %. On average, breast-height lignin content was about 0.47 % lower than whole-stem lignin content. Coefficients of determination for wood density ranged from 0.27 to 0.85. Coefficients of determination ranged from 0.42 to 0.95 and 0.59 to 0.85 for α-cellulose and lignin content respectively. For juvenile wood, correlations between breast-height wood properties and whole-stem wood properties ranged from 0.62 to 0.92 and correlations with whole-stem wood properties ranged from 0.77 to 0.90 for breast-height transition wood and

from 0.44 to 0.84 for mature wood. Positive correlations were found between lignin measurements and growth measurements (0.12 to 0.24). For mature loblolly pine, the entire breast-height sample was the best predictor of whole-stem wood properties. Depending upon the trait of interest, breast-height transition wood also was an adequate predictor when compared to juvenile and mature wood.

RELATING BREAST-HEIGHT WOOD PROPERTIES TO WHOLE-STEM WOOD PROPERTIES IN LOBLOLLY PINE

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BIOGRAPHY

The author, Michael J. Aspinwall was born May 6, 1981 in Cincinnati, Ohio to Thomas and Maryanne Aspinwall. He spent his childhood in Cincinnati where he graduated from Elder High School in 1999. After high school, he attended Cincinnati State Technical and Community College where he began studying Horticulture. In 2001, he graduated from Cincinnati State with an associate's degree in Landscape Horticulture. In September 2001, he further pursued an education in Horticulture and Crop Science by enrolling at The Ohio State University. Throughout his education, Mr. Aspinwall worked in a variety of horticultural fields including the landscape and nursery industry. Also, during his undergraduate education, Mr. Aspinwall participated in study abroad trips to the United Kingdom and the Dominican Republic. In June 2004, Mr. Aspinwall graduated Cum Laude with a degree in Horticulture and Crop Science while minoring in International Studies.

Mr. Aspinwall enrolled at North Carolina State University in January 2005 where he pursued a Masters of Science in Forestry. Over the next two years, under the direction of Dr. Bailian Li, Dr. Steve McKeand, Dr. Fikret Isik, and Dr. Marcia Gumpertz, Mr. Aspinwall worked in the North Carolina State University - Industry Cooperative Tree Improvement Program. During his Masters education Mr. Aspinwall studied and performed research in the areas of forest genetics and wood properties. Recently, Mr. Aspinwall has decided to further pursue a doctoral degree at North Carolina State University where he will be a research assistant studying forest genetics and tree physiology.

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INTRODUCTION

Tree improvement programs have made enormous genetic improvements to economically important traits such as stem straightness, disease resistance, and volume growth (Li et al. 1999). In addition to these form and growth traits, economically important wood quality traits such as specific gravity (wood density), lignin content, cellulose content, and tracheid (commonly called fibers) length show large amounts of genetic variation (Zobel & Talbert 1984). Specific gravity and tracheid length show especially high levels of inheritance and have shown great gain through genetic manipulation. Within a species, wood quality traits can vary between geographic populations, between trees in a population, and also within a single tree (Zobel & Talbert 1984). Wood property variation in trees can be influenced by environmental conditions and genetic differences. Environmental factors include competition, soil fertility, climate, and water availability. When the same genotypes are planted across different environments there may be a significant amount of interaction. The interaction of genotype and environment together can produce a wide range of differences in wood properties between trees, but genotype × environment interaction is generally small. It has been established for a broad range of species, such as loblolly pine (*Pinus taeda* L.), that density, tracheid length, microfibril angle and chemical properties have distinctive patterns of variation from pith to bark, along the length of the stem for a given ring number, from the pith, tangentially, and within a growth ring (Burdon et al. 2004, Baas 1982, Megraw 1985).

For loblolly pine within-tree variation patterns have been documented and general predictions have been defined for the relationship between some breast-height wood properties and whole-stem wood properties (Zobel et al. 1972, Zobel and Jett 1995, Megraw

1985, Larson et al. 2001, Burdon et al. 2004). For example, specific gravity regression models have been produced by sampling open-pollinated loblolly pine families. However, these relationships represent variation patterns within the loblolly pine species and may not accurately predict the overall variation patterns in wood properties of different genotypes at different ages growing in different environments.

Consequently, there is no specific model for predicting the relationship between wood properties at breast-height (BH) and whole-stem properties for juvenile and mature trees of different loblolly pine genotypes. The usual method for determining the overall wood properties of a tree involves calculating a weighted average by taking several samples at incremental points along the length of the stem. This method of sampling is time consuming, destructive, expensive and is impractical for selecting trees for implementation into tree improvement breeding programs. Therefore, a more feasible method of predicting whole-stem wood properties derived from breast-height samples would be extremely valuable for advanced-generation selection. The development of prediction models would be an extremely valuable and practical tool for breeding programs, and wood and paper science research. As Igartua et al. (2003), stated, "Finding a single sampling point representative for the whole tree simplifies the assessment and comparison between trees and stands."

Wood Property Variation in Loblolly Pine

Specific gravity (wood density) is the first wood property included in this study, and is the most important indicator of wood quality (Williams and Megraw 1994). Specific gravity is the ratio of the dry weight of a given volume of wood to the weight of an equal volume of water (Zobel and van Buijtenen 1989). The specific gravity of a given annual growth ring is a function of the average size of cells, the thickness of the cell walls, and whether or not the cells were produced during the earlywood or latewood portion of the growing season (Larson et al. 2001, Megraw 1985). Mature wood is the portion of the stem where a higher percentage of latewood cells are produced and juvenile wood is the portion of the stem where a higher percentage of earlywood cells are produced. The core and upper sections of the stem are made up of almost entirely all juvenile wood. Juvenile wood has thin-walled cells and low amounts of latewood when compared to mature wood. Hence, mature wood has higher specific gravity. Much of the variation patterns in wood quality traits are either determined or are directly related to the relative amounts of juvenile and mature wood in a given tree. In general, specific gravity gradually increases with age or increases as the number of growth rings increases away from the pith of the tree (Larson et al. 2001). Also, specific gravity decreases as height increases since the percentage of juvenile wood increases up the tree bole (Zobel and Sprague 1998). Overall, specific gravity increases as the number of rings increase outward from the juvenile core. Juvenile wood specific gravity is typically well correlated with mature wood specific gravity (Jett et al., 1991).

Specific gravity is a trait that is highly inherited and is typically the most important trait for a breeding program with the goal of genetic improvement (Zobel and Talbert 1984, Zobel and Jett 1995). The heritability of wood specific gravity in loblolly pine is mostly due to strong levels of additive variance, which allows specific gravity traits to readily be passed from parent to offspring. Devey et al. (1994), found there to be 5 regions harboring QTL for wood specific gravity and these 5 regions explained 23% of the total phenotypic variance for wood specific gravity in a single cross. Moreover, Williams and Megraw (1994), found when testing the genetic covariance structure between juvenile and mature wood that there were strong age-age relationships (0.76 - 0.90) between the juvenile wood of young loblolly pine and older loblolly pine. Specific gravity is the reliable index of the quality and yield of solid wood and paper products and therefore is of critical concern to the wood products industry (Zobel & Jett 1995). There are a variety of methods for calculating specific gravity. The basic laboratory method is volumetric, where the dry weight of a piece of wood is divided by its volume. One of the more recent and more efficient methods for measuring specific gravity is by scanning the wood using x-ray densitometry (Echols 1973, Gwaze et al. 2002, Megraw 1985).

Lignin content is another wood property characteristic that will be included in this study. Lignin is a hydrophobic phenolic material that encases and encrusts the carbohydrate complexes of wood (Winandy and Rowell 2005). At the microscopic level, lignin assists in holding together the different constituents of the cell wall. The stiffness of wood has been correlated with lignin content and lignin is further responsible for the omission of water from the moisture-sensitive carbohydrates (Winandy and Rowell 2005). Lignin is the least understood and most complex chemical in wood, but lignin is the most important facet of wood's capacity to maintain its strength as moisture content is brought into the structure (Winandy and Rowell 2005).

All plants produce lignin, which the plant uses in its cell walls as a structural component. Woody plants in particular have high levels of lignin. This chemical component of wood is influenced by the interaction of developmental, seasonal, and geographic conditions (Sewell et al. 2002). Just as with specific gravity and tracheid length, lignin content is directly related to the type of wood; juvenile or mature. The thicker cell walls of mature wood contain the lowest concentrations of lignin (Saka & Goring 1985).

Furthermore, there can be considerable radial and vertical variation in lignin content within an individual tree trunk. Lignin is strongly associated with the strength of wood and the cost of kraft pulp paper production (Zobel and Talbert, 1984). In kraft pulp paper production, lignin is extracted and the more lignin that is found in a given piece of wood, the higher the cost and the lower the yield (Bendtsen 1978). The reason that lignin affects yield and costs is that more intensive use of chemicals are needed to breakdown lignin during the process of pulping. Not only are costs higher for wood with higher amounts of lignin, but also the time needed to separate the wood fibers and lignin can affect the overall output of a pulp mill. Evidence has also been found that since lignin content is strongly correlated (0.50-0.73) with the specific gravity of wood, it too can be manipulated through genetic improvement (Sewell et al. 2002). Lignin content determination is measured using microanalytical techniques, chemical treatments and near-infrared spectroscopy (Sykes et al. 2003, Sykes et al. 2005, So et al. 2004).

The third wood property included in this study is α-cellulose content. Like lignin, α-cellulose is another chemical compound found in wood that shows variation from pith to bark, as well as vertically throughout the stem. However, lignin and cellulose are inversely related. The more lignin in wood, the less cellulose content there will be. Cellulose is anhydro-D-glucopyranose ring units bonded together by β-1-4 glycosidic linkages (Winandy and Rowell 2005). The covalent bonding within the pyranose rings and between cells makes cellulose exceptionally resistant to tensile stress (Winandy and Rowell 2005). α-cellulose is a highly stable, un-branched polysaccharide that like lignin, is found in the cell wall. All together, α-cellulose is a component of holocellulose and a complex mixture of polymers formed from simple sugars known as hemicellulose's (Smook & Kocurek 1998). Cellulose content is yet another trait that is genetically controlled and also has an economic impact on production. α-cellulose content is related to the amount of pulp which can be produced from wood. Wood with higher α-cellulose content can produce more pulp. Therefore, a mill that can produce more pulp from higher α-cellulose trees can maximize its production efficiency and reduce its costs (Zobel and Jett 1995). Thus, pulp yield and cohesiveness are positively associated with α-cellulose and hemicellulose content, respectively, and energy consumption during pulping is inversely related to lignin content (Smook & Kocurek 1998).

To summarize, variation patterns in loblolly pine wood properties are strongly correlated to levels of juvenile and mature wood. In loblolly pine, juvenile wood forms from the pith of the tree and gradually turns more mature. As stated by Zobel & Talbert (1984), loblolly pine produces juvenile wood up to about the 10^{th} ring. Therefore, juvenile wood is produced up through age six and slowly changes to mature wood between ages six and twelve. However, the number of rings from the pith may not necessarily reflect the transition from juvenile to mature wood because wood properties can vary significantly within a given ring from the pith as well as long the stem (Megraw 1985, Larson et al. 2001). Therefore, levels of juvenile and mature wood change vertically within the bole of the tree. The natural process of maturation is an important cause of variation of wood properties in the vertical direction (Burdon et al., 2004). The basal portion of the trunk contains a higher proportion of mature wood while the top of the tree contains a larger proportion of juvenile wood. For example, basal wood of loblolly pine can produce 800 kg more dry fiber than the same volume of upper logs obtained from the same trees (Zobel and Talbert, 1984). Furthermore, variation patterns in wood properties due to maturation (juvenile and mature wood) can be very complex and may not be easy to assess when comparisons are made between species, genotypes, sites, and silvicultural treatments. The fluctuating variations in economically important traits can cause problems for processing and utilization of timber. Finally, in order to understand relationships between breast-height wood properties and the inherent variation patterns in a given tree, it is critical to have access to information about the site, silviculture and the genetic identity of the samples to be analyzed (Burdon et al., 2004).

Predicting Whole-Stem Wood Properties

Specific gravity data collected by Zobel et al. (1972) was used to develop some regression models describing within tree variation patterns in natural stands of loblolly pine. 270 samples of loblolly pine were taken in Virginia and regression models were developed that showed correlations between weighted average specific gravity at 1.5m and weighted average specific gravity of the whole-tree. The correlation coefficient was very strong and was calculated to be 0.88. Similar correlations were also found for 68 loblolly pines of the same age growing on similar sites. Also, different correlations were found between breast-height and whole-tree values, depending on the method of sampling. For example, increment core-to-total tree coefficients of determination (R^2) values ranged from 0.55 to 0.85 and wedge samples-to-total tree R^2 values ranged from 0.65 to 0.95. Overall, it was found that breast-height specific gravity was about 0.02 to 0.04 higher than whole-tree weighted specific gravity values. Zobel et al., 1972 also stated that breast-height total tree relationships are typically quite similar within loblolly pine. Furthermore, Zobel et al., 1972 recommended using the mature wood portion of increment cores to develop a regression that explained the relationship between breast-height specific gravity and whole-tree specific gravity since juvenile wood can contain chemicals that may distort the accuracy of the correlation. A recommendation was also made that if samples were taken from natural stands, about 80 trees should suffice and 40 to 50 trees sampled from plantations should be sufficient for developing a solid regression model. However, Zobel et al. (1960) found a strong relationship between breast-height and whole-stem specific gravity in loblolly pine when only 14 trees were sampled. It must be emphasized that the trees sampled were from natural stands of un-known genetic material and environmental effects were not assessed. This reinforces the comment made by Burdon et al. 2004, that wood properties among genotypes and environments are not constant.

Megraw (1999) has also done research to further understand how wood quality traits vary in loblolly pine by ring position and height in a given tree. Megraw modeled how stiffness varied and to what degree stiffness was controlled by microfibril angle and specific gravity. Stiffness and microfibril angle will not be involved in this study, but Megraw's study does emphasize the importance of cellulose and specific gravity to wood quality. Most importantly, these results shed some light on creating prediction models for variation of other wood properties throughout the stem. The results of Megraw's work show that specific gravity increases rapidly from pith to bark within the first 1.2 m of the tree. Megraw's results further reiterate how wood quality traits i.e. specific gravity, microfibril angle, and stiffness, are all strongly correlated with juvenile and mature wood.

For various eucalyptus species as well as radiata pine (*Pinus radiata)*, relationships between breast-height wood properties and whole-tree wood properties have also been described. In most of the literature, relationships between BH and whole-tree wood properties seems to be primarily dependent on the species, the method of sampling, the sampling height(s), and the site and/or environments from which trees sampled were growing. The species closest to loblolly pine that has had this relationship examined is radiata pine. Generally, research has shown that variation patterns in wood properties of loblolly pine and radiata pine are very similar (Burdon et al. 2004). In radiata pine, both genotype and site influences have a major impact on variation patterns. Also, the radial variation within the stem of radiata pine is related heavily to ring number, therefore variation according to position along the bole is very predictable (Burdon et al. 2004).   Evans et al. (1997) sampled 2 trees from each of 10 radiata pine clones and 4 trees from another clone. Cores for microstructure analysis were cut from disks at breast-height and five other heights at intervals of 5.5m. SilviScan-1 was then used to make profiles of the distributions of specific gravity and tracheid dimensions. Next, within-tree and within clone averages were estimated from the cross section and height curves. Using SilviScan-1, they found strong correlations between BH wood properties and whole-tree estimates in radiata pine. Furthermore, wood properties within trees of the same clone were very similar and regardless of growth rate, clones had similar wood and tracheid properties (Evans et al. 1997).

A more recent study done by Igartua et al. (2003) involved analyzing wood density and fiber length properties at breast-height to whole-tree wood properties. The samples were taken from two 35 year-old *Eucalyptus globulus* plantations in Argentina. A total of 20 trees were harvested and disks were removed at breast-height, 30%, and 60% of tree height. Using regression models, Igartua et al. (2003) developed prediction equations for this species. The model they developed and the comparisons between actual whole-tree estimates and predicted estimates showed high correlations for wood density over both sites (0.91 and 0.85 respectively). However, the model for fiber length showed a strong correlation on only one site (0.87). Overall, Igartua et al. 2003 concluded that wood density and fiber length cannot be considered equal between sites and more detailed sampling procedures are needed to analyze within tree variation.

Others such as Muneri and MacDonald (1998), used disk, core, and Pilodyn sampling techniques to measure correlated results predicting whole-tree densities for *Eucalyptus globulus* and *E. nitens*. One of their objectives was to determine which method of sampling was the most efficient and accurate for predicting whole-tree wood traits. The five methods they compared were: 1.) taking a single pilodyn reading; 2.) taking pilodyn readings from four sides of the tree (north, south, east and west); 3.) removing a single core sample; 4.) removing a single disk sample; and 5.) taking several disks at 10, 30, 50, and 70% of total tree height. The average means, standard deviations, and variances were calculated for each method and coefficients of variation were calculated for each trait. The two species were divided into 5 and 10 year age classes and were sampled from three different sites. They found disk samples to be the most accurate, explaining 95% of the variation and correlations. Pilodyn samples explained little of the variation (26 to 27%), while cores explained 81 to 82% of the variation. Also, Muneri and Macdonald found that depending on the species, different sampling heights would more accurately predict whole-tree wood density. A follow up study by Raymond and Muneri (2001), found core samples explained 84 to 89% of variation with a sampling height of 1.1m for *Eucalyptus globulus* and 0.7m for *Eucalyptus nitens* being the best sampling heights for predicting whole-tree values.

Raymond et al. 1998, found similar results while working with *Eucalyptus regnans.* They found that different sampling heights were required to acquire a greater whole tree correlation. Furthermore, their results indicate that the reliability of using core samples for this particular species will vary between traits such as density, fiber length, and fiber coarseness. But most importantly, they found correlations between the BH samples and actual whole-tree values ranged from 0.83 for fiber length, 0.70 for density, and 0.59 for fiber coarseness (Raymond et al. 1998). The highest correlations were 0.88 for density and 0.95 for fiber length which were both measured at 15% of the tree height. Breast-height gave the next highest correlations; 0.82 for density and 0.92 for fiber length.

Kube and Raymond 2002 evaluated methods for predicting whole-tree wood density and pulp yield from core samples in *Eucalyptus nitens*. They first determined vertical patterns of variation in wood density, cellulose content and extractives and then they assessed correlations between the core samples and whole-tree values. Using mechanical and chemical processes, data for cellulose content and extractives content was produced and using the water displacement method, wood density was determined. From the data, they developed linear models using analysis of variance, for both wood density and cellulose/extractives content. They found core samples to be efficient predictors of variation in whole-tree density, cellulose content, and kraft pulp yield in the whole-tree for *Eucalyptus nitens*. For density, values decreased between the stump and 10% of the tree height, and then increased linearly to 70% of the tree height. Cores explained 85 to 92% of the variation in whole-tree wood density when site differences were separated and 80% of the variation when all the sites were combined. Cellulose content was found to vary greatly between different heights and increased to 20% of tree height and then decreased up to 60%. Core measurements for extractives content however, were less explanatory with only 56% of total-tree variation being described. With pulp yield, core samples explained 78% of total-tree variation. Overall, the core sampling method was found to be heavily dependent on the trait being analyzed and the sample height, but core samples did seem to be very valuable predictors of whole-tree values.

