PLANTING DENSITY AND SILVICULTURAL INTENSITY: IMPACTS ON TAPROOT, SOIL, AND FOREST FLOOR CARBON AND NUTRIENTS IN THE LOWER COASTAL PLAIN AND PIEDMONT AND UPPER COASTAL PLAIN IN THE SOUTHEAST USA

by

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(Under the Direction of DANIEL MARKEWITZ)

ABSTRACT

This research investigated the effects of initial planting density and silvicultural intensity on taproot, mineral soil, and forest floor carbon (C) and nutrients. Total taproot and 5-50 mm diameter root C contents of 34 sampled trees were negatively affected by increasing planting density. Stand level estimates of taproot C, however, were not affected by planting density. Taproot biomass was higher in the LCP than in the PUCP. Taproot nutrient concentration increased with decreasing root diameter. Planting density did not have an effect on soil or forest floor mass, C, or nutrient concentrations. There was an increase in forest floor mass and C with more intensive culture, but this effect was not evident on soil C. Increased culture increased N in forest floor but not in soil. These results suggest that the use of high planting densities within intensively managed forest stands may not affect belowground C pools despite growing more aboveground biomass with increasing density. This is positive in that C and nutrient pools are not declining and may be sustained through multiple rotations.

INDEX WORDS: Loblolly pine, Upper Coastal Plain, Piedmont, Soil, Taproot, Forest floor, Carbon, Macronutrients, Planting density, Intensive culture, Growth response

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Literature Review

The burning of fossil fuels has caused an increase in carbon dioxide in the atmosphere. This has caused concern, and sparked active research regarding alternative energy sources. The utilization of woody biomass for bioenergy or biofuel has been suggested as a cleaner, more sustainable alternative to fossil fuels (Gustavsson et al., 2015; Volk et al., 2004). In the southeastern United States, loblolly pine (*Pinus taeda*) is grown in intensively managed, high yield stands and is being utilized as a feedstock for bioenergy.

The native range of loblolly pine extends eastward from eastern Texas to Florida as far north as southern Tennessee, and then north along the East Coast to southern New Jersey. Loblolly pine stands offer fast growth and can be managed on short rotations (i.e., 10-30 years). The amount of carbon sequestered within a loblolly pine plantation is contingent upon the management decisions made. These decisions include rotation age (Gonzalez-Benecke et al., 2011; Markewitz, 2006), silvicultural applications (Borders and Bailey, 2001; Samuelson et al., 2008; Will et al., 2006), and initial planting density (Carlson et al., 2009; Subedi et al., 2012; Zhao et al., 2012). In order to fully assess the carbon neutrality of bioenergy produced from loblolly pine stands, the carbon budget within these stands must be accounted for both aboveground and belowground. The purpose of this research is to evaluate carbon and nitrogen contents belowground within loblolly pine stands including taproots, soil, and forest floor. Models describing aboveground biomass growth have been well researched while there are

relatively fewer models that examine belowground biomass (Albaugh et al., 1998; Colbert et al., 1990; King et al., 1997; Subedi et al., 2012).

Taproot Biomass, Carbon, and Nutrients

Compared to aboveground biomass sampling and modeling, there are relatively few models that quantify belowground biomass growth and subsequent decomposition. This is due, in part, to the amount of labor required to excavate and remove taproots. In studies that have extracted taproots, this portion of the tree accounts for approximately 12-25% of total tree biomass of loblolly pine in the southeastern US (Miller et al., 2006; Pehl et al., 1984; Shelton et al., 1984). Carbon in taproots has the potential to remain in the soil for long periods of time following tree mortality (Wang et al., 2012). For example, Ludovici et al. (2002) found carbon was still sequestered within mature loblolly pine roots following 55 years of decomposition in the Piedmont of North Carolina. Moreover, beyond simply serving to sequester carbon, decomposing taproots have also been found to increase productivity within loblolly pine stands. Van Lear et al. (2000) determined that channels originating from decomposing tree roots served to increase productivity of stands and increase the density of live roots. Sucre and Fox (2009) also found that material from decomposing stumps, or "stump soil", contained higher levels of nutrients and densities of live roots. As such, taproots represent a very important part of the carbon and nutrient budget.

Studies that have quantified belowground biomass using destructive sampling suggest that the range of taproot biomass within juvenile to mature loblolly pine stands may be 36.3 to 62.4 Mg ha^{-1} (Miller et al., 2006; Pehl et al., 1984; Van Lear and Kapeluck, 1995). More recently, less intensive methods have been utilized to estimate taproots including ground

penetrating radar (GPR) and terrestrial laser scanning (TLS). Samuelson et al. (2008) predicted belowground woody biomass to be 34-50 Mg ha^{-1} in a 10 year loblolly pine stand using GPR that parallels other predictions made using a destructive technique. Liski et al. (2014) investigated the application of TLS to estimate belowground woody biomass within a recently harvested Norway spruce site located in Finland. Estimates of individual root system dry mass ranged from 9-92 kg with up to 10% of total mass being contained in roots < 2 mm in diameter. Results from this study, however, concluded that taproot biomass was not captured completely when the structure of the taproot system was not exposed enough to be detected by the laser device. Adegbidi et al. (2002) found that even at a young age (i.e., by age four), belowground biomass could account for a large percentage (i.e., 32%) of total biomass accumulation. In order to develop a robust model that will accurately estimate root biomass, knowledge of root allometry, particularly in relation to soil chemical and physical factors, must continue to be investigated across more locations.

One soil physical factor that can impact belowground biomass is bulk density. Ludovici (2008) found that belowground biomass is significantly reduced at high bulk densities, which may be a concern for long-term site productivity if equipment usage increases bulk density. In Ludovici (2008), however, changes in aboveground biomass were not impacted by increasing bulk density, which suggests the aboveground biomass to belowground biomass ratio may increase with increasing bulk density. Another factor that influences root growth is soil moisture. Parker and Van Lear (1996) found root density was impacted by soil moisture; root density was higher on xeric and subxeric sites than on intermediate sites. The growth of tree taproots is also influenced by decomposing stumps and old root channels. Root density was found to be higher in the presence of decomposing stumps and/or old root channels (Sucre and

Fox, 2009; Van Lear et al., 2000). The combination of all of these factors makes modeling of such systems challenging. One objective of this study is to examine the effects of planting density and cultural intensity on stand-level belowground biomass.

Soil Carbon and Nutrients

Soil is an important carbon sink in forest ecosystems, sequestering approximately two times more carbon than in vegetation or in the atmosphere (Schimel, 1995). Forest soils are responsible for sequestering approximately 1146 Pg C ha^{-1} worldwide (Dixon et al., 1994). There are other benefits to managing soil carbon including improving water infiltration, soil structure, site productivity, and reducing nutrient leaching.

In managing for soil carbon, consideration must be given to inputs and outputs of carbon. Litterfall is a substantial soil C input that accumulates as forest floor (i.e., the soil O horizon). In one pine plantation forest floor accumulated ~6% of total carbon accumulation following 18 years of growth (Johnson et al., 2003). The amount of carbon sequestered in the forest floors of the US southeast may range from 9-38 Mg C ha^{-1} (Binkley, 2002; Johnson et al., 2003; Vogel et al., 2011). Increasing fertilizer application rates in loblolly pine stands often results in an increase in forest floor mass (Rifai et al., 2010). Increasing fertilizer and herbicide application rates simultaneously, however, may result in a decrease in forest floor mass possibly due to loss of herbaceous inputs (Vogel et al., 2011).

There is some discussion over the role of forest floor in site productivity. Several recent studies have shown that the forest floor decreases available N in the mineral soil and may have a negative effect on tree growth (Zerpa et al., 2010; Zerpa et al., 2014). However, more typically the forest floor within a loblolly pine stand is considered to act as an nitrogen (N) and

phosphorus (P) sink, suggesting higher availability may be achieved through disturbance events such as prescribed fire or after timber harvesting (Kiser et al., 2013; Piatek and Allen, 2001).

Soil respiration is a major output in the carbon budget and total soil respiration rates in juvenile loblolly pine stands have been measured between 6.9-14.1 Mg C ha^{-1} (Lee and Jose, 2003; Maier and Kress, 2000). There is some debate as to the effects of silvicultural treatments on soil respiration. Vegetative control has been found to decrease total soil C while increasing O horizon C:N (Rifai et al., 2010). Fertilization of loblolly pine stands, on the other hand, has resulted in a decrease or no change in soil respiration in some studies (Butnor et al., 2003; Maier and Kress, 2000; Tyree et al., 2008) while others have reported an increase in soil respiration (Gough and Seiler, 2004).

The net balance of these inputs and outputs determines the net storage of soil C and there remains uncertainty as to the extent to which soils may store additional carbon. Some research shows soils to have a relatively low potential to store additional carbon (Matamala and Schlesinger, 2000; Richter et al., 1999), while others suggest that soils have a relatively high potential to store additional carbon (Lal, 2004). The net effect of silvicultural practices also remains uncertain but a meta-analysis by Johnson and Curtis (2001) suggests fertilization resulted in a slight increase in soil carbon. Pine plantations in the southeastern United States are typically located in areas dominated by kaolinitic clays or quartz sand, and are limited by N and P (Fox et al., 2007b; Kiser et al., 2013). Due to these nutrient limitations fertilization treatments are commonly utilized to increase the growth of loblolly pine. Common applications of 168-224 kg N ha^{-1} and 28 kg P ha^{-1} may result in an average growth increase of 3.5 m^3 ha^{-1} yr^{-1} over an 8 year period in loblolly pine plantations in the Southeast (Fox et al., 2007a).

Differences in soil texture (i.e., sand vs clay) may similarly affect the carbon storage potential of soil. Soils with higher clay fractions are often associated with higher aggregation which protects soil organic matter increasing the carbon storage capacity (Malamoud et al., 2009; Silver et al., 2000; Stockmann et al., 2013).

Planting Density

One of the first decisions a forest manager must make is planting density. Operationally, this decision should be made based on the desired final product class (Amateis and Burkhart, 2012). Relative to simply growing biomass, increasing planting density can be beneficial early in stand rotation. For example, increased planting density from 741-2224 TPH was found to increase total biomass on loblolly pine stands through 12 years of age (Zhao et al., 2012). Amateis and Burkhart (2012) arrived at a similar conclusion when they found that high density plantations can be managed on short rotations for biomass, and pulpwood yields may be maximized at 1680 trees ha^{-1}. In a 47-year-old loblolly pine spacing study, Samuelson et al. (2010) found that volume was not effected by planting density suggesting that original planting density has diminishing effects on stand biomass as the stand matures. Harms et al. (2000) conducted a spacing study in which they also found density to increase biomass early in rotation. Interestingly, they also found that the location in which trees are planted has an effect on tree mortality with density. Loblolly pine planted in Hawaii had a higher survival rate at all planting densities than those planted in the southeastern United States. Trees planted in Hawaii also attained a maximum basal area of 100 m^2 ha^{-1} double the maxima attained in the southeast. The effects of density on decreasing average tree diameter are well-known (Carlson et al., 2009; Harms et al., 2000; Zhao et al., 2012). Carlson et al. (2009) found that the average diameter of

loblolly pine trees planted at 897 trees ha^{-1} was 15.3 cm and decreased to 12.9 cm at a stand density of 1794 trees ha^{-1}. Finally, Akers et al. (2013) reported an increase in foliar biomass with increasing initial planting density suggesting that forest floor biomass (and thus soil carbon) may have a positive relationship with planting density.

Motivating this work is the recognition that high planting densities in loblolly pine plantations increase standing biomass early in stand rotation and thus can provide an opportunity for increasing biomass energy feedstock production through early stand thinnings or short-rotation cropping. Improved understanding of carbon cycling in forest ecosystems both above and belowground and impacts on total stand carbon is necessary to evaluate the potential of this silvicultural approach to offset fossil fuel emissions of CO_2 to the atmosphere.

Thesis Structure

Chapter 1 outlines past research on carbon and nutrients within taproots, soil, and forest floor. In chapter 2, research investigating the main effects of density and silvicultural intensity on taproot biomass, carbon, and nutrients is reported. Chapter 3 reports on research investigating the main effects of density and silvicultual intensity on soil and forest floor carbon and nutrients. Chapter 4 briefly summarizes the main findings of these research chapters.

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CHAPTER 2

PLANTING DENSITY AND SILVICULTURAL INTENSITY: IMPACTS ON TAPROOT CARBON AND NUTRIENTS IN THE LOWER COASTAL PLAIN AND PIEDMONT AND UPPER COASTAL PLAIN OF THE SOUTHEAST USA[1]

[1] Ward, G.D. and Markewitz, D.M. To be submitted to *Forest Ecology and Management.*

Abstract

Relatively few empirical studies quantify belowground biomass and subsequent decomposition even though loblolly pine taproots account for ~20% of total tree biomass. Taproots provide benefits including but not limited to carbon (C) sequestration and increased stand productivity. The purpose of this study is to examine the effects of initial planting density on belowground biomass under intensive culture. This research utilizes six installations of a culture x density experiment, three of which represent the Lower Coastal Plain, and three represent the Piedmont and Upper Coastal Plain. Taproot C of sampled trees was negatively influenced by increasing planting density, however, estimated stand level C was not affected by planting density. Initial planting density did not influence nutrient concentration. This may suggest that nutrient pools are not declining with increased initial planting density and may be able to sustain multiple rotations. As such, harvesting at a younger age (i.e., before age 12) may enable forest managers to better meet the increasing demand for wood bioenergy.

Introduction

Loblolly pine (*Pinus taeda*) stands occupy 21 million hectares in the southeastern USA. They offer fast growth and can be managed on short rotations (i.e., 10-30 years), providing a means to increase bioenergy feedstock production. In order to fully assess the carbon neutrality of bioenergy produced from loblolly pine stands, the carbon budget within these stands must be evaluated both aboveground and belowground. Models describing aboveground biomass growth have been well researched while there are relatively few models that examine belowground biomass (Albaugh et al., 1998; Colbert et al., 1990; King et al., 1997; Subedi et al., 2012). The purpose of this research is to evaluate belowground carbon (and nutrient) contents within commercial loblolly pine stands with a particular focus on taproots.

