EFFECT OF CULTURAL INTENSITY AND PLANTING DENSITY ON ABOVEGROUND BIOMASS ACCUMULATION AND ALLOCATION OF 12-YEAR-OLD LOBLOLLY PINE TREES GROWING IN THE UPPER COASTAL PLAIN AND PIEDMONT OF ALABAMA AND GEORGIA

by

SANTOSH SUBEDI

(Under the Direction of Michael Kane)

ABSTRACT

I examined the effects of cultural intensity (operational and intensive), planting density (741, 1482, 2223, 2964, 3705 and 4446 trees ha^{-1}) and their interaction on aboveground biomass accumulation and allocation for 12-year-old loblolly pine trees. I also tested if cultural intensity, planting density, or their interaction affects biomass accumulation after accounting for their effects on stem size. Cultural intensity significantly affected accumulation of stem, bark, dead-branch and total aboveground biomass and biomass allocation in dead-branch, live-branch and foliage components. Accumulation and allocation for total aboveground biomass and for each biomass component differed significantly among planting densities. The only significant culture x density interaction was for dead-branch biomass accumulation. Generally, biomass accumulation in trees at planting densities from 2223 to 4446 trees ha^{-1} was not affected by cultural intensity and planting density treatments after taking into consideration their effects on stem size.

INDEX WORDS: Loblolly pine, Biomass allocation, Intensive culture, Planting density, Allometric equation

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

PURPOSE OF THE STUDY

Loblolly pine (Pinus taeda L.) is a commercially important tree species and is very responsive to silvicultural treatments. The effects of cultural treatments on biomass production of loblolly pine have been extensively researched. Similarly, some studies have tested the effects of planting density on biomass allocation and accumulation of aboveground components. The purpose of this study was unique in that it examined both the individual effects of cultural intensity and planting density as well as the culture x density interaction effect on biomass accumulation and allocation for stem, bark, dead-branch, live-branch, and foliage components of 12-year-old loblolly pine trees. An additional objective of this study was to evaluate if predictions of biomass components using stem size fully described the variance in biomass accumulation or if cultural intensity, planting density, or their interaction affected biomass accumulation after accounting for stem size.

Challenges in biomass assessment of tree species are cost and accuracy (de Gier 2003). Destructive biomass sampling is a laborious and expensive process but is the most precise method to obtain results of biomass production. Determining the effects of intensive culture, planting density, and their interaction on tree-level biomass accumulation and allocation for aboveground biomass components of 12-year-old loblolly pine is of practical value. The results from this study will provide forest managers knowledge of how cultural intensity and planting density affect biomass accumulation and may affect yield of different products. This research will also be useful for those seeking or developing biomass prediction equations for total aboveground and component biomass of loblolly pine planted for the cultural intensities and planting densities evaluated.

LOBLOLLY PINE PLANTATION IN US SOUTH

Loblolly pine is the most important and most planted species in the southern United States with over 800 million seedlings planted annually (McKeand et al. 1999, Jordan et al. 2008). Pine plantations in 1950 covered 0.73 million ha, accounting for less than 1% of the forested area. By 1999, plantations covered 12.95 million ha and accounted for 15% of the South's timberland area and 47% of the pine forest area (Conner and Hartsell 2002, Wear and Greis 2002). The US South has the most intensively and extensively managed forested area in the world (Johnsen et al. 2004). The Piedmont and the Upper Coastal Plain of Georgia and Alabama consist of approximately 6.45 million ha and 14.55 million ha of land area, respectively. Loblolly pine is a native and commercially important timber species in both of these physiographic provinces. It naturally dominates well drained sites in the Coastal Plain and disturbed sites in the Piedmont (Hodler and Schretter 1986).

INTENSIVE FOREST MANAGEMENT AND PRODUCTIVITY

Forest plantation productivity is affected by climatic factors such as precipitation, temperature, and photoperiod; edaphic factors such as physical, chemical, and biological properties of soil; topographic factors such as aspect, geology, and slope; and the potential of the species to utilize the available resources (Baker and Langdon 1990). In plantation forests, productivity may be enhanced by soil quality improvement, competition control, fertilization, density management and genetic improvement. An objective for foresighted managers is to maintain or enhance the productive potential of a given site over successive rotations. This can be done through site specific management (Nambiar 1996) or intensive forest management (Fox 2000).

Intensive forest management is a practice of growing forest crops to gain increased productivity from a given site. It involves the manipulation of soil and stand conditions to ameliorate factors that limit tree growth (Fox 2000) by various practices such as chemical and mechanical site preparation, deployment of better genotypes, fertilization to overcome nutrient deficiencies, sustained competition control, and necessary silvicultural treatments to improve the quality of a stand. This differs from extensive management where timber is harvested and the regeneration and development of the subsequent stand occurs without intervention (Fox 2000). Twenty-five years of intensive forest management in northeast Florida resulted in gains of 7 m and 4 m of site index for loblolly and slash pine respectively (Jokela et al. 2010). Loblolly pine in Georgia with a planting density of 1432 trees ha^{-1} receiving sustained competition control and phosphorous (P), nitrogen (N), and potassium (K) fertilization during the first growing season and N fertilization every growing season produced 138 m^3 ha^{-1} more stand volume at age 10 than where competition was not controlled and fertilizer not applied (Borders and Bailey 2001). Early P fertilization on poorly drained, P-deficient Ultisols of the Atlantic and Gulf Coastal Plain increased loblolly pine volume growth by 2.8 to 3.5 m^3 ha^{-1} yr^{-1}

and one-time, mid-rotation fertilization with N+P produced a 3.5 m^3 ha^{-1} yr^{-1} response for 8 years (Fox et al. 2006).

CULTURAL INTENSITY AND PLANTING DENSITY EFFECTS ON BIOMASS ACCUMULATION AND ALLOCATION

Effects of silvicultural treatments on biomass accumulation and allocation with loblolly pine have been extensively studied. Trees partition carbohydrate to different organs during growth but the partitioning differs with species, site, climate, silvicultural treatments, genetics, and age (Naidu et al. 1998, Jokela and Martin 2000, Retzlaff et al. 2001, Burkes et al. 2003, Ares and Brauer 2005, Albaugh et al. 2004). Theoretically, when the uptake of a resource is limiting, biomass allocation is higher in organs responsible for the uptake of the limiting resources (King et al. 1999). Effects of thinning and tree spacing on bole biomass and volume of 38-year-old loblolly pine in southwestern Louisiana were highly significant. Both bole volume and biomass increased dramatically from non-thinned to the lowest intensity thinning treatments and individual trees on heavily thinned plots had more foliage and branch biomass than those on non-thinned plots (Baldwin et al. 2000). Similarly, Naidu et al. (1998) found that in light limiting conditions loblolly pine allocates less biomass to leaves and branches and more to boles as a result of self pruning. Another study on the Upper Coastal Plain of Georgia by Samuleson et al. (2004) found that the loblolly pine stand that received weed control, irrigation, fertilization, and pest control treatment had increased aboveground biomass three-fold from ages 3 to 6 and that with increased age, trees allocated more biomass to the bole (from 35% of aboveground biomass at age 3 to 66% of aboveground biomass at age 6) and less to foliage and branches. The researchers reported that there were no significant differences in biomass allocation at ages 3, 4, 5, or 6 years among treatment regimes ranging from weed control only to weed control, irrigation, fertilization, and pest control. In contrast Albaugh et. al. (2004) found greater biomass allocation to the bole with increased intensity of culture (fertilization + irrigation) on 16-year-old loblolly pine planted at 1176 trees ha^{-1} in North Carolina.

Biomass accumulation and allocation are greatly influenced by site quality, nutrient amendments, and stand conditions (Gower et al. 1995, Haynes and Gower 1995, Albaugh et al. 1998, Wang et al. 1998, Ares and Brauer 2005). Higher planting density increases intraspecific competition which can alter biomass partitioning priorities (Burkes et al 2003). Ares and Brauer (2005) found that planting spacing had a significant effect on bole and foliage biomass partitioning on 19-year-old loblolly pine with more partitioning to the bole for the trees planted at higher planting densities and to foliage for the trees planted at lower planting densities. Fertilization and weed control had a significant effect on biomass accumulation and allocation of 13-year-old loblolly pine planted at 1543 trees ha^{-1}, with the stand that received fertilization and weed control producing 2.6-fold more stem biomass than the stand that did not receive fertilization and weed control (Jokela and Martin 2000). i

It is important to understand forest biomass allocation and the factors that regulate it to better understand forest structure, biogeochemical cycles, and various aspects of potential importance to climate change (Brown et al. 1993, Dixon et al. 1994, Sanford and Cuevas 1996). Most research on biomass allocation shows that planting density, site quality, fertilization, competition control, and age are the main factors in plantation forestry that determine the biomass allocation of a particular tree species. According to the Functional equilibrium model, plant allocates its biomass in such a manner that its growth rate is maximal under the given environmental conditions (Poorter and Nagel 2000).