A more broad experiment by McKinley et al. 2000 was done on various plantation species in Australia. It was found that variation patterns in whole-tree density for all species within a site and within age classes was large. Overall, much of this literature has shown promising results regarding the relationship between BH wood properties and whole-tree wood properties. Yet, this relationship seems to be dependent on species, sampling procedure, and the traits being measured.

Objectives

There is no doubt about the value of gains from including wood in a breeding program (Zobel & Talbert 1984), and if larger efforts in tree improvement were put into genetically improving quality characteristics such as wood, mill profitability would be profoundly affected (Carlisle and Teich 1970b). The objective of this research project is to develop prediction models for whole-stem wood properties in order to select for improvement of wood products. More specifically, the goals are to: 1.) Develop models that are practical and accurately predict whole-stem wood property values for loblolly pine. 2.) Collect a large data set for both juvenile and mature trees and examine variation patterns between different genotypes. 3.) Examine the relationship between breast-height wood properties and whole-stem wood properties while assessing genetic and environmental effects. Most importantly, by predicting the relationship between wood properties from a single point at breast-height and the wood properties throughout the stem, we can more effectively select for genetic improvement of important wood traits. The formal parameters created by a prediction model would be of critical importance when describing variation patterns of various wood properties within the stem. By examining the results of this experiment, tree improvement programs may further advance their selection methods and the forest products industry could advance their production efficiency.

In this study, the hypothesis to be tested is that wood property measurements taken at breast-height can be used to accurately predict whole-stem wood property values in loblolly pine. In addition, this hypothesis will be expanded to test that there is a correlation between juvenile, transition, or mature wood property measurements at breast-height and whole-stem values. The overall results obtained from this research will be used to develop strategies for integrating tree breeding, wood/paper science, and genome technology.

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CHAPTER 1

PREDICTION OF WHOLE-STEM WOOD PROPERTIES FOR JUVENILE LOBLOLLY PINE

Abstract

Relationships between breast-height (BH) and whole-stem wood density, α-cellulose content, and lignin content were evaluated for a set of 14-year-old clones of loblolly pine (*Pinus taeda* L.) growing in Florida and Alabama. Wood disks were cut at breast-height and at eight-foot increments from each tree, and whole-stem weighted averages for each wood property were calculated. Whole-stem wood property weighted averages were calculated and weighted on bolt volume. Both linear and polynomial regression models were developed for describing the relationship between breast-height wood properties and whole-stem wood properties. Coefficients of determination for wood density ranged from 0.72 to 0.92 when data from both sites were combined. Across sites, coefficients of determination ranged from 0.43 to 0.73 for α-cellulose and 0.58 to 0.82 for lignin content. Correlations between breast-height wood properties and whole-stem wood properties were high and ranged from 0.84 to 0.92. Despite site (environmental) differences in wood density, α-cellulose content, lignin content and all growth traits, the whole-stem wood property prediction models among different genotypes of loblolly pine were similar. Over both sites, no clonal differences in breast-height and whole-stem wood properties were found except for breast-height juvenile wood α-cellulose content. There were significant differences between clones for height and no significant genotype by environment interaction was present for any growth measurement. Across sites and genotypes, regression models were effective and accurate for prediction of whole-stem wood properties in juvenile loblolly pine.

Introduction

Historically, tree improvement programs have focused on breeding for genotypes that demonstrate fast growth and excellent form. As a result, the use of fast-growing genotypes, combined with intensive silviculture has dramatically decreased pine plantation rotation ages in the South. In young plantations, a significant amount of wood produced is composed of juvenile wood (Isik and Li 2003, Atwood et al. 2002, Sykes et al. 2003). Since there are tremendous differences in juvenile wood properties between and within trees, and since many wood properties are economically valuable and under a high degree of genetic control, the improvement of wood quality has become a highly emphasized operation (Isik and Li, 2003, Baas 1982, Zobel and Sprague 1998). Within a given tree, we generally know how some wood properties in loblolly pine vary from pith to bark and from the base of the tree moving up the stem. However, the overall patter of variation for most wood properties of interest is strongly influenced by genetic and environmental factors. Furthermore, the pattern of variation along the bole of the tree can influence the overall economic and structural value of the tree. Therefore, selecting genotypes based on their overall whole-stem wood properties is a critical step towards improving the quality of wood produced in southern pine plantations. The problem is that there is no rapid, cost-effective method of assessing many wood properties throughout the length of the stem. The development of prediction models for estimating whole-stem wood property values would be a practical tool that tree breeders could use in selecting genotypes with superior wood properties.

Wood density or specific gravity is the single most important determinant of wood quality in loblolly pine (*Pinus taeda*) (Jett et al. 1991, Williams and Megraw 1985, Zobel and Jett 1995, Isik and Li 2003, Gwaze et al 2002). Wood density has the most import affect on structural and strength properties of wood products (Megraw 1985, Zobel and van Buijtenen 1989). Because of economic reasons, and since wood density is under a high degree of genetic control, researchers have searched for years for a method of capturing the gains to be made by breeding for high wood density (Atwood et al 2002, Larson et al. 2001, Stonecypher and Zobel 1966, Zobel and Talbert 1984). There are many factors that affect wood density. For loblolly pine, significant genetic differences have been found at various genetic levels. Provenance variation or seed source variation can also have a significant impact on wood density in loblolly pine (Zobel and van Buijtenen 1989, Jett et al. 1991, Byram and Lowe 1988). Also, variation in wood density can differ significantly between genetic levels such as clones, full-sib families and half-sib families (Zobel and Jett 1995).

Other than genetic factors, growth rate is the most highly discussed factor affecting wood density (Zobel and van Buijtenen 1989). Many studies have found that there is no relationship between growth rate and wood density (Taylor and Burton 1982, Pearson and Ross 1984, Larson et al 2001, Megraw 1985). Other studies have found strong and weak negative correlations between wood density and growth rate (Byram et al. 2005, Zobel and Talbert 1984, Zobel and van Buijtenen 1989, Megraw 1985). Another important observation has been that the effects of growth rate on wood density are most evident in young trees (Stonecypher and Zobel 1966). Therefore, silvicultural treatments such as fertilization and thinning that influence growth rate can have a dramatic impact on wood density in young stands.

Lignin content is another wood property characteristic that is influenced by genetics and can have a significant impact on the production of different wood products. Lignin is strongly associated with the strength of wood and the costs of kraft pulp production (Zobel and Jett 1995). In kraft pulp production, lignin is extracted and the more lignin in a given piece of wood, the higher the costs and the lower the yield (Bendtsen 1978). Lignin affects pulp yields and costs because of the more intensive use of chemicals needed to breakdown lignin during the process of pulping. Not only are production costs higher for wood with higher amounts of lignin, but also the time needed to separate the wood fibers and lignin can affect the overall output of a pulp mill.

Lignin is a hydrophobic phenolic material that encases and encrusts the carbohydrate complexes of wood (Winandy and Rowell 2005). At the microscopic level, lignin assists in holding together the different constituents of the cell wall. The stiffness of wood has been correlated with lignin content, and lignin is further responsible for the omission of water from the moisture-sensitive carbohydrates (Winandy and Rowell 2005). This chemical component of wood is influenced by the interaction of developmental, seasonal, and geographic conditions (Sewell et al. 2002). Just as with wood density and tracheid length, lignin content is directly related to the type of wood, juvenile or mature. The thicker cell walls of mature wood contain the lowest concentrations of lignin (Saka & Goring 1985). There can be considerable radial and vertical variation in lignin content within an individual tree trunk. Previous studies have found significant differences in lignin content among individual loblolly pine trees and genotypes (Zobel and Jett 1995). Lignin content determination is measured using microanalytical techniques, chemical treatments and near-infrared spectroscopy

Another chemical wood property that influences production and strength characteristics of wood is α-cellulose content. In general, cellulose is a linear polymer made up of β-1-4 D-glucopyranose units (Winandy and Rowell 2005). Cellulose microfibrils are the primary source of structure and stability found within the wood of a tree (Higuchi 1997, Winandy and Rowell 2005). α-cellulose is a highly stable, un-branched polysaccharide that like lignin, is found in the cell wall. All together, α-cellulose is a component of holocellulose and a complex mixture of polymers formed from simple sugars knows as hemicelluloses (Smook & Kocurek 1998, Higuchi 1997). α-cellulose content is related to the amount of pulp which can be produced from wood. Wood with higher α-cellulose content can produce more pulp. Therefore, a mill that can produce more pulp from higher α-cellulose trees can maximize its production efficiency and reduce its costs. Like lignin, α-cellulose shows variation from pith to bark, as well as vertically throughout the stem. α-cellulose content is also genetically controlled and does have a large economic impact on production. Previous studies have found significant differences in α-cellulose content among and within families of loblolly pine (*Pinus* taeda) (Sykes et al. 2003). However, α-cellulose is inherited in a non-additive manner and therefore the improvement of cellulose yield may be accomplished through the use of a controlled pollination breeding program or vegetative propagation (Zobel and Jett 1995). Studies involving the use of rooted cuttings of *Eucalyptus grandis* have found that pulp yields could be increased by 23% by using clones displaying high density and cellulose (Zobel and Jett 1995). Pulp yield and cohesiveness are positively associated with α-cellulose and hemicellulose content, respectively, and energy consumption during pulping is inversely related to lignin content (Smook & Kocurek 1998).

Recently, accurate and efficient tools for measuring and predicting wood properties have been developed. X-ray densitometry has become the standard method for accurately determining wood density (Gwaze et al. 2002, Raymond and Muneri 2001, Echols 1973) and near-infrared (NIR) spectroscopy has proven to be a very useful and rapid method for nondestructively estimating various wood properties (Jones et al. 2005).

Near-infrared spectroscopy (NIR) is a spectroscopic method that involves the measurement of the wavelength and intensity of the absorption of near-infrared light by a material. The NIR method involves the study of the interactive relationship of electromagnetic radiation and a given material (So et al. 2004). Typically, NIR has been applied for uses in the pharmaceutical, biochemical, agrochemical, and medical diagnostics field.

NIR spectroscopy can provide information about a materials chemical composition quickly and with limited sample preparation (Schimleck et al. 2002; So et al. 2004). The NIR spectral data can also provide information that can be used for predicting the mechanical properties of a material. The range of NIR spectra reaches from 780 to 2500 nm. Within this range, the observed spectra can be described by assigning absorption bands to overtones and mixtures of elemental vibrations related to O-H, C-H, and N-H bonds (So et al. 2004). Through statistical analysis, these absorption bands of spectra can be used for estimating different chemical and mechanical properties of a sample.

For NIR spectral data to be useful, the relationship with chemical or mechanical traits measured directly must be determined. Multivariate analysis (MVA) is the statistical tool used to describe the relationship between a set of measurements that are quickly and efficiently obtained and another set of measurements that obtained through more difficult and time consuming methods (So et al. 2004). Both quantitative and qualitative analyses can be performed based on MVA calibration models that make use of wood chemical data (So et al. 2005). Different MVA techniques such as partial least squares (PLS) and principle component analysis (PCA) can be used to classify data and predict responses (Naes and Isaksson 1990).

The PCA technique mathematically transforms a group of correlated variables into reduced set of uncorrelated variables or principle components (So et al. 2005). The different principle components help to restrict the variability in the data.

The PLS technique uses a regression approach to correlate slight changes in spectral data with independently measured material properties (Martens and Naes 1991). PLS regression can be used to interpret the underlying composition of the prediction variables and the response variables (Kelley et al. 2004). The calibration set that is developed through PLS regression can then be used for prediction purposes (So et al. 2005). The prediction models that are based on PLS regression can further produce coefficients of determination (R^2). These regression coefficients based on the chemical spectra data can be then related to the measured properties of the sample material (So et al. 2005).

There are different spectral data processing techniques that can be used to exclude irrelevant information that NIR spectroscopy can sometimes produce. Spectral data transformation techniques include first and second order derivatives. Second derivative transformations can be applied to remove the baseline offset and sloping effects that are not uncommon in NIR spectra (Sykes et al. 2005). Overall, NIR spectroscopy has proven to be a very efficient and useful tool for the prediction of wood properties.

Prediction Models for Whole-stem Wood Properties

A significant amount of research has been done to try and model or predict whole-stem wood properties. Most studies have concentrated on predicting wood density. Other studies have modeled the ring by ring pattern of wood density and microfibril angle (Jordan et al. 2005, Megraw 1999). Zobel et al. (1960) developed regression models and observed strong correlations between breast-height specific gravity and whole-stem specific gravity for loblolly pine. Zobel et al. (1972) used breast-height specific gravity for predicting whole-stem specific gravity and coefficients of determination from linear regression models were as high as 0.85 to 0.95.

Many of these studies have been done on other species such as *Pinus radiata* and *Eucalyptus sp*. For example, Evans et al. (1997) found strong correlations between breast-height wood properties and whole-tree estimates in *Pinus radiata.* Raymond et al. (1998) also found strong correlations between breast-height wood properties and whole-stem wood properties in *Eucalyptus regnans*. They found that correlations between the prediction model from BH samples and actual whole-tree values ranged from 0.83 for fiber length, 0.70 for density, and 0.59 for fiber coarseness. Kube and Raymond 2002 found core samples to be efficient predictors of variation in whole-tree density, cellulose content, and kraft pulp yield in the whole-tree for *Eucalyptus nitens*. Overall, much of this research and literature has shown promising results regarding the relationship between breast-height wood properties and whole-tree wood properties. However, this relationship seems to be dependent on species, age, environment, genetics, sampling procedure, and the traits being measured. Efficient and accurate prediction models for predicting whole-stem physical and chemical wood properties in loblolly pine would be valuable for tree improvement operations.

The objectives of this research are: 1) The development of practical models for accurately predicting whole-stem wood density, α-cellulose, and lignin in juvenile loblolly pine; 2) The examination of the relationship between juvenile and transition wood density, α-cellulose, and lignin content at breast-height and overall whole-stem weighted averages; and 3) The examination of the relationship between breast-height and whole-stem wood property values while assessing genetic and environmental effects.

Materials and Methods

Sample Collection

The trees used in this study were selected from 14-year old clonal genetic tests replicated at two sites. The first site was located in Monroe County, Alabama and the second site was located in Nassau County, Florida. The experimental design at each site consisted of a split plot design with six replications. Nine full-sib families were planted along with 5 to 9 clones of each fullsib family. The study was designed to compare genetic variance components and performance differences from cuttings and seedlings of the same families (Cumbie 2002, Isik et al. 2003, Isik et al. 2004).

In a previous study using the same clones, measurements were taken to determine wood density, lignin content, α-cellulose yield, fiber length and coarseness (Sykes et al. 2003). Based on wood density and α-cellulose content, the 2 clones with the highest wood density and highest cellulose content, were selected for analysis along with the 2 clones with the lowest wood density and lowest cellulose content. 3 ramets of each of the 4 clones were harvested from each site. Diameter at breast-height and height were recorded prior to harvest. The Goebel-Warner equation was used to estimate total-tree volume:

[1] $$V_{ib} = 0.03371 + 0.0196128\ ((D^2H)/10)$$

Where V_{ib} = estimated total inside-bark volume in cubic feet (Goebel and Warner 1966). Diameter and height were measured in inches and feet. All growth measurements were then converted to metric units.

One of the trees sampled was excluded so overall, a total of 23 14-year old trees were harvested, and disks were cut from the base of the tree to a 4" merchantable top at 8 ft. intervals. After harvest, each of the disks were labeled and placed in a cooler to sustain optimum moisture content until processing could begin.

Before preparing each of the incremental height disks for cutting, inside bark diameter was recorded. The next step in the process involved cutting a 12mm by 12mm rectangular core from each of the disks. An average of 5 cores were collected from each tree, so a total of 115 to 120 cores total were cut for analysis. These rectangular cores were cut from each of the disks using a heavy-duty band saw. Care was taken to ensure that each core contained the pith of the tree so that pith to bark variation could be measured. Once the 12mm by 12mm rectangular cores were cut from all disks, the bark and cambium was removed and the cores were then split in half at the pith. One half of the core was analyzed using X-ray densitometry to determine wood density and the other was analyzed using reflectance near-infrared (NIR) spectroscopy to determine α-cellulose content and lignin content.

In addition, the second half of the breast-height increment core was further divided into juvenile and transition wood sections. The point at which the samples were divided into juvenile and transition/mature wood sections was chosen based on where the trees began producing rings that were composed of 40% latewood cells. The point at which a tree begins producing 40% latewood cells was used as an indicator of the transition from juvenile to more transition wood (Faust et al 1999, Cumbie 2002). The ring position at which the trees began producing rings composed of 40% latewood differed between the Florida and Alabama sites (Figure 1). The breast-height samples taken from clones growing in Florida reached latewood 40% at ring 4 while the same clones growing in Alabama reached latewood 40% at ring 6. Therefore, the breast-height samples were divided into juvenile and transition/mature wood sections based on ring 4 in Florida and ring 6 in Alabama. The ring by ring data and ring width data within each of the divided sections was then used to calculate a wood density weighted average for each section. The divided breast-height samples were then used to test for correlations between juvenile, and transition wood properties at breast-height and whole-stem wood properties.

Wood Density Measurements

The wood cores used for X-ray densitometry provided percent earlywood and latewood while measuring wood density (specific gravity). The first step in using the X-ray densitometer involved removing a 2mm thick, pith to bark strip of wood from each disk that passed through the pith of the tree. This was accomplished by placing the 12mm core samples in between two poplar carrier strips that hold the cores while a saw with two parallel blades cut the 2mm wood strip out of the core, revealing the radial face of the core.

The densitometer gave readings at 0.04 mm intervals and measured the density of earlywood and latewood rings, and thus produced a wood density pattern of variation in from pith to bark. The ring by ring pattern of variation provided data that was then used to calculate a weighted average of wood density at each height. The weighted density of each core was a function of the actual density reading and the ring width. The weighted average accounts for the change in wood density between pith and bark.

Reflectance near-infrared (NIR) spectroscopy

Reflectance near-infrared (NIR) spectroscopy was used to predict α-cellulose content and lignin content. Reflectance NIR was chosen since individual ring measurements at each height were not of interest. Instead, the overall percent α-cellulose content and lignin content from each increment core was of key importance for the development of whole-stem prediction models.