There are relatively few empirical studies that quantify belowground biomass growth and subsequent decomposition. This is due, in part, to the amount of labor required to excavate and remove taproots. Taproots account for approximately 12-25% of total tree biomass (Miller et al., 2006; Pehl et al., 1984; Shelton et al., 1984). In addition, taproots have the potential to store C for long periods of time following tree mortality. Ludovici et al. (2002) found C was still sequestered within mature loblolly pine roots following 55 years of decomposition. Wang et al. (2012) estimated C stored belowground in the Southeastern USA from decaying taproots due to timber harvest to be 124 Tg C.

Beyond simply serving to sequester carbon decomposing taproots have also been found to increase productivity within loblolly pine stands. Van Lear et al. (2000) determined that channels originating from decomposing tree roots may serve to increase productivity of stands and increase the density of live roots. Sucre and Fox (2009) found that material from decomposing stumps, or "stump soil", contains high levels of nutrients and higher densities of live roots. As such, taproots represent a stock of carbon but are also an important part of the carbon and nutrient cycle.

The studies that have quantified belowground biomass suggest that the range of taproot biomass within juvenile to mature loblolly pine stands may be 36.3 to 62.4 Mg ha^{-1} (Miller et al., 2006; Pehl et al., 1984; Van Lear and Kapeluck, 1995). Even at a young age, taproots may account for a large percentage of total biomass production. Adegbidi et al. (2002) found that by age four, taproots and lateral roots accounted for 32% of total biomass production in loblolly pine planted in Spodosols located in the Coastal Plain of southern Georgia. In order to develop a model that will accurately estimate root biomass, knowledge of root allometry, in addition to knowledge of soil chemical and physical factors must be understood.

One soil physical factor that can impact belowground biomass is bulk density. Ludovici (2008) found that belowground biomass is significantly reduced due to high bulk densities. Interestingly, changes in aboveground biomass in this study were not impacted by increasing bulk density which suggests the aboveground biomass to belowground biomass ratio may increase with increasing bulk density. Another factor that influences root growth is soil moisture. Parker and Van Lear (1996) found root density was higher on xeric and subxeric sites when compared with intermediate sites. Finally, as noted above, the growth of tree taproots is increased by decomposing stumps and old root channels. Root density was found to be higher in the presence of decomposing stumps and/or old root channels (Sucre and Fox, 2009; Van Lear et al., 2000). The combination of all of these factors makes modeling of such systems challenging.

Motivating this work is the recognition that high planting densities in loblolly pine plantations increase standing biomass early in stand rotation and thus can provide an opportunity for increasing biomass energy feedstock production through early stand thinnings or short rotation cropping. A recent study demonstrated increasing initial planting density increased total aboveground biomass from ~108 to 120 Mg ha^{-1}, by age 12 when going from 1480 to 2224 trees ha^{-1} (Subedi et al., 2012; Zhao et al., 2012). How these aboveground biomass increases are translated belowground has not been quantified. Furthermore, if aboveground biomass is harvested and CO_2 returned to the atmosphere during energy production, is this energy pathway net carbon neutral or might belowground carbon storage in taproots even provide a net sequestration of carbon? Improved understanding of carbon cycling in forest ecosystems both above and belowground and impacts on total stand carbon is necessary to evaluate the potential of this silvicultural approach to offset fossil fuel emissions of CO_2 to the atmosphere.

Specific hypotheses tested in this study were (*i*) belowground carbon will increase with additions of cultural treatments and planting density due to an increase in near-taproot root production, (*ii*) belowground carbon partitioning will increase with increasing planting density due to increasing belowground competition for resources (water and nutrients) and (*iii*) higher clay contents will decrease near-taproot root mass.

Methods

Site Description

Six installations of a culture x density experiment that was established by the Plantation Management Research Cooperative (PMRC) across the southeastern United States from 1996-1998 (Figure 1a) were utilized. This research is building on the work of previous studies using these culture x density plots. Three of these sites are located in northeastern Florida and represent the Lower Coastal Plain (LCP), while the other three sites are located in Georgia and Alabama and represent the Piedmont and Upper Coastal Plain (PUCP) (Table1). Each of these sites contains two levels of silviculture defined as intensive and operational (Table 2). Within each level of culture, plots with planting densities of 741, 1483, 2224, 2965, 3706, and 4448 trees ha^{-1} (i.e., 300, 600, 900, 1200, 1500, and 1800 trees ac^{-1}) were established in a randomized split-plot design. The locations have no replication so serve as blocks within the larger experimental installation (Figure 1b). For this study, plots with 741 trees ha^{-1} were not utilized as these are not a rational density for bioenergy feedstock production.

Taproot Biomass

Four trees were sampled in each plot to develop aboveground biomass equations (Zhao, 2015) in these locations in February/March of 2010 for LCP and 2011 for PUCP. Shortly after these harvests, belowground biomass was sampled by using a subset of these felled trees. At each installation, one (and in few cases two) tree(s) were sampled in each density of the intensive cultural treatments (LCP n=19, PUCP n=15). A ~1 m^3 volume of soil was excavated around each tree stump. The shape of the pit was defined as a cube with the tree stump being the center. All lateral roots and the taproot within the soil volume were collected. After excavation soils were replaced in the hole while passing through a 5 mm screen to improve small diameter root recovery. Some of the finest roots (i.e., $\leq$ 2 mm) were undoubtedly lost in this process. Roots were returned to the Phillips Wood Utilization Laboratory located in Athens, GA where soil material was removed using a garden hose while roots were atop a 5 mm mesh screening. After cleaning, roots were dried at 65^{o}C to a constant weight. Root material was separated based on five diameter classes (0-5, 5-10, 10-20, 20-50, and >50 mm) and weighed. The amount of soil contaminant remaining on the roots was estimated by loss on ignition (LOI) (SSSA, 1996).

A subsample of roots (taproot and lateral roots) for each diameter class per taproot extracted was randomly selected and ground using a Wiley Mill Model 4 (Thomas Scientific, Swedesboro, NJ). These samples were digested in nitric acid/hydrogen peroxide following Method 3050B (Environmental Protection Agency) with one modification. In Method 3050B samples are heated to a temperature of 95^{o}C for 2 hours. For this study, the temperature was increased from 95^{o}C to 180^{o}C to ensure complete digestion. Digests were analyzed for phosphorus (P), magnesium (Mg), calcium (Ca), and potassium (K). Element concentrations in the digests were measured using an Elan 9000 Inductively Coupled Plasma Mass Spectrometer

(ICP/MS, Perkin Elmer-Sciex). Complete digestion and recovery was assessed with standard reference materials 1547 (peach leaves) and 1575 (pine needles) (NIST, 1991; NIST, 1993). A subsample of root material from each of the Wiley milled samples was ball mill ground to a fine powder (SPEX 8000) and analyzed for total carbon (C) and total nitrogen (N) using a NC Soil Analyzer Flash 2000 (Thermo Scientific, Waltham, MA).

Taproot Decomposition

To estimate taproot decomposition rates both harvested root and dimension lumber were utilized. Representative oven dried subsamples of the taproots from 0-10, 10-20, 20-50, 50-80 and >80 mm were weighed, and diameters and lengths were recorded. In addition, southern yellow pine dimensional lumber was cut using a miter saw to dimensions of 19x32x301, 38x38x301, and 90x38x301 mm (i.e., 1x2, 2x2, and 2x4 inch lumber cut to 12 inches). Aluminum tree tags were attached to a ~80 cm length of aluminum wire which was then attached to each of the root and wood samples to serve as identification markers. In the three Lower Coastal Plain sites a total of sixteen pits per study site of 30 x 30 cm were excavated to a 30 cm depth. In June 2013, a total of five roots (one from each diameter class) were buried in each of eight of these pits. In addition, three pieces of southern yellow pine were buried (one from each diameter class) in each of the remaining eight pits. One year later four pits containing root samples and four pits containing wood samples were excavated from each site. Root and wood samples were transported to the laboratory in Athens where all remaining soil material was removed using a garden hose while atop a 5 mm mesh screening. Root and wood samples were dried at 65^{o}C to a constant weight and dry weights were recorded. Initial and 1-year root mass were used to estimate decomposition rate of the first year.

Statistical Analysis

This experiment was set up as a split- plot design with plots in each location serving as a replication so that there were three replications in the LCP and PUCP, respectively, although for this component only intensive plots were sampled. A mixed model approach was used to determine the main effects of location (LCP vs PUCP) and density with the sites nested within location and treated as a random effect. Normality was tested using Shapiro-Wilks test and QQ-plot. Data were logarithmically transformed to better approximate a normal distribution if needed. Multivariate analysis of variance (MANOVA) was used to assess the treatment effects on total taproot mass, taproot mass by diameter class, and N, P, K, Ca, and Mg concentrations. In addition to the ANOVA approach above regression analysis was performed to predict root biomass by tree diameter and height. A backward stepwise regression approach was utilized to eliminate non-significant variables. Residuals were plotted to ensure that no bias existed. Plot inventory data (i.e., DBH and height) from the PMRC were used with the above regression results to estimate taproot biomass at the plot level. This was done for both intensive and operational cultural regimes using the results from sampling intensive culture plots.

Results

Taproot biomass among the 34 sampled trees was affected by location ($p=0.07$), but total taproot C was not effected by location ($p=0.15$). On average, taproots accounted for 17.4±3.0% and 16.9±3.6% of total tree biomass, and 21.3±4.3% and 20.6±5.3% of aboveground biomass in the LCP and PUCP, respectively. Average taproot biomass, C, and N per tree was 32.3±18.8 kg, 15.5±9.1 kg, and 120.9 ±76.7 g, respectively, in the LCP and 22.8±9.5 kg, 10.5±4.3 kg, 32.7±18.5 g, respectively, in the PUCP (Table 2.3). Average C, N, P, K, Ca, and Mg

concentrations in taproots were 48.0±2.0%, 0.5±0.2%, 209±102, 624±267, 1736±519, and 453±132 mg kg^{-1}, respectively, in the LCP, and 47.1±2.8%, 0.3±0.2 %, 212±109, 757±435, 1519±647, and 380±147 mg kg^{-1}, respectively, in the PUCP (Table 2.4 and 2.5). Initial planting density did not have a significant effect on tree level biomass, C, or macronutrient levels. Initial planting density did, however have an effect on tree DBH ($p= 0.0106$) of the sample trees. Average DBHs were 24.3±2.1, 20.0±4.5, 18.4±2.9, 18.9±2.4, and 17.8±4.8 cm for 1483, 2224, 2965, 3706, and 4448 trees ha^{-1}, respectively.

Regression equations were developed to predict belowground biomass using diameter, height, and DBH^2xHt (Table 2.6). Regression equations for total taproot biomass were significantly different for the LCP and PUCP ($p<0.07$) and explained 89.5 and 78.5% of the variance, respectively (Figure 2.2). Regression relationships for the 5-50 and <5 mm root fractions were not specific to location and explained much less of the variation (i.e., <45%). Using the live tree inventory data from all plots, total taproot biomass was estimated by culture, density, and location recognizing this assumes operational treatments did not alter the relationships (Table 2.7). On average total stand taproot mass was 34.1±10.3 and 29.1±7.7 Mg ha^{-1} for LCP and PUCP sites, respectively.

Root decomposition k-values based on 1 year collections from the LCP were -0.0007±0.0005 and -0.0008±0.0003 for roots >50mm and <10 mm, respectively (Table 2.8). The mean residence time for these roots is approximately 5.4±2.8 and 4.0±1.7 years for >50 and <10mm, respectively.

Discussion

Working in the same culture x density experiment, Burkes et al. (2003) reported an increase in partitioning to stem growth relative to foliage or fine roots with increasing planting density, thus increasing the proportion of fixed carbon used in stem production, in 4-year-old loblolly and slash pine plots at four locations in the Coastal Plain of Georgia. By age 12, Zhao et al. (2012) found that planting density still had an effect on aboveground biomass for 23 sites in the Piedmont and Upper Coastal Plain. Although this greater aboveground growth suggests that planting density may affect belowground biomass no data was collected at the time. In the current research at age 15 and 16, however, density did not affect belowground taproot biomass.

On the other hand, taproot biomass represents a significant fraction of whole tree biomass in all densities. Taproot biomass as a percent of total tree biomass in this study (i.e., 17.4 and 16.9% for LCP and PUCP sites, respectively), is within the range of values reported previously (Miller et al., 2006; Pehl et al., 1984; Shelton et al., 1984). There is some evidence, however, suggesting that the aboveground to belowground biomass ratio differs between the LCP and PUCP (Figure 2.2) and that the ratio decreases more quickly with increasing aboveground biomass in loblolly pine planted in the PUCP (Figure 2.3). Similarly the ratio of root:total tree biomass appears relatively invariant with tree size in the LCP but declines in the PUCP (Figure 2.4). Ludovici (2008) also found that taproot biomass was less in more clay rich sites. Taproot biomass, in this study, was greater in the LCP than in the PUCP most likely due to increased resistence to penetration within the more clay rich PUCP sites.

King et al. (1997) found that root diameter class had an effect on root concentration. Fine roots had lower C:N and C:P ratios. Similarly, taproot N and P concentrations in this study were higher in fine roots than in coarse roots. In addition to the similarities with these other pine root

ratios the taproot nutrient concentrations (Table 2.5) also closely match those found by Zhao et al. (2014) for aboveground wood and bark in the same LCP stands. As such, nutrient contents belowground relative to those aboveground are largely driven by differences in biomass accumulation rather than differences in concentrations.

Total stand level loblolly pine taproot mass in this study aligns with values determined in other studies (Miller et al., 2006; Pehl et al., 1984; Van Lear and Kapeluck, 1995). Total belowground biomass was estimated using the belowground allometric equations develped for these sites assuming there was no effect of culture. This assumption is not unreasonable as King et al. (2002) found fertilization using N, P, K, Ca, Mg, and B may effect fine roots but not coarse roots working in excessively drained, sandy soils located in North Carolina. In the current study approximately 2.1 and 1.8 Mg ha^{-1} of taproot mass was gained each year in the LCP and PUCP, respectively. Combining soils and biomass data from these sites (Ward (2015); (Zhao 2014) with the current taproot data, on average, 46.5% of total C stock was found aboveground, while 53.5% was found belowground (Figure 2.5).