APPROACHES TO PREDICT BIOMASS ACCUMULATION

Pearsall (1927) first demonstrated allometric analysis for plants by plotting log-transformed biomass of the shoot along one axis against the log-transformed biomass of the roots along the other axis. He observed a strong linear relationship between the variables (Poorter and Nagel 2000). According to Navar et al. (2000) biomass equations have been developed for estimating forest production, comparing production between species, and estimating carbon sinks (Moore 2010). Biomass estimation of a forest stand is important for commercial uses, national development planning and scientific studies of ecosystem productivity, energy and nutrient flows and for assessing the contribution of changes in forestland to the global carbon cycle (Parresol, 1999). Accurate tree biomass estimation models are necessary to predict harvestable standing biomass.

Generally, there are three approaches to estimate tree biomass. One approach is using physiologically based-models such as 3PG (Physiological Principles Predicting Growth), a second approach includes the use of biomass expansion factors (BEFs), and a third approach is using allometric equations (Moore 2010). The 3PG model calculates gross primary production from utilizable absorbed photosynthetically active radiation (PAR), canopy quantum efficiency coefficient, and dry matter production by multiplying utilizable absorbed PAR, canopy quantum efficiency, and net primary productivity (Landsberg and Waring 1997). The biomass expansion factor approach calculates biomass stock of forest trees by converting timber volume to dry weight (density factor) and thereafter to whole tree biomass (expansion factor) (Lehtonen et al.

2004). Allometric equations predict tree biomass from easily measured variables, such as diameter at breast height (DBH), height, and some combination of diameter and height (e.g. Ter-Mikaelian and Korzukhin 1997, Parresol 1999, Moore 2010). A regression approach is commonly used for tree biomass estimation. The tree is separated into aboveground components, such as stem, bark, and crown, and equations are developed for each component to determine the amount of biomass accumulation. A desirable feature of these component regression models is the sum of predictors for each of the component equations equals the predictor for total tree (Kozak 1970, Cunia and Briggs 1985, Parresol 1999). Researchers have developed a variety of regression models to predict total tree biomass and component biomass, that according to Parresol (1999), can be broadly categorized into the following three forms

1. Linear-additive (in the form of $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \epsilon$
2. Nonlinear-additive (in the form of $Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \ldots . + \epsilon$)
3. Nonlinear-multiplicative (in the form of $Y = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \ldots . \epsilon$)

In these equations, Y = dependent variable (biomass), X_i = independent variable (size variables), ϵ is the error term and β_i = model parameters.

Bole biomass prediction using DBH and height is a convenient method because bole size is directly related with these two variables. Determining crown related biomass (branch and foliage) is more difficult because of its complex structure and irregular distribution. Crown related biomass estimation has been described as the least understood aspect of tree and forest structure (Zhang et al. 2004).

CHAPTER 2

EFFECT OF CULTURAL INTENSITY AND PLANTING DENSITY ON ABOVEGROUND BIOMASS ACCUMULATION AND ALLOCATION OF 12-YEAR-OLD LOBLOLLY PINE TREES GROWING IN THE UPPER COASTAL PLAIN AND PIEDMONT OF ALABAMA AND GEORGIA[1]

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INTRODUCTION

The plantation forests of the southern United States are predominantly loblolly pine (*Pinus taeda* L.), a native and commercially important species in the region, and are mostly actively managed. About 800 million loblolly pine seedlings are planted annually in the South (McKeand et al. 1999). There are currently about 13 million hectares of pine plantation in the region (Fox et al. 2006). With an area of approximately 21 million hectares, the Piedmont and the Upper Coastal Plain of Georgia and Alabama are major regions where loblolly pine plantation management has been carried out for more than four decades. Naturally, loblolly pine is a dominating species on well-drained sites in the Coastal Plain and disturbed sites in the Piedmont (Holder and Schretter 1986). The productive potential of this species has been estimated at 24.7 tons ha^{-1} yr^{-1} given improvements in silviculture and genetics (Stanturf et al. 2003).

Research on forest biomass production has been conducted over the past four decades due to the growing demands for timber, and scientific study for ecosystem productivity, energy and nutrient flow evaluation and assessment of forest land contribution to the global carbon cycle (Zeide 1987, Waring and Running 1998, Parresol 1999). Particular interest has been directed towards carbon (C) stocks in forests because these ecosystems are the main terrestrial sinks for C (Murias et al. 2006). Recently, there has been a renewed interest in biomass research due to the need to predict forest C stocks and the potential amount of biomass available as a source of energy (Moore 2010). Many countries have adopted the Kyoto Protocol, which stipulates mechanisms whereby post-1990 C-storage in forests can be used as an available C sink to offset some greenhouse gas (GHG) emissions

(IPCC 2003). It is important to quantify forest biomass to assess forest productivity and C sequestration as approximately 50% of the tree dry biomass is C (Losi et al. 2003).

Intensive silvicultural practices are widely used in the U.S. South to increase productivity of loblolly pine plantations. For traditional products of pulpwood, chip & saw, and sawtimber, it is favorable to have maximum biomass allocation to the stem and lesser to branches, bark, foliage, and roots. The effects of fertilization and irrigation (Albaugh et al. 1998, King et al. 1999, Jokela and Martin 2000), competition control (Colbert et al. 1990), planting density (Baldwin et al. 2000, Burkes et. al. 2003, Ares and Brauer 2005), and age (Larsen et al. 1976, Pehl et al. 1984, Van Lear and Kapeluck 1995) on loblolly pine biomass accumulation and allocation have been extensively studied. The results show that biomass accumulation and allocation to different components of the tree are affected by resource availability and age. Overcoming resource deficiencies causes greater biomass allocation to aboveground components at the expense of roots (Linder 1989, Coyle et al. 2008, Albaugh et al. 1998). In the humid southeastern United States, nutrition is often a more limiting factor for pine growth than moisture (Jokela et al. 2004), and fertilization, spacing, and competition control are key factors for greater biomass production. However, accurate estimates of biomass accumulation and partitioning to components are needed to better estimate potential yield for different products. While many researches have focused on the cultural intensity or planting density effects on stem biomass accumulation, relatively less is known about the effects of planting density, cultural intensity, and their interaction on biomass accumulation in other tree components and biomass allocation among components.

Allometric equations have been developed for predicting the biomass of loblolly pine trees and stands (Baldwin 1989, Adegbidi and Jokela 2002, Ares and Brauer 2005). Most of these allometric equations relate tree biomass to a given stem size variable (diameter at breast height (D), total height (H), and volume index (D^2H)). Bole biomass prediction using D and H is a convenient method because bole size is directly related to these variables. Estimating crown related biomass (branch and foliage) is more difficult because of its complex structure and irregular distribution (Zhang et al. 2004). Explaining the effects of cultural intensity and planting density on biomass accumulation in different aboveground tree components and how these effects may or may not alter allometric relationships is important to developing accurate biomass prediction approaches.

The present study examined the effects of different cultural regimes and planting densities on biomass accumulation and allocation on aboveground tree biomass components in 12-year-old loblolly pine stands. This study also evaluated if cultural intensity, planting density, or their interaction effects provide predictive value for biomass accumulation and allocation patterns additional to those due to their effects on stem size. The following three hypotheses were examined: (i) The main effects of culture, density, and their interaction have significant effects on aboveground biomass accumulation of loblolly pine trees; (ii) Culture, density, and their interaction have significant effects on the biomass allocation to aboveground components of loblolly pine trees and; (iii) Culture, density, and their interaction have no significant effect on biomass accumulation for trees of a given stem size.

METHODS

Study Sites

This study was conducted on four installations in Georgia and Alabama established by the Plantation Management Research Cooperative (PMRC) of the University of Georgia in 1998 (Figure 2.1). Location (county/state, latitude/longitude), soil types and rainfall information of the study sites are presented in the Table 2.1.

Experimental Design and Treatments

Two levels of cultural intensity (operational and intensive) and six levels of planting densities (741, 1482, 2283, 2964, 3705, 4446 trees ha^{-1}) were tested at each of the four locations. There was one replication per installation. At each installation cultural intensity treatments were randomly assigned to the main plots and planting density treatments randomly assigned to density subplots. In testing for treatment effects (culture, density, and interaction) on total aboveground and component biomass accumulation and allocation, a split plot experimental design was used. Culture was used as the main plot, density was used as the split plot and the four installations were used as four replications.

Plots with operational culture received chemical site preparation, 560 kg per hectare of 10-10-10 at planting, and 224 kg per hectare of nitrogen (N) and 28 kg per hectare of phosphorous (P) before the 8th growing season and the 12th growing season. They also received a banded application of sulfometuran methyl (220 gm/ha) and directed spraying with glyphosate and triclopyr for hardwood control during the first growing season. In addition to operational treatments, plots with intensive treatment received 672 kg per hectare of 10-10-

10, 131 kg per hectare of ammonium nitrate and micronutrients at age 2; 131 kg per hectare and 336 kg per hectare of ammonium nitrate before the 4th and the 6th growing season; 224 kg per hectare of N and 28 kg of P before the 8th, 10th and 12th growing season; and repeated directed spraying for complete competition control. PMRC cooperators selected the genetic material to plant at each installation. First or second generation open-pollinated stock considered good quality at the time of plantation establishment was used. Initial planting spacing, plot size, and number of trees per plot in each planting density plot are given in Table 2.2.