For reflectance NIR, the increment core samples were ground into wood meal using a standard Wiley knife mill with a 2 mm screen. The wood meal was ground until it passed through a 20 mesh screen. The breast-height increment cores were separated into juvenile and transition wood sections by site. For the Florida samples, cores sections between ring 1 and 4 were ground into wood meal and were considered juvenile wood. In contrast, for the Alabama samples, the core sections between rings 1 and 6 were ground into wood meal and considered juvenile wood. The wood meal ground from breast-height increment core sections beyond ring 4 (Florida) and ring 6 (Alabama) was considered to be transition wood.

Prior to NIR scanning, the samples were conditioned in the lab for one week under constant temperature and relative humidity. The wood meal samples were analyzed using a NIR spectrometer (FOSS Model 6500). When data collection was conducted, each individual wood meal sample was placed into the sample cup and scanned. Each sample was scanned to measure the amount of NIR light that was transmitted through the wood meal. The spectral data was collected in 2 nm increments the full spectral range (400 nm – 2500 nm).

The collected spectral data was then fitted to models for predicting alpha-cellulose and lignin content in loblolly pine. The prediction models were based on wet-chemistry and NIR data collected from breast-height samples of loblolly pine over a range of genotypes and geographic regions. The prediction models were based on partial least squares (PLS) regression analyses and 2nd derivative transformation (FOSS NIRSystems 2001, Hodge et al. 2006).

The predicted α-cellulose and lignin content data derived from these prediction models was then used to calculate whole-stem weighted averages.

Calculating Weighted Averages and Whole-stem Weighted Averages

Before any models were developed using the collected, a weighted average of each wood property in all the trees sampled was calculated. Data needed for calculating wood core density weighted averages at each height included ring width (mm) and the actual wood density measurement (kg/m^3). As an example, the formula used for calculating the wood density of each increment core was:

[2] $$\frac{(\text{Ring Width \#1} \times \text{Ring Density \#1}) + (\text{Ring Width \#2} \times \text{Ring Density \#2})\ldots\text{etc}}{\sum \text{Ring Width \#1, Ring Width \#2} \ldots\ldots\text{etc.}}$$

For calculating whole-stem wood density weighted averages, inside bark diameter, bolt length, sample height, and wood core weighted wood density were needed from each height. Before a whole-stem weighted average can be calculated for wood density, the volume of each bolt was calculated since whole-stem wood density is weighted upon volume. Smalian's formula was used for calculating bolt volume (Avery and Burkhart 1994). To calculate the volume of the bottom bolt below breast-height, the formula was:

[3] $$\text{Volume} = \text{Diameter}^2 \times 0.005454 \times \text{Bolt Length}$$

Smalian's formula was used to calculate the inside-bark volume for each bolt above breast-height (Avery and Burkhart 1994):

[4] $$\text{Volume} = [[(0.005454 \times \text{Bottom Diameter}^2) + (0.005454 \times \text{Top Diameter}^2)] \div 2] \times \text{Bolt Length}$$

Whole-stem wood density was then calculated using the formula:

[5]

(Bolt #1 Volume × Breast-height Wood Density) + (Bolt #2 Volume × Incremental Height #2 Wood Density) + (Bolt #3 Volume × Incremental Height #3 Wood Density)……………etc. ÷ ∑ Volume Bolt #1, Volume Bolt #2, Volume Bolt #3……………etc.

All volume and bolt volume measurements were calculated based on inches and feet. The volume measurements (cubic feet) were then converted into metric units. The calculated weighted averages for wood density and the data collected at breast-height were then used to develop prediction models.

Lignin content and α-cellulose content whole-stem weighted averages were calculated using the same formula used to calculate whole-stem wood density. All wood property whole-stem weighted averages were calculated and weighted on bolt volume. Weighting each wood property according to bolt volume helps to account for differences in volume due to changes in stem taper. Hence, data collected from bolts of larger volume had a larger impact on the calculated whole-stem weighted average.

Statistical Analysis

Basic statistics (mean, minimum, maximum, and standard deviation) were calculated to look at variability between site wood property measurements, volume, DBH, and height (Proc MEANS, SAS Institute, 2002-2003).

Hypothesis tests were conducted to detect significant differences among sites and clones. Genotype × environment interaction was also conducted using analysis of variance (Proc GLM, SAS Institute, 2002-2003). All effects were assumed fixed. P-values based on type III sums of squares and mean square errors were reported at a significance level of $P \leq 0.05$. Least squared means and significant differences in least squared means were also calculated for each effect and interaction. Data were analyzed using a linear model in the form:

[6] $$Y_{ijk} = \mu + S_i + C_j + SC_{ij} + Eijk$$

Where:

Y_{ijk} = the *k-th* observation of the *j-th* fixed clone within the fixed *i-th* site
μ = overall mean
S_i = fixed site effect
C_j = fixed clone effect
SC_{ij} = site by clone interaction
$Eijk$ = Random error term – normally and independently distributed $(0, \sigma^2_e)$

Linear and polynomial regression models were developed using breast-height wood properties, breast-height juvenile wood properties, or breast-height transition wood properties as the independent variables (Proc REG SAS Institute, 2002-2003). The coefficients of determination were used to evaluate the predicted power of regression models to predict the calculated whole-stem wood property values. The basic linear regression model used was:

[7] $$\hat{Y} = \beta_0 + \beta_1 X_i + \varepsilon$$

Where:

$\hat{Y}$ = predicted value of the trait of interest
β_0 = intercept parameter
β_1 = slope parameter
X_i = *i-th* independent variable
ε = random error, $(0, \sigma_\varepsilon^2)$

Assumptions of a linear model are that ε are independent, identically distributed $(0, \sigma_\varepsilon^2)$ random variables.

The polynomial model used was in the form:

[8] $$\hat{Y} = \beta_0 + \beta_2 x^2 - \beta_1 x + + \varepsilon$$

Where:

$\hat{Y}$ = predicted value of the trait of interest
β_0 = intercept parameter
β_1 = slope parameter
β_2 = parameter fitted to the quadratic of the independent variable
x = independent variable
x^2 = quadratic term
ε = random error, $(0, \sigma_\varepsilon^2)$

Assumptions of a polynomial model are that ε are independent, identically distributed $(0, \sigma_\varepsilon^2)$ random variables.

Plots of the standardized residuals and the predicted values were constructed to check for the presence of outliers. The assumptions were that the standardized residuals should be independent normal deviates randomly distributed around zero. Standard residual values that were above or below 2.5 and -2.5, respectively were omitted from the analysis (Chatterjee and Price 1977, Giesbrecht and Gumpertz 2004). The linear or polynomial models were selected using the stepwise selection and the REG procedure in SAS (SAS Institute, 2002-2003). The stepwise selection method includes variables in the model that have an *F*-statistic that is significant at a given probability level. This method begins by including all variables in the model and then deleting variables that are not significant. Given that the objective of this research was to develop practical prediction models, the only two variables included in the model were the independent breast-height variable and the quadratic term for the breast-height variable. Variables that were included in the prediction models were significant at the $P \leq 0.15$ level. Overall, the stepwise model selection method helped to determine which variables significantly improved the adequacy of the model (SAS Institute, 2002-2003).

Regression models based on effects (site or clone) that were found to be significant in the ANOVA were tested for significant differences. Tests were done by including site and clone in the model as well as the given independent variable(s) and interaction of the independent variable(s) and site or clone. If the interaction of the site or clone and the independent variable was significant, it was determined that the prediction models significantly differed between sites or clones. Polynomial models that were the same except with different intercepts were tested by including the quadratic term in the model as well as the interaction of the quadratic term and site or clone. The tests for differences in prediction models were done at the significance level $P \leq 0.05$.

Pearson correlation coefficients were also calculated to determine the strength of the correlation between each of the independent variables and the dependent variable (whole-stem wood density) (Proc CORR, SAS Institute, 2002-2003).

Results

Site differences were significant for height (p-value <0.0001), volume (p-value <0.0001), and DBH (p-value <0.0001). The reason for the difference was that trees growing in Florida had a much lower mean volume, DBH, and height than the trees growing in Alabama (Table 1). There were significant differences in height between sites but there were also significant differences between clones (p-value = 0.0057). Across sites, the results also showed that volume and height were strongly and negatively correlated with breast-height (r = -0.68 and -0.73 respectively) and whole-stem wood density (r = -0.68 and -0.79 respectively) (Table 3). This means that individual trees that showed high volume and height had lower breast-height and whole-stem wood density. However, when divided by site, the negative correlations between wood density and growth were insignificant (Table 3).

Wood Density

Across both sites, breast-height wood density values ranged from 373 kg/m^3 to 531 kg/m^3. Whole-stem values ranged from 352 to 484 kg/m^3 (Table 1). Analysis of variance showed significant differences in breast-height (p-value = 0.0002), breast-height transition wood (p-value = 0.001), breast-height juvenile wood (p-value = 0.0179), and whole-stem wood density (p-value <0.0001) between the Florida and Alabama sites at $P \leq 0.05$ (Table 2, Figure 2A). Trees growing on the Florida site had a higher mean breast-height, whole-stem, breast-height transition wood, and breast-height juvenile wood density than the trees growing in Alabama (Table 1).

Relating breast-height wood density to whole-stem wood density

The results of wood density data collection at incremental heights and calculated weighted averages of whole-stem wood density indicated that breast-height wood density was a reliable and accurate predictor of whole-stem wood density. Overall, the coefficients of determination (R^2) and Pearson correlation coefficients (r) were high when using breast-height wood density as a predictor of whole-stem wood density (Table 2). The relationship between breast-height wood density and whole-stem wood density was linear (Figure 3A). When separate linear regressions were performed for the Florida and Alabama sites, R^2

values for breast-height and whole-stem wood density data were similar. Breast-height wood density explained 70% of the variation whole-stem wood density at the Florida site (Figure 3B). At the Alabama site, the R^2 value when using breast-height wood density as a predictor of whole-stem wood density was 0.72 (Figure 3B). When data from both sites were combined, the R^2 value and correlation increased and the R^2 value when using breast-height wood density as a predictor of whole-stem wood density was 0.90 (Table 2, Figure 3A). Based on slope comparisons, there were no significant differences between linear models for sites or clones (p-value = 0.4720 and 0.1931 respectively). Breast-height, whole-stem correlations (r) for the Florida site were 0.84, 0.85 for the Alabama site, and 0.95 for both sites combined (Table 3).

Relating breast-height juvenile wood density to whole-stem wood density

When breast-height juvenile wood density was used as a predictor of whole-stem wood density, the R^2 values and correlations varied. Linear regression models were developed for describing the relationship between breast-height juvenile wood density and whole-stem wood density. Linear regression of whole-stem wood density on breast-height juvenile wood density at the Florida site produced an R^2 value of 0.33 (Figure 3D). The linear regression model of whole-stem wood density on breast-height juvenile wood density at the Alabama site produced an R^2 value of 0.65 (Figure 3D). Also, significance tests revealed that there were no significant differences between the prediction models between sites (P-value = 0.6714). Across both sites, a linear regression model produced an R^2 value of 0.53, which is a slightly higher coefficient of determination than that produced by using breast-height transition wood density as the independent variable (Figure 3C, and Figure 3E).

Since there were no clonal differences in breast-height juvenile wood density, no model was developed or tested.

There were also site differences in the strength of the correlation between breast-height juvenile wood density and whole-stem wood density. The correlation between breast-height juvenile wood density and whole-stem wood density at the Florida site was 0.57 (p-value = 0.0651). The correlation between breast-height juvenile wood density and whole-stem wood density at the Alabama site was 0.81 (p-value = 0.0015). Overall, the correlation between breast-height juvenile wood density and whole-stem wood density was 0.73 (p-value = 0.0001).

Relating breast-height transition wood density to whole-stem wood density

When breast-height transition wood density was used as a predictor of whole-stem wood density, the R^2 values were not as strong (Figure 3E and 3F). For the Alabama site, no model could be developed to adequately describe the relationship between breast-height transition wood density and whole-stem wood density. A linear model best described the relationship between whole-stem wood density and breast-height transition wood density for the Florida site. However, the linear model explained only 23% of the variation in whole-stem wood density (Figure 3F). Across both sites, a linear regression model based on breast-height transition wood density explained 51% of the variation in whole-stem wood density (Figure 3E). Since there were no clonal differences in breast-height transition wood density, no model was developed or tested.

Within the Florida and Alabama sites, breast-height transition wood density did not show a strong relationship with whole-stem wood density and the correlations were low. The correlation coefficient describing the relationship between breast-height transition wood density and whole-stem wood density was high when data from both sites were combined (r = 0.72, p-value = 0.0001).

Alpha-Cellulose

Across both sites, breast-height α-cellulose content ranged from 41.2 % to 43.9 %. Calculated whole-stem α-cellulose content ranged from 40.2 % to 42.8 % (Table 1). On average, across both sites, breast-height α-cellulose content was about 1% higher than whole-stem α-cellulose content. The results of an ANOVA showed that there were significant differences between sites in breast-height α-cellulose content (P-value = 0.0340) and whole-stem α-cellulose content (P-value = 0.0418) (Table 2, Figure 2C). The juvenile trees growing in Florida had a higher mean breast-height and whole-stem α-cellulose content, but had a lower mean breast-height and whole-stem lignin content percentage (Table 1). There was no significant difference in breast-height juvenile wood α-cellulose content or breast-height transition wood α-cellulose between sites. However, there were significant clonal differences in breast-height juvenile wood α-cellulose content (p-value = 0.0391) (Table 2). This was due to one clone having significantly lower mean wood α-cellulose content than the other three. Furthermore, there were no significant significant site × clone interactions.

Relating breast-height α-cellulose content to whole-stem α-cellulose content

The results suggested that breast-height α-cellulose content was a good predictor of whole-stem α-cellulose content. The results of linear regression between sites and across sites suggested that there was a strong and predictable relationship between measurements at breast-height and whole-stem calculations. A linear regression equation fitted to the α-cellulose content data from the Florida site resulted in an R^2 of 0.71 (Figure 4B). A linear model fitted to the α-cellulose content data from Alabama and across both sites resulted in a

R^2 of 0.79 and 0.80, respectively (Figure 3A and 3B). Since there were no clonal differences in α-cellulose yield, no model was developed or tested. No significant difference was found between breast-height α-cellulose content prediction models between sites. The correlation between breast-height α-cellulose content and whole-stem α-cellulose content was highly positive (r = 0.90) (Table 3). Breast-height α-cellulose content was negatively correlated with volume and height; however these negative correlations were insignificant across sites and insignificant correlations were found within sites (Table 3). In contrast, breast-height α-cellulose content was positively correlated with breast-height and whole-stem wood density (Table 3). The correlations between breast-height α-cellulose content and breast-height juvenile and transition wood density were positive, yet insignificant (Table 3).

Relating breast-height juvenile wood α-cellulose content to whole-stem α-cellulose content

When breast-height juvenile wood α-cellulose content was used as a predictor of whole-stem α-cellulose content, the coefficients of determination resulting from both linear and polynomial regression models were non-significant. The α-cellulose content data and calculated whole-stem weighted averages from between sites and across sites did not show a strong relationship. Furthermore, the correlation between the overall breast-height α-cellulose content measurement and the breast-height juvenile wood α-cellulose content was weak (Table 3). Overall, breast-height juvenile wood α-cellulose content proved to be an unreliable predictor of whole-stem α-cellulose content.

Relating breast-height transition wood α-cellulose content to whole-stem α-cellulose content

When breast-height transition wood α-cellulose content was used as a predictor of whole-stem α-cellulose content, the coefficients of determination resulting from both linear and polynomial regression models were high (R^2 = 0.60 to 0.70). The prediction models that were developed for each site were very different in curve and fit (Figure 4D). For Florida, a linear regression model describing the relationship between breast-height transition wood α-cellulose content and calculated whole-stem α-cellulose content produced a coefficient of determination of 0.70 (Figure 4D). For Alabama, a polynomial equation fitted to the α-cellulose content resulted in a R^2 of 0.60 (Figure 4D). Across both sites, a linear model fitted to the breast-height transition wood α-cellulose content data predicted the overall whole-stem α-cellulose content with an R^2 of 0.66 (Figure 4C). Also, the correlation coefficient describing the relationship between breast-height transition wood α-cellulose content and whole-stem α-cellulose content was significant (r = 0.69, p-value = 0.0003).

Lignin Content

Across both sites, breast-height lignin content ranged from 26.5% to 29.1%. Calculated whole-stem lignin content ranged from 26.1% to 29.1% (Table 1). On average, across both sites, breast-height lignin content was about 0.25% lower than the calculated whole-stem lignin content. ANOVA results showed significant differences between site breast-height lignin content (p-value = 0.0008), whole-stem lignin content (p-value <0.0001), and breast-height transition wood lignin content (p-value = 0.0002) (Table 2, Figure 2B). No significant differences were found for breast-height juvenile wood lignin content between sites. The juvenile trees growing in Florida were shown to have significantly lower breast-height and whole-stem lignin content percentages than the trees growing in Alabama (Table 1). No significant differences between sites were found for breast-height transition wood lignin content (Figure 2B). Also, for all lignin content measurements, no significant differences were found between clones. Furthermore, no site × clone interactions were present for any lignin content measurement.

Relating breast-height lignin content to whole-stem lignin content

Both linear and polynomial models were evaluated based on their accuracy of predicting whole-stem lignin content. Linear models were effective when breast-height lignin content was used as a predictor of whole-stem lignin content, however, the results varied between sites. For example, with the Florida site, a linear model fitted to the breast-height and whole-stem lignin content values produced an R^2 of 0.34 (Figure 5B). For the Alabama trees, a linear model produced an R^2 value of 0.67 (Figure 5B). Across both sites, a linear model produced an R^2 of 0.71 (Figure 5A). Also, significance tests revealed that there no significant differences in the prediction models between sites (p-value = 0.9527). Overall, linear models were effective at predicting whole-stem lignin content based on breast-height lignin content in juvenile trees. Furthermore, the calculated correlation coefficient describing the relationship between breast-height lignin content and whole-stem lignin content was high (r = 0.84, p-value = 0.0001) (Table 2).

Relating breast-height juvenile wood lignin content to whole-stem lignin content

When breast-height juvenile wood lignin content was used for prediction of whole-stem lignin content, the coefficients of determination and calculated correlation coefficients showed variable results. For the Florida site, no model could be developed to adequately describe the relationship between breast-height lignin content and whole-stem lignin content. Since no clonal differences were found for juvenile wood lignin content, no models were developed or tested. A linear model based on breast-height lignin content data from the Alabama site resulted in an R^2 value of 0.48 (Figure 5D). Across both sites, linear regression resulted in an R^2 value of 0.63 (Figure 5C). Also, across both sites, the calculated correlation coefficient describing the relationship between breast-height juvenile wood lignin content and whole-stem lignin content was highly significant (r = 0.74, p-value = 0.0001).