If these high initial planting density stands in the LCP were harvested on a 16 yr cycle as a short-rotation woody feedstock, 16.5 Mg-C ha^{-1} of belowground root biomass would be left in the soil at harvest. Given the measured mean residence time for these roots of approximately 5.4±2.8 and 4.0±1.7 years for >50 and <10 mm, respectively, or roughly five years for all classes combined, the accumulated roots would retain ~0.5 Mg-C ha^{-1} by the end of the next 16-yr rotation. This rate of accumulation is consistent with a range of soil C accumulation estimates under afforestation (Post and Kwon, 2000; Schlesinger and Andrews, 2000) but would account for a relative limited sequestration of C.

The results of this study suggest that the use of high initial planting densities within intensively managed forest stands may have an effect on taproot C of individual trees. The effect of initial planting density is lost, however, when investigating taproot C at the stand level. Initial planting density did not have an effect on nutrients. This may suggest that nutrient pools are not declining with increased initial planting density and may be able to sustain multiple rotations. As such, harvesting at a younger age (i.e., age 12) may enable forest managers to better meet the increasing demand for wood bioenergy without compromising site quality.

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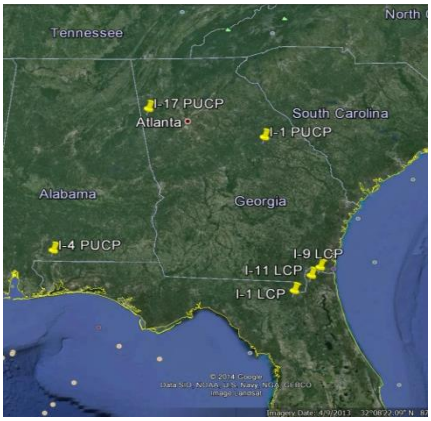
A) 

B) 

Figure 2.1. Location of six Culture x Density trials utilized for the current research (A), and areal image of a Culture x Density installation in the Piedmont/ Upper Coastal Plain study demonstrating variation in density conditions (B). Note numbers in the figure are trees per acre at planting (equivalent trees/ha are 741, 1482, 2223, 2964, 3705, and 4446) and O=operational treatments with fertilizers and herbicides and I=intensive treatments with fertilizers and herbicides.

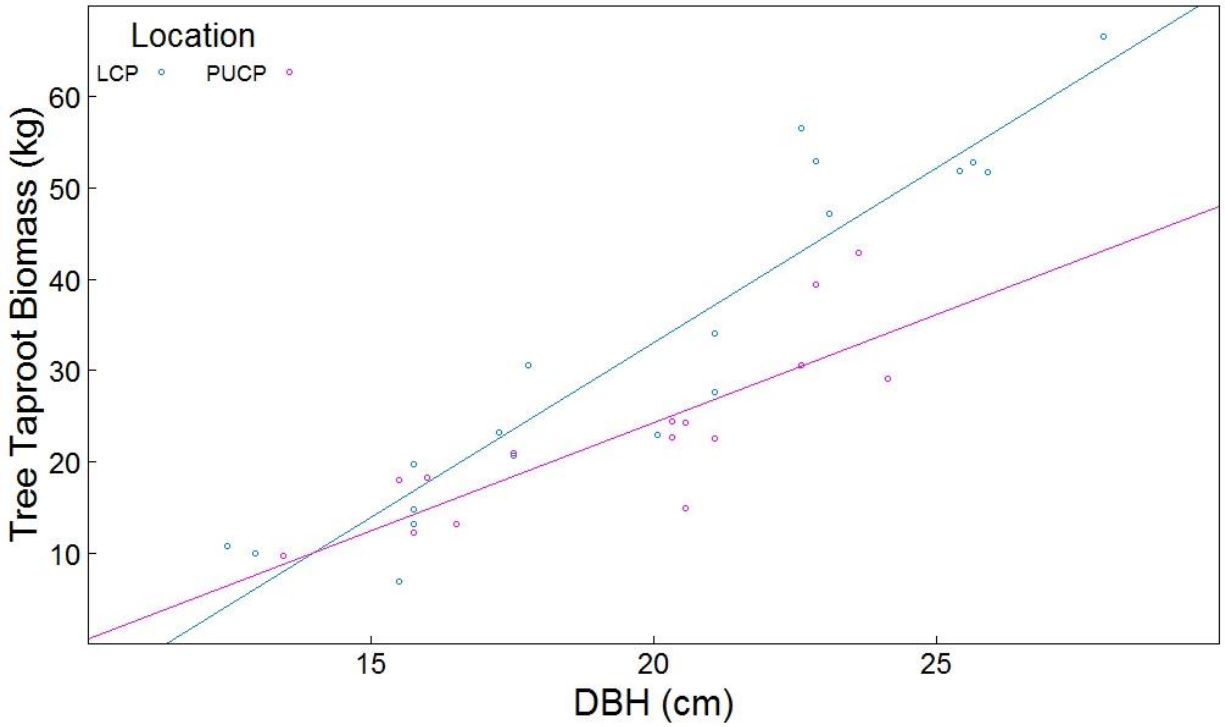


Figure 2.2. Belowground biomass of 15/16-year-old loblolly pine as a function of DBH in Lower Coastal Plain (LCP) and Piedmont Upper Coastal Plain (PUCP) Culture x Density trials (n=34 trees). Linear equations determining total taproot biomass are LCP= -43.633 + 3.834 * DBH, (R^2=0.88) and PUCP= -23.0776 + 2.3700 * DBH, (R^2=0.67).

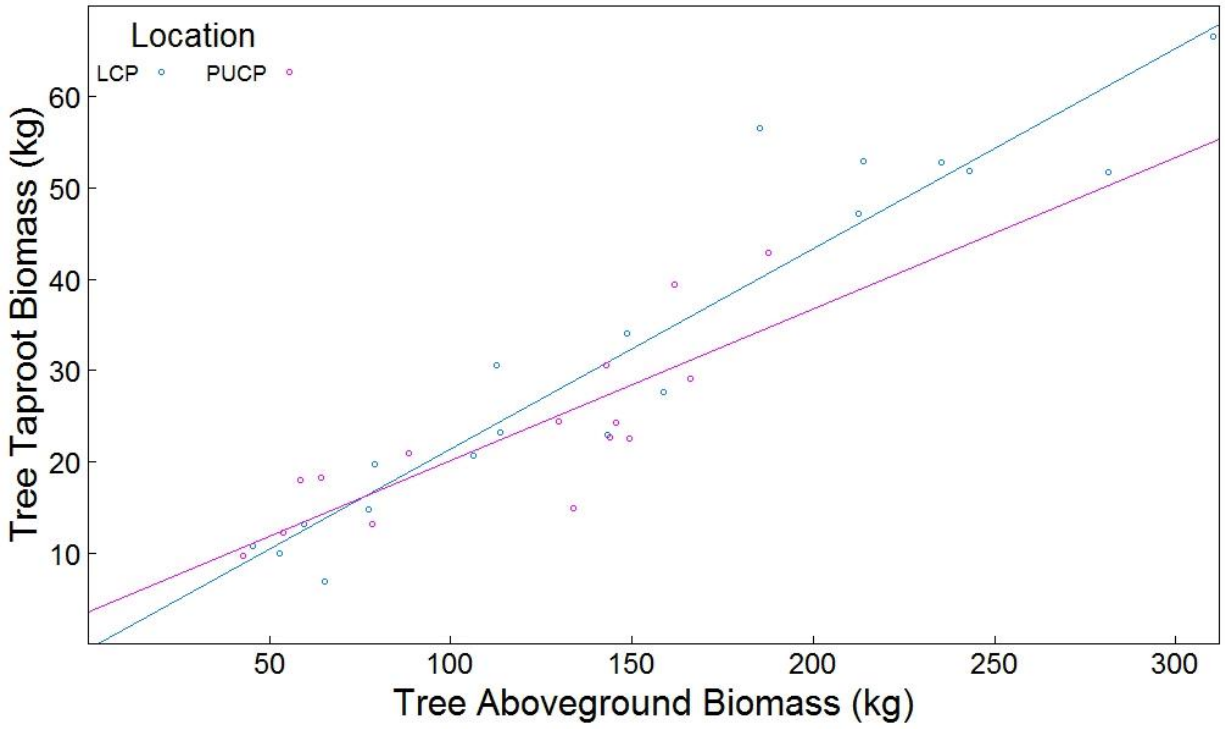


Figure 2.3. Belowground biomass of 15/16-year-old loblolly pine as a function of aboveground biomass in the Lower Coastal Plain (LCP) and Piedmont Upper Coastal Plain (PUCP) Culture x Density trials (n=34 trees). Linear equations determining total taproot biomass are LCP= -0.58418 + 0.21991 * aboveground biomass, (R^2=0.90) and PUCP= 3.4779 + 0.1665 * aboveground biomass, (R^2=0.66)

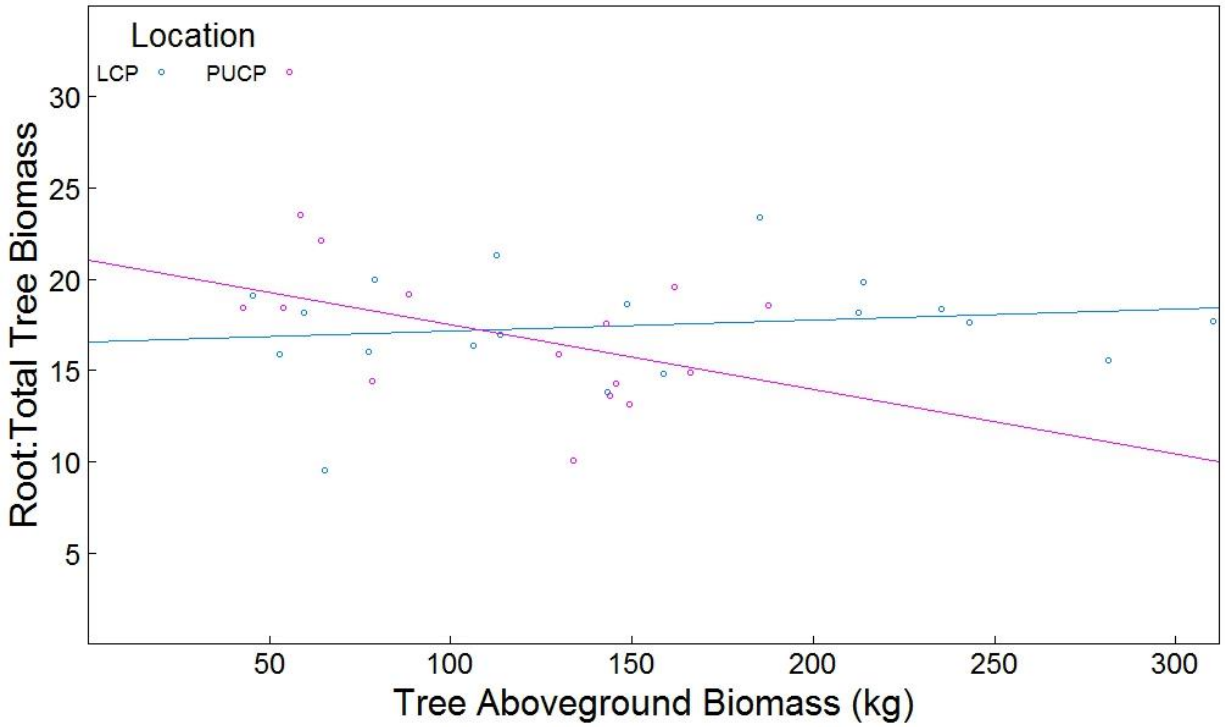


Figure 2.4. Taproot to aboveground tree biomass ratio of 15/16-year-old loblolly pine as a function of aboveground tree biomass in the Lower Coastal Plain (LCP) and Piedmont Upper Coastal Plain Culture x Density trials (n=34 trees). Linear equations determining root:total tree mass are LCP= 20.040127 + 0.008157 * aboveground biomass, (R^2=-0.03) and PUCP= 26.68384 + -0.05248 * aboveground biomass, (R^2=0.16)