Field and Laboratory

All measurement trees on a plot were measured for DBH and every other tree was measured for height during the age 12 dormant season. Total height of trees not measured for height were estimated from the model $\ln(\text{Height}) = \beta_0 + \beta_1 \text{DBH}^{-1}$. One hundred and ninety two trees (4 trees/plot x 2 cultural intensities x 6 planting densities x 4 installations) were destructively sampled in February/ March of 2010. Trees were selected based on their crown classes, on each plot 2 trees were selected from the dominant/co-dominant, 1 from the intermediate and 1 from the suppressed class. Trees were cut 15 cm above ground-line and the stem was marked at 0.60 m, 1.21 m, 2.43 m, 3.65 m, 6.10 m and, subsequently at 2.43 m interval. Diameter at the marked points was measured to allow volume calculation. The crown was divided into three equal sections. Two live branches with foliage were randomly selected from each section, weighed individually and placed in paper bags for lab processing. All other live branches with foliage for a crown section were weighed together. Similarly, all the dead branches were weighed by crown section. The stem was sectioned at the marked points and each section was weighed green in the field. A 2.5 cm thick disk was cut from the base of each section; the green weight and the diameter of each disk were measured and the disks were transported to the laboratory in sealed plastic bags.

In the laboratory, sampled live branches with needles were placed in an oven for drying at a constant temperature of 65^0C. Dried needle weight and branch weight were determined for each branch. Oven-dry weight of sample live branches and needles were calculated based on the green weight measured in the field and sampled dry weight. The bark was separated from the wood for each sample disk, and the green weight of both components was measured. The bark samples were then oven-dried at a constant temperature of 65^0C. The disks were submerged in water until fiber saturation point at which point disk volume was measured. Disks were then oven-dried at a constant temperature of 65^0C. Oven-dry weight of tree stem and bark were estimated based on the green weight measured in the field and dry weight measured in the lab.

Statistical Analysis

The main effects of culture and density and their interaction were analyzed using a split-plot design with culture as the main plot effect and planting density as the split-plot effect. Effects of culture, density, and their interaction on mean tree DBH, height, volume of sample trees, total aboveground biomass, and stem, bark, dead-branch, live-branch, and foliage biomass accumulation and allocation were analyzed using a mixed-model approach with culture and planting density as the fixed effects with installation and installation x culture as random effects (Littell et. al. 1996). Biomass allocation expressed as proportions was transformed using the arcsine square root function prior to performing ANOVAs. The statistical model was

$$Y_{ijk} = \mu + \alpha_i + c_{ij} + \beta_j + (\alpha\beta)_{ij} + e_{ijk}$$

Where Y_{ijk} represents the biomass on the dependent variable at the i^{th} level of culture and j^{th} level of density and k^{th} tree; μ is the overall mean effect; α_i is the i^{th} level of cultural effect; β_j is the j^{th} level of density effect; c_{ij} is a whole plot error; $(\alpha\beta)_{ij}$ is the interaction effect between i^{th} level of culture and j^{th} level of density; and e_{ijk} is a split plot error. All analyses were performed using mixed-model procedure (proc mixed) of SAS (version 9.1.3 SAS Institute Inc., Cary, North Carolina) with a type-I error rate of 0.05. Least square means comparisons for significant treatment effects were conducted using Fisher's LSD test. The Bonferroni method was used for least square means comparisons in the absence of significant effects overall.

To examine whether total aboveground biomass and component biomass can be fully explained by stem size (diameter at breast height (D), total tree height (H) and D^2H), I first develop prediction models in the following two forms:

i. Linear (additive): $Y = \beta_0 + \beta_1 X + \epsilon$

ii. Non linear (multiplicative): $Y = \beta_0 X^{\beta_1} \epsilon$

$$\ln Y = \ln \beta_0 + \beta_1 \ln X + \ln \epsilon$$

Where Y = dependent (biomass) variable, X = independent (stem size variables) variable, β_i= model parameters and ϵ is the error term.

Resulting models were compared for goodness of fit. Coefficient of determination (R^2) and Root Mean Square Error (RMSE) were used to compare models with the same form and

Furnival's Index (Furnival 1961) was used to compare models of different forms. Furnival's Index was calculated as follows:

$$\mathrm{F.I.} = \frac{1}{\mathrm{Geomean}[\mathrm{f}\,(\mathrm{y})]} * \mathrm{RMSE}$$

Where $\mathrm{f}\,(\mathrm{y})$ is the first derivative of the dependent variable with respect to biomass and Geomean denotes geometric mean. Analysis of residuals (observed value minus predicted value from the model) for biomass accumulation for best fitting models was performed to determine if culture, planting density, or their interaction explained variation additional to that accounted for by stem size. Effects of culture, density, and their interaction on the residuals were examined using the same mixed-model and means comparison approaches as described above.

Residual analysis results were used to identify the need to develop classes of culture and density combinations with distinct patterns of biomass accumulation for trees of similar size. Regression equations predicting biomass accumulation from stem size were developed for one of these classes as an example.

RESULTS

Tree Size

Mean DBH, height, and total outside bark stem volume of sample trees and mean DBH and height of all trees for each planting density and cultural intensity combination are shown in Table 2.3 and Table 2.4, respectively. DBH, height, and stem volume of sample trees were significantly affected by the main effects of culture and density (p-value < 0.07 for culture and p-value < 0.001 for density) but not by their interaction. The greatest mean diameter and height occurred with the 741 trees ha^{-1} planting density and intensive culture combination. The smallest mean DBH and height were found with the 4446 trees ha^{-1} planting density and operational culture combination. Mean diameter and height of sample trees on intensively managed plots were 16.9 cm and 14.65 m, respectively, and on operationally managed plots were 15.9 cm and 13.4 m, respectively.

Biomass Accumulation

There was a significant effect of cultural treatment on stem, bark, dead-branch, and total aboveground biomass accumulation (Table 2.5). Planting density had a significant effect on the biomass accumulation for all components. The interaction was significant only for dead-branch biomass accumulation. Across densities, intensive culture produced 86.43 kg per tree of mean aboveground biomass and operational culture produced 70.30 kg per tree of mean aboveground biomass. Across cultural intensities, trees planted at 741 trees ha^{-1} had significantly greater total aboveground and component biomass than trees at any other planting density (Table 2.6). Trees at and above planting densities of 2223 trees ha^{-1} did not show any significant difference in foliage and live-branch biomass accumulation. Similarly, trees planted at 2223 to 3705 trees ha^{-1} of planting density range did not show significant difference in stem, bark, dead-branch and total aboveground biomass accumulation. The greatest mean aboveground biomass per tree (151.78 kg) occurred on the intensive culture and 741 trees ha^{-1} planting density combination (Figure 2.2). The lowest aboveground biomass per tree (45.65 kg) was found on the operational culture and 4446 trees ha^{-1} planting density combination. Dead-branch biomass was greatest for the intensive culture and 741 trees ha^{-1}

planting density combination (8.4 kg per tree) and least for the operational culture and 4446 trees ha^{-1} combination (1.22 kg per tree) (Figure 2.3).

Biomass Allocation

Biomass allocation to dead-branch, live-branch, and foliage components was significantly affected by culture (Table 2.7). Planting density had a significant effect on biomass allocation for all components. The culture x planting density interaction had no significant effect on biomass allocation. Mean biomass allocation to the stem across cultures was 72.35 percent. Trees with intensive culture had greater allocation in dead branches and trees with operational culture had greater allocation to foliage and live-branch components (Figure 2.4). Trees planted at higher planting densities allocated relatively more biomass to stem than trees planted at lower planting densities (Figure 2.4, Table 2.8). Trees at lower planting densities (741 and 1442 trees ha^{-1}) allocated a significantly greater proportion of biomass to live branches than trees at greater densities and those planted at the lowest density (741 trees ha^{-1}) allocated a greater proportion of biomass to foliage than trees at 1482 trees ha^{-1} or greater densities.

Allometric Relationships and Treatment Effects

There existed a strong linear relationship between tree total aboveground biomass (AGB), stem biomass, and bark biomass with D^2H and D on the log scale (Figure 2.5) and original scale (Figure 2.6). The relationship between AGB and H was strongly non-linear. On the original scale of measurement, I found increasing variance in AGB, stem biomass, and bark biomass with increasing values of all three size variables. Relationships on logarithmic scales had reduced heterogeneity in variance compared with those in arithmetic scale.

Model parameters and fit statistics (adjusted R^2 value, RMSE, and Furnival Index) using log transformed and original scale for dependent variables (tree components) and independent variables (D^2H, D, and H) showed that D^2H was the best size variable for stem, bark, and total aboveground biomass prediction and D was best suited to predict live-branch and foliage biomass (Table 2.9).