Relating breast-height transition wood lignin content to whole-stem lignin content

Linear models were most effective when using breast-height transition wood lignin content as a predictor of whole-stem lignin content. For each site individually, and for both sites combined, a linear model was used for prediction purposes. No significant differences were found in the prediction models between sites (p-value = 0.8290). Since no clonal differences were found for transition wood lignin content, no models were developed or tested. For the juvenile trees from Florida, data fitted to the model resulted in a low R^2 value of 0.27 (Figure 5F). For the juvenile trees from Alabama, data fitted to the model resulted in a significant R^2 value of 0.50 (Figure 5F). When lignin content data from both sites were combined and breast-height transition wood lignin content was used to predict whole-stem lignin content, the model produced an R^2 value of 0.39 (Figure 5E). Also, the calculated correlation coefficient describing the relationship between breast-height transition wood lignin content and whole-stem lignin content was significant (r = 0.62, p-value = 0.0015). Overall, across both sites, breast-height juvenile wood lignin content was a better predictor of whole-stem lignin content than breast-height transition wood lignin content. When divided by site, breast-height transition wood lignin content was more useful for predicting whole-stem lignin content.

Discussion

The objective of this study was the development of models for predicting whole-stem wood properties in juvenile loblolly pine based on wood properties at breast-height. For wood density, α-cellulose content and lignin content, breast-height measurements were highly correlated with calculated whole-stem weighted averages. Breast-height wood density showed a strong linear relationship with whole-stem wood density. On average, over both sites, breast-height wood density was about 45 kg/m³ higher than whole-stem wood density. This difference is slightly higher than what was reported by Zobel et al.(1972). However, Zobel's study was based older trees destructively sampled from natural stands in Virginia. This difference may also be due to the fact that the older trees in Zobel's study contained juvenile wood mostly in the upper portion of the stem. Most importantly, the results from this study are similar to that of Zobel's. The findings of Zobel et al. (1960) are also similar to the findings of this study. Highly significant correlations were found between breast-height specific gravity and total bole specific gravity (wood density). Zobel et al. (1960) also stated that it is possible to predict the specific gravity (wood density) of a mature tree based on knowledge of the specific gravity (wood density) of the wood in a young tree. In both cases, linear models showed that breast-height wood density can be used as a good predictor of whole-stem wood density.

Breast-height juvenile wood density had a slightly higher coefficient of determination for predicting whole-stem wood density than breast-height transition wood density. The correlations between breast-height juvenile wood density and whole-stem wood density were also stronger than the correlations between breast-height transition wood and whole-stem wood density. This is interesting since juvenile wood at breast-height can be unstable and unpredictable (Zobel and Sprague 1998). This is also contrary to what others have found. Zobel et al. (1960) found that sometimes, when only juvenile wood is used; there may be an adequate whole-stem specific gravity (wood density) relationship. However, the best correlations for breast-height – whole-stem relationships were found when using mature wood as a predictor. When looking at the R^2 values and the correlations in this study, there were differences in the strength of the correlation between sites. Therefore, in these clonal trials, the same genotypes growing in different environments may significantly vary in their juvenile wood properties. Zobel et al. (1972) also stated that breast-height-total tree relationships are typically quite similar within the loblolly pine species. The major difference in this study was due to environmental variation.

The differences in breast-height wood density, whole-stem wood density, breast-height transition wood, and breast-height juvenile wood density between the Florida and Alabama sites is most likely due to differences in growth. The clones growing in Florida had much lower mean values for volume, DBH, and height than the same clones growing in Alabama. It was found that wood density measurements were strongly and negatively correlated with each of these growth measurements across both sites. This finding is similar to other wood density studies in loblolly pine (Byram et al. 2005, Zobel and Talbert 1984, Zobel and van Buijtenen 1989, Megraw 1985, Belonger 1998). The implications are that some environmental effects such as increased water availability, nutrition, soil types or competitive effects may have caused differences in growth, and the smaller, more suppressed trees displayed higher values for wood density. Weighted averages at each height are based on the ring density and ring width measurements. Smaller diameter trees that are the same age as larger diameter trees had more narrow growth rings. In Florida, more high density latewood was present in the narrow growth rings and therefore the wood density at any given height was higher than the wood density measurements in Alabama. For example, at the Florida site, the point at which the growth rings at breast-height produced 40% latewood cells was at ring 4, while at the Alabama site, the point at which 40% latewood was reached was at ring 6. Other studies have found similar relationships between growth and wood density when comparing flatwoods sites like those found in Florida to upland sites similar to those found in Alabama (Belonger 1998). This means that if the trees were 14 years old at harvest, the Florida trees had more growth that was considered to be transition or even mature wood. Overall, the environmental factors that affected growth and latewood production resulted in higher density values for the juvenile trees growing in Florida.

When the correlations between growth and wood density measurements were broken down by site, they were not significant. This is an important finding for researchers interested in improving wood quality while maintaining high density. For example, for the Alabama site, the correlations between growth and wood density ranged between -0.30 to -0.37. For the Florida site, correlations between growth and wood density ranged from -0.21 to -0.34. These correlations were not significant and therefore, it implies that when growing trees on a specific site, fast growth may not significantly inhibit the production of high density wood.

Although no clonal differences were found to be significant for any wood density measurement in this study, genotype differences in wood properties such as wood density are real and have been documented. For example, Jett et al. 1991 found that 14 of 18 loblolly pine families showed stability in specific gravity (wood density) over different geographic areas. Given that wood density is under a high degree of genetic control and heritability estimates are commonly 0.44 in loblolly pine, selection and improvement based on whole-stem wood density should be very useful (Zobel and van Buijtenen 1989). Although genetic affects were not significant in this study, they do play an important role in wood property variation and predicting whole-stem wood properties. What is important is that the whole-stem wood density prediction models proved to be accurate for juvenile loblolly pine grown over two very different environments. If some genotypes prove to have higher breast-height wood density values across different environments, these results imply that they will also have higher whole-stem wood density. Therefore, these models may help tree breeders select genotypes that inherently produce strong, high quality wood products.

The two chemical wood properties included in this study; α-cellulose content and lignin content, also showed strong correlations between breast-height values and calculated whole-stem weighted averages. Both linear and polynomial regression models were developed that produced strong coefficients of determination for each wood property. When breast-height samples were divided into juvenile and transition wood sections, the accuracy of the models varied. For α-cellulose, breast-height transition wood α-cellulose content was more effective at predicting whole-stem α-cellulose content than breast-height juvenile wood. For lignin, breast-height juvenile wood lignin content was more effective at predicting whole-stem lignin content than breast-height transition wood. A significant amount of research has been done on genetic differences in chemical wood properties and general within-stem patterns of variation have been described (Sykes et al. 2003, Baas 1982, Higuchi 1997). However, in loblolly pine, prediction models for whole-stem chemical wood properties such as α-cellulose content and lignin content have not been defined. In *Eucalyptus nitens*, linear regression and correlation coefficients were determined for the relationship between breast-height cellulose and extractives content and whole-stem values. Measurements from wood cores were used for prediction purposes, but the results were variable (Kube and Raymond 2002). The results of the chemical wood property prediction models may prove to be useful for selecting genotypes with advantageous chemical properties.

It is interesting to note the correlations between breast-height α-cellulose content and lignin content and breast-height wood density. α-cellulose content was positively correlated with all breast-height and whole-stem density measurements while lignin content was negatively correlated with all breast-height and whole-stem density measurements. This observation is not unexpected since higher density wood should contain higher α-cellulose yield. Also, the lowest correlations occurred between breast-height α-cellulose content and lignin content and breast-height juvenile wood density. This too is not unexpected since juvenile wood can be highly variable and unpredictable. For example, breast-height juvenile wood density showed better correlations with whole-stem wood density than breast-height transition wood. However, there was considerable variation in the accuracy of predicting whole-stem α-cellulose content and lignin content based on breast-height juvenile wood measurements. Like the wood density prediction models, the R^2 values from the chemical prediction models were further dependent upon the environmental conditions and growth of the trees.

Given the finding of this study and many other genetically inherited wood property studies, prediction model based selection of high wood density, high α-cellulose, and low lignin content genotypes may prove to be a useful tool for improving wood quality.

Conclusions

In juvenile loblolly pine, predicting whole-stem wood properties using breast-height wood properties proved to be effective. Both linear and polynomial regression models were significant for describing the relationship between breast-height wood properties and whole-stem wood properties. Coefficients of determination for wood density ranged from 0.51 to 0.90 when data from both sites were combined. Across sites, coefficients of determination ranged from 0.71 to 0.82 for α-cellulose and 0.39 to 0.71 for lignin content. Correlations between breast-height wood properties and whole-stem wood properties were high and ranged from 0.84 to 0.95. Despite site (environmental) differences in wood density, α-cellulose content, lignin content and all growth traits, the prediction models among different genotypes of loblolly pine were similar. Over both sites, no clonal differences in breast-height and whole-stem wood properties were found with exception to breast-height juvenile wood α-cellulose content. Across sites and genotypes, both linear and polynomial regression models were effective for prediction of whole-stem wood properties in juvenile loblolly pine. Modeling studies involving more replication of different genotypes may detect significant differences. Based on this research, genetic differences in breast-height wood properties can be used to select genotypes that have higher or lower overall whole-stem wood property values.

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Tables and Figures

Table 1. Descriptive statistics for all breast-height and whole-stem wood property measurements.

	BH Density (kg/m^3)	WT Density (kg/m^3)	BH ACY (%)	WT ACY (%)	BH LIG (%)	WT LIG (%)	Volume (m^3)	Diameter (cm)	Height (m)
Florida (n = 11)									
Min	437.8	399.5	41.6	40.9	26.5	26.1	0.06	12.2	12.6
Max	531.9	484.3	43.9	42.8	28.5	27.8	0.18	20.1	16.3
Mean	479.8	425.5	42.9	41.9	27.1	27.2	0.11	15.7	14.4
St. Dev.	27.44	25.67	0.71	0.58	0.56	0.50	0.04	2.56	1.29
Alabama (n = 12)									
Min	373.2	352.9	41.2	40.2	26.8	27.8	0.11	15.8	15.4
Max	468.6	404.3	43.9	42.8	29.1	29.2	0.36	27.7	18.2
Mean	424.4	383.7	42.1	41.3	28.2	28.5	0.27	22.7	17.4
St. Dev.	25.05	14.84	0.79	0.75	0.76	0.45	0.09	4.11	0.79
Combined Sites (n = 23)									
Min	373.2	352.9	41.2	40.2	26.5	26.1	0.06	12.2	12.6
Max	531.9	484.3	43.9	42.8	29.1	29.2	0.39	27.4	18.2
Mean	450.9	405.5	42.5	41.6	27.7	27.9	0.19	19.4	15.9
St. Dev.	38.16	30.86	0.85	0.74	0.87	0.84	0.11	4.94	1.8

Note: BH, breast-height wood density; WT, whole-stem wood density; BH ACY, breast-height α-cellulose content; WT ACY, whole-stem α-cellulose content; BH LIG, breast-height lignin content; WT LIG, whole-stem lignin content.

Table 2. P-values for site, clone, and site by clone interaction for all wood property and growth measurements.

Wood Density	Site	Clone	Site × Clone
BH	0.0002	0.3229	0.6904
BH juvenile	0.0179	0.2797	0.2725
BH transition	0.0010	0.1720	0.5439
WT	<0.0001	0.0577	0.9383
Alpha-Cellulose Content			
BH	0.0340	0.7634	0.7595
BH juvenile	0.0533	0.0391	0.2556
BH transition	0.0634	0.7163	0.5378
WT	0.0418	0.8598	0.4252
Lignin Content			
BH	0.0008	0.1424	0.6324
BH juvenile	0.0002	0.2401	0.2862
BH transition	0.1262	0.3677	0.9293
WT	<0.0001	0.3946	0.4180
Growth Measurements			
Volume (m^3)	<0.0001	0.0574	0.5004
Diameter (cm)	<0.0001	0.0517	0.4710
Height (m)	<0.0001	0.0057	0.1742

Note: BH, breast-height wood property; WT, whole-stem wood property; BH transition, breast-height transition-wood property; BH juvenile, breast-height juvenile wood property; $P \leq 0.05$.

Table 3. Correlations between alpha-cellulose content, lignin content, wood density and growth measurements from breast-height and whole-stem.

Variable	Combined Sites	Alabama Site	Florida Site
Breast-height ACY (%)			
WT ACY (%)	0.89	0.89	0.84
JUV ACY (%)	0.18	0.17	0.45
TR ACY (%)	0.86	0.41	0.91
Volume (m^3)	-0.35	-0.03	0.20
DBH (cm)	-0.31	-0.04	0.31
HT (m)	-0.44	-0.01	-0.10
BH Density (kg/m^3)	0.54	0.37	0.22
WT Density (kg/m^3)	0.59	0.62	0.26
JUV Density (kg/m^3)	0.25	0.40	0.28
TR Density (kg/m^3)	0.41	0.19	0.30
Breast-height LIG (%)			
WT LIG (%)	0.84	0.82	0.59
JUV LIG (%)	0.88	0.75	0.51
TR LIG (%)	0.82	0.92	0.67
Volume (m^3)	0.30	-0.35	-0.53
DBH (cm)	0.24	-0.40	-0.60
HT (m)	0.43	-0.26	-0.33
BH Density (kg/m^3)	-0.40	0.43	-0.30
WT Density (kg/m^3)	-0.49	0.23	0.59
JUV Density (kg/m^3)	-0.08	0.54	0.22
TR Density (kg/m^3)	-0.58	0.17	-0.75
Breast-height density (kg/m^3)			
WT Density (kg/m^3)	0.95	0.85	0.84
JUV Density (kg/m^3)	0.83	0.95	0.74
TR Density (kg/m^3)	0.79	0.64	0.53
Volume (m^3)	-0.68	-0.35	-0.22
DBH (cm)	-0.68	-0.37	-0.21
HT (m)	-0.74	-0.30	-0.34

WT, whole-stem measurement; BH, breast-height measurement; JUV, breast-height juvenile wood measurement, and TR, transition wood measurement. LIG = lignin content. ACY = alpha-cellulose yield.

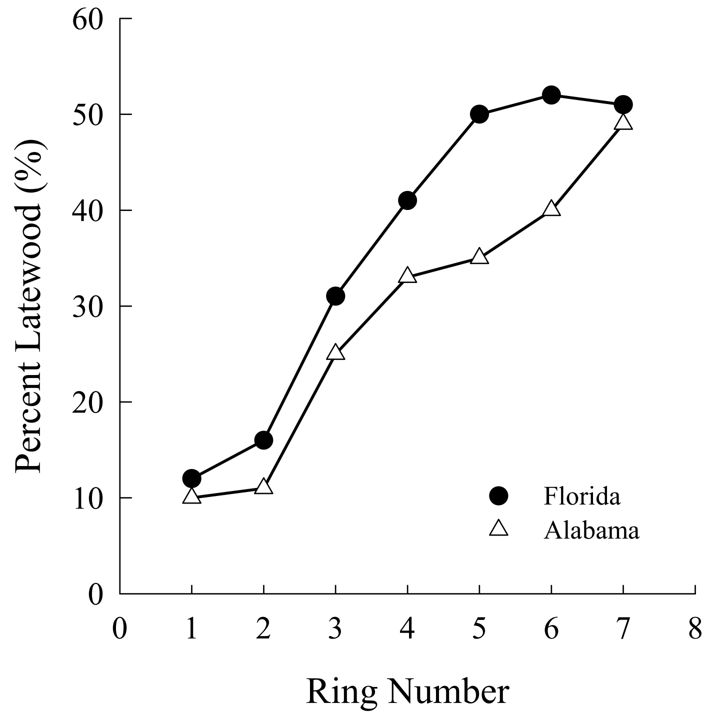

Figure 1. Percent latewood by ring for trees in the Florida and Alabama sites. Trees at the Florida site reached 40% latewood at ring 4, whereas trees at the Alabama site reached 40% latewood at ring 6.

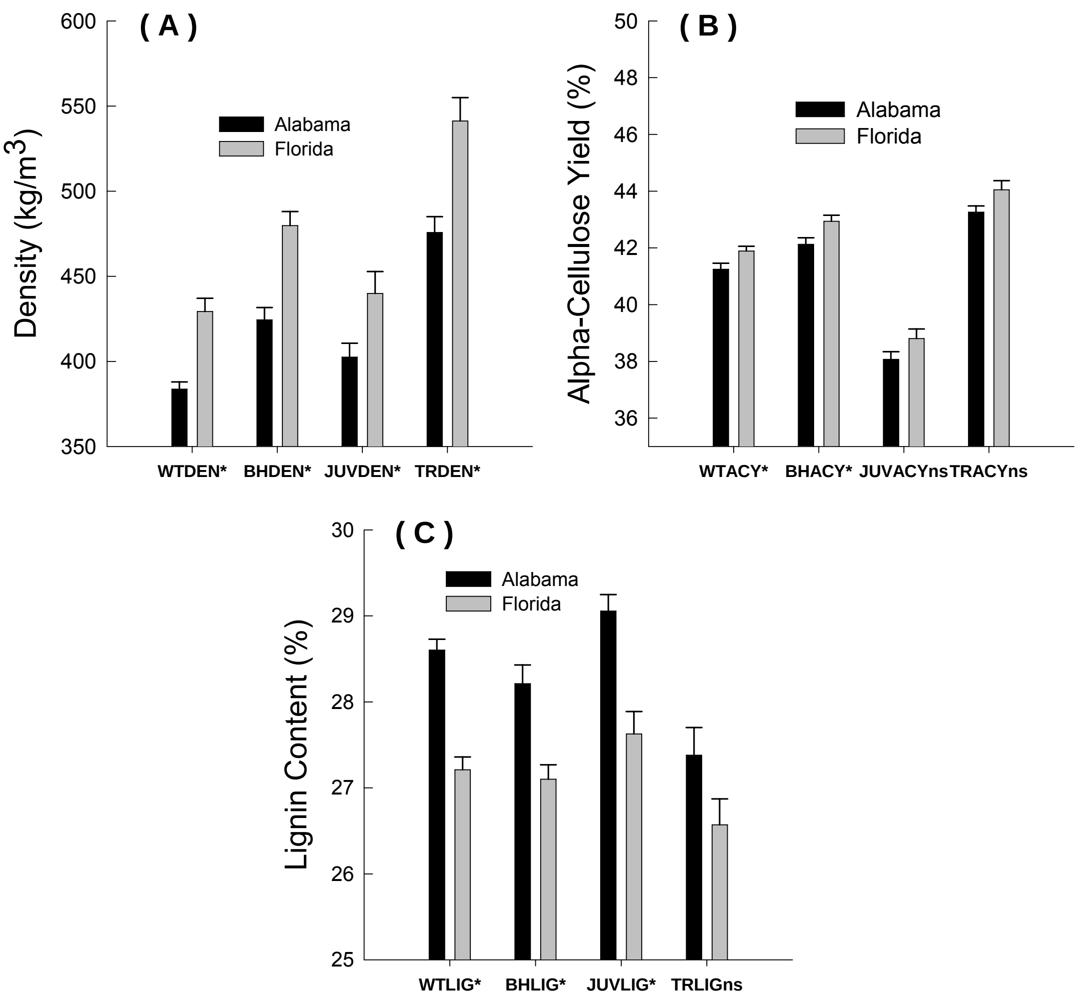

Figure 2. (A) Mean and standard error values for whole-stem wood density (WTDEN), breast-height wood density (BHDEN), breast-height juvenile wood density (JUVDEN), and breast-height transition wood density (TRDEN) between both Florida and Alabama. (B) Mean and standard error values for whole-stem alpha-cellulose yield (WTACY), breast-height alpha-cellulose yield (BHACY), breast-height juvenile wood alpha-cellulose yield (JUVACY), and breast-height transition wood alpha-cellulose yield (TRACY) between Florida and Alabama. (C) Mean and standard error values for whole-stem lignin content (WTLIG), breast-height lignin content (BHLIG), breast-height juvenile wood lignin content (JUVLIG), and breast-height transition wood lignin content (TRLIG) between Florida and Alabama. * = significant at $P \leq 0.05$ or ^{NS} = no significant difference.