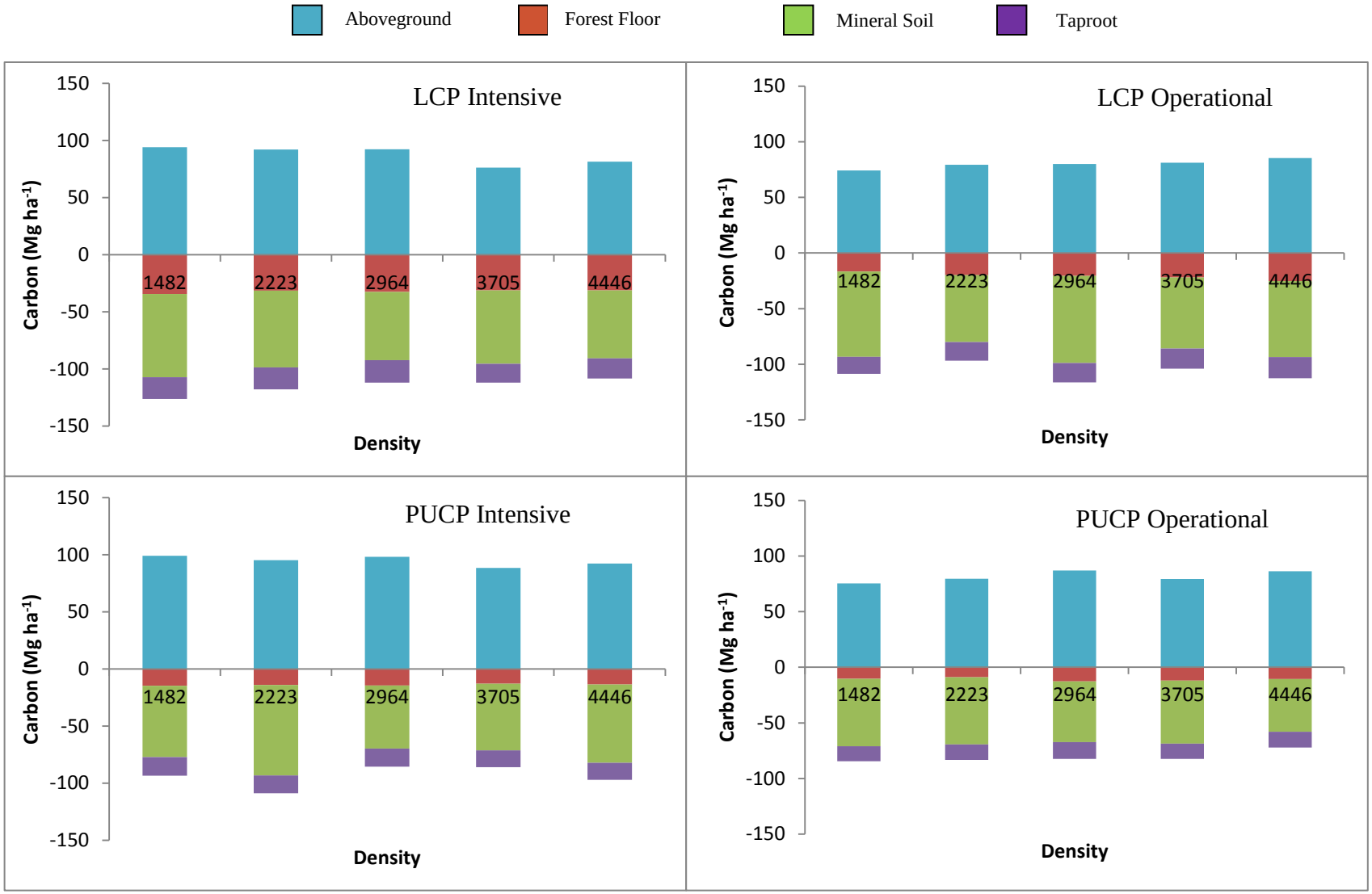


Figure 2.5. Aboveground and belowground carbon stocks at the stand level for aboveground, forest floor, mineral soil, and taproot.

Table 2.1. Physiographic regions (Lower Coastal Plain and Piedmont Upper Coastal Plain), locations, and soil series associated with each installation of the culture x density experiment.

Installation	Physiographic Region	Location	Soil Series
1	LCP	Macclenny, FL	Sapelo
9	LCP	Hilliard, FL	Ocilla
11	LCP	Callahan, FL	Ridgewood
1	PUCP	Sparta, GA	Bonifay
4	PUCP	Flomaton, AL	Orangeburg
17	PUCP	Carrollton, GA	Grover

Table 2.2. Silvicultural treatments for Lower Coastal Plain (LCP) and Piedmont Upper Coastal Plain (PUCP) sites within the culture x density experiment.

LCP Sites		PUCP Sites	
Operational Treatment	Intensive Treatment	Operational Treatment	Intensive Treatment
Bedding	Bedding	Tillage including subsoiling on some sites	Tillage including subsoiling on some sites
Fall banded chemical site preparation	Fall banded chemical site preparation	Broadcast chemical site preparation	Broadcast chemical site preparation
	Tip moth control		
Herbaceous weed control: 1st year banded	Repeated herbicide application to achieve complete vegetation control	Herbaceous weed control: 1st year banded	Repeated herbicide application to achieve complete vegetation control
Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Beginning before 8th growing seasons and at four year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131 kg ha^{-1} NH_4NO_3; Spring 6th growing season 336 kg ha^{-1} NH_4NO_3, Beginning before 8th growing season and at two year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Beginning before 8th growing seasons and at four year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131 kg ha^{-1} Na_4NO_3; Spring 6th growing season 336 kg ha^{-1} NH_4NO_3, Beginning before 8th growing season and at two year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P

Table 2.3. Average root mass (±1SD), C, and N by initial planting density and diameter class in the Lower Coastal Plain (n=19) and Piedmont Upper Coastal Plain (n=15).

		LCP			PUCP		
Diameter	TPA	Taproot Mass (g)	Taproot C (g)	Taproot N (g)	Taproot Mass (g)	Taproot C (g)	Taproot N (g)
0-5 mm	1483	447 (124)	212 (58)	2.4 (0.7)	187 (113)	90 (55)	0.9 (0.6)
	2224	392 (335)	181 (169)	3.1 (1.7)	188 (135)	88 (61)	1.0 (0.7)
	2965	282 (137)	135 (66)	1.8 (0.9)	200 (141)	96 (68)	0.7 (0.7)
	3706	289 (152)	138 (70)	2.0 (0.8)	135 (97)	63 (45)	0.7 (0.6)
	4448	230 (101)	111 (49)	1.5 (0.7)	182 (105)	84 (47)	0.9 (0.8)
5-50 mm	1483	6231 (1367)	3010 (661)	26.1 (2.8)	3057 (1117)	1425 (517)	8.0 (1.1)
	2224	5020 (1044)	2449 (556)	26.7 (6.4)	2919 (1027)	1348 (448)	8.1 (4.2)
	2965	4620 (3318)	2273 (1615)	22.3 (17.4)	2758 (1174)	1310 (606)	5.3 (1.8)
	3706	4830 (1432)	2344 (698)	24.2 (6.9)	2670 (480)	1258 (207)	8.8 (2.9)
	4448	3531 (1795)	1721 (877)	16.3 (7.3)	3037 (492)	1429 (213)	6.3 (4.8)
>50 mm	1483	48922 (11356)	22962 (5775)	125.0 (97.9)	34357 (5356)	15549 (2988)	32.3 (25.2)
	2224	32152 (21014)	14869 (11505)	157.9 (117.7)	19576 (6809)	8971 (3070)	28.1 (15.6)
	2965	19828 (18741)	9685 (9405)	85.0 (79.6)	16774 (5706)	7669 (2765)	26.2 (16.3)
	3706	21222 (10588)	10254 (5070)	79.8 (51.5)	18930 (3227)	8666 (1532)	25.9 (18.5)
	4448	24260 (17800)	11695 (8456)	82.5 (61.7)	9185 (3241)	4512 (1393)	13.6 (13.9)

Table 2.4. Average(±1SD) C and N concentrations by initial planting density and root diameter class in the Lower Coastal Plain and Piedmont Upper Coastal Plain

		LCP		PUCP	
Density	Diameter	C	N	C	N
1483	0-5	47.48 (0.34)	0.55 (0.05)	47.92 (0.95)	0.54 (0.17)
	5-10	48.11 (0.54)	0.45 (0.19)	49.02 (2.25)	0.41 (0.14)
	10-20	48.10 (0.32)	0.40 (0.12)	47.84 (1.38)	0.33 (0.09)
	20-50	47.95 (0.00)	0.47 (0.00)	45.88 (0.52)	0.27 (0.15)
	>50	47.06 (1.08)	0.27 (0.17)	45.62 (0.84)	0.10 (0.09)
2224	0-5	43.63 (5.83)	0.95 (0.37)	47.26 (1.61)	0.63 (0.27)
	5-10	48.72 (1.12)	0.64 (0.06)	47.29 (1.69)	0.37 (0.18)
	10-20	49.81 (0.86)	0.61 (0.04)	46.48 (1.24)	0.34 (0.11)
	20-50	47.99 (0.78)	0.45 (0.01)	46.17 (0.98)	0.26 (0.19)
	>50	43.93 (7.07)	0.47 (0.06)	45.75 (0.06)	0.15 (0.06)
2965	0-5	47.59 (0.98)	0.62 (0.07)	47.86 (0.36)	0.38 (0.17)
	5-10	48.45 (0.30)	0.53 (0.07)	47.39 (1.01)	0.25 (0.09)
	10-20	47.70 (0.46)	0.46 (0.06)	46.63 (1.60)	0.25 (0.15)
	20-50	49.23 (3.16)	0.44 (0.05)	47.08 (2.51)	0.18 (0.07)
	>50	47.09 (2.17)	0.36 (0.13)	45.63 (1.09)	0.19 (0.13)
3706	0-5	47.79 (0.63)	0.69 (0.12)	46.76 (0.38)	0.47 (0.24)
	5-10	48.44 (0.69)	0.56 (0.13)	46.52 (0.42)	0.40 (0.24)
	10-20	48.47 (0.85)	0.48 (0.16)	47.54 (3.19)	0.31 (0.20)
	20-50	48.09 (1.05)	0.47 (0.17)	47.23 (3.17)	0.19 (0.12)
	>50	48.54 (1.60)	0.30 (0.14)	44.98 (1.91)	0.15 (0.10)
4448	0-5	47.91 (0.54)	0.64 (0.05)	46.14 (0.86)	0.48 (0.19)
	5-10	49.80 (3.10)	0.56 (0.07)	53.48 (12.11)	0.40 (0.34)
	10-20	48.81 (0.71)	0.49 (0.06)	47.08 (0.87)	0.27 (0.21)
	20-50	48.17 (0.55)	0.39 (0.11)	45.93 (0.44)	0.17 (0.13)
	>50	48.66 (0.95)	0.43 (0.10)	47.84 (1.59)	0.14 (0.11)

Table 2.5. Average P, K, Ca, and Mg concentrations (± 1 SD) by initial planting density and root diameter class in the Lower Coastal Plain and Piedmont Upper Coastal Plain

		LCP				PUCP			
TPA	Diameter (mm)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
1483	0-5	417 (178)	1062 (526)	2252 (828)	550 (3)	334 (37)	1104 (441)	1959 (350)	456 (174)
	5-10	266 (31)	689 (290)	2035 (674)	466 (10)	267 (10)	1629 (1000)	1930 (521)	478 (146)
	10-20	173 (13)	718 (500)	1571 (354)	417 (21)	198 (40)	819 (456)	1389 (197)	410 (173)
	20-50	-	-	-	-	188 (71)	816 (428)	1320 (412)	321 (100)
	>50	101 (30)	432 (212)	1527 (840)	273 (22)	92 (18)	666 (188)	798 (136)	227 (33)
2224	0-5	310 (53)	929 (392)	1871 (579)	575 (100)	356 (114)	1154 (825)	2255 (349)	477 (244)
	5-10	386 (146)	702 (59)	1818 (187)	611 (138)	214 (52)	612 (398)	1739 (304)	444 (80)
	10-20	186 (43)	510 (233)	1317 (335)	512 (185)	207 (89)	685 (553)	1592 (329)	524 (203)
	20-50	135 (18)	416 (210)	1232 (286)	440 (151)	130 (59)	558 (248)	1117 (701)	272 (108)
	>50	111 (22)	332 (120)	1241 (350)	318 (55)	104 (24)	535 (91)	950 (232)	288 (50)
2965	0-5	389 (67)	912 (409)	2194 (439)	575 (129)	317 (71)	958 (124)	2026 (518)	545 (166)
	5-10	216 (25)	638 (333)	1826 (301)	457 (119)	220 (44)	607 (152)	1623 (382)	414 (112)
	10-20	216 (48)	774 (469)	1838 (621)	512 (148)	179 (34)	628 (206)	1971 (1158)	420 (146)
	20-50	159 (21)	665 (188)	1517 (130)	458 (117)	104 (8)	559 (112)	1207 (601)	261 (111)
	>50	122 (23)	457 (128)	1194 (346)	321 (58)	103 (3)	635 (159)	849 (94)	243 (94)
3706	0-5	322 (87)	783 (71)	2134 (398)	532 (156)	382 (144)	830 (636)	1913 (925)	417 (107)
	5-10	198 (37)	511 (85)	1690 (329)	470 (97)	302 (130)	737 (575)	1901 (880)	416 (99)
	10-20	173 (41)	507 (39)	1740 (263)	479 (84)	247 (49)	775 (497)	1560 (519)	400 (107)
	20-50	122 (66)	458 (117)	1417 (43)	387 (200)	140 (54)	419 (17)	1077 (360)	229 (30)
	>50	97 (37)	368 (87)	1303 (419)	252 (89)	126 (27)	660 (92)	922 (397)	263 (100)
4448	0-5	290 (15)	726 (207)	2434 (528)	543 (112)	357 (126)	1003 (495)	2230 (795)	482 (190)
	5-10	238 (30)	726 (252)	2248 (513)	557 (121)	267 (79)	823 (525)	1904 (911)	492 (128)
	10-20	191 (8)	587 (169)	2164 (411)	473 (119)	265 (105)	641 (290)	1793 (622)	488 (119)
	20-50	128 (34)	547 (199)	1531 (344)	388 (134)	94 (18)	546 (89)	926 (76)	309 (79)
	>50	99 (22)	444 (102)	1120 (209)	335 (68)	114 (47)	532 (143)	1033 (142)	236 (35)

Table 2.6. Regression equations for total taproot biomass and taproot diameter classes located in the Lower Coastal Plain and Piedmont and Upper Coastal Plain

Location	Biomass Component	Equation	R^2
LCP	Total Taproot Biomass	$-3303 + 41722(DBH^2H)$	0.895
	Biomass Fine Roots (0-5 mm)	$1571.36 + 339.74(DBH^2H) - 77.13(H)$	0.359
	Biomass Coarse Roots (5-50 mm)	$-8759 + 1952(DBH) - 449.3(H) - 393402.2(DBH^2)$	0.379
	Biomass Taproot (>50 mm)	$-6014 + 39134(DBH^2H)$	0.906
PUCP	Total Taproot Biomass	$-28404 + 2649(DBH)$	0.785
	Biomass Fine Roots (0-5 mm)	$947.45 - 42.85(H)$	0.449
	Biomass Coarse Roots (5-50 mm)	$-15301.9 + 1054.6(H) + 519291.8(DBH^2) - 29494.3(DBH^2H)$	0.070
	Biomass Taproot (>50 mm)	$30692.7 - 2289.7(H) + 43062.0(DBH^2H)$	0.825