Results from residual analysis showed that cultural intensity had no significant effect on the mean residuals for any tree component or total aboveground biomass. Density had a significant effect on dead-branch and live-branch mean residual and I found significant culture x density interaction effects for stem, bark, and total aboveground mean residual (Table 2.10). Mean comparison tests show no significant differences among the planting densities 2223 to 4446 trees ha^{-1} for live-branch and dead-branch residual (Table 2.11). The live-branch residual for the 741 trees ha^{-1} planting density (0.12) was significantly different than that for the 2223 to 4446 planting density range (0.0 to -0.10). The dead-branch residual for the 1482 trees ha^{-1} planting density (0.31) was significantly different than that for the 2223 to 4446 trees ha^{-1} planting density range (0.01 to -0.20).

While interaction effects were significant for mean residual for stem, bark, and total aboveground biomass, patterns in the mean residuals are not evident (Table 2.12). The most consistent indicator of interaction occurred for the 1482 trees ha^{-1} density where mean residuals were consistently positive for intensive culture trees and negative for operational culture trees.

Based on the above results, aboveground total tree and component biomass accumulation for a tree of given stem size was considered little affected by planting density or cultural intensity for the 2223 to 4446 trees ha^{-1} planting density range. Biomass models developed to estimate total aboveground and component biomass based on stem size for the 2223 to 4446 trees ha^{-1} planting density range are presented in Table 2.13.

DISCUSSION

The sample of trees used to evaluate biomass accumulation and allocation for different cultural intensity and planting density combinations generally reflected trends in the overall population in average DBH and height. Mean size of the sample trees was lower than the plot mean for low planting densities and was greater than the plot mean on higher planting densities.

The results partly supported the first hypothesis that cultural intensity, planting density, and their interaction significantly affect aboveground biomass accumulation. Culture significantly affected the accumulation of stem, bark and dead-branch biomass with intensive culture having more per tree biomass in each component. Planting density significantly affected biomass accumulation for all components with greater accumulation per tree at lower planting densities than higher planting densities. The culture x planting density effect was only significant for dead-branch biomass accumulation.

On average intensive culture produced 23.6% more stem biomass and 24.2% more total aboveground biomass than operational culture. This intensive culture effect was greatest for stem (30%) and total aboveground biomass (33%) for trees planted at 741 ha^{-1} and least for stem (16%) and aboveground biomass (15%) for trees planted at 4446 ha^{-1}. This result is consistent with the study conducted by Albaugh et al. (2004) where maximum culture (competition control + fertilization) resulted in significantly higher stem biomass of 16-year-old loblolly pine as compared to the stand that received only competition control. Results for dead-branch biomass are consistent with dead-branch results of Williams and Gresham (2006) where maximum culture (irrigation + fertilization + pest control) produced significantly more dead branches than irrigation alone and irrigation only produced significantly more dead branches than without irrigation. Faster growth and larger sized branches occurred with lower planting densities combined with intensive culture than with greater planting densities combined with operational culture. This leads to interior shading and dying of branches and greater dead-branch accumulation in trees at lower planting density with intensive culture. On a study conducted by Coyle et al. (2008), foliage biomass increased by 16% on fertilized plots in comparison to the control plots. In this study, foliage biomass at age 12 was not affected by the cultural intensity. The fertilization on both operational and intensive plots before the 12th growing season may explain the similar foliage biomass for the different cultural intensities.

The results show that increasing planting density significantly affected both stem biomass and foliage biomass. There was a trend of lower stem and foliage biomass with increasing planting density. Mean stem and foliage biomass on per tree basis were 90.57 kg and 8.51 kg for trees planted at 741 ha^{-1}; 64.14 kg and 5.18 kg for trees planted at 1482 ha^{-1}; 50.51 kg and 3.34 kg for trees planted at 2223 ha^{-1}; 50.77 kg and 3.42 kg for trees planted at 2964 ha^{-1}; 43.09 kg and 2.98 kg for trees planted at 3705 ha^{-1} and 36.86 kg and 2.30 kg for trees planted at 4446 ha^{-1}.

My second hypothesis that cultural intensity, planting density, and their interaction affect per tree aboveground biomass allocation was partially confirmed. Culture had a significant effect on dead-branch, live-branch, and foliage biomass allocation. Density had a significant effect on allocation for all biomass components. The culture x density interaction did not affect the allocation for any component. The lower proportion of biomass in live-branch and foliage components for intensive culture trees than operational culture trees are related to a larger stem for trees with intensive culture. This is consistent with the assertion by Givnish (1995) that trees allocate more to stem and less to crown components as they age. Results from this study indicate that trees at higher planting densities allocate more biomass to stem and bark and less to foliage, dead-branch, and live-branch components which is consistent with the results reported by Naidu et al.(1998). In this study, trees planted at 4446 ha^{-1} allocated 75.4% of the total aboveground biomass to stem as compared to 67.1 % for the trees planted at 741 ha^{-1}. This result is consistent with findings of Ares and Brauer (2005) on loblolly pine and Nilsson and Albrektson (1993) on Scots pine.

Allocation proportions reported here are similar to those in the literature. These results are consistent with those reported by Wells et al. (1975) on 16-year-old loblolly pine planted at 2223 trees ha^{-1}. They found bole (stem + bark) biomass and foliage biomass allocation of 80% and 5%, respectively compared with 83% bole biomass and 5% foliage biomass on the 2223 trees ha^{-1} planting density in the current study. Similarly, this result is consistent with those reported by Jokela and Martin (2000) on 13-year-old fertilized loblolly pine planted at 1538 trees ha^{-1}. They reported stem + bark biomass allocation of 74.8 % and on branch biomass allocation of 18.8% as compared with the stem + bark biomass allocation of 76.8% and branch biomass allocation of 17.6% on trees planted at 1482 trees ha^{-1} for the present study.

My third hypothesis that culture, planting density, and their interaction have no significant effect on biomass accumulation for trees of a give stem size was partially rejected as there appears to be significant planting density effects for branch biomass residual and significant culture x density interaction effects on stem, bark, and total aboveground biomass residual. I found greater residuals for live-branch and dead-branch component at lower than higher planting density. The results suggest that general predictive equations may underpredict branch biomass at lower planting densities and overpredict at higher planting densities. Significant culture x density interaction on stem, bark, and total aboveground biomass also suggest treatment effects for a given stem size but interaction trends are not clear especially for the 2223 to 4446 trees ha^{-1} planting range. Given the apparent planting density effects, biomass prediction based on stem size may be improved by developing predictive equations for a planting density range with consistent biomass accumulation patterns. The biomass equations developed for the 2223 to 4446 trees ha^{-1} range represent an example of this approach.

The best suited stem size variable for the allometric equations to estimate stem, dead-branch, and total tree biomass was D^2H. D is the best suited size variable to estimate bark, live-branch, and foliage biomass. The reduced heterogeneity in variance with the logarithmic scale in comparison to arithmetic scale is consistent with the study by Moore (2010) on radiata pine. The results of fit statistics for allometric equations were consistent with the results by Jokela and Martin (2000) for loblolly pine and Moore (2010) for radiata pine. The results reported here are applicable to loblolly pine plantations in the Upper Coastal Plain and Piedmont of Alabama and Georgia of similar genetics, age, cultural regime, and planting density as those for the study.

TABLES AND FIGURES

Table 2.1. Location (county, state), latitude/longitude, soil taxonomy, and average annual precipitation for four study installations.

Location	Latitude/Longitude	Soil taxonomy*	Avg. annual precipitation**
Baldwin, AL	30.833/-87.686	Fine-loamy, kaolinitic, thermic Plinthic Kandiudult	64
Escambia, AL	31.1954/-87.315	Fine loamy, kaolinitic, thermic Rhodic Kandiudult	58
Greene, GA	33.6235/-83.028	Coarse loamy, mixed, semi active, thermic Typic Dystudept	48***
Barbour, AL	31.7467/-85.674	Loamy, kaolinitic, thermic Grossarenic Kandiudult	54

* Soil information is based on NRCS general and detail soil map of 1963 and 1972 and NRCS SSURGO data

**Average annual precipitation information is based on average annual rainfall map produced by Department of Geography, College of Arts and Sciences at the University of Alabama, average annual precipitation map of Georgia produced by PRISM group and Oregon Climate Service at Oregon State University and US weather data of average temperatures and rainfall in US cities available at coutrystudies.com.

***Greene County installation faced three years drought from 2006 and 2009.

Table 2.2. Spacing, trees per measurement plot, and plot size for planting density subplots

Planting Density (Trees per hectare)	Spacing (m x m)	Trees per measurement plot	Measurement plot size (ha)
741	3.65 x 3.65	80	0.1052
1482	2.43 x 2.74	80	0.0526
2223	2.43 x 1.83	96	0.0445
2964	1.83 x 1.83	120	0.0404
3705	1.83 x 1.46	160	0.0445
4446	1.83 x 1.22	184	0.0404

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Table 2.3. Mean DBH, height, and total outside bark stem volume of sampled trees by planting density and culture combination for loblolly pine at age 12.