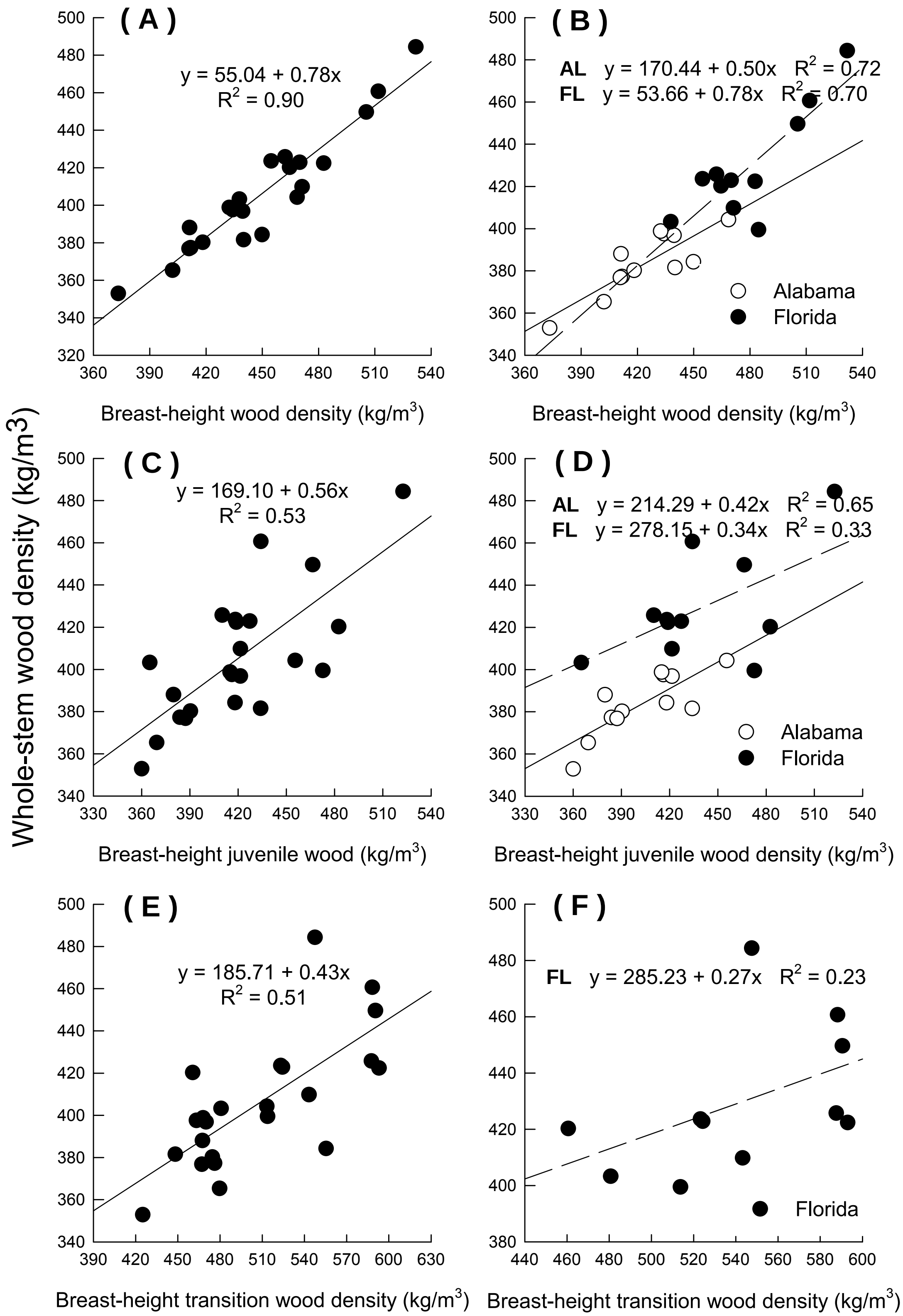

Figure 3. Whole-stem regression models based on: (A) breast-height wood density, (B) breast-height wood density for Florida and Alabama, (C) breast-height juvenile wood density, (D) breast-height juvenile wood density for Florida and Alabama, (E) breast-height transition wood density, and (F) breast-height transition wood density in Florida and Alabama.

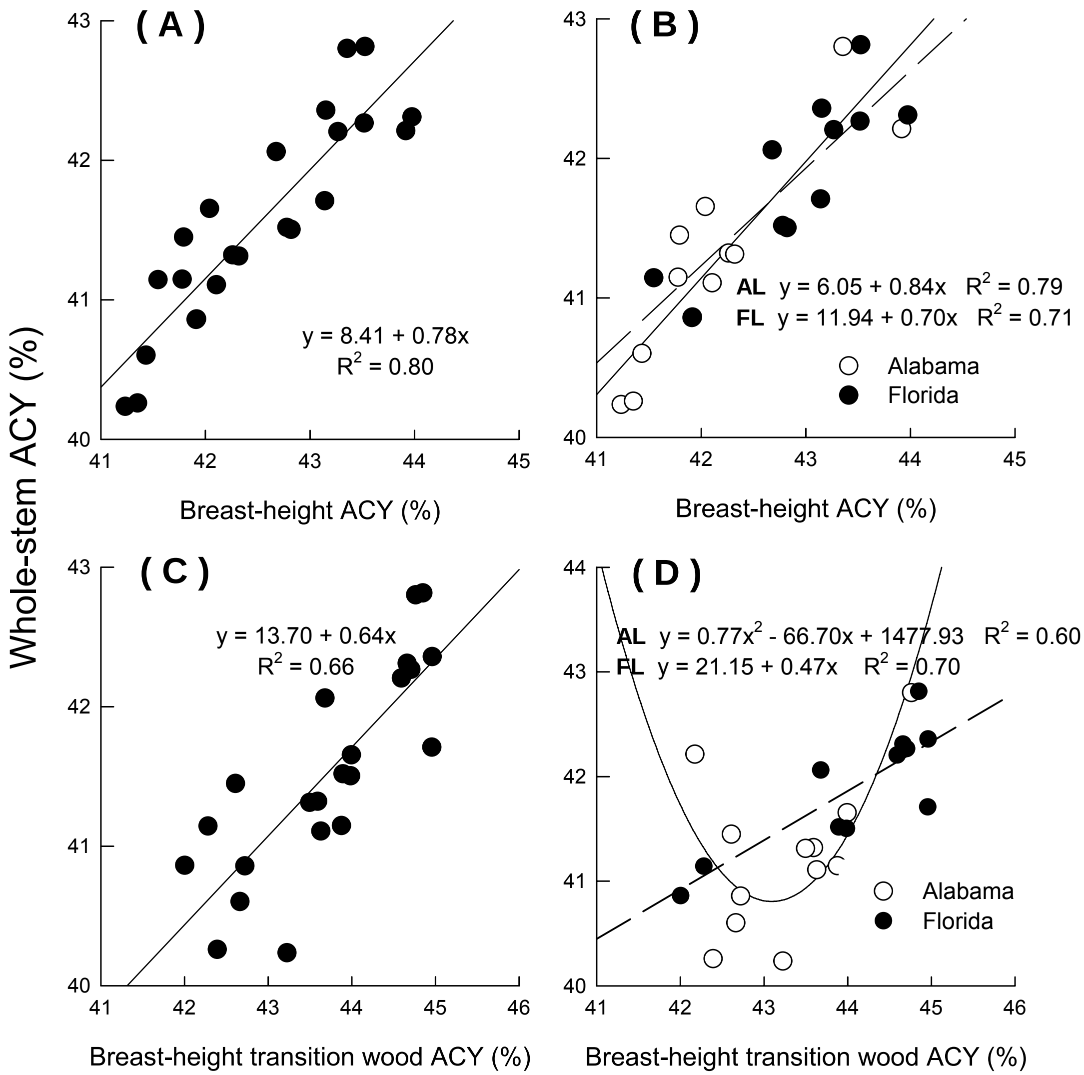

Figure 4. Whole-stem regression models based on: (A) breast-height alpha-cellulose yield, (B) breast-height alpha-cellulose yield for both Florida and Alabama, (C) breast-height transition wood alpha-cellulose yield, and (D) breast-height transition wood alpha-cellulose yield for both Florida and Alabama. No sufficient model was found describing the relationship between whole-stem alpha-cellulose yield and breast-height juvenile wood alpha-cellulose yield.

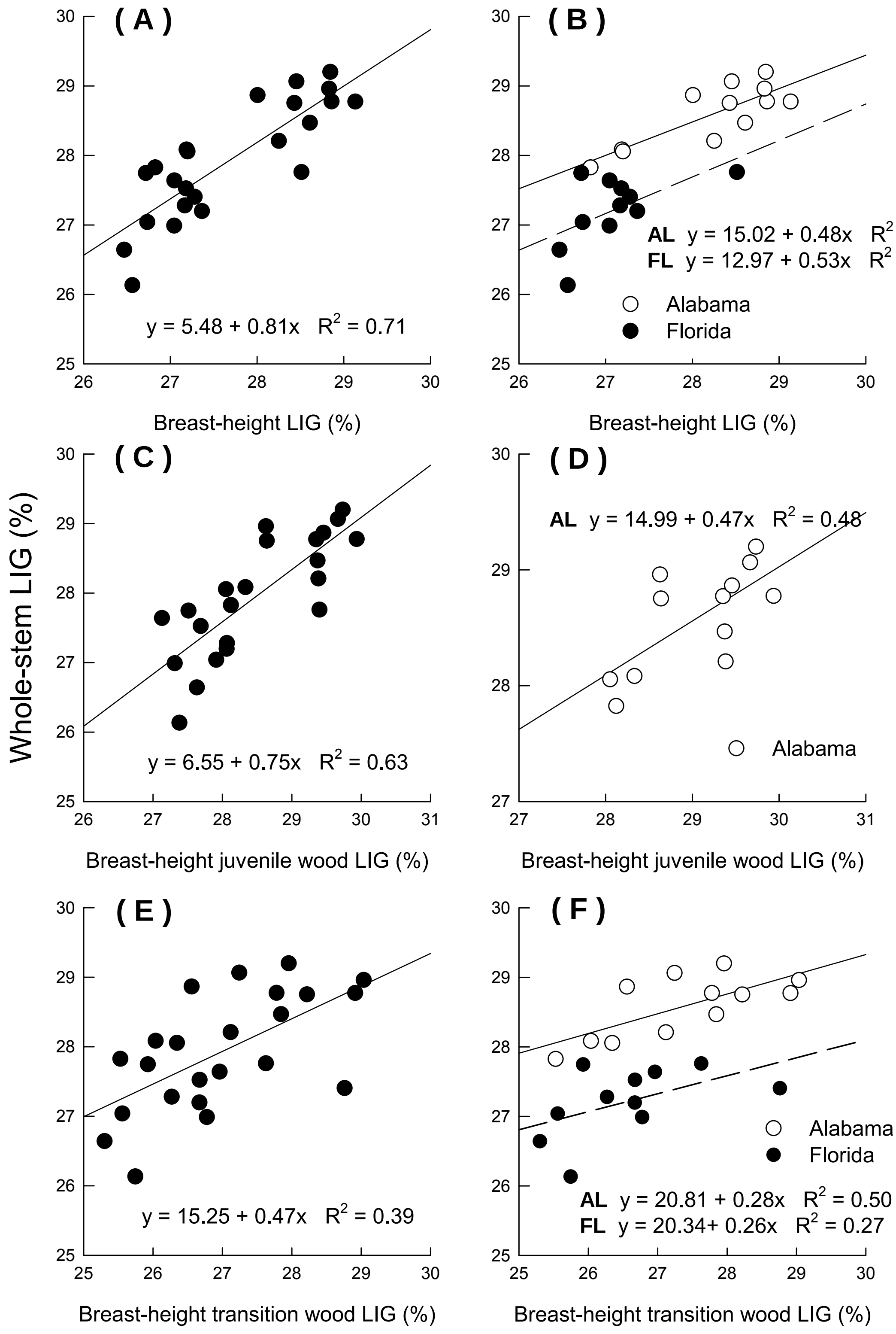

Figure 5. Whole-stem regression models based on: (A) breast-height lignin content, (B) breast-height lignin content for Florida and Alabama, (C) breast-height juvenile wood lignin content, (D) breast-height juvenile wood lignin content for Florida and Alabama, (E) breast-height transition wood lignin content, and (F) breast-height transition wood lignin content in Florida and Alabama.

CHAPTER 2

PREDICTION OF WHOLE-STEM WOOD PROPERTIES FOR MATURE LOBLOLLY PINE

Abstract

Relationships between breast-height and whole-stem wood density, α-cellulose content, and lignin content were evaluated for a set of mature 20-year-old loblolly pine (*Pinus taeda* L.) trees growing on the coastal plain of North Carolina. Samples were cut at breast-height and 2.4 m (8 ft.) increments from each tree, and whole-stem weighted averages for each wood property were calculated. Linear regression models were significant and accurate for describing the relationship between breast-height wood properties and whole-stem wood properties. Coefficients of determination for wood density ranged from 0.27 to 0.85; 0.42 to 0.95 for α-cellulose and 0.59 to 0.85 for lignin content respectively. For juvenile wood, correlations between breast-height wood properties and whole-stem wood properties ranged from 0.62 to 0.92 and correlations with whole-stem wood properties ranged from 0.77 to 0.90 for breast-height transition wood and from 0.44 to 0.84 for mature wood. Negative correlations were found between wood density measurements and growth measurements (-0.07 to -0.35) as well as between α-cellulose yield measurements and growth measurements. However, positive correlations were found between lignin measurements and growth measurements (0.12 to 0.24). Overall, linear prediction models were developed for predicting whole-stem wood properties based on breast-height wood properties in mature loblolly pine.

Introduction

With forestry in the southeastern U.S. becoming more and more competitive and the demand for high quality wood products increasing, researchers have intensified the search for methods of improving wood quality. Increased use of faster growing genotypes and intensive silviculture has shortened pine plantation rotation ages (Atwood et al. 2002, Clark and Saucier 1989, Zobel and Sprague 1998, Taylor and Burton 1982). Although production efficiency has increased and significant profits have been made growing trees on shorter rotations, the sacrifice has been decreased wood quality (Zobel 1984, Larson et al. 2001). The primary determinant of many wood quality factors is cambial age, and trees that are harvested at a young age are made up of mostly juvenile wood. Many characteristics of juvenile wood negatively influence the strength and structural properties of wood products (Faust et al. 1999, Megraw 1985). Fortunately, research has proven that juvenile wood quality can vary greatly among species, populations and individual genotypes (Zobel and Jett 1995). Given the fact that there is significant variation in juvenile wood properties and several wood properties are strongly inherited, selective breeding for genotypes demonstrating advantageous wood property characteristics would be worthwhile. If breast-height values are poorly correlated with whole-stem values, other options must be implemented to select for genotypes displaying advantageous whole-stem wood properties.

Within the loblolly pine species, we generally know how some wood properties vary from pith to bark and from the base of the tree moving up the stem (Zobel and van Buijtenen 1989, Burdon et al. 2004). However, the overall pattern of variation for most wood properties of interest is strongly influenced by genetic and environmental factors. Moreover, the pattern of variation along the bole of the tree can influence the overall economic and structural value of the tree (Burdon et al. 2004). Therefore, selecting genotypes based on their overall whole-stem wood properties seems to be a critical step towards improving the quality of wood being produced in the southeastern U.S. The problem is that there is no rapid method of predicting an overall whole-stem weighted average for some wood properties of interest. The development of practical prediction models for estimating whole-stem wood property values would be a valuable tool that tree breeders could use in selecting genotypes with superior wood properties.

Wood density (specific gravity) is of critical importance in the production of wood products due to its effect on yield and quality. Wood density is under a high degree of genetic control and is inherited in an additive manner. Wood density is so important that in many cases, it is the only wood property that is genetically improved (Isik and Li 2003, Megraw 1985). Internally, wood density is primarily determined by the ratio of earlywood to latewood cells, as well as cell size and wall thickness. (Larson et al. 2001, Zobel and van Buijtenen 1989). Wood density is also strongly influenced by radial position within the stem. For instance, great differences in wood density are found when measuring the change from juvenile to mature wood. There are also great differences in wood density at varying heights within the stem. Since a higher percentage of mature wood is present in the butt of the tree and since this portion of the tree is more physiologically mature, it will demonstrate higher wood density than that of stemwood that is higher along the bole (Zobel and van Buijtenen 1989). Overall, several factors including site quality, fertilization, growth rate, stocking, and provenance can significantly affect wood density.

Although there are volumes of information pertaining to the cellular chemistry of wood (Timell 1967, Higuchi 1997), little research has been done with respect to wood chemistry variation and the ability to manipulate it through silviculture, breeding, and biotechnological methods. Also, little research has been done to relate chemical differences among individuals in a population to the overall value of the product they produce. However, a few studies have emphasized the importance of the cellular chemistry of wood and the influence it has on the structural and strength properties of different products

(Winandy and Rowell 2005). Variation due to differences in wood chemistry also has been found to cause differences in wood density and the utility of the product. (Zobel and van Buijtenen 1989).