Table 2.7. Taproot mass and C (±1SD) by initial planting density and cultural intensity in the Lower Coastal Plain and Piedmont Upper Coastal Plain

	LCP				PUCP			
	Taproot Mass		Taproot C		Taproot Mass		Taproot C	
TPH	Operational	Intensive	Operational	Intensive	Operational	Intensive	Operational	Intensive
	(Mg ha-1)							
1483	31.1 (17.5)	40.9 (2.6)	15.3 (7.3)	19.1 (1.2)	28.7 (8.3)	35.2 (6.0)	13.5 (3.5)	16.3 (2.9)
2224	32.8 (18.7)	39.4 (5.6)	16.7 (7.8)	19.2 (2.6)	29.9 (7.0)	34.2 (4.7)	14.1 (2.9)	15.8 (2.0)
2965	31.5 (13.6)	38.3 (3.1)	17.4 (5.4)	19.7 (0.4)	29.3 (9.0)	33.4 (6.4)	15.0 (3.5)	15.9 (2.3)
3706	30.9 (12.4)	30.7 (5.5)	18.0 (4.2)	16.5 (1.4)	23.9 (10.1)	29.3 (5.4)	13.6 (3.2)	14.8 (1.6)
4448	32.3 (15.8)	32.3 (0.1)	19.0 (6.1)	17.8 (2.0)	19.4 (10.6)	28.0 (4.6)	14.2 (2.7)	14.9 (1.2)

Table 2.8. Belowground decomposition rates estimated over 1 year in the Lower Coastal Plain

Size Class*	Roots	Wood
1	-0.0008 (0.0003)	-0.0011 (0.0014)
2	-0.0011 (0.0011)	-0.0005 (0.0003)
3	-0.0012 (0.0011)	-0.0005 (0.0003)
4	-0.0006 (0.0004)	
5	-0.0007 (0.0005)	

*Root size classes 1-5 are 0-10, 10-20, 20-50, 50-80, and >80 mm, respectively. Wood size classes 1-3 are 19x32x301, 38x38x301, and 90x38x301 mm, respectively

CHAPTER 3

PLANTING DENSITY AND SILVICULTURAL INTENSITY: IMPACTS ON SOIL AND FOREST FLOOR CARBON AND NUTRIENTS IN THE LOWER COASTAL PLAIN AND PIEDMONT AND UPPER COASTAL PLAIN OF THE SOUTHEAST USA[1]

[1] Ward, G.D. and Markewitz, D.M. To be submitted to *Soil Science Society of America Journal.*

Abstract

Increasing loblolly pine (*Pinus taeda*) harvest for bioenergy has led to interest in ensuring the sustainability and carbon neutrality of this feedstock as a means of offsetting fossil fuel emissions of CO_2. Furthermore, possibilities for further increasing feedstock production include increasing silvicultural treatments and initial planting density. This research makes use of an ongoing silvicultural intensity x initial planting density experiment to investigate the effects of increased silvicultural treatments and increased planting density on soil carbon and nutrient stores. Six installations of a culture x density experiment were utilized, three of which represent the Lower Coastal Plain, and three represent the Piedmont and Upper Coastal Plain. The experiment includes operational and intensive levels of silviculture inputs (fertilizers and herbicides) and five planting densities (1483, 2224, 2965, 3706, and 4448 trees ha^{-1}). Total forest floor mass, total C, and total N content, as well as total N, and total P concentration differed between the LCP and PUCP sites. The effects of culture by location impacted forest floor mass, C, N, P, and Ca contents on LCP sites. On PUCP sites, culture impacted N and Mg contents, and N concentrations. Density did not have a significant effect on forest floor carbon or nutrient. The main effect of culture was apparent for a few elements in each mineral soil layer (0-10, 10-20, and 20-50 cm) with the impacted elements often being the same (P, K, and Mg). Neither location nor density had significant effects on mineral soil concentrations. Results of this study suggest that using high initial planting densities within intensively managed forest lands may not have an effect on soil C stores.

Introduction

Increasing quantities of CO_2 in the atmosphere has led to a desire to displace fossil fuels with alternative, carbon neutral energy sources (Balat et al., 2003; Oelkers and Cole, 2008). One potential alternative energy source is woody biomass. In North America, capacity for wood pellet production has increased from 1.1 million metric tonnes in 2003 to 6.2 million metric tonnes in 2009. The United States is responsible for 72% of this capacity with 46% of the United States capacity coming from the South (Spelter and Toth, 2009). Given this growth in wood use for bioenergy there is a need to test the assumption of carbon neutrality of loblolly pine feedstock production as a means of offsetting fossil fuel emissions of CO_2 (Gladstone and Ledig, 1990; Maier et al., 2004).

There are 32 million ha of pine plantations in the southeastern United States, the majority of which is loblolly pine (*Pinus taeda L.*) (Fox, 2006). Loblolly pine stands offer fast growth and can be managed on short rotations (i.e., 10-30 years), providing a readily accessible pathway to increase feedstock production. One proposed method to increase feedstock production is to increase the planting density of loblolly pine on commercial stands. Although logistics of harvesting small stems are still uncertain, increasing planting density in pine stands increases biomass accumulation early in the rotation (Burkes et al., 2003) and, thus, may provide a means to augment feedstock production either through early thinning or short-rotation cropping.

In addition to manipulation of planting density, pine plantations in the southeastern United States are typically located in areas dominated by kaolinitic or sandy soils, and are limited by nitrogen and phosphorus (Fox et al., 2007b; Kiser et al., 2013), as such, increased cultural activity (i.e. fertilization) is often used to ameliorate this limitation. Fertilization results in increased stand growth rates (Samuelson et al., 2008; Scott and Dean, 2006; Will et al., 2002).

Fertilization, however, increases growth in both pine and non-pine vegetation such that herbicide use with fertilization is common practice. Applications of 168-224 kg N ha^{-1} and 28 kg P ha^{-1} result in an average growth increase of 3.5 m^3 ha^{-1} yr^{-1} over an 8 year period in loblolly pine plantations in the southeast (Fox et al., 2007a). Carlson et al. (2014) reported an average growth response of loblolly pine to N and P of 4.28 m^3 ha^{-1} yr^{-1} in stands 9-25 years old. These cultural amendments may increase aboveground, belowground, and soil C sequestration but also have a C cost (i.e., emit CO_2) in production and application (Markewitz, 2006). The carbon emissions associated with these silvicultural activities, however, tends to be outweighed by the increased carbon sequestration in tree growth.

A persistent uncertainty in the carbon budget of these pine plantations is whether soil carbon storage is enhanced with these silvicultural activities (Johnson and Curtis, 2001). Soil is an important carbon sink in forest ecosystems, sequestering approximately two times more carbon than in vegetation or in the atmosphere (Schimel, 1995). Forest soils and vegetation are responsible for sequestering approximately 1146 Pg C worldwide (Dixon et al., 1994). Vogel et al. (2011) found that fertilization increased net carbon accumulation by 40% in one 26-year-old loblolly pine stand in Florida, the combination of fertilization and herbicide treatments, however, slightly decreased the net carbon increase produced by fertilization alone. The combination of high planting densities and silvicultural amendments may augment belowground C storage in soil. There is some debate, however, as to the extent to which soils may store additional carbon.

The amount of carbon sequestered in the forest floor (i.e., the soil O horizon) may range from 9-38 Mg C ha^{-1} (Johnson et al., 2003; Kinerson et al., 1977; Vogel et al., 2011). Eighteen years following establishment, forest floor accounted for 6% of net ecosystem C accumulation in one loblolly pine plantation (Johnson et al., 2003). Increasing fertilizer application rates in

loblolly pine stands often results in an increase in forest floor mass (Rifai et al., 2010). Akers et al. (2013) reported an increase in foliar biomass with increasing initial planting density suggesting that forest floor biomass may have a positive relationship with planting density. In mineral soil some research proposes a relatively low potential to store additional carbon (Matamala and Schlesinger, 2000; Richter et al., 1999), while others suggest that soils have a relatively high potential to store additional carbon (Lal, 2004). Johnson and Curtis (2001) conducted a meta-analysis to determine the effects of forest management on C and N storage. Their investigation concluded that forest management has little effect on C and N storage, but the type of harvest (i.e., whole tree vs stem only) may affect these stores. Sawlog only harvesting resulted in an 18% increase in C and N stores within coniferous species while whole tree harvesting resulted in a decrease of 6%. There are other benefits to managing soil carbon beyond CO_2 sequestration such as improving water infiltration, soil structure, nutrient retention, and soil productivity.

There is some discussion over the role of forest floor in site productivity. Some studies have shown that the forest floor increases available N in the soil and may have a negative effect on tree growth if removed (Zerpa et al., 2010; Zerpa et al., 2014). Other studies found that forest floors within loblolly pine stands act as N and P sinks, suggesting higher productivity may be achieved through disturbance events such as timber harvesting (Kiser et al., 2013; Piatek and Allen, 2001).

Motivating this work is the recognition that high planting densities in loblolly pine plantations increase standing biomass early in stand rotation and thus can provide an opportunity for increasing biomass energy feedstock production through early stand thinnings or short-rotation cropping. Improved understanding of carbon cycling in these plantation systems both

above and belowground and impacts on total stand carbon is necessary, however, to evaluate the potential of this silvicultural approach to offset fossil fuel emissions of CO_2 to the atmosphere as well as the sustainability of these practices from a nutrient perspective.

The objectives of this study were to determine the effect of planting density and increased silvicultural intensity on soil C (including both forest floor and 0-50 cm mineral soil) and macronutrients. Hypothesis tested were (*i*) forest floor (i.e., soil O horizon) carbon will increase with additions of cultural treatments and planting density due to increased foliar biomass, and (*ii*) mineral soil carbon will remain unchanged with increasing cultural treatments and planting density due to the rapid turnover of soil organic matter inputs.

Methods

Site Description

Detailed description of the study design and growth results are provided by Zhao et al. (2012). We used a subset of these sites for the present study. This research utilizes six installations of a culture x density experiment established by the Plantation Management Research Cooperative (PMRC) across the southeastern United States from 1996-1998 (Figure 1a). Three of these sites were 16 years old and are located in northeastern Florida and represent the Lower Coastal Plain (LCP), while the other three sites were 15 years old and located in Georgia and Alabama and represent the Piedmont and Upper Coastal Plain (PUCP) (Table1). Each of these sites contains two levels of silviculture defined as intensive and operational (Table 2). Within each level of culture, plots with planting densities of 741, 1483, 2224, 2965, 3706, and 4448 trees ha^{-1} (300, 600, 900, 1200, 1500, and 1800 trees ac^{-1}) were established in a randomized split-plot design. The locations have no replication so serve as blocks within the

larger experimental design (Figure 1b). For this study, plots with 741 trees ha^{-1} were not utilized as these are not a rational density for bioenergy feedstock production.

Forest Floor Collection and Analysis

Forest floor samples were collected at each of the planting densities for each of the six study sites. Samples were collected by extracting all forest floor material (Oi, Oe, and Oa horizons), within a 35 x 35 cm wooden square. Eight locations for sampling were selected at random within a plot and composited into a single sample bag. These samples were returned to the Phillips Wood Utilization Laboratory located in Athens, GA where they were oven dried at 65^{o} C to a constant weight. A subsample was ashed to correct for soil mineral contamination (SSSA, 1996).

A second forest floor subsample was ground through 1 mm mesh using a Wiley Mill Model 4 (Thomas Scientific, Swedesboro, NJ). These subsamples were then digested in nitric acid/hydrogen peroxide following Method 3050B (Environmental Protection Agency) with one modification. In Method 3050B samples are heated to a temperature of 95^{o}C for 2 hours. For this study, the temperature was increased from 95^{o}C to 180^{o}C to ensure complete digestion. Digests were analyzed for phosphorus (P), magnesium (Mg), calcium (Ca), and potassium (K). Element concentrations in the digests were measured using an Elan 9000 Inductively Coupled Plasma Mass Spectrometer (ICP/MS, Perkins Elmer-Sciex). Complete digestion and recovery was assessed with standard reference materials 1547 (peach leaves) and 1575 (pine needles) (NIST, 1991; NIST, 1993). A final subsample of forest floor from each of the Wiley milled samples was ball mill ground to a fine powder (SPEX 8000) and analyzed for total nitrogen (N) and total carbon (N) using a CN Soil Analyzer Flash 2000 (Thermo Scientific, Waltham, MA).

Mineral Soil Collection and Analysis

Mineral soil samples were collected after removal of the forest floor from each of the eight subsample locations at each of the planting densities for each of the six study sites. Samples were collected with a 7.5 cm diameter soil auger to a depth of 50 cm in layers of 0-10, 10-20, and 20-50 cm. The eight cores were composited into individual bags by depth increment. These samples were returned to the laboratory where they were air dried for at least one week. Samples were passed through a 2 mm sieve to remove rock and root material. A subsample of sieved soil was extracted by Mehlich 1 (0.05 N H_2SO_4, 0.025 N HCl) (Mehlich, 1953). Extractions were analyzed for P, K, Ca, and Mg. Element concentrations in the extractions were measured using an Elan 9000 Inductively Coupled Plasma Mass Spectrometer (ICP/MS, Perkins Elmer-Sciex). A subsample of soil material from each of the sieved samples was ball mill ground to a fine powder (SPEX 8000) and analyzed for total carbon (C) and total nitrogen (N) using a NC Soil Analyzer Flash 2000 (Thermo Scientific, Waltham, MA).

In addition to chemical analysis, one or two bulk density samples per depth per planting density per study site were collected using a bulk density hammer with a 331.4 cm^3 stainless steel core (7.5 cm diameter x 7.5 cm deep). Samples were obtained for each depth increment, 0-10, 10-20, and 20-50 cm. The 0-10 cm sample was collected by removing all organic material (Oa, Oe, and Oi horizons) as done for forest floor collections to bare mineral soil and then using the bulk density hammer to drive the stainless steel core 7.5 cm into the ground. Soil was then removed to a depth of 10 cm and then the 10-20 cm sample was measured in the same manner. The 20-50 cm samples were collected from soil pits used to excavate taproots as part of another study at these sites (Ward, 2015).