Planting Density (trees per ha)	Culture	No. of Sampled Trees	DBH (cm)	Height (m)	Volume (cu. m)
741	Intensive	16	22.2	15.20	0.516
	Operational	16	20.6	13.74	0.294
1481	Intensive	16	17.7	14.88	0.322
	Operational	16	17.7	13.58	0.260
2223	Intensive	16	16.0	15.04	0.241
	Operational	16	15.2	13.41	0.185
2964	Intensive	16	16.3	14.60	0.274
	Operational	16	14.7	13.87	0.263
3705	Intensive	16	15.0	14.16	0.230
	Operational	16	14.2	12.90	0.188
4446	Intensive	16	14.0	14.11	0.180
	Operational	16	13.2	13.01	0.175

Table 2.4. Mean DBH and height of total population by planting density and culture combination for loblolly pine at age 12.

Planting Density (Trees per ha)	Culture	Total no. of trees	DBH (cm)	Height (m)
741	Intensive	295	24.3	15.43
	Operational	298	21.9	14.46
1481	Intensive	274	19.4	15.36
	Operational	292	17.3	14.10
2223	Intensive	318	16.6	15.11
	Operational	344	14.7	13.34
2964	Intensive	391	14.8	14.29
	Operational	416	13.4	12.51
3705	Intensive	525	13.6	13.96
	Operational	556	11.9	11.94
4446	Intensive	532	13.1	13.71
	Operational	632	11.2	12.20

Table 2.5. P-value for the effects of culture, density, and their interaction on mean total aboveground and component biomass accumulation per tree for 12-year-old loblolly pine.

Source	Stem	Bark	Dead-branch	Live-branch	Foliage	Total Aboveground
Culture	.021	.033	.022	.130	.871	.032
Density	.001	.001	.001	.001	.001	.001
Interaction	.610	.891	.011	.720	.982	.546

Table 2.6. Least square mean values for total aboveground and component biomass accumulation (kg per tree) at different levels of planting density for 12-year-old loblolly pine.

Planting Density (trees/ ha)	No. of observation	Stem	Bark	Dead-branch	Live-branch	Foliage	Total Aboveground
741	32	90.57^{a}	9.16^{a}	6.42^{a}	20.52^{a}	8.51^{a}	135.20^{a}
1482	32	64.14^{b}	6.71^{b}	5.24^{b}	10.96^{b}	5.18^{b}	92.25^{b}
2223	32	50.51^{c}	5.48^{c}	2.16^{cd}	5.77^{c}	3.34^{c}	67.30^{c}
2964	32	50.77^{c}	5.44^{c}	2.66^{c}	6.20^{c}	3.42^{c}	68.53^{c}
3705	32	43.09^{cd}	4.87^{cd}	2.17^{cd}	4.98^{c}	2.98^{c}	58.11^{cd}
4446	32	36.89^{d}	4.14^{d}	1.56^{d}	3.87^{c}	2.30^{c}	45.80^{d}
Standard Error		(6.26)	(0.39)	(0.67)	(1.12)	(0.58)	(7.92)

Note: Mean values within a column followed by the same letter are not significantly different (alpha=0.05) from each other.

Table 2.7. P-value for the effects of culture, density, and their interaction on aboveground biomass allocation by component for 12-year-old loblolly pine.

Source	Stem	Bark	Dead-branch	Live-branch	Foliage
Culture	.691	.483	.041	.032	.040
Density	.001	.001	.001	.001	.001
Interaction	.712	.553	.463	.475	.941

Table 2.8. Observed mean values for aboveground biomass allocation by component at different levels of planting density for 12-year-old loblolly pine.

Planting Density (trees/ha)	Number of observations	Stem	Bark	Dead-branch	Live-branch	Foliage
741	32	0.671^{c}	0.070^{c}	0.045^{b}	0.148^{a}	0.065^{a}
1482	32	0.695^{b}	0.077^{b}	0.057^{a}	0.114^{b}	0.055^{b}
2223	32	0.749^{a}	0.084^{a}	0.032^{c}	0.084^{cd}	0.049^{bc}
2964	32	0.734^{a}	0.082^{a}	0.040^{bc}	0.090^{c}	0.052^{bc}
3705	32	0.739^{a}	0.086^{a}	0.039^{bc}	0.083^{cd}	0.052^{bc}
4446	32	0.754^{a}	0.087^{a}	0.034^{c}	0.076^{d}	0.047^{c}

Note: Mean values within a column followed by the same letter are not significantly different (alpha=0.05) from each other based on least square mean separation.

Table 2.9. Parameter estimates and fit statistics for allometric equations predicting biomass accumulation across all cultural intensities and planting densities for 12-year-old loblolly pine trees. Best fit equations are in italics.[*]

Biomass Component	Volume Index (D^2H)	DBH (D)	Height (H)
ABG	*ln(ABG)=-4.03 + 1.00 ln(D^2H)* *R^2=0.95; RMSE=0.11* *F.I. =7.64*	ln(ABG)=-2.28+2.34 ln(D) R^2=0.94; RMSE=0.13 F.I.=8.84	ln(ABG)=-3.35+2.88 ln(H) R^2=0.41; RMSE=0.39 F.I.=27.08
Stem	*ln(stem)=-4.04+ 0.97ln(D^2H)* *R^2=0.94; RMSE=0.11* *F.I.= 5.50*	ln(stem)=-2.27+2.22ln(D) R^2=0.90; RMSE=0.15 F.I.=7.35	ln(stem)=-4.05+3.02 ln(H) R^2=0.49; RMSE=0.35 F.I.=19.60
Bark	ln(bark)=-4.45+0.75ln(D^2H) R^2=0.83; RMSE=0.16 F.I.=0.87	*ln(bark)=-3.29+1.80ln(D)* *R^2=0.86; RMSE=0.15* *F.I.= 0 .82*	ln(bark)-3.25+1.88 ln(H) R^2=0.28; RMSE=0.34 F.I.=1.87
Dead-branch	*ln(D.B.)=-8.10+ 1.10 ln(D^2H)* *R^2=0.52; RMSE=0.52* *F.I.=1.31*	ln(D.B.)=-6.12+2.53 ln(D) R^2=0.51; RMSE=0.53 F.I.=1.33	ln(D.B.)=-7.86+3.33 ln(H) R^2=0.25; RMSE=0.65 F.I.=1.63
Live-branch	ln(L.B.)=-9.39+ 1.37 ln(D^2H) R^2=0.75; RMSE=0.39 F.I.=2.44	*ln(L.B.)=-7.39+3.33 ln(D)* *R^2=0.82; RMSE=0.33* *F.I. =2.10*	ln(L.B.)=-5.63+2.84 ln(H) R^2=0.18; RMSE=0.71 F.I.=4.55
Foliage	ln(leaf)=-7.59+ 1.07 ln(D^2H) R^2=0.64; RMSE=0.39 F.I.=1.27	*ln(leaf)=-5.94+2.58 ln(D)* *R^2=0.70; RMSE=0.36* *F.I. =1.25*	ln(leaf)=-4.27+2.09 ln(H) R^2=0.13; RMSE=0.61 F.I.=2.10
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ABG	ABG=-1.65+0.02 D^2H R^2=0.94; RMSE=9.88	ABG=-109.06+11.41 D R^2=0.90; RMSE=13.66	ABG=-149.20+16.24 H R^2=0.35; RMSE=34.40
Stem	Stem=2.32+ 0.01 D^2H R^2=0.94; RMSE=7.29	Stem=-68.39+7.57 D R^2=0.87; RMSE=10.54	Stem=-115.35+12.22 H R^2=0.44; RMSE=21.57
Bark	Bark=1.59+0.001 D^2H R^2=0.84; RMSE=1.02	Bark=-4.73+0.65 D R^2=0.85; RMSE=0.96	Bark=-5.52+0.82 H R^2=0.26; RMSE=2.14
Dead-branch	D.B.=-0.90+ 0.001 D^2H R^2=0.53; RMSE=2.10	D.B.=-6.40+0.59 D R^2=0.48; RMSE=2.20	D.B.=-7.98+0.81 H R^2=0.17; RMSE=2.79
Live-branch	L.B.=-4.43+ 0.003 D^2H R^2=0.74; RMSE=4.03	L.B.=-22.60+1.90 D R^2=0.73; RMSE=4.08	L.B.=-16.20+1.77 H R^2=0.12; RMSE=7.44
Foliage	Leaf=-0.22+ 0.001 D^2H R^2=0.59; RMSE=1.97	Leaf=-6.93+0.68 D R^2=0.63; RMSE=1.84	Leaf=-4.13+0.60 H R^2=0.09; RMSE=2.92

ABG stands for aboveground biomass

D is in centimeter and H is in meter, and biomass accumulation is in kg

R^2=1-SSE/SST where SSE is error sums of square and SST is total sums of square; RMSE, root mean square error; F.I. stands for Furnival's Index

Table 2.10. P-value for the effects of culture, density, and their interaction on mean residuals (observed biomass minus predicted biomass) for total aboveground and component biomass accumulation for 12-year-old loblolly pine.