α-Cellulose is a chemical component of wood that is related to wood density and can have major implications on pulp yield and strength properties of different wood products. For example, it has long been known that α-cellulose content is positively correlated with pulp yield (Zobel and van Buijtenen 1989). Not only does increased α-cellulose content increase pulp yields but it also reduces pulping costs and maximizes the production efficiency of the mill (Zobel and Talbert 1984). α-Cellulose content is higher in mature wood than in juvenile wood, however there can be significant genetic variation associated with juvenile wood α-cellulose content. Lignin content is another chemical component of wood that strongly influences production efficiency, yield, and product quality. In the process of kraft pulping, about 90% of lignin is removed from pulp. Consequently, lignin content is negatively correlated with pulp yield. The thin cell walls of juvenile wood contain higher proportions of lignin than the thick cell walls of mature wood and for this reason younger trees containing mostly juvenile wood may produce much lower pulp yields than normal wood (Zobel and Sprague 1998). Fortunately, both α-cellulose and lignin content show definite relationships with wood density and significant genetic differences in these chemical components have been found between individual genotypes. Given the important role of these chemical wood properties on yield and quality and given that these properties are under a certain degree of genetic control, there is certainly room for genetic improvement.

Recently, wood property determination has been simplified due to more efficient methods such as x-ray densitometry and NIR spectroscopy. X-ray densitometry has been used for some time and has proven to be highly accurate and effective (Gwaze et al 2002, Raymond and Muneri 2001, Echols 1973). The advancement of NIR spectroscopy has also proven to be a reliable tool for predicting physical, chemical and morphological properties of wood (Jones et al., 2005, Kelly et al., 2004, Schimleck et al., 2002, Sykes et al., 2005). The use of both x-ray densitometry and NIR spectroscopy has opened up many opportunities for implementation into tree improvement programs. In the case of this study, these tools for determining different wood properties will be used for developing whole-stem wood property prediction models based on breast-height wood properties.

In the previous chapter, prediction models were developed that described the relationships between breast-height wood properties and whole-stem wood properties in juvenile loblolly pine. The objectives of this research are: 1.) The development of practical models for accurately predicting whole-stem wood density, α-cellulose, and lignin in mature-harvest age loblolly pine; 2.) The collection of wood property data and the examination wood property variation patterns in mature-harvest age loblolly pine; and 3.) The examination of the relationship between juvenile, transition, and mature wood density, α-cellulose, and lignin content at breast-height and overall whole-stem weighted averages.

Materials and Methods

Sample Collection

The trees used in this study were harvested from a diallel test located in Jones County, on the Coastal Plain of North Carolina. The sample was composed of twenty 20 – year-old trees, each from a different full-sib family (control cross). Only dominant or co-dominant trees were selected for harvest. This particular test was composed of 2nd generation North Carolina Coastal Plain genetic material. The test was part of forest genetics research and cooperation between the North Carolina State University Industry Tree-Improvement Cooperative Program and Weyerhauser Co. The soils were defined as Croatan muck; hence this soil type could be described as having high nutrient and water holding capacity. At the time of harvest, height, diameter at breast-height (DBH), inside bark diameter, competition, sweep, and branch angle measurements were recorded. The Goebel-Warner equation was used to estimate total tree volume:

[1] $$V_{ib} = 0.03371 + 0.0196128\ ((D^2H)/10)$$

Where V_{ib} = estimated total inside-bark volume in cubic feet (Goebel and Warner, 1966). Diameter and height were measured in inches and feet. All growth measurements were then converted to metric units.

After the trees were felled, increment cores and wedge samples were cut at breast-height and 8-foot incremental heights up to a 4 inch top. The cores and wedges were then taken back to the lab where they were dried in an oven and conditioned to prevent deterioration. The next step in the process involved cutting 12mm by 12mm rectangular cores from each of the wedges. The bark and cambium was removed from the samples and care was taken to ensure that each core contained the pith so that pith to bark variation could be measured. On average, 7 wedges were removed from each tree. From each wedge, one section was cut into a core that would be used for X-ray densitometry. Before removing cores from the wedge samples, each wedge was marked for cutting to ensure that no visible compression wood, knots, or defects would affect the X-ray measurements. To prepare the samples for determination of α-cellulose content and lignin content, extra 12mm by 12mm rectangular cores were cut from each wedge and ground into wood meal that was in turn used for reflectance NIR. Also, to ensure that α-cellulose content and lignin content data were not biased, each section of the wedge was marked and cut properly to avoid any abnormal defects in the wood.

In addition, the second half of the breast-height increment core was further divided into juvenile, transition, and mature wood sections. The division of the breast-height sample allowed us to test for a correlation between breast-height values and whole-stem values. Furthermore, the division of the breast-height sample allowed us to develop prediction models that related breast-height juvenile, transition and mature wood properties to whole-stem wood properties.

Wood Density Measurements

The wood cores used for X-ray densitometry provided percent earlywood and latewood while measuring wood density. The first step in using the X-ray densitometer involved removing a 2mm, pith to bark strip of wood from each disk that passed through the pith of the tree. This was accomplished by placing the 12mm by 12mm core samples in between two poplar carrier strips that hold the cores while a specialized saw cut the 2mm wood strip out of the core. The densitometer gave readings at 0.04 mm intervals and measured the density of earlywood and latewood rings, and thus produced a wood density pattern of variation in from pith to bark. The ring by ring pattern of variation provided data that was then used to calculate a weighted average of the wood density at each height. The weighted wood density of each core was a function of the actual density reading and the ring width. The weighted average accounts for the change in density between pith and bark.

To test for correlations between different breast-height measurements and whole-stem measurements, the breast-height ring by ring x-ray densitometry data was split up according to ring number. Growth ring density data between rings 1 and 7 was considered to be juvenile wood. The growth ring density data collected between rings 8 and 13 was considered transition wood. Lastly, ring by ring density data from rings 14 and up was considered mature wood (Larson et al, 2001, Zobel and Talbert, 1984).

Reflectance near-infrared (NIR) spectroscopy

Reflectance near-infrared (NIR) spectroscopy was used to predict α-cellulose content and lignin content. Reflectance NIR was chosen since individual ring measurements at each height were not of interest. Only the overall percent α-cellulose content and lignin content from each increment core was of key importance since whole-stem weighted averages were to be calculated and used for prediction purposes. At breast-height, the overall percentage α-cellulose content and lignin content in juvenile, transition, and mature wood was important for testing correlations between breast-height values and whole-stem values. Therefore, there was no need for ring by ring data, only average values from each section.

For reflectance NIR, the increment core samples were ground into wood meal using a standard Wiley knife mill with a 2 mm screen. The wood meal was ground until it passed through a 20 mesh screen. The breast-height increment cores were separated into juvenile, transition, and mature wood sections so that breast-height to whole-stem correlations could be tested. To test for different correlations between different breast-height measurements and whole-stem measurements, the breast-height samples were divided according to ring number. The breast-height samples were divided by ring number using the same criteria as used for the x-ray densitometry samples (Larson et al, 2001, Zobel and Talbert, 1984).

The ground wood meal was conditioned in the lab for one week prior to NIR scanning so that samples could equilibrate to a constant room temperature and relative humidity. The wood meal samples were analyzed using a NIR spectrometer (FOSS Model 6500). When data collection was conducted, each individual wood meal sample was placed into the sample cup and scanned. Each sample was scanned to measure the amount of NIR light that was transmitted through the wood meal. The spectral data was collected in 2 nm increments the full spectral range (400 nm – 2500 nm).

The collected spectral data were then fitted to models for predicting alpha-cellulose and lignin content in loblolly pine. The prediction models were based on wet-chemistry and NIR data collected from breast-height samples of loblolly pine over a range of genotypes and environments. The prediction models were based on partial least squares (PLS) regression analyses and 2nd derivative transformation (FOSS NIRSystems 2001, Hodge et al. 2006).

The predicted α-cellulose and lignin content data derived from these prediction models were then used to calculate whole-stem weighted averages.

Calculating Weighted Averages and Whole-stem Weighted Averages

Before developing the models, a weighted average of each wood property in all the trees sampled was calculated. Since wood density was measured ring by ring, the formula for calculating the weighted wood density of each increment core was:

[2] $$\sum_{i=1}^{n} x_i y_i / \sum_{i=1}^{n} x_i$$

where x is the width of i-th ring and y is the density of i-th ring. For calculating whole-stem weighted averages, inside bark diameter, bolt length, sample height, and wood core weighted values were needed from each height. Before calculating each whole-stem weighted average, the volume of each bolt was calculated since whole-stem wood properties were weighted upon volume. Weighting each wood property according to bolt volume accounted for differences in volume due to changes in stem taper. Hence, data collected from bolts of larger volume had a larger impact on the calculated whole-stem weighted average. To calculate the volume of the bottom bolt below breast-height, the formula was:

[3] $$D^2 \times 0.005454 \times BL$$

where D is the diameter of the bolt and BL is the length of the bolt below breast-height. Smalian's formula was used to calculate the inside-bark volume for each bolt above breast-height (Avery and Burkhart 1994):

[4] $$[[(0.005454 \times D_b^2) + (0.005454 \times D_t^2)] \div B_i] \times BL_i$$

where D_b is the diameter at the bottom of the bolt and D_t is the diameter at the top of the bolt; B is i-th bolt above breast-height; and BL is the length of i-th bolt (i = 1, 2, 3, 4 etc.). Whole-stem weighted averages for each wood property where then calculated using the formula:

[5] $$\sum_{i=1}^{n} a_i b_i / \sum_{i=1}^{n} a_i$$

where a is the volume of the i-th bolt and b is the wood property measurement of the i-th bolt (height). The calculated weighted averages for each wood property and the data collected at breast-height were then used to develop regression models using breast-height measurements as independent variables.

Statistical Analysis

Basic statistics (mean, standard deviation, confidence limits, standard errors, coefficients of variation) were calculated to look at variability in the wood density data and growth data (Proc MEANS, SAS Institute, 2002).

Based on the collected and calculated measurements, linear regressions were performed and coefficients of determination were calculated using overall breast-height wood density, breast-height juvenile wood density, breast-height transition wood density, and breast-height mature wood density as the independent variables (Proc REG, SAS Institute, 2002). The coefficients of determination showed how a linear regression model, based on breast-height wood properties, breast-height juvenile wood properties, or breast-height transition wood properties, predicted the calculated whole-stem wood property values. The basic linear regression model used was:

[6] $$\hat{Y} = \beta_0 + \beta_1 X_i + \varepsilon$$

Where:

$\hat{Y}$ = predicted value of the trait of interest
β_0 = intercept parameter
β_1 = slope parameter
X_i = *i-th* independent variable
ε = random error, $(0, \sigma_\varepsilon^2)$

Assumptions of a linear model are that ε are independent, identically distributed $(0, \sigma_\varepsilon^2)$ random variables.

Plots of the standardized residuals and the predicted values were constructed to check for the presence of outliers. The assumptions were that the standardized residuals should be independent normal deviates randomly distributed around zero. Standard residual values that were above or below 2.5 and -2.5, respectively were omitted from the analysis (Chatterjee and Price 1977, Giesbrecht and Gumpertz 2004).

The linear models were selected using the stepwise selection and the REG procedure in SAS (SAS Institute, 2002-2003). The stepwise selection method includes variables in the model that have an *F*-statistic that is significant at a given significance level. This method begins by including all variables in the model and then deleting variables that are not significant. Given that the objective of this research was to develop practical prediction models, the only two variables included in the model were the independent breast-height variable and the quadratic term for the breast-height variable. Variables that were included in the prediction models were significant at the $P \leq 0.15$ level. Overall, the stepwise model selection method helped to determine which variables significantly improved the adequacy of the model (SAS Institute, 2002-2003).

Separate models were developed describing the relationship between whole-stem wood density and breast-height juvenile, transition, mature, and mature wood density using the REG procedure (SAS Institute, 2002). Pearson correlation coefficients were also calculated to determine how strong the correlation was between each of the independent variables and the dependent variable (whole-stem wood density) (Proc CORR, SAS Institute, 2002).

Results and Discussion

Wood Density

Breast-height wood density ranged from 427.76 kg/m^3 to 489.3 kg/m^3 and calculated whole-stem wood density values ranged from 392.92 kg/m^3 to 434.37 kg/m^3. On average, breast-height wood density was about 40 kg/m^3 higher than whole-stem wood density. No significant correlation was found between breast-height and whole-stem wood density and growth. The R^2 value resulting from simple linear regression was high, indicating that breast-height wood density was an effective predictor of whole-stem wood density (Figure 1). The correlation between overall breast-height density and whole-stem density was also very high (r = 0.9219) (Table 1).

When the breast-height samples were divided into juvenile, transition, and mature wood sections according to ring by ring data, breast-height juvenile wood density was highly correlated with whole-stem wood density (Table 1). A linear prediction model based on breast-height juvenile wood explained 64% of the variation in whole-stem wood density (Table 2). Another linear model was fitted to the data describing the relationship between breast-height transition wood density and whole-stem wood density. When breast-height transition wood density was used as a predictor of whole-stem wood density, the R^2 value was lower (0.59) than when using breast-height juvenile wood as a predictor (Table 2). Similarly, the correlation between breast-height transition wood density and whole-stem wood density was lower than that of the correlation between juvenile wood and whole-stem values (Table 1).

When breast-height mature wood density was used as a predictor of whole-stem wood density, the correlations and relationships were not strong. Breast-height mature wood density showed no significant correlation with whole-stem wood density (Table 1). Furthermore, there was no recognizable relationship between breast-height mature wood density and whole-stem wood density and a linear fitted to the data resulted in an R^2 of 0.19 (Table 2).

α-Cellulose

Breast-height α-cellulose yield ranged from 38.66 % to 42.80 % and whole-stem α-cellulose yield ranged from 38.52 % to 42.40 % (Table 1). On average, breast-height α-cellulose yield was about 0.33 % higher than whole-stem α-cellulose yield. Both breast-height and whole-stem α-cellulose yield were negatively correlated with volume, diameter and height (Table 2). A linear model describing the relationship between breast-height α-cellulose yield and whole-stem α-cellulose yield resulted in a high R^2 value of 0.95 (Figure 2A). The correlation between breast-height α-cellulose and whole-stem α-cellulose was also very high (Table 3). These results strongly indicate that overall, breast-height α-cellulose yield is an accurate predictor of whole-stem α-cellulose yield.

When the breast-height sample was divided into juvenile, transition and mature wood sections, the correlation between breast-height juvenile wood α-cellulose yield and whole-stem α-cellulose yield was 0.62 (Table 3). A linear model was fitted to the data describing the relationship between breast-height juvenile wood α-cellulose yield and whole-stem α-cellulose yield ($R^2 = 0.44$) (Figure 2B).

A simple linear model was used to describe the relationship between breast-height transition wood α-cellulose yield and whole-stem α-cellulose yield. This prediction model resulted in an R^2 value of 0.73 (Figure 2C). The correlation between breast-height transition wood and whole-stem α-cellulose yield was also high ($r = 0.85$) (Table 3). The relationship between breast-height mature wood and whole-stem α-cellulose yield was similar to the relationship between breast-height transition wood and whole-stem α-cellulose yield. A linear model fitted to the data resulted in an R^2 of 0.71 and the calculated correlation coefficient describing the relationship between breast-height mature wood and whole-stem α-cellulose yield was 0.84 (Figure 2D, Table 3).

The results of the α-cellulose yield data analysis and prediction model development showed that the overall breast-height α-cellulose yield value was the most accurate predictor of whole-stem α-cellulose yield. Breast-height juvenile wood was not a very accurate predictor of whole-stem values and breast-height transition and mature wood α-cellulose yield showed similar relationships with whole-stem α-cellulose yield. However, breast-height transition wood showed a slightly stronger relationship with whole-stem α-cellulose yield.

Lignin Content

Breast-height lignin content ranged from 26.86 % to 29.41 %. Calculated whole-stem lignin content ranged from 27.47 % to 29.58 % (Table 1). On average, breast-height lignin content was about 0.47 % lower than whole-stem lignin content. Both breast-height and whole-stem lignin content had a slightly positive correlation with volume, diameter and height (Table 2). A linear model fitted to both the breast-height and whole-stem lignin content data produced an R^2 of 0.85 (Figure 3A). The calculated correlation coefficient describing the relationship between overall breast-height lignin content and whole-stem lignin content was also strongly positive (Table 3).

When the sample taken at breast-height was further divided into juvenile, transition and mature-wood sections, the relationships with whole-stem lignin content were variable. A linear prediction model fitted to the breast-height juvenile wood and whole-stem lignin content data produced an R^2 of 0.57 (Figure 3B). The calculated correlation coefficient describing the relationship between breast-height juvenile wood lignin content and overall whole-stem lignin content was 0.76 (Table 3). The correlation between breast-height transition wood and whole-stem lignin content was 0.90 (Table 3). Not only was this relationship stronger than that of juvenile wood, but a simple linear model fitted to breast-height transition wood and whole-stem lignin content data resulted in an R^2 0.82 (Figure 3C). A linear model using breast-height mature wood lignin content explained 59% of the variation in whole-stem lignin content (Figure 3D). This was a slightly higher R^2 value than that resulting from using breast-height juvenile wood lignin content. However, the correlation coefficient was higher when using mature wood instead of juvenile wood (Table 3).

Overall, the results show that breast-height lignin content was strongly correlated with whole-stem lignin content and the relationship between the two measurements was linear. Breast-height transition wood lignin content also showed a strong linear relationship and was highly correlated with overall whole-stem lignin content. Juvenile and mature wood prediction models were less accurate; however, there were strong correlations with whole-stem lignin content.

Discussion

In this research, prediction models were developed that related whole-stem wood property measurements to breast-height wood property measurements in mature loblolly pine. For wood density, α-cellulose content, and lignin content, the correlations between breast-height and whole-stem measurements were strong. The results related to wood density are very similar to what was found by Zobel et al, 1972. The coefficient of determinations and the correlations between breast-height and whole-stem wood density (specific gravity) measurements were high in Zobel's study and in this study. The results of Zobel et al, 1960 were also similar; however, the correlations between breast-height and whole-stem were stronger in this study. When the breast-height sample was divided into juvenile, transition and mature wood sections, juvenile wood density had the highest correlation with whole-stem wood density. This observation is interesting since juvenile wood can vary significantly in its wood properties. Juvenile wood can be unstable and unpredictable compared to mature wood (Zobel and Sprague 1998). This is also interesting since the sample trees were of mature age and the juvenile core would not consume the entire cross section of wood at breast-height. Transition wood also showed a strong correlation with whole-stem wood density; however mature wood did not show any significant relationship with whole-stem wood density. One might think that mature wood would provide a better association with whole-stem wood density since it is more stable (Zobel and Jett 1995). In fact, mature wood has been seen to be more accurate at predicting whole-stem wood density than juvenile wood (Zobel et al, 1972).