Samples were brought to the laboratory in Athens, GA where they were dried in an oven at 105 ^{o}C to a constant weight. Total oven dry weight was measured and then samples were passed through a 2 mm sieve to remove rock and root material. The weight and volume of rocks and roots were measured for bulk density corrections (SSSA, 1986).

Statistical Analysis

This experiment was set up as a split- plot design with plots in each location serving as a replication so that there were three replications in the LCP and PUCP, respectively. A mixed model approach was used to determine the main effects of culture, density, location, and their interactions. Replications were nested within location and treated as a random effect. Analyses were done by depth recognizing that values spatially co-vary with depth. If there was a significant location x culture or location x density interaction then analyses were run by location. A multivariate analysis of variance (MANOVA) was combined with an analysis of variance (ANOVA) to assess the treatment effects on forest floor mass, as well as total carbon, and nitrogen content, percent carbon, percent nitrogen, P, K, Ca, and Mg in forest floor and soil.

Results

Forest Floor Carbon and Macronutrients

In the full MANOVA model for forest floor C and macronutrients, location was a significant main effect for a number of attributes as was culture and there was a significant location x culture interaction (Table 3.3). Total forest floor mass, total C, and total N content, as well as N, and total P concentration differed between the LCP and PUCP sites (Figure 3.2). The effects of culture by location impacted forest floor mass, C, N, P, and Ca contents on LCP sites

while on PUCP culture impacted N and Mg contents, and N concentrations. Density did not have a significant effect on forest floor carbon or nutrients.

Average (±1SD) forest floor mass, and carbon, and nitrogen content were 64.3±8.0, 32.2±4.1 and 0.8±0.2 Mg ha^{-1}, respectively, for intensive treatment plots and 41.1±11.9, 20.9±5.8, and 0.5±0.2 Mg ha^{-1}, respectively, for operational treatment plots on LCP sites, and 26.9±6.6, 13.9±2.7, and 0.4±0.1 Mg ha^{-1}, respectively, for intensive treatment plots and 20.7±6.0, 11.0±3.2, and 0.2±0.1 Mg ha^{-1}, respectively, for operational treatment plots on PUCP sites (Tables 3.4 and 3.5). Average concentrations were 348±32, 320±170, 2409±307, and 455±81 mg kg^{-1} for forest floor P, K, Ca, and Mg, respectively, on intensively managed sites and 371±37, 370±145, 3032±507, 520±125 mg kg^{-1} for forest floor P, K, Ca, and Mg, respectively, on operationally managed sites in the LCP. Average concentrations were 529±77, 623±162, 2023±422, and 555±100 mg kg^{-1} for forest floor P, K, Ca, and Mg, respectively, on intensively managed sites and 556±121, 693±204, 2419±635, and 606±109 mg kg^{-1} for forest floor P, K, Ca, and Mg, respectively, on operationally managed sites in the PUCP (Table 3.6).

Mineral Soil Carbon and Macronutrients

Location did not have a large effect on soil concentrations for any layer. The main effect of culture was apparent for a few elements in each layer with the elements often being the same (P, K, and Mg). Density had few significant effects on mineral soil concentrations. Bulk density was not affected by location, culture, or density. Finally, few interactions among location, density, or culture were significant (Table 3.7).

In the 0-10 cm layer, K was significantly lower in LCP compared to PUCP sites. In LCP, intensive culture plots had lower K concentration in the first 10 cm of soil. In PUCP, intensive

culture had higher P concentrations but lower Mg concentrations. No significant interactions between culture and density were found for PUCP sites (Table 3.7). Average bulk density for 0-10 cm was 1.26±0.14 g cm^{-3}.

Average total soil carbon and nitrogen contents were 21.1±7.3 and 0.9±0.3 Mg ha^{-1}, respectively, for intensive treatment plots and 24.2±7.8 and 0.9±0.2 Mg ha^{-1}, respectively, for operational treatment plots on LCP sites, and 26.1±9.9 and 1.2±0.4 Mg ha^{-1}, respectively, for intensive treatment plots and 20.4±9.4 and 1.0±0.3 Mg ha^{-1}, respectively, for operational treatment plots on PUCP sites (Table 3.5). Average concentrations were 6.99±4.66 mg kg^{-1}, 0.03±0.01, 0.18, and 0.08±0.06 $cmol_c$ kg^{-1} for P, K, Ca, and Mg, respectively, for intensively managed sites and 6.10±2.70 mg kg^{-1}, 0.06±0.01, 0.19±0.12, and 0.13±0.10 $cmol_c$ kg^{-1} for P, K, Ca, and Mg, respectively, for operationally managed sites in the LCP for 0-10 cm of soil. Average concentrations were 15.49±6.01 mg kg^{-1}, 0.08±0.02, 0.24±0.14, and 0.09±0.05 $cmol_c$ kg^{-1} for P, K, Ca, and Mg, respectively, for intensively managed sites, and 9.20±5.88 mg kg^{-1}, 0.11±0.04, 0.36±0.17, and 0.12±0.04 $cmol_c$ kg^{-1} for operationally managed sites in the PUCP for 0-10 cm of soil (Table 3.10).

No significant differences were found between LCP and PUCP locations for 10-20 cm of soil. The effects of culture impacted K in soil at a depth of 10-20 cm in LCP sites. The effects of culture impacted P and Mg on PUCP sites for 10-20 cm soil. No significant interactions between culture and density were found for soils in 10-20 cm on PUCP sites (Table 3.8). Average total soil carbon and nitrogen contents were 17.7±5.5 and 0.8±0.2 Mg ha^{-1}, respectively, for intensive treatment plots and 16.1±7.0 and 0.8±0.3 Mg ha^{-1}, respectively, for operational treatment plots (Table 3.5). Average concentrations were 8.12±6.06 mg kg^{-1}, 0.04±0.03, 0.14±0.13, and 0.04±0.03 $cmol_c$ kg^{-1} for P, K, Ca, and Mg, respectively, for intensively managed

sites, and 3.70±2.53 mg kg^{-1}, 0.07±0.04, 0.17±0.20, and 0.06±0.04 $cmol_c$ kg^{-1} for operationally managed sites (Tables 3.10 and 3.11). Average bulk density for 10-20 cm was 1.68 ± 0.28 g cm^{-3}.

No significant differences were found between LCP and PUCP locations for 20-50 cm of soil. The effects of culture impacted Mg in soil at a depth of 20-50 cm on LCP sites. No effects of culture or density were found on PUCP sites. No significant interactions between culture and density were found for LCP or PUCP sites (Table 3.9). Average total soil carbon and nitrogen were 23.4±13.4 and 1.7±0.6 Mg ha^{-1}, respectively, for intensive treatment plots and 24.3±16.1 and 1.6±0.6 Mg ha^{-1}, respectively, for operational treatment plots (Table 3.5). Average concentrations were 3.43±5.69 mg kg^{-1}, 0.04±0.03, 0.11±0.08, and 0.04±0.05 $cmol_c$ kg^{-1} for P, K, Ca, and Mg, respectively, for intensively managed sites, and 1.61±1.41 mg kg^{-1}, 0.07±0.05, 0.15±0.11, and 0.06±0.07 $cmol_c$ kg^{-1}, respectively, for operationally managed sites (Table 3.10 and 3.11). Average bulk density for 20-50 cm was 1.67 ± 0.08 g cm^{-3}

Average total soil C (i.e., mineral soil and forest floor) was 96.8±12.5, 90.4±29.7, 76.9±26.3, and 66.8±24.4 Mg ha^{-1} for LCP intensive and operational treatments and PUCP intensive and operational treatments, respectively.

Discussion

Working with four LCP installations of the culture x density experiment, Burkes et al. (2003) reported a >2 fold increase in standing biomass from ~13 Mg ha^{-1} in 740 trees ha^{-1} to 29 Mg ha^{-1} in 4400 trees ha^{-1} at age 4. By age 12, Zhao et al. (2012) found that initial planting density still had an effect on aboveground biomass for 23 sites of the culture x density experiment in the PUCP with biomass increasing from ~108 to 120 Mg ha^{-1} for the 1483 to 4440

trees ha^{-1} planting densities, respectively, although biomass increases from 2220 to 4440 trees ha^{-1} were no longer significant. By rotation age 25, in a separate spacing study, Amateis and Burkhart (2012) similarly concluded that high planting density plantations can be used for woody biomass production, although they too saw a decline in initial planting density differences with age. As such, the potential to increase biomass feedstock production with increased initial planting density is well supported by growth data. Despite the impact of planting density on aboveground biomass early in the rotation, as reported above, planting density did not have an effect on forest floor mass, carbon, or nutrient concentrations in the 16 (LCP) and 15 (PUCP) year old stands of this study. It is curious that a difference in forest floor mass with planting density was not observed given the greater growth, although partitioning of biomass to needles relative to stem was reported to decrease with higher densities at age four by Burkes et al. (2003) suggesting forest floor inputs will similarly decline with increasing planting density. Akers et al. (2013) working in four culture x density replicates of age 13 also reported no increase in foliar biomass with increasing initial planting density from 1440 to 4880 trees ha^{-1}. Thus, despite suggesting that forest floor biomass and N content may have a positive relationship with planting density, neither of these were seen in this study.

The objectives of this study were to investigate both the effects of increased planting density as well as silvicultural treatments on soil carbon and nutrients. Hypothesis *i*, that focused specifically on the forest floor, was partially supported since forest floor mass and carbon did increase with increased cultural management in the LCP, although this was not true in the PUCP. Others have reported an increase in forest floor mass with fertilization (Rifai et al., 2010; Shan et al., 2001). Vogel et al. (2011), in particular, found that forest floor carbon increased with fertilization, but the combination of fertilization with herbicide use resulted in a decrease in

forest floor carbon accumulation with respect to fertilizer only treatments. All plots in this study received some herbicide inputs and the increased herbicide use on intensive plot locations may have decreased total forest floor C accumulation relative to fertilization alone but in the absence of a no fertilizer treatment, this could not be assessed.

Hypothesis *ii* was accepted as neither planting density nor culture affected total soil carbon to a depth of 50 cm. This study reached similar conclusions to Johnson et al. (2003) who found no statistical difference in soil C regardless of depth. Richter et al. (1999) report an accumulation of soil C within the first 7.5 cm of soil within a re-established pine system that was once used for agriculture, but this effect was not evident below 7.5 cm. Soil C changes with plantation management have been intensively studied but increases in mineral soil have been difficult to demonstrate (Johnson and Curtis, 2001). Other forest management practices, investigated in other studies, have the potential to change soil carbon storage. For example, Nave et al. (2010) conducted a meta-analysis using 75 publications to determine the effects of harvesting on soil C. Harvesting was found to reduce forest floor C storage by approximately 20% in coniferous species, while Ultisols lost approximately 7% C in mineral soil. Johnson and Curtis (2001) further investigated the effects of forest management on soil C and N stores by examining effects of harvesting methods used (i.e. whole tree vs stem only). Whole tree harvesting was found to decrease C and N stores more than stem only harvesting. C and N storage have often decreased with the inclusion of prescribed burning (Nave et al., 2011). The interaction of these impacts with density have not been directly addressed.

We found that N fertilization increased the amount of N found in forest floor, but not in soil. This finding agrees with Kiser and Fox (2012) that found N did not accumulate on sandy soils, but increased in forest floor. These results also agree with Piatek and Allen (2001) who

found that forest floor in the Piedmont of North Carolina served as an N sink. Zerpa et al. (2014) report an increase of available C, N, and P in mineral soil when forest floor was doubled on a Lower Coastal Plain site but no mineral soil increase was found in the current study. Mg in the top 10 cm of mineral soil decreased with planting density. This may suggest increased nutrient acquisition by loblolly pine with increased planting density. Markewitz et al. (1998) found a decrease in soil Ca and Mg during the first three decades of pine plantation growth in the Piedmont of South Carolina. This current study also included some use of NH_4NO_3 as a fertilizer as well as micronutrients on intensive plots that may also serve to acidify the soil but why this would interact with density is hard to justify.

The results of this study suggest that the use of high planting densities within intensively managed forest stands may not affect soil C (i.e., mineral and O horizon) pools despite growing more biomass. This is positive in that C and nutrient pools are not declining and may be able to sustain multiple rotations. Forest managers, however, need to recognize that various management practices may have different effects on C and N such as those effects of harvesting cited above. As such, harvesting at a younger age (i.e., before age 12) may enable forest managers to better meet the increasing demand for energy feedstocks but will require continued investigation.

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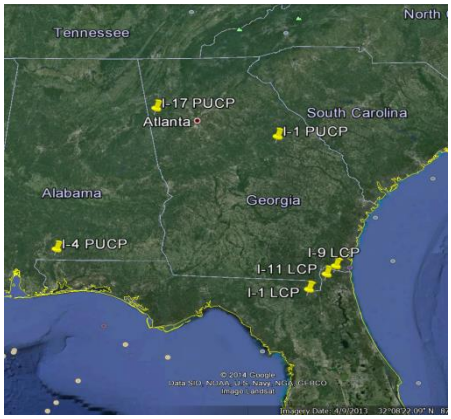
A) 

B) 

Figure 3.1. Location of six Culture x Density trials utilized for the current research (A), and areal image of a Culture x Density installation in the Piedmont/ Upper Coastal Plain study demonstrating variation in density conditions (B). Note numbers in the figure are trees per acre at planting (equivalent trees/ha are 741, 1482, 2223, 2964, 3705, and 4446) and O=operational treatments with fertilizers and herbicides and I=intensive treatments with fertilizers and herbicides.