Source	Stem	Bark	Dead-branch	Live-branch	Foliage	Total Aboveground
When D^2H was used as the size variable [$\ln(Biomass)=b_0+b_1 \ln(D^2H)$]						
Culture	.816		.062			.575
Density	.448		.001			.321
Culture x Density	.007		.399			.001
When D was used as the size Variable [$\ln(Biomass)=b_0+b_1 \ln(D)$]						
Culture		.053		.814	.060	
Density		.700		.041	.273	
Culture x Density		.035		.060	.547	

Table 2.11. Least square mean values for live-branch and dead-branch residual (observed biomass minus predicted biomass) at different levels of planting density for 12-year-old loblolly pine.

Planting Density (trees ha^{-1})	Live-branch Residual	Dead-branch Residual
741	0.12^{a}	0.07^{b}
1482	0.06^{ab}	0.31^{a}
2223	-0.10^{c}	-0.20^{bc}
2964	0.00^{bc}	0.01^{bc}
3705	-0.03^{bc}	-0.01^{bc}
4446	-0.06^{bc}	-0.20^{bc}
Standard Error	(0.078)	(0.155)

Note: Mean values within a column followed by the same letter are not significantly different (alpha=0.05) from each other.

Table 2.12. Least square mean values for stem, bark, and total aboveground residual (observed biomass minus predicted biomass) at different culture x planting density combination for 12-year-old loblolly pine.

Culture and Density Combination	Stem Residual	Bark Residual	Total Aboveground Residual
I * 741	-0.02^{abcd}	0.00^{abc}	0.02^{abc}
I*1482	0.04^{ab}	0.08^{a}	0.07^{a}
I*2223	0.01^{abc}	0.04^{abc}	-0.03^{cd}
I*2964	-0.02^{abcd}	0.00^{abc}	-0.04^{bcd}
I*3705	0.01^{abc}	0.07^{ab}	-0.01^{bcd}
I*4446	-0.04^{cd}	-0.01^{abcd}	-0.07^{d}
O*741	-0.03^{bcd}	-0.03^{cd}	0.03^{abc}
O*1482	-0.07^{d}	-0.10^{d}	-0.04^{cd}
O*2223	0.01^{abc}	0.00^{abc}	0.00^{abcd}
O*2964	0.05^{a}	0.03^{abc}	0.04^{ab}
O*3705	0.00^{abc}	-0.05^{cd}	0.01^{abcd}
O*4446	0.05^{a}	-0.02^{bcd}	0.02^{abc}
Standard Error	(0.036)	(0.045)	(0.034)

Note: 'I' stands for intensive culture and 'O' stands for operational culture. Mean values within a column followed by the same letter are not significantly different (alpha=0.05) from each other.

Table 2.13. Parameter estimates and fit statistics for equations predicting total aboveground and aboveground component biomass (kg per tree) for the 2223 to 4446 trees ha^{-1} planting density range for 12-year-old loblolly pine. *

Biomass Component	Prediction Equation and Fit Statistics
ABG	$\ln(ABG)=-3.80+0.98\ln(D^2H)$; $R^2=0.92$; RMSE=0.12; F.I.=7.06
Stem	$\ln(stem)=-4.33+1.00\ln(D^2H)$; $R^2=0.94$; RMSE=0.10; F.I.= 4.00
Bark	$\ln(bark)=-3.78+1.99\ln(D)$; $R^2=0.85$; RMSE=0.13; F.I.= 0 .62
Dead-branch	$\ln(d.b.)=-5.98+0.82\ln(D^2H)$; $R^2=0.34$; RMSE=0.46;F.I.=0.83
Live-branch	$\ln(l.b.)=-6.16+2.85\ln(D)$; $R^2=0.69$; RMSE=0.31 ;F.I. =1.37
Foliage	$\ln(leaf)=-5.20+2.30\ln(D)$; $R^2=0.53$; RMSE=0.35 ;F.I. =0.93

ABG stands for total aboveground biomass.

D is in centimeter and H is in meter, and biomass accumulation is in kg

R^2=1-SSE/SST where SSE is error sums of square and SST is total sums of square; RMSE, root mean square error; F.I. stands for Furnival's Index

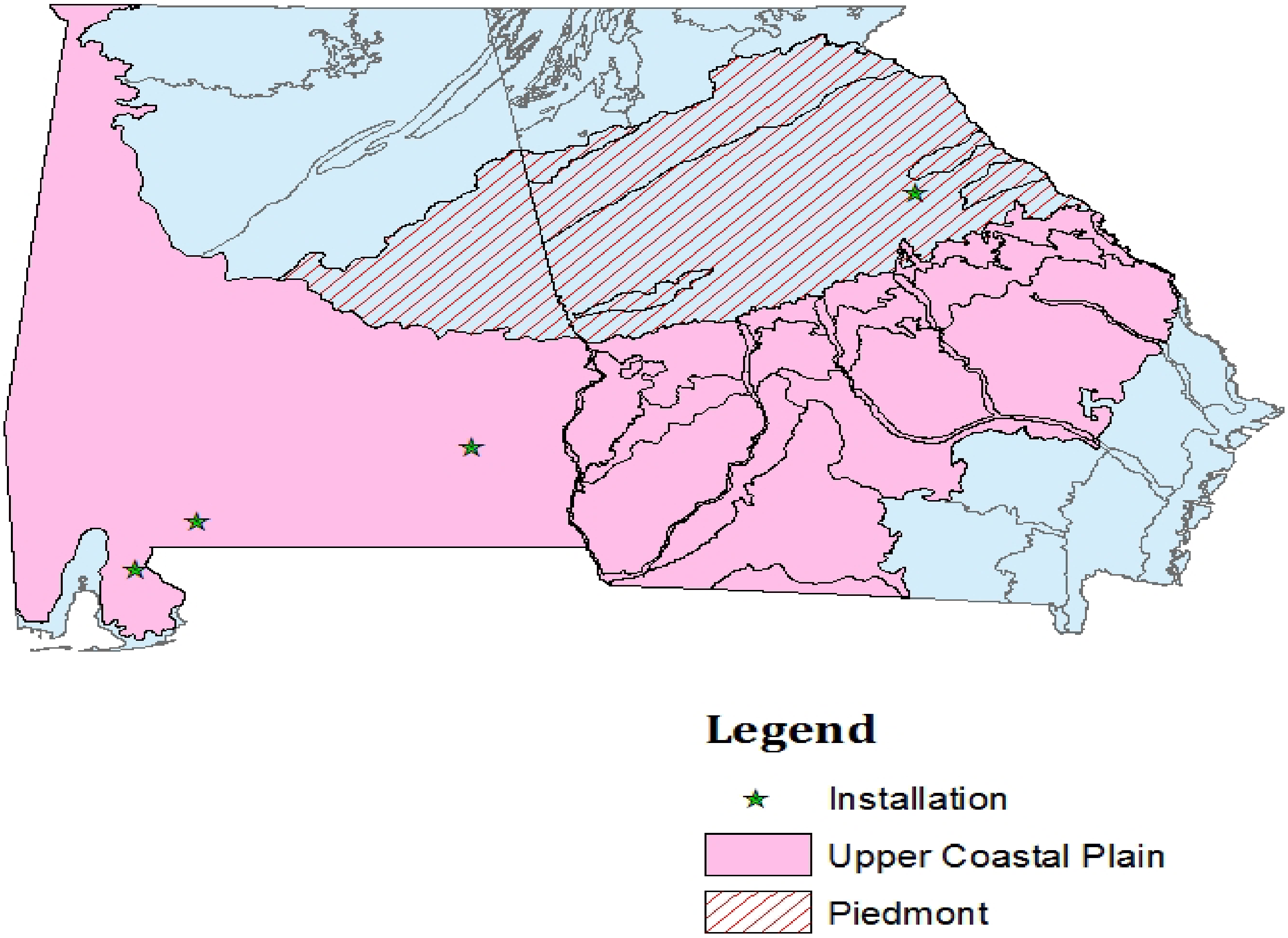

Figure 2.1. Plantation Management Research Cooperative study sites sampled for loblolly pine biomass accumulation and allocation. Three installations were in the Upper Coastal Plain of Alabama and one installation was in the Piedmont of Georgia (shape file source: US-EPA: Western Ecology Division).