There have little or no studies that have showed how whole-stem chemical wood properties in relate to breast-height wood properties in loblolly pine. However, the regression models developed in this study and the results involving α-cellulose yield are similar to the findings of Zobel et al, 1960. Zobel et al, 1960 also used mature samples of loblolly pine (*Pinus taeda*) (3 – 50 year old and 7 – 17 year old) from the coastal plain of North Carolina. The results of this study and Zobel's showed that breast-height α-cellulose yield was strongly correlated with whole-stem α-cellulose yield. When the breast-height sample was further divided into juvenile, transition and mature wood sections, different associations were found. Juvenile wood α-cellulose yield had a weaker correlation with whole-stem α-cellulose yield than did breast-height transition wood and mature wood. Overall, breast-height α-cellulose yield had the strongest correlation with whole-stem α-cellulose yield. There were also differences in the nature of the relationship between each of the breast-height sections and whole-stem α-cellulose yield. Overall, a simple linear model proved accurate for predicting whole-stem α-cellulose yield based on overall breast-height, transition wood and mature wood sections.

The third wood property examined in this study was lignin content. The results of linear regression and the calculation of correlation coefficients proved that the relationship between breast-height lignin and whole-stem lignin was similar to the relationship between breast-height α-cellulose yield and whole-stem α-cellulose yield. Overall, the entire breast-height sample and the transition wood section showed the strongest correlations and associations.

The results of this study show that depending upon the wood property of interest, different sections (juvenile, transition, mature) may be more useful than others for prediction purposes. The most important result in this study was the development of prediction models for whole-stem wood properties based on breast-height wood properties. There may a considerable amount of variation in these wood properties between geographic areas, populations and specific genotypes. However, the practical models developed in this study may be useful for selecting genotypes with superior whole-stem wood properties.

Conclusions

In mature loblolly pine, predicting whole-stem wood properties using breast-height wood properties proved to be effective. Linear regression models were significant and accurate for describing the relationship between breast-height wood properties and whole-stem wood properties. Coefficients of determination for wood density ranged from 0.27 to 0.85. Coefficients of determination ranged from 0.42 - 0.95 to 0.59 - 0.85 for α-cellulose and lignin content respectively. Correlations between breast-height wood properties and whole-stem wood properties were high and ranged from 0.92 to 0.98. For juvenile wood, correlations between breast-height wood properties and whole-stem wood properties ranged from 0.62 to 0.92 and correlations with whole-stem wood properties ranged from 0.77 to 0.90 for breast-height transition wood and from 0.44 to 0.84 for mature wood. Negative correlations were found between wood density measurements and growth measurements. Negative correlations were also found between α-cellulose yield measurements and growth measurements. However, positive correlations were found between lignin measurements and growth measurements. Overall, linear prediction models were developed for predicting whole-stem wood properties in mature loblolly pine (*Pinus taeda*). The development of these whole-stem prediction models may be useful for selection of genotypes with superior whole-stem wood properties.

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Tables and Figures

Table 1. Descriptive statistics for growth measurements and breast-height and whole-stem wood property measurements of mature loblolly pine.

	BH Density (kg/m³)	WT Density (kg/m³)	BH ACY (%)	WT ACY (%)	BH LIG (%)	WT LIG (%)	Diameter (cm)	Volume (m³)	Height (m)
Minimum	427.7	392.9	38.7	38.5	26.9	27.5	21.1	0.24	19.4
Maximum	489.3	434.4	42.8	42.4	29.4	29.6	34.5	0.86	25.5
Mean	455.3	414.5	41.9	40.8	27.9	28.4	27.8	0.49	21.9
Standard Deviation	18.5	15.3	0.98	0.89	0.66	0.53	3.06	0.14	1.63

BH, breast-height density; WT, whole-tree density; BH ACY, breast-height α-cellulose yield; WT ACY, whole-stem α-cellulose yield; BH LIG, breast-height lignin content; WT LIG, whole-stem lignin content.

Table 2. Correlation coefficients between breast-height – whole-stem wood properties and growth measurements.

Variable	Breast-height Wood Density (kg/m³)			Whole-stem Wood Density (kg/m³)		
	(r)	*P-value*	*n*	*(r)*	*P-value*	*n*
Volume (m³)	-0.12	0.6127	20	-0.07	0.7767	20
Diameter (cm)	-0.01	0.9649	20	0.06	0.8124	20
Height (m)	-0.28	0.2370	20	-0.19	0.4349	20
	Breast-height α-Cellulose Yield (%)			**Whole-stem α-Cellulose Yield (%)**		
Volume (m³)	-0.33	0.1525	20	-0.35	0.1289	20
Diameter (cm)	-0.33	0.1576	20	-0.34	0.1369	20
Height (m)	-0.26	0.2606	20	-0.27	0.2452	20
	Breast-height Lignin Content (%)			**Whole-stem Lignin Content (%)**		
Volume (m³)	0.16	0.5045	20	0.24	0.3143	20
Diameter (cm)	0.12	0.6017	20	0.24	0.3129	20
Height (m)	0.19	0.4340	20	0.15	0.5403	20

Table 3. Correlation coefficients between breast-height wood properties and whole-stem wood properties in mature loblolly pine.

	Whole-stem Wood Property Measurements		
Breast-height Variable	***(r)***	***P-value***	***n***
BH Density (kg/m^3)	0.92	<0.0001	20
Density (kg/m^3) at 3.8 m	0.92	<0.0001	20
JUV Density (kg/m^3)	0.80	<0.0001	20
TRANS Density (kg/m^3)	0.76	<0.0001	20
MAT Density (kg/m^3)	0.43	0.0528	20
BH ACY (%)	0.97	<0.0001	20
JUV ACY (%)	0.62	0.0033	20
TRANS ACY (%)	0.85	<0.0001	20
MAT ACY (%)	0.84	<0.0001	20
BH LIG (%)	0.92	<0.0001	20
JUV LIG (%)	0.75	<0.0001	20
TRANS LIG (%)	0.90	<0.0001	20
MAT LIG (%)	0.76	<0.0001	20

BH, breast-height; JUV, breast-height juvenile wood; TRANS, breast-height transition wood; MAT, breast-height mature wood.

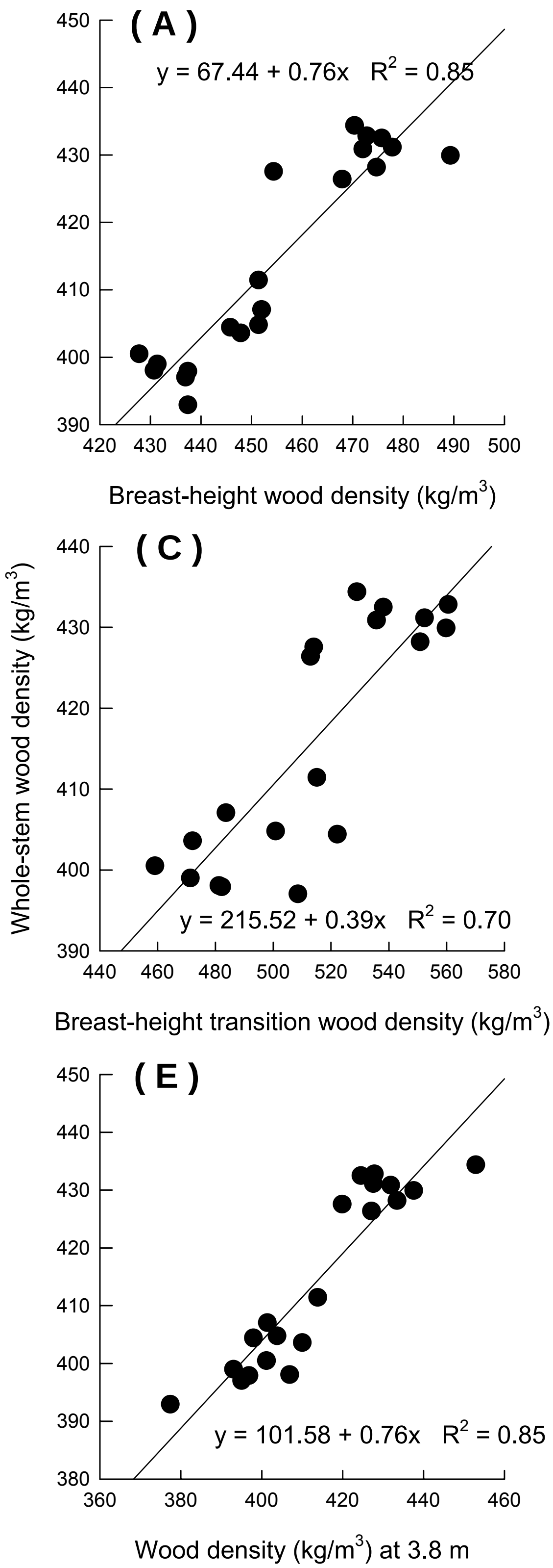

Figure 1. Whole-stem regression models based on: (A) breast-height wood density, (B) breast-height juvenile wood density, (C) breast-height transition wood density (D) breast-height mature wood density, and (E) wood density at 3.8 m (12.5 feet).

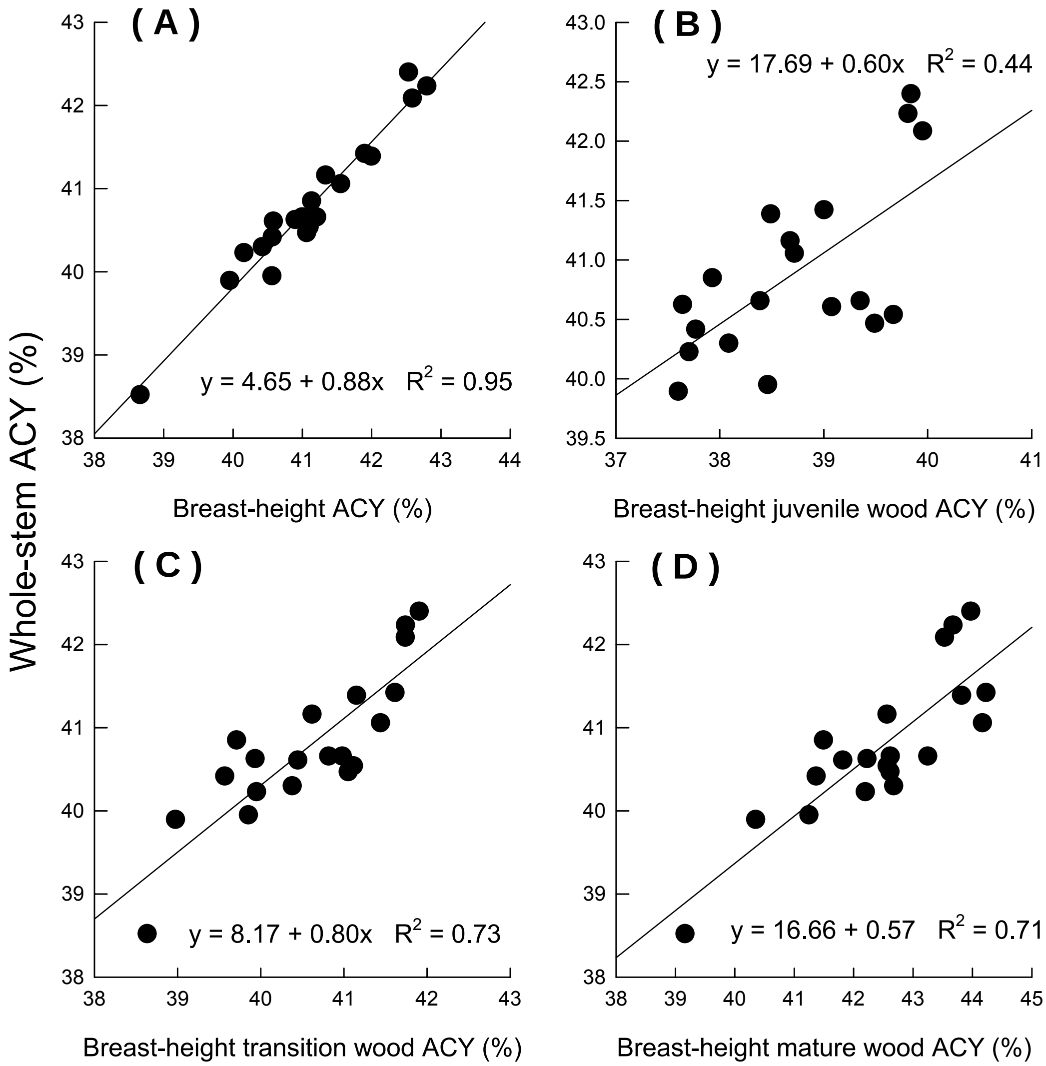

Figure 2. Whole-stem regression models based on: (A) breast-height α-cellulose yield, (B) breast-height juvenile wood α-cellulose yield, (C) breast-height transition wood α-cellulose yield, and (D) breast-height mature wood α-cellulose yield.

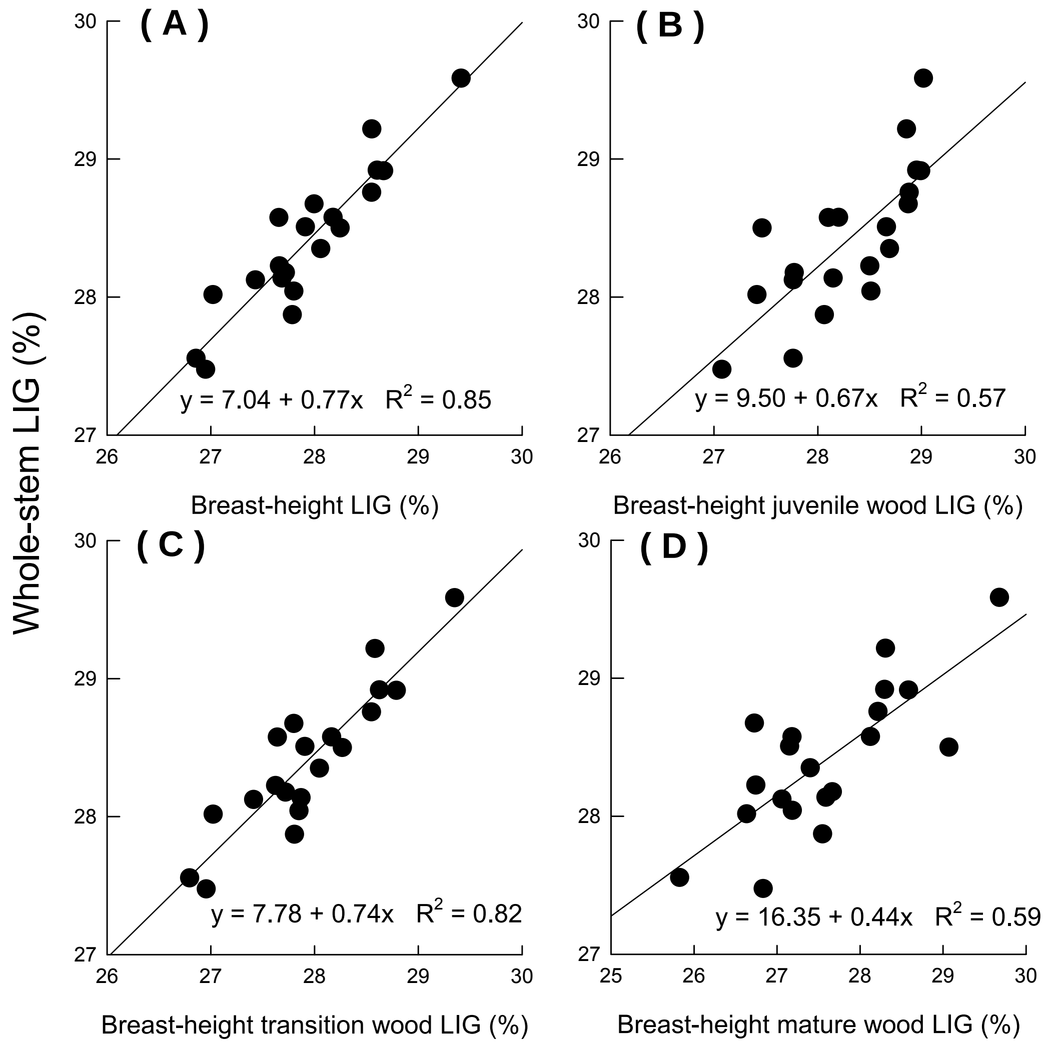

Figure 3. Whole-stem regression models based on: (A) breast-height lignin content, (B) breast-height juvenile wood lignin content, (C) breast-height transition wood lignin content, and (D) breast-height mature wood lignin content.

CONCLUSION

The combined use of fast growing genotypes and intensive silviculture has drastically reduced pine plantation rotation ages in the southeastern U.S. As a result, the proportion of wood that is considered juvenile has increased (Sykes et al. 2003, Atwood et al. 2002, Larson et al. 2001, Isik and Li 2003). The impact of increased production of juvenile wood has major economic and wood quality implications. The structural and strength characteristics of juvenile wood are poor compared to mature wood (Larson et al. 2001, Megraw 1985, Zobel and Sprague 1998). For pulp and paper production, juvenile wood can negatively influence pulp yields and increase costs due to the removal of high amounts of lignin, low cellulose content and shorter tracheids (Zobel and Sprague 1998). For high quality wood products and structural lumber production, juvenile wood is not suitable due to low wood density, low stiffness and increased susceptibility to shrinkage and swelling (Zobel and Sprague 1998, Larson et al. 2001). Given that juvenile wood properties may vary within and between trees of the same species and many wood properties are under a certain degree of genetic control, genetic improvement of wood properties looks promising (Zobel and Jett 1995, Byram et al. 1988, Williams and Megraw 1994).

Over the years, many researchers have studied and described the within-stem pattern of variation for wood properties loblolly pine (*Pinus taeda* L.) (Zobel and van Buijtenen 1989, Megraw 1985, Larson et al. 2001, Burdon et al. 2004). Also, whole-stem prediction models and breast-height to whole-stem correlations for loblolly pine specific gravity have been established (Zobel 1960, Zobel et al. 1972, Zobel and van Buijtenen 1989). However, there has been little effort to examine the relationship between breast-height wood properties and whole stem wood properties while assessing genetic and environmental effects in juvenile and mature loblolly pine. Therefore, the goal of this study was to develop practical and efficient prediction models that accurately describe the relationship between breast-height and whole-stem wood properties in juvenile and mature loblolly pine. Another goal of this study was to describe the correlation or relationship between different sections (juvenile, transition, mature) of wood at breast-height and whole-stem weighted averages. It is important to assess the whole-stem value of the wood properties of a tree since wood properties vary with height due changes in the proportion of juvenile wood and changes in stem taper (Zobel and van Buijtenen 1989, Burdon et al. 2004). Weighted averages help to account for the patterns of variation in wood properties due to differences in stem taper, volume, and height.

The results of this study have many implications related to forest genetics and wood quality research. Models for predicting whole-stem wood properties could help to select genotypes of loblolly pine which display more profitable wood property characteristics. Since fast-grown intensively managed plantations contain high proportions of juvenile wood, selective breeding for genotypes with beneficial juvenile wood properties could help improve the quality of wood produced on southern pine plantations.

In the future, further research which analyzes quantitative genetic differences of many genotypes over several sites needs to be done for comparing and ranking families and clones for selection. The following sections will summarize the important findings of this study and will further emphasize the major implications relating to the results.