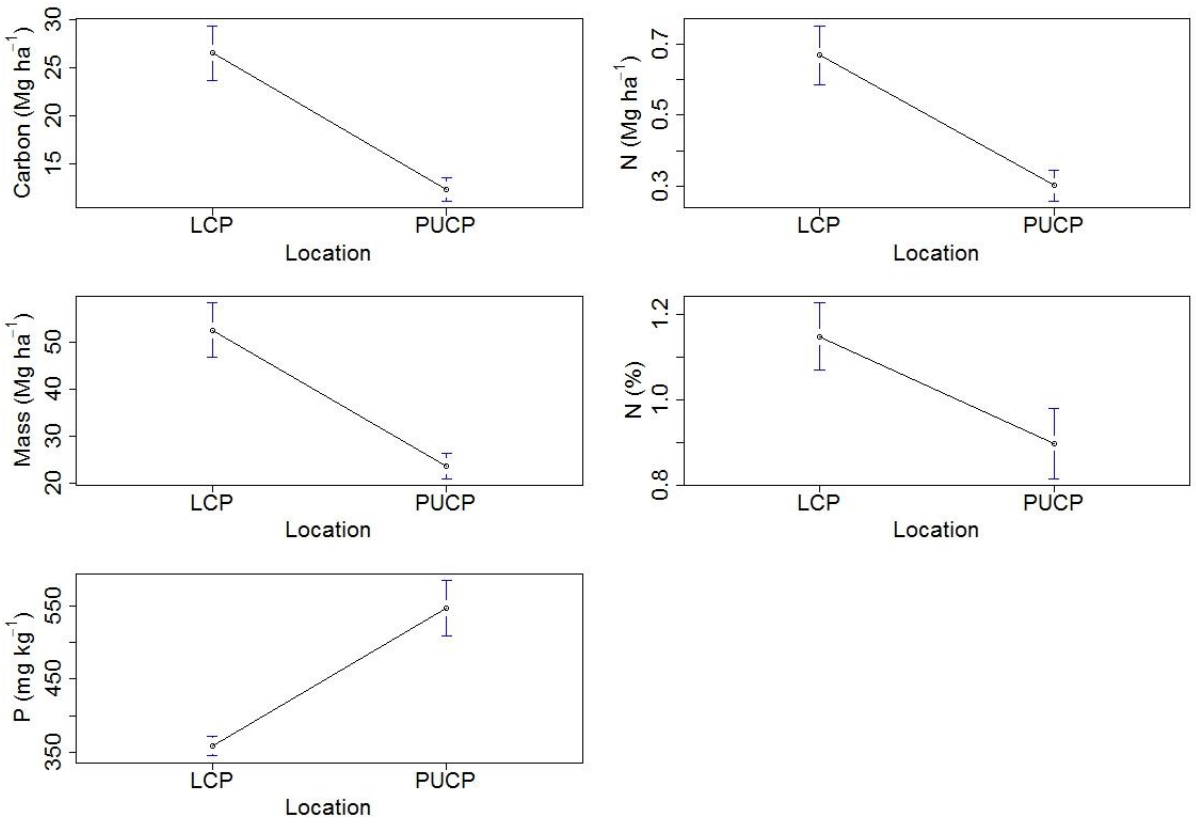


Figure 3.2. Main effects of location (Lower Coastal Plain vs Piedmont Upper Coastal Plain) on forest floor carbon, N, mass, and P concentration in loblolly pine stands within a culture x density experiment. Symbols indicate mean values. Bars indicate standard error. Samples were collected in 2013/2014 when stands were 15/16 years old.

Table 3.1. Physiographic regions (Lower Coastal Plain and Piedmont Upper Coastal Plain), locations, and soil series associated with each installation of the culture x density experiment.

Installation	Physiographic Region	Location	Soil Series
1	LCP	Macclenny, FL	Sapelo
9	LCP	Hilliard, FL	Ocilla
11	LCP	Callahan, FL	Ridgewood
1	PUCP	Sparta, GA	Bonifay
4	PUCP	Flomaton, AL	Orangeburg
17	PUCP	Carrollton, GA	Grover

Table 3.2. Silvicultural treatments for Lower Coastal Plain (LCP) and Piedmont Upper Coastal Plain (PUCP) sites within the culture x density experiment.

LCP Sites		PUCP Sites	
Operational Treatment	Intensive Treatment	Operational Treatment	Intensive Treatment
Bedding	Bedding	Tillage including subsoiling on some sites	Tillage including subsoiling on some sites
Fall banded chemical site preparation	Fall banded chemical site preparation	Broadcast chemical site preparation	Broadcast chemical site preparation
	Tip moth control		
Herbaceous weed control: 1st year banded	Repeated herbicide application to achieve complete vegetation control	Herbaceous weed control: 1st year banded	Repeated herbicide application to achieve complete vegetation control
Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Beginning before 8th growing seasons and at four year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131 kg ha^{-1} NH_4NO_3; Spring 6th growing season 336 kg ha^{-1} NH_4NO_3, Beginning before 8th growing season and at two year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Beginning before 8th growing seasons and at four year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P	Fertilization: At planting, 561 kg ha^{-1} of 10-10-10; Spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131 kg ha^{-1} Na_4NO_3; Spring 6th growing season 336 kg ha^{-1} NH_4NO_3, Beginning before 8th growing season and at two year intervals, 224 kg ha^{-1} N + 28 kg ha^{-1} P

Table 3.3. P-values for culture and density main effects and associated interactions on loblolly pine forest floor mass, carbon, and macronutrient concentrations on 3 sites in the Lower Coastal Plain and 3 sites in the Piedmont Upper Coastal Plain.*

		Mass	C	N	C%	N %	P	K	Ca	Mg
LCP	Culture	**0.0330**	**0.0200**	**0.0042**	0.4951	0.3398	**0.0356**	0.2450	**0.0343**	0.2052
	Density	0.8468	0.9251	0.9177	0.2607	0.0767	0.7137	0.6618	0.1413	0.3426
	Culture*Density	0.5072	0.5117	0.4048	0.3757	0.4771	0.4652	0.7553	0.2356	0.9703
PUCP	Culture	0.1276	0.1406	**0.0467**	0.3930	**<0.0001**	0.4822	0.1296	0.4313	**0.0006**
	Density	0.1091	0.0760	0.3143	0.0741	0.2047	0.1959	0.7655	0.1053	0.5629
	Culture*Density	0.7630	**0.0385**	0.9507	0.1061	0.5866	0.2883	0.6156	0.0758	0.2143
LCP+PUCP	Culture	**0.0051**	**0.0034**	**0.0009**	0.3318	**0.0258**	0.2726	0.2156	0.0672	0.0744
	Density	0.7959	0.7561	0.6154	0.3481	0.1874	0.3285	0.6103	0.0804	0.3257
	Culture*Density	0.2506	0.1457	0.5385	0.8810	0.7774	0.3619	0.6844	0.0911	0.5772
	Location	**0.0048**	**0.0039**	**0.0129**	0.0708	**0.0130**	**0.0132**	0.0727	0.1917	0.1936
	Culture*Location	**0.0304**	**0.0205**	**0.0279**	0.8840	0.3690	0.9523	0.8812	0.5757	0.7658
	Density*Location	0.4722	0.8108	0.7569	0.2142	0.0732	0.1769	0.1695	0.3729	0.6185

*Values in bold indicate significant differences at α=0.05 level.

Table 3.4. Total mass of forest floor (±1SD) by density in loblolly pine stands within Lower Coastal Plain and Piedmont Upper Coastal Plain locations. Samples were collected in 2013/2014 when stands were 15/16 years old.

	LCP		PUCP	
	Operational	Intensive	Operational	Intensive
TPH*	Mass (Mg ha^{-1})		Mass (Mg ha^{-1})	
1483	33.0 (14.6)	68.9 (10.7)	10.4 (2.0)	27.8 (10.0)
2224	39.8 (12.9)	62.6 (10.5)	8.9 (1.2)	25.8 (5.1)
2965	39.9 (5.6)	65.0 (12.0)	12.8 (3.8)	28.9 (8.3)
3706	42.4 (13.9)	60.9 (2.6)	12.0 (4.5)	26.7 (8.1)
4448	50.2 (12.5)	64.0 (4.4)	10.7 (4.1)	24.4 (3.8)

*Trees per hectare

Table 3.5. Soil carbon contents (mean±1SD) for loblolly pine stands within the culture x density experiment. Samples were collected in 2013/2014 at three locations in the Lower Coastal Plain and three in the Piedmont Upper Coastal Plain.

		LCP				PUCP			
		Operational	Intensive	Operational	Intensive	Operational	Intensive	Operational	Intensive
TPH*		C Mg ha^{-1}		N Mg ha^{-1}		C Mg ha^{-1}		N Mg ha^{-1}	
1483	O horizon	16.5 (6.8)	34.4 (5.3)	0.4 (0.2)	0.9 (0.1)	10.4 (2.0)	14.6 (3.6)	0.3 (0.1)	0.4 (0.1)
	0-10 cm	24.3 (12.7)	20.6 (9.4)	1.0 (0.3)	1.1 (0.5)	18.7 (9.8)	25.8 (18.5)	0.9 (0.4)	1.2 (0.7)
	10-20 cm	13.9 (7.6)	23.6 (8.8)	0.7 (0.1)	0.9 (0.1)	21.0 (7.3)	21.1 (8.5)	1.1 (0.4)	1.1 (0.3)
	20-50 cm	38.6 (42.6)	28.4 (12.2)	1.0 (0.3)	1.1 (0.5)	20.8 (11.6)	15.7 (4.0)	1.6 (0.7)	1.5 (0.3)
2224	O horizon	19.9 (6.2)	31.5 (5.1)	0.4 (0.1)	0.8 (0.1)	8.9 (1.2)	13.9 (3.9)	0.2 (0.0)	0.4 (0.1)
	0-10 cm	18.9 (10.7)	23.9 (3.2)	0.7 (0.3)	0.9 (0.1)	17.9 (8.0)	27.5 (10.1)	0.9 (0.3)	1.2 (0.4)
	10-20 cm	14.7 (4.0)	20.8 (7.1)	0.6 (0.1)	0.9 (0.2)	19.4 (12.7)	15.9 (4.9)	1.1 (0.7)	0.8 (0.2)
	20-50 cm	26.7 (9.5)	22.6 (5.2)	1.2 (0.9)	1.4 (0.8)	23.1 (19.8)	35.8 (39.0)	1.7 (1.0)	2.2 (1.5)
2965	O horizon	20.6 (2.9)	32.6 (6.9)	0.5 (0.2)	0.9 (0.2)	12.8 (3.8)	14.4 (3.4)	0.3 (0.1)	0.4 (0.2)
	0-10 cm	28.2 (6.1)	19.5 (11.2)	1.1 (0.2)	0.8 (0.3)	23.4 (12.9)	22.7 (7.3)	1.1 (0.5)	1.0 (0.3)
	10-20 cm	19.5 (3.4)	15.8 (0.5)	0.8 (0.0)	0.8 (0.1)	11.5 (6.3)	13.8 (2.9)	0.7 (0.2)	0.8 (0.1)
	20-50 cm	30.6 (16.3)	24.4 (3.1)	1.6 (0.2)	1.8 (0.1)	19.6 (14.2)	18.7 (2.9)	1.7 (0.7)	1.6 (0.3)
3706	O horizon	22.1 (6.8)	31.2 (2.1)	0.6 (0.2)	0.8 (0.2)	12.0 (4.5)	12.8 (3.3)	0.2 (0.1)	0.3 (0.1)
	0-10 cm	26.7 (4.4)	20.7 (5.4)	1.0 (0.3)	0.8 (0.1)	23.0 (12.7)	23.5 (8.4)	1.2 (0.3)	1.0 (0.3)
	10-20 cm	13.6 (8.6)	13.8 (1.0)	0.8 (0.1)	0.8 (0.1)	16.2 (9.5)	15.4 (2.0)	0.9 (0.3)	0.8 (0.1)
	20-50 cm	23.5 (5.3)	29.7 (15.0)	1.6 (0.1)	1.9 (0.4)	17.5 (6.0)	19.4 (9.4)	1.5 (0.7)	1.5 (0.5)
4448	O horizon	25.3 (6.0)	31.1 (1.4)	0.6 (0.1)	0.8 (0.1)	10.7 (4.1)	13.5 (2.0)	0.2 (0.1)	0.4 (0.1)
	0-10 cm	22.7 (3.7)	21.0 (10.1)	0.9 (0.1)	0.8 (0.1)	19.0 (9.4)	31.0 (7.0)	1.0 (0.2)	1.3 (0.3)
	10-20 cm	17.6 (5.7)	18.4 (3.8)	0.8 (0.2)	0.8 (0.1)	13.1 (6.5)	18.2 (6.0)	0.8 (0.2)	0.9 (0.3)
	20-50 cm	27.9 (8.8)	20.1 (4.1)	1.8 (0.2)	1.5 (0.1)	15.2 (7.4)	19.5 (4.8)	1.3 (0.4)	1.5 (0.4)

*Trees per hectare

Table 3.6. Forest floor macronutrient concentrations (±1SD) for 15/16-year-old loblolly pine stands in the culture x density experiment on 3 Lower Coastal Plain sites and 3 Piedmont Upper Coastal Plain sites.