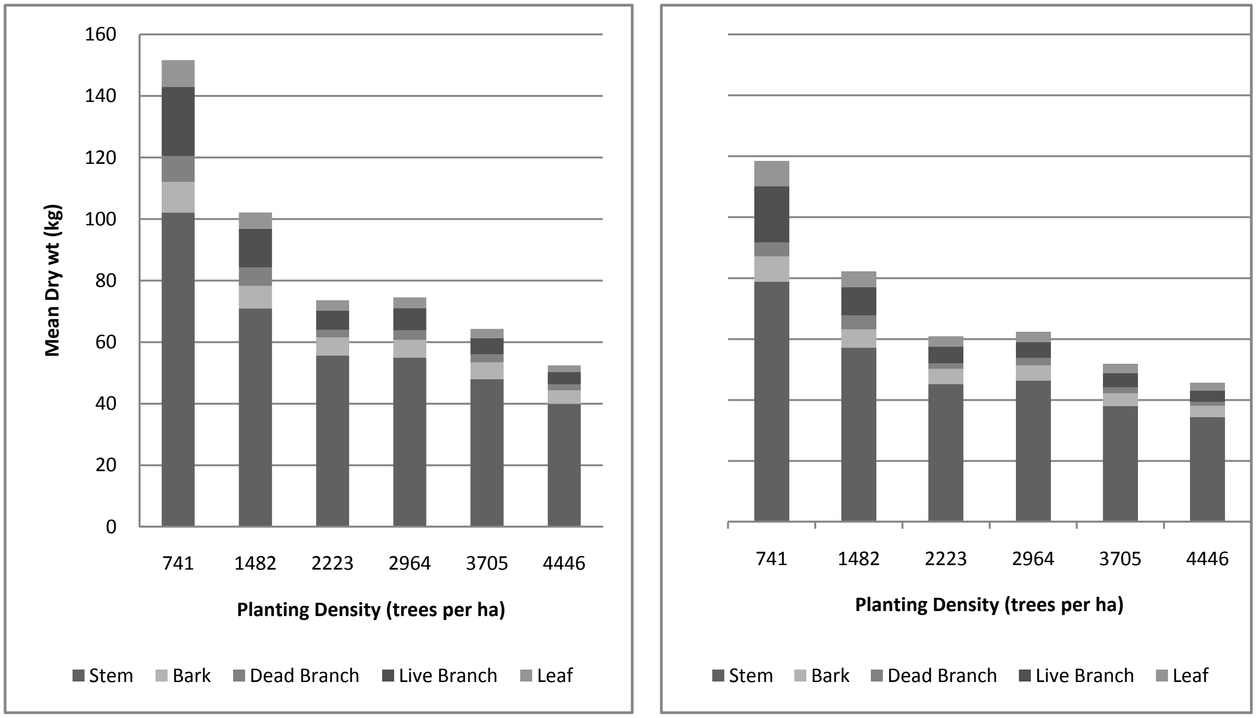

Figure 2.2. Mean aboveground biomass (kg per tree) by component and planting density for intensive (left) and operational (right) culture for 12-year-old loblolly pine.

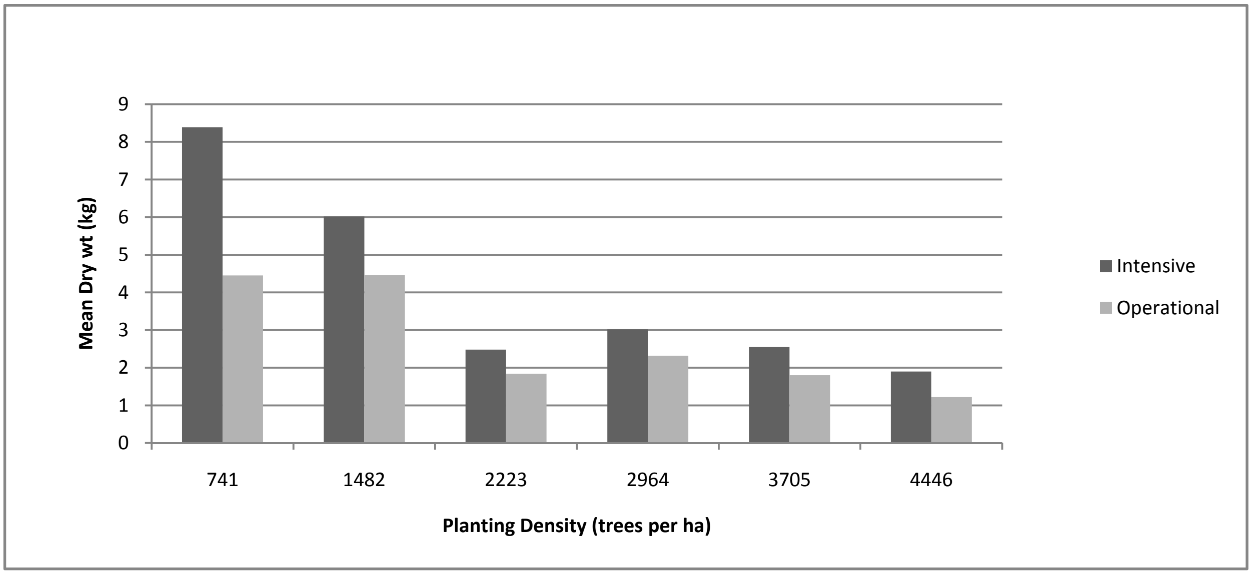

Figure 2.3. Mean dead-branch biomass (kg per tree) by cultural treatment and planting density for 12-year-old loblolly pine.

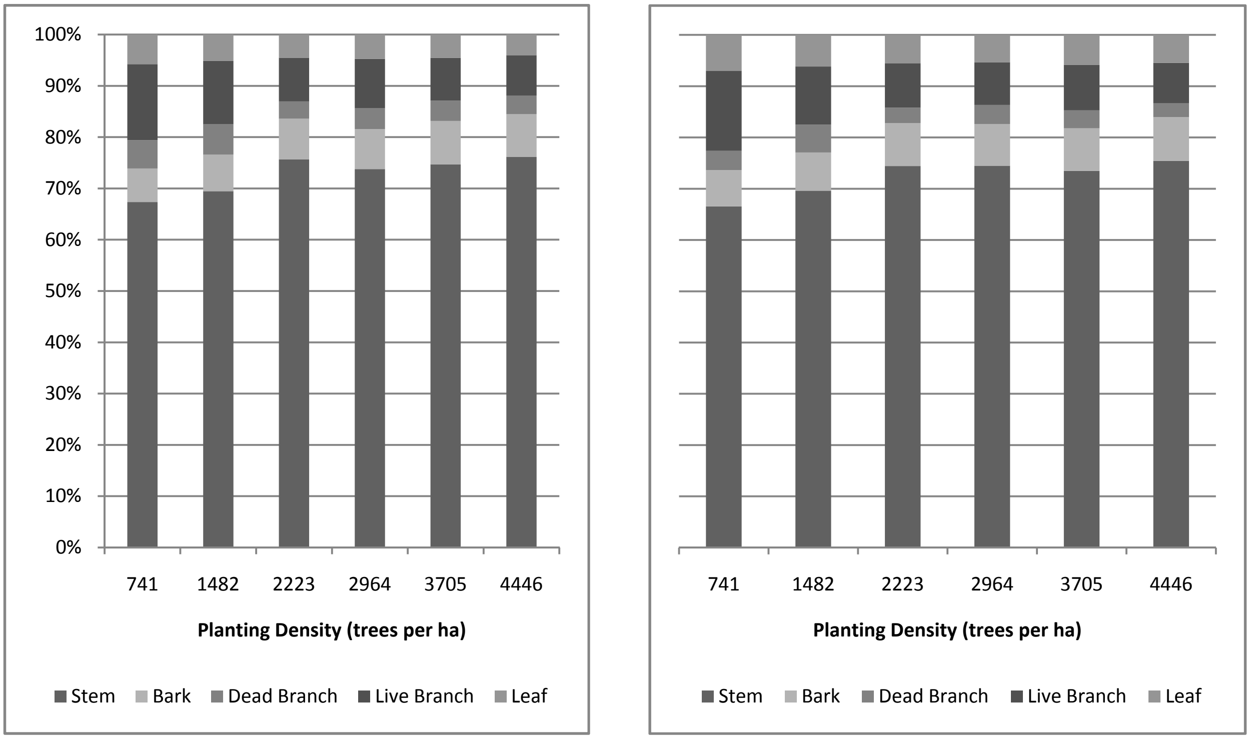

Figure 2.4. Mean aboveground biomass allocation per tree by component and planting density for intensive (left) and operational (right) culture for 12-year-old loblolly pine.