Prediction of whole-stem wood properties for juvenile loblolly pine

The first portion of this study focused on relating breast-height wood properties to whole-stem wood properties of juvenile loblolly pine while assessing genetic and environmental effects. Also, the relationship between breast-height juvenile and transition wood properties and whole-stem wood properties was investigated. The three wood properties included in this study were: wood density, α-cellulose, and lignin. Four clones and three ramets per clone were replicated over two sites; one site in Florida and the other in Alabama. Overall, 24 trees were destructively sampled for analysis but one tree was excluded. The study was initially established to compare genetic variance components and performance differences from cuttings and seedlings of the same families (Cumbie 2002, Isik et al. 2003, Isik et al. 2004).

The results showed that there were significant site differences in all wood property measurements except for breast-height transition wood lignin content, breast-height transition wood α-cellulose content and breast-height juvenile wood α-cellulose content. No clonal differences were found for any wood property trait except breast-height juvenile wood α-cellulose content. Site differences were also found for all growth measurements and significant clonal differences were found for height. Volume and height were strongly and negatively correlated with breast-height and whole-stem wood density. Overall, the trees growing in Florida showed the lowest growth and the highest average wood density values.

For both sites, the relationship between breast-height wood density and whole-stem wood density was linear and R^2 values were 0.70 and 0.72 for Florida and Alabama, respectively. There were no significant model differences between sites or clones.

Correlations between breast-height and whole-stem wood density were also strong for both sites. Combining data from both sites increased the R^2 to 0.90.

The relationship between breast-height juvenile wood density and whole-stem wood density was not as strong. Furthermore, two different models were developed; one for each site. For the Florida site, breast-height juvenile wood density explained 34% of the variation in whole-stem wood density while breast-height juvenile wood density explained 72% of the variation in whole-stem wood density at the Alabama site. The reason for the differences may be attributed to the fact that a higher proportion of juvenile wood was present in the trees growing in Alabama. For example, the trees growing in Alabama reached transition wood at age 6 while the trees growing in Florida reached transition wood at age 4. Across both sites, a linear model described 53% of the variation between breast-height juvenile wood density and whole-stem wood density.

Also, breast-height transition wood density was not as strong of a predictor of whole-stem wood density as the overall breast-height sample. For the Alabama site, no model could be developed that adequately described the relationship between breast-height transition wood density and whole-stem wood density. However, a linear model explained 23% of the variation in whole-stem wood density at the Florida site. A linear model explained 51% of the variation when data from both sites were combined. Given that the 14-year-old trees growing on both sites are composed of mostly juvenile wood, it is understandable that the small amount of transition wood present did not serve as a good predictor of whole-stem wood density. Overall, the results derived from the prediction models and the calculated correlation coefficients showed that the entire breast-height section was the best predictor of whole-stem wood density. Neither juvenile wood nor transition wood alone predicted whole-stem wood density with more accuracy than the overall breast-height sample that contained both juvenile and transition wood. The results prove that it is reasonable to say that a pith to bark breast-height sample explained a significant amount of the variation between breast-height and whole-stem wood density. Therefore, it is recommended that the overall breast-height sample be used for predicting whole-stem wood density.

When breast-height α-cellulose content was used as a predictor of whole-stem α-cellulose content, the results showed similarities with the breast-height/whole-stem models. For breast-height α-cellulose content, a different model was developed for predicting whole-stem α-cellulose content at each site. Both models showed strong relationships and correlations between breast-height and whole-stem values were strong. When data from both sites were combined, the relationship was described by a polynomial model ($R^2 = 0.82$). Interestingly, no relationship could be determined between breast-height juvenile wood α-cellulose content and whole-stem α-cellulose content and therefore, no model was developed. This is much different than what was found for breast-height juvenile wood density, where juvenile wood density showed a strong relationship with whole-stem wood density. It was not clear why so much variation was present in the juvenile wood α-cellulose content data and why the correlation with whole-stem α-cellulose content was so weak ($r = 0.21$). Breast-height transition wood α-cellulose content showed much stronger relationships with whole-stem α-cellulose content and R^2 values were 0.60 and 0.70 respectively. However, the relationship between breast-height transition wood α-cellulose content and whole-stem α-cellulose content was much different between sites. One site was fitted to a linear model while the other site's data was fitted to a polynomial. Across both sites, breast-height transition wood α-cellulose content explained 71% of the variation in whole-stem α-cellulose content. Overall, the results showed that the entire breast-height sample, from pith to bark, explained most of the variation in whole-stem α-cellulose content. Therefore, it is recommended that the entire breast-height sample be used as a predictor of whole-stem α-cellulose content.

For lignin content, the entire breast-height sample also served as the best predictor of whole-stem lignin content. A linear model was used at each site (Alabama, $R^2 = 0.67$ and Florida, $R^2 = 0.34$) and over both sites combined ($R^2 = 0.71$). The same model with different parameters was used at each site; however, significance tests revealed that there were no significant differences in the prediction models between sites.

Breast-height juvenile wood lignin content served as a good predictor of whole-stem lignin content at the Alabama site but no model could be developed for the Florida site. The reason for the differences may be due to the fact that the trees in Alabama had a higher proportion of juvenile wood and therefore juvenile wood explained a greater amount of variation in whole-stem wood density. In other words, the juvenile core of the trees in Alabama was larger than the juvenile core of the trees in Florida. Across both sites, the linear model describing the relationship between breast-height juvenile wood lignin content and whole-stem lignin content produced an R^2 of 0.63.

For breast-height transition wood lignin content, linear models were also used to predict whole-stem lignin content. The models for each site were more similar than the models used for breast-height juvenile wood lignin content; however significance tests revealed there were significant differences in the prediction models between sites ($P = 0.0057$). The model at the Alabama site was more accurate at predicting whole-stem lignin content than the model used at the Florida site. Across sites, the linear model describing the relationship between breast-height transition wood lignin content and whole-stem lignin content produced and R^2 of 0.39. One site had a higher proportion of juvenile wood, yet overall, at both sites juvenile wood was the most important factor affecting the relationship between breast-height wood properties and whole-stem wood properties. Environmental effects were the most significant factor affecting the growth of the trees. It is obvious to see that the significant differences in growth across sites played a key role in determining the wood properties that were developed. The smaller trees in Florida contained a smaller juvenile core and therefore showed higher wood density and α-cellulose content values. Lignin content at the Florida site was also significantly lower at both the breast-height and whole-stem levels.

The main finding of the study involving prediction models for whole-stem wood properties in juvenile loblolly pine was that the overall breast-height sample served as the most accurate and efficient predictor of the overall whole-stem weighted average. Site differences did significantly affect the growth and wood properties of the juvenile trees, but, the prediction models that were developed showed strong relationships when data was combined over both sites.

Prediction of whole-stem wood properties for mature loblolly pine

The second portion of this study focused on relating breast-height wood properties to whole-stem wood properties of harvest-age loblolly pine. Also, the relationship between breast-height juvenile, transition, and mature wood properties and whole-stem wood properties was investigated. The three wood properties included in this study were: wood density, α-cellulose, and lignin. The trees used in this study were harvested from a diallel test located in Jones County, on the Coastal Plain of North Carolina. The sample set was composed of 20 20 – year-old trees, each from a different full-sib family (control cross). Only dominant or co-dominant trees were selected for harvest. This particular test was composed of 2nd generation North Carolina Coastal Plain genetic material.

The prediction model relating breast-height wood density to whole-stem wood density showed a strong linear relationship ($R^2 = 0.85$) and correlation ($r = 0.92$). For breast-height juvenile wood density, the relationship with whole-stem wood density was not as strong. However, when compared to the accuracy of predicting whole-stem wood density using transition wood or mature wood density, juvenile wood density was the most accurate. It is important to note that juvenile wood explained only 6% more of the variation in whole-stem wood density than transition wood. Mature wood was not a very useful predictor. Overall, it was found that the overall breast-height wood sample acted as the most accurate and efficient predictor of whole-stem wood density. Therefore, similar to the findings of the study involving juvenile loblolly pine, it is recommended that the entire breast-height sample be used to predict whole-stem wood density.

Also, overall breast-height α-cellulose content proved to be the best predictor of whole-stem α-cellulose content ($R^2 = 0.95$). Breast-height juvenile wood α-cellulose content was not as strong of a predictor of whole-stem α-cellulose content as breast-height transition wood and mature wood α-cellulose content. Both transition and mature wood showed linear relationships while the relationship between juvenile wood α-cellulose content and whole-stem α-cellulose content was described using a linear model. This finding is also similar to what was found in the portion of this study involving juvenile loblolly pine where juvenile wood α-cellulose content showed no relationship with whole-stem α-cellulose content. The most important finding was that the entire breast-height sample served as the best predictor of whole-stem α-cellulose content.

As for lignin content, the results showed that breast-height and breast-height transition wood lignin content were the best predictors of whole-stem lignin content. In both cases the relationship was linear. The most important finding to understand in this portion of the study is that mature loblolly pine whole-stem wood properties are best predicted using the entire breast-height sample that contains the pattern of variation in wood properties from juvenile to mature wood. Although significant correlations and relationships were found for individual sections of wood at breast-height, the entire sample provided the best measure of estimating whole-stem wood properties.

In conclusion, the results of this study show that breast-height wood properties are effective predictors of whole-stem wood properties in juvenile and mature loblolly pine. For juvenile loblolly pine, both genotype and environment can have a significant effect on this relationship. In this study, the environmental factors affecting growth of juvenile trees had the largest impact on whole-stem wood properties and levels of variation. In general, juvenile trees that grew faster due to better resource availability or less competition contained a higher proportion of juvenile wood. Trees that grew slower produced higher density growth rings at a younger age and therefore had higher whole-stem wood density, α-cellulose content, and lower lignin values. For juvenile trees, the size of the juvenile core was the most likely reason for the stronger relationship between breast-height juvenile wood properties and whole-stem wood properties. On the practical side, the most effective predictor of whole-stem wood properties in juvenile loblolly pine was the entire pith to bark breast-height sample. The weighted average of the entire pith to bark breast-height sample may have accounted for the variation between sections of juvenile and transition wood. This technique in turn helped to account for the pattern of variation and made the relationship between breast-height and whole-stem wood properties more comprehensive. For mature loblolly pine, the same statement held true. The entire breast-height sample was the best predictor of whole-stem wood properties. Depending upon the trait of interest, breast-height transition wood also was an adequate predictor when compared to juvenile and mature wood. The entire breast-height sample may have served as the best predictor since the entire sample is basically an average across all sections between the pith and the bark.

The results of this study also showed that the pattern of variation in whole-stem wood properties from the base of the tree moving upwards is fairly predictable. When the mean wood property values at each height were plotted for each site for both juvenile and mature loblolly pine, similar trends were found (Figure 1, 2 & 3). This finding supports the application of these prediction models since the models account for the changes in wood properties between breast height and wood properties at varying heights. Since wood properties do show variation patterns that are predictable along the length of the stem and we can predict whole-stem weighted averages for wood properties, there is room for these methods to become feasible applications in tree improvement operations.

Finally, the results of this study may serve as important information to researchers involved in tree improvement, silviculture and wood and paper science. The decline in wood quality due to the use of faster growing genotypes and intensive silviculture may be remedied by selectively breeding for genotypes which show advantageous and economically valuable wood property characteristics. Future research should further focus on the genetic differences in whole-stem wood properties so that whole-stem prediction model methods can be incorporated into tree improvement operations.

Tables and Figures

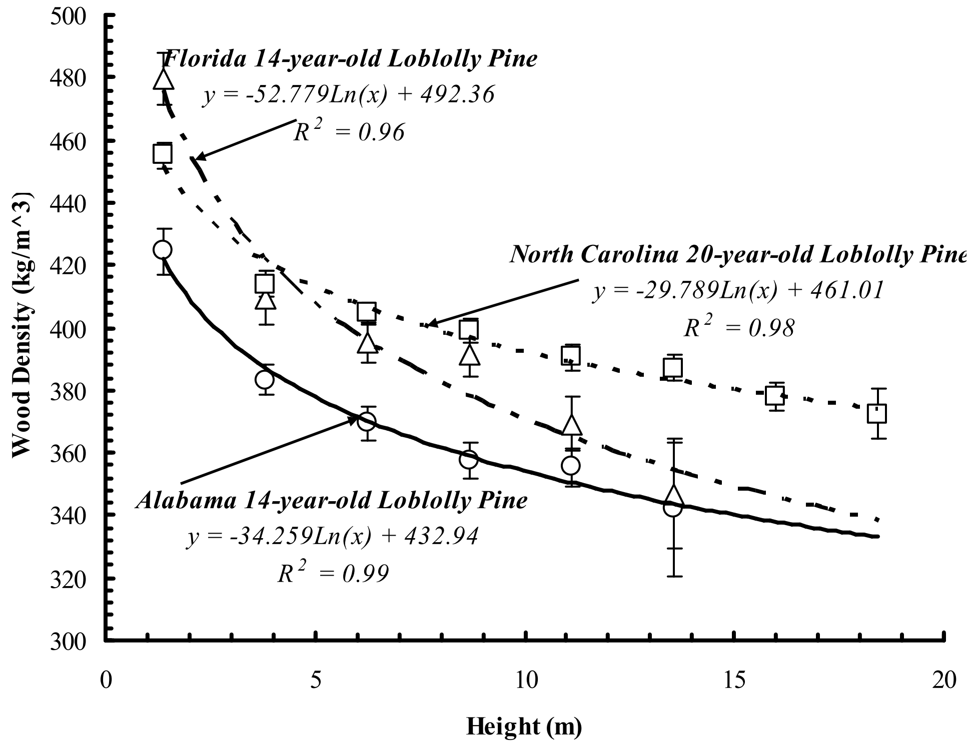

Figure 1. Mean wood density at incremental heights along the length of the stem for both juvenile loblolly pine in Florida and Alabama, and mature loblolly pine in North Carolina.

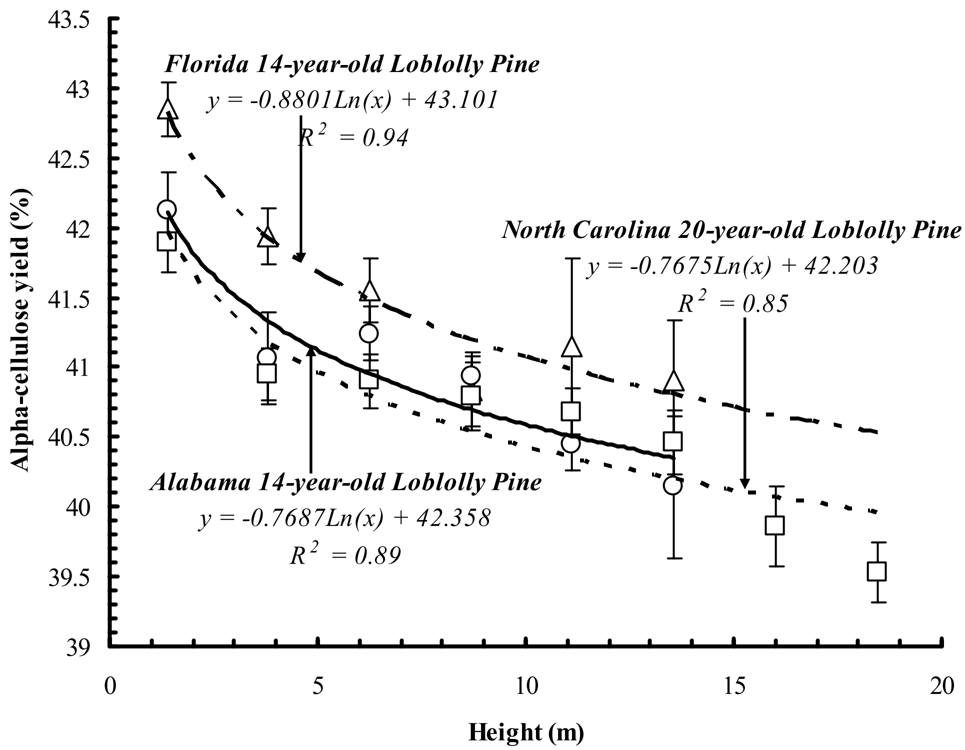

Figure 2. Mean α-celluloseat incremental heights along the length of the stem for both juvenile loblolly pine in Florida and Alabama, and mature loblolly pine in North Carolina.

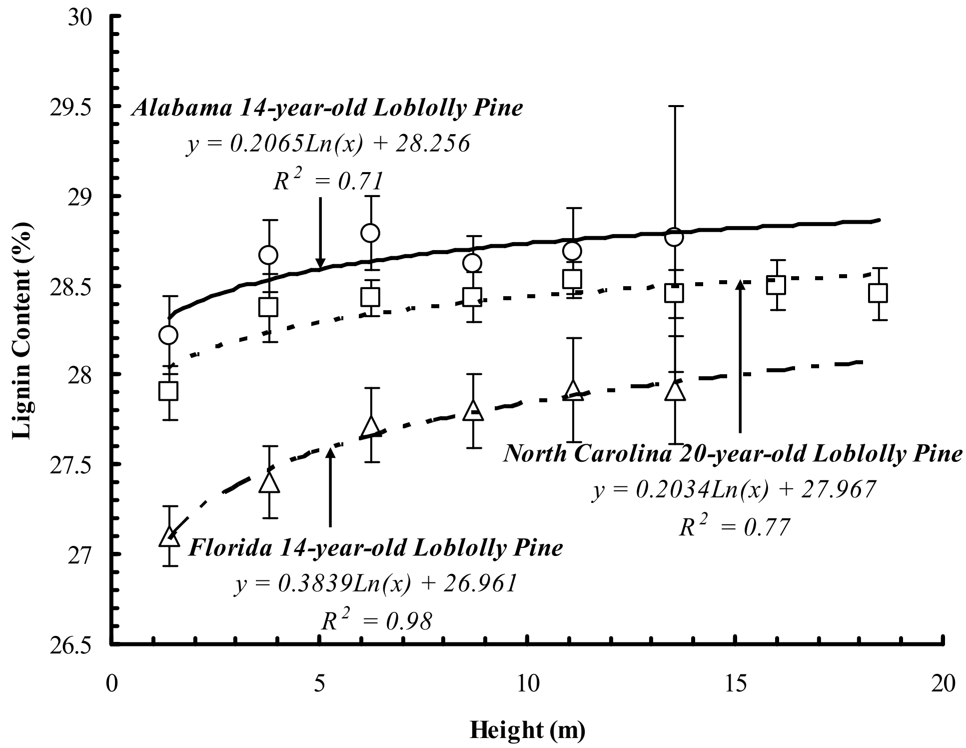

Figure 3. Mean lignin content at incremental heights along the length of the stem for both juvenile loblolly pine in Florida and Alabama, and mature loblolly pine in North Carolina.

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