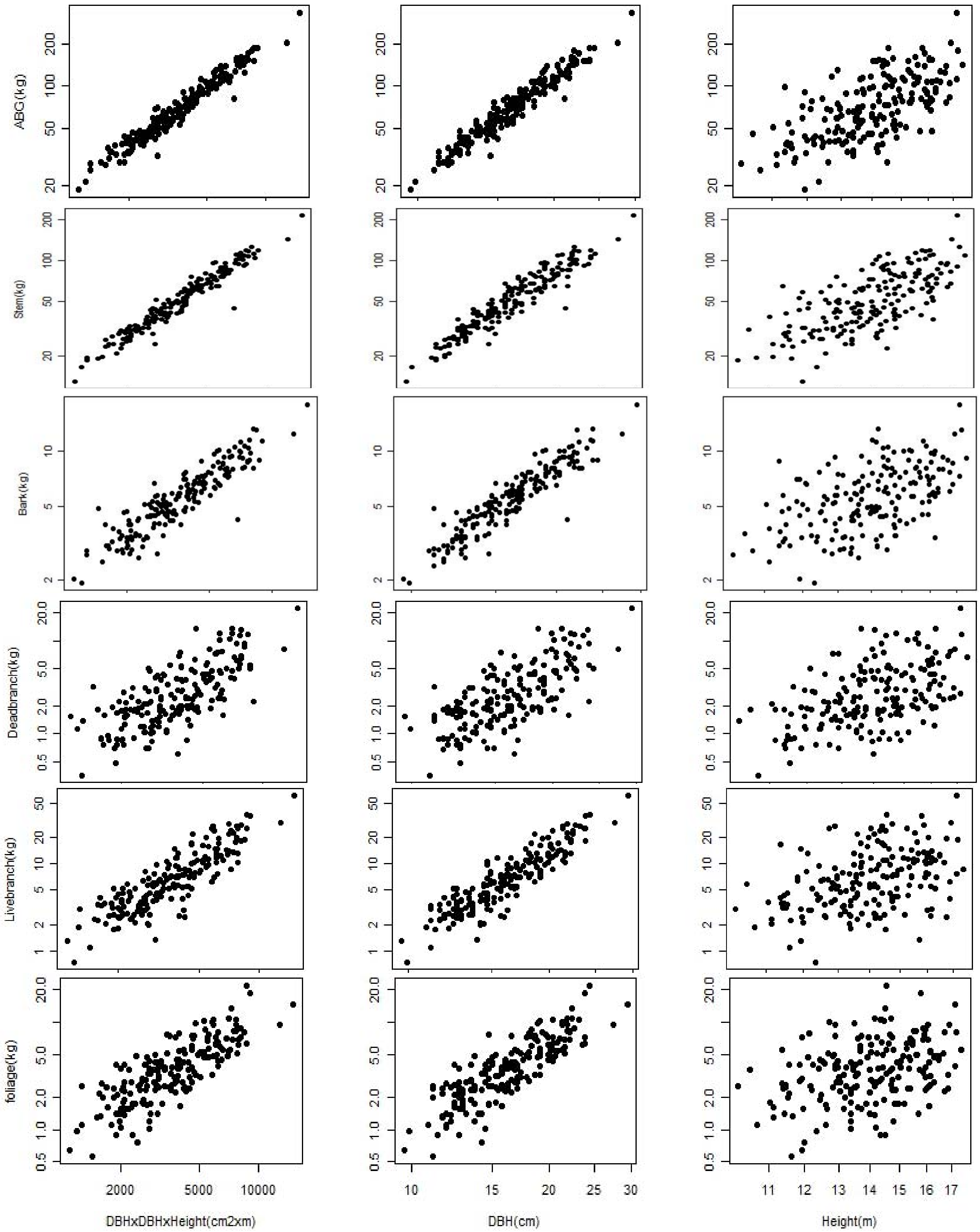

Figure 2.5. Relationship between total aboveground biomass and component biomass accumulation for an individual tree with size variables (D^2H, D and H) on a logarithmic scale for x and y axes for 12-year-old loblolly pine.

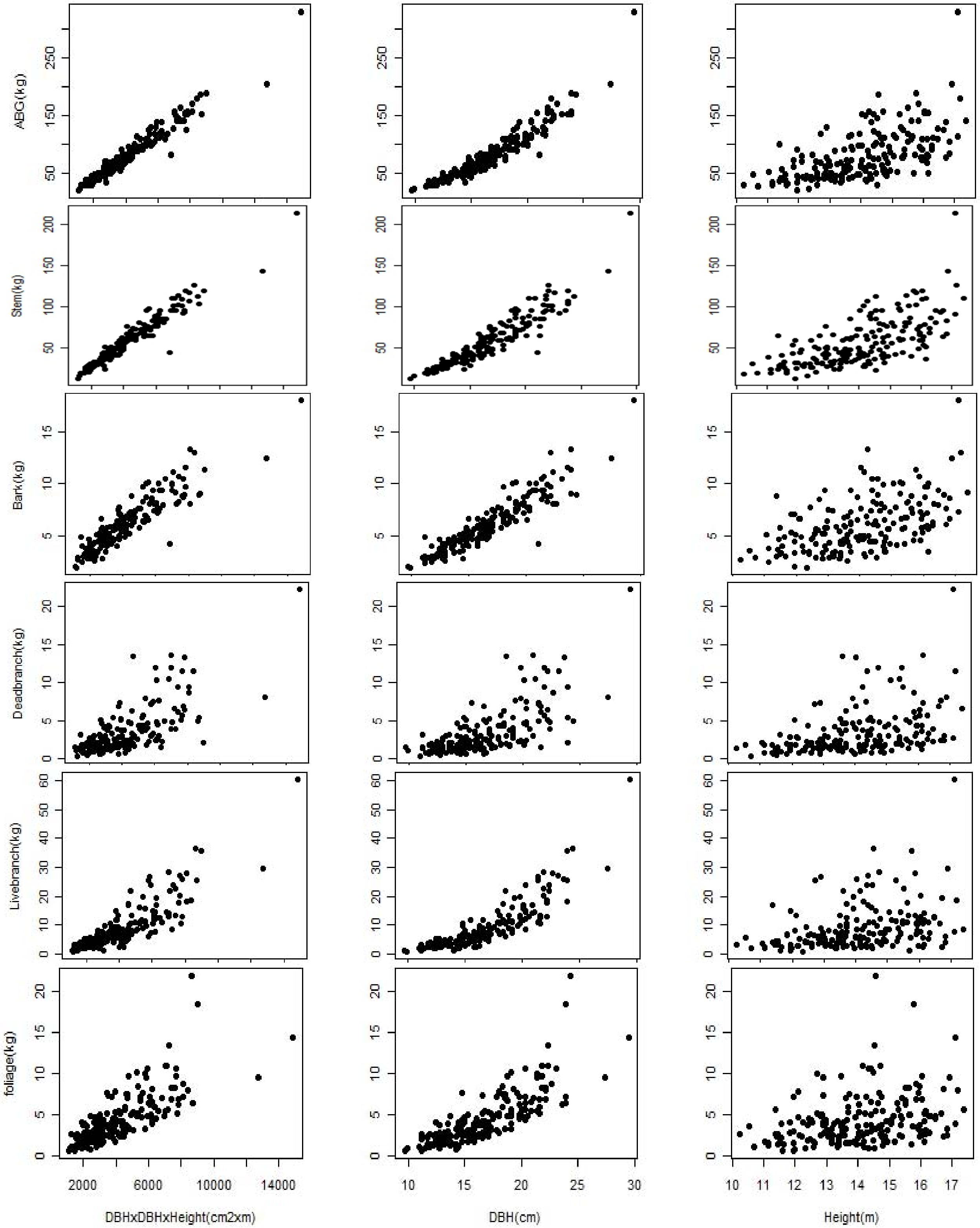

Figure 2.6. Relationship between total aboveground biomass and component biomass accumulation for an individual tree with size variables (D^2H, D and H) on an arithmetic scale for x and y axes for 12-year-old loblolly pine

CHAPTER 3

CONCLUSION

Intensive culture increased total aboveground biomass accumulation and stem, bark, and dead-branch component accumulation of 12-year-old loblolly pine trees. Intensive culture did not affect live-branch or foliage biomass accumulation. Decreasing planting density within the range examined increased total aboveground and component biomass accumulation with the greatest per tree biomass on the 741 trees ha^{-1} planting density. Biomass accumulation did not vary among planting densities for 2223 to 3705 trees ha^{-1} planting density. The culture x planting density interaction was significant only for dead-branch biomass accumulation. Lower planting density-intensive culture trees had more dead-branch biomass than other treatments. Some aboveground tradeoffs occurred in biomass allocation due to culture and density. Operational culture trees had higher foliage and live-branch allocation and lower proportion in dead-branch biomass compared to intensive culture trees. Trees on low density plots had a higher proportion of biomass in the dead-branch, live-branch, and foliage components and a lower proportion allocated to stem and bark as compared to trees on higher density plots. Wider spacing in lower density plots leads to the larger biomass accumulation in branches and narrower spacing in higher density plots to smaller accumulation in branches. Biomass allocation was similar for trees planted at densities from 2223 to 4446 trees ha^{-1}. The differences in biomass allocation patterns among planting densities from 741 to 2223 ha^{-1} should be considered when estimating plantation yields for aboveground biomass components.

Results from analysis of residuals from equations predicting total aboveground and component biomass accumulation from stem size suggest that planting density affects dead-branch and live-branch biomass accumulation in addition to that explained by its effect on stem size alone. Significant culture x density interactions for mean residuals for stem, bark, and total aboveground biomass appear related to model underprediction for intensive culture and overprediction for operational culture trees at the 1482 trees ha^{-1} planting density. This type of residual analysis can be used to identify ranges of treatments, such as planting density or cultural intensity, where stem size alone explains the variance in biomass accumulation. Predictive equations were fit for the 2223 to 4446 trees ha^{-1} planting density range as an example of the application of this approach.

CHAPTER 4

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