		Operational	Intensive	Operational	Intensive	Operational	Intensive	Operational	Intensive
Location	TPH*	P mg kg.$^{-1}$		K mg kg.$^{-1}$		Ca mg kg.$^{-1}$		Mg mg kg.$^{-1}$	
LCP	1483	383 (76)	349 (21)	360 (80)	466 (338)	3450 (216)	2428 (95)	578 (59)	496 (50)
	2224	381 (21)	372 (26)	468 (148)	315 (53)	3040 (671)	2538 (224)	529 (118)	496 (64)
	2965	356 (18)	353 (37)	362 (264)	292 (86)	2929 (683)	2265 (407)	501 (197)	448 (103)
	3706	370 (38)	341 (27)	343 (120)	296 (167)	2655 (440)	2375 (376)	500 (175)	444 (117)
	4448	360 (4)	325 (48)	289 (50)	232 (72)	3110 (185)	2441 (484)	480 (123)	390 (62)
PUCP	1483	549 (122)	544 (109)	677 (325)	637 (135)	2906 (954)	2038 (614)	707 (110)	538 (158)
	2224	486 (58)	515 (71)	622 (176)	661 (264)	2273 (493)	2093 (558)	584 (32)	521 (60)
	2965	604 (209)	583 (102)	699 (185)	619 (184)	2111 (91)	2063 (370)	569 (185)	551 (154)
	3706	653 (81)	511 (51)	770 (161)	642 (166)	2741 (664)	2060 (260)	619 (90)	567 (27)
	4448	491 (54)	532 (103)	698 (276)	671 (274)	2066 (592)	2077 (675)	550 (70)	616 (72)

*Trees per hectare

Table 3.7. P-values for culture and density main effects and associated interactions on forest soil (0-10 cm) carbon and nitrogen content and concentration, and macronutrient concentrations on 3 sites in the Lower Coastal Plain and 3 sites in the Piedmont Upper Coastal Plain.*

		C	N	C%	N %	P	K	Ca	Mg
LCP	Culture	0.5219	0.8802	0.4487	0.7309	0.5727	**0.0226**	0.8363	0.0665
	Density	0.9878	0.8597	0.9729	0.8598	0.8776	0.5213	0.0876	**0.0260**
	Culture*Density	0.7871	0.6835	0.6006	0.4648	0.5554	0.1781	0.6669	0.2471
PUCP	Culture	0.4141	0.5787	0.4514	0.6986	**0.0168**	0.2048	0.4596	**0.0480**
	Density	0.9706	0.9484	0.9992	0.9488	0.4845	0.9449	0.2492	0.1341
	Culture*Density	0.5249	0.5134	0.3469	0.3047	0.3388	0.0630	0.4919	0.3240
LCP+PUCP	Culture	0.7172	0.6925	0.8953	0.9643	**0.0181**	**0.0341**	0.4021	**0.0358**
	Density	0.9795	0.8254	0.9702	0.7248	0.4800	0.8359	0.0547	**0.0279**
	Culture*Density	0.2502	0.1666	0.0872	**0.0499**	0.4535	0.0617	0.9224	0.6670
	Location	0.8938	0.3951	0.7938	0.3871	0.1778	**0.0459**	0.1793	0.9884
	Culture*Location	0.2699	0.5634	0.2608	0.5832	**0.0438**	0.6653	0.4725	0.6259
	Density*Location	0.9647	0.8973	0.9773	0.9707	0.7269	0.9798	0.9404	0.8178

*Values in bold indicate significant differences at α=0.05 level.

Table 3.8. P-values for culture and density main effects and associated interactions on forest soil (10-20 cm) carbon and nitrogen content and concentration, and macronutrient concentrations on 3 sites in the Lower Coastal Plain and 3 sites in the Piedmont Upper Coastal Plain.*

		C	N	C%	N %	P	K	Ca	Mg
LCP	Culture	0.2450	0.2456	0.1368	0.0856	0.1679	**0.0076**	0.3888	0.1013
	Density	0.3587	0.6141	0.4042	0.5822	0.5308	0.6382	0.4675	0.9424
	Culture*Density	0.1542	0.0573	0.2137	0.0797	0.4571	0.4091	0.3894	0.7471
PUCP	Culture	0.8256	0.7839	0.8588	0.6879	**0.0249**	0.2263	0.4775	**0.0377**
	Density	0.0830	0.1084	0.0362	0.0759	0.5445	0.6559	0.3731	0.5003
	Culture*Density	0.5388	0.4029	0.2831	0.3755	0.8420	0.1620	0.9300	0.9590
LCP+PUCP	Culture	0.3394	0.9411	0.3343	0.9992	**0.0423**	0.0525	0.5825	0.0550
	Density	0.1618	0.3109	0.1908	0.3965	0.7056	0.5788	0.1164	0.5742
	Culture*Density	0.7014	0.5239	0.5950	0.7341	0.5018	0.4780	0.8260	0.6557
	Location	0.8654	0.3985	0.4220	0.8558	0.3081	0.0710	0.1651	0.5231
	Culture*Location	0.5448	0.5298	0.4593	0.4138	0.2755	0.5156	0.2665	0.9175
	Density*Location	0.4473	0.2827	0.3596	0.2104	0.3803	0.9005	0.2147	0.6936

*Values in bold indicate significant differences at α=0.05 level.

Table 3.9. P-values for culture and density main effects and associated interactions on forest soil (20-50 cm) carbon and nitrogen content and concentration, and macronutrient concentrations on 3 sites in the Lower Coastal Plain and 3 sites in the Piedmont Upper Coastal Plain.*

		C	N	C%	N %	P	K	Ca	Mg
LCP	Culture	0.0730	0.7900	0.0729	0.7922	0.2796	0.0818	0.7448	**0.0079**
	Density	0.8144	0.4184	0.8145	0.4223	0.2930	0.5317	0.3586	0.2946
	Culture*Density	0.8882	0.6911	0.8882	0.6949	0.2624	0.9582	0.9628	0.7600
PUCP	Culture	0.4649	0.5154	0.4471	0.5005	0.3486	0.2542	0.2262	0.0759
	Density	0.1913	0.0722	0.1687	0.0666	0.5756	0.1823	0.1748	0.7249
	Culture*Density	0.5202	0.2721	0.5303	0.3177	0.6668	0.0738	0.3632	0.6155
LCP+PUCP	Culture	0.8079	0.7513	0.8090	0.7634	0.2371	0.0807	0.3066	**0.0205**
	Density	0.7856	0.8139	0.7429	0.7885	0.2454	0.0829	**0.0088**	0.4817
	Culture*Density	0.7864	0.5973	0.7955	0.6440	0.2020	0.0508	0.6399	0.2736
	Location	0.4137	0.8399	0.4926	0.8886	0.1449	0.0699	0.0536	0.1716
	Culture*Location	0.3717	0.5392	0.3840	0.5567	0.2108	0.4912	0.1961	**0.0398**
	Density*Location	0.4954	0.1010	0.4681	0.0956	0.2438	0.4097	0.3483	0.5179

*Values in bold indicate significant differences at α=0.05 level.

Table 3.10. Soil macronutrient concentrations (±1SD) in loblolly pine plantations for carbon x density experiment at 3 locations on Lower Coastal Plain. Samples were collected in 2013/2014 when stands were 16 years old.

		LCP							
		Operational	Intensive	Operational	Intensive	Operational	Intensive	Operational	Intensive
TPH*	Depth (cm)	P mg kg^{-1}		K cmolc kg^{-1}		Ca cmolc kg^{-1}		Mg cmolc kg^{-1}	
1483	0-10	5.66 (2.51)	7.44 (4.72)	0.06 (0.01)	0.03 (0.01)	0.27 (0.18)	0.37 (0.45)	0.20 (0.17)	0.10 (0.09)
	10-20	3.95 (1.60)	9.05 (8.06)	0.05 (0.02)	0.02 (0.00)	0.10 (0.04)	0.13 (0.09)	0.07 (0.07)	0.03 (0.02)
	20-50	1.30 (0.50)	10.13 (8.09)	0.04 (0.01)	0.01 (0.00)	0.06 (0.01)	0.09 (0.01)	0.03 (0.02)	0.02 (0.01)
2224	0-10	4.72 (0.62)	8.31 (7.31)	0.05 (0.01)	0.04 (0.00)	0.19 (0.11)	0.16 (0.09)	0.14 (0.12)	0.12 (0.09)
	10-20	2.91 (0.67)	12.26 (8.45)	0.04 (0.00)	0.03 (0.02)	0.09 (0.03)	0.19 (0.13)	0.05 (0.04)	0.05 (0.03)
	20-50	1.64 (1.08)	4.06 (3.13)	0.03 (0.00)	0.01 (0.00)	0.03 (0.02)	0.06 (0.01)	0.01 (0.00)	0.01 (0.00)
2965	0-10	6.05 (2.78)	6.43 (4.54)	0.06 (0.03)	0.03 (0.01)	0.15 (0.16)	0.11 (0.05)	0.09 (0.06)	0.06 (0.03)
	10-20	3.36 (0.43)	7.16 (7.97)	0.04 (0.00)	0.02 (0.01)	0.07 (0.05)	0.08 (0.03)	0.08 (0.10)	0.03 (0.01)
	20-50	2.78 (1.50)	10.84 (13.41)	0.03 (0.01)	0.01 (0.00)	0.07 (0.02)	0.06 (0.02)	0.01 (0.01)	0.01 (0.01)
3706	0-10	6.81 (3.27)	8.73 (5.68)	0.06 (0.01)	0.03 (0.01)	0.19 (0.12)	0.13 (0.07)	0.13 (0.07)	0.07 (0.05)
	10-20	4.22 (1.78)	14.67 (7.80)	0.04 (0.00)	0.01 (0.00)	0.07 (0.03)	0.15 (0.14)	0.05 (0.03)	0.03 (0.02)
	20-50	1.70 (0.53)	2.31 (1.28)	0.05 (0.03)	0.02 (0.01)	0.16 (0.18)	0.15 (0.10)	0.02 (0.00)	0.01 (0.01)
4448	0-10	7.28 (4.48)	4.04 (1.54)	0.05 (0.00)	0.03 (0.01)	0.16 (0.08)	0.13 (0.10)	0.08 (0.05)	0.07 (0.05)
	10-20	6.43 (5.64)	9.26 (8.99)	0.05 (0.01)	0.02 (0.01)	0.11 (0.05)	0.10 (0.05)	0.05 (0.03)	0.03 (0.01)
	20-50	2.73 (1.10)	1.97 (0.54)	0.03 (0.00)	0.01 (0.00)	0.06 (0.05)	0.06 (0.01)	0.02 (0.01)	0.01 (0.00)

*Trees per hectare

Table 3.11. Soil macronutrient concentrations (mean±1SD)) in loblolly pine plantations for culture x density experiment at 3 locations on Piedmont Upper Coastal Plain. Samples were collected in 2013/2014 when stands were 15 years old.

		PUCP							
		Operational	Intensive	Operational	Intensive	Operational	Intensive	Operational	Intensive
TPH*	Depth (cm)	P mg kg^{-1}		K cmolc kg^{-1}		Ca cmolc kg^{-1}		Mg cmolc kg^{-1}	
1483	0-10	10.55 (7.64)	18.41 (6.47)	0.11 (0.04)	0.09 (0.03)	0.49 (0.33)	0.28 (0.25)	0.14 (0.05)	0.12 (0.10)
	10-20	4.47 (1.45)	6.85 (5.75)	0.10 (0.03)	0.07 (0.03)	0.52 (0.58)	0.27 (0.37)	0.09 (0.03)	0.07 (0.08)
	20-50	0.80 (0.63)	0.73 (0.22)	0.10 (0.06)	0.05 (0.01)	0.30 (0.10)	0.15 (0.17)	0.12 (0.08)	0.06 (0.06)
2224	0-10	5.89 (4.41)	14.91 (3.90)	0.11 (0.05)	0.08 (0.03)	0.33 (0.06)	0.28 (0.18)	0.15 (0.05)	0.08 (0.04)
	10-20	1.56 (1.31)	5.32 (1.86)	0.11 (0.07)	0.07 (0.03)	0.19 (0.07)	0.16 (0.09)	0.06 (0.01)	0.05 (0.03)
	20-50	2.55 (3.59)	1.15 (0.92)	0.10 (0.07)	0.06 (0.03)	0.18 (0.03)	0.12 (0.12)	0.09 (0.06)	0.06 (0.07)
2965	0-10	10.49 (9.41)	12.72 (7.61)	0.12 (0.06)	0.07 (0.02)	0.31 (0.08)	0.22 (0.12)	0.10 (0.02)	0.09 (0.04)
	10-20	4.62 (4.65)	5.12 (0.99)	0.10 (0.06)	0.05 (0.00)	0.17 (0.03)	0.12 (0.02)	0.06 (0.02)	0.03 (0.02)
	20-50	0.77 (0.18)	1.43 (0.85)	0.11 (0.07)	0.06 (0.03)	0.20 (0.03)	0.16 (0.07)	0.12 (0.09)	0.09 (0.07)
3706	0-10	11.99 (4.13)	14.42 (7.73)	0.12 (0.04)	0.07 (0.03)	0.41 (0.19)	0.22 (0.08)	0.14 (0.04)	0.08 (0.02)
	10-20	2.90 (1.47)	5.90 (0.77)	0.10 (0.06)	0.06 (0.03)	0.22 (0.06)	0.11 (0.05)	0.07 (0.03)	0.05 (0.01)
	20-50	0.86 (0.43)	1.04 (0.89)	0.13 (0.07)	0.05 (0.01)	0.29 (0.06)	0.14 (0.12)	0.10 (0.06)	0.08 (0.09)
4448	0-10	7.07 (4.25)	16.99 (6.92)	0.10 (0.04)	0.09 (0.02)	0.24 (0.04)	0.23 (0.11)	0.10 (0.04)	0.08 (0.03)
	10-20	2.61 (1.59)	6.64 (2.93)	0.09 (0.05)	0.07 (0.03)	0.17 (0.06)	0.10 (0.04)	0.06 (0.03)	0.03 (0.01)
	20-50	0.94 (1.09)	0.84 (0.67)	0.11 (0.07)	0.08 (0.03)	0.19 (0.05)	0.11 (0.06)	0.12 (0.12)	0.05 (0.04)

*Trees per hectare

CHAPTER 4:

CONCLUSIONS

Motivating this work is the recognition that high planting densities in loblolly pine plantations increase standing biomass early in stand rotation and thus can provide an opportunity for increasing biomass energy feedstock production through early stand thinnings or final harvests. Improved understanding of carbon cycling in forest ecosystems both above and belowground and impacts on total stand carbon is necessary, however, to evaluate the potential of this silvicultural approach to offset fossil fuel emissions of CO_2 to the atmosphere. The specific objective of this research was to determine if initial planting density and cultural treatments in intensively managed loblolly pine (*Pinus taeda*) plantations affect belowground taproot, forest floor, and soil carbon and nutrient contents and concentrations

Effects of planting density and silvicultural treatments on taproot biomass, carbon, and nutrients were investigated in chapter 2 of this thesis. At the tree level (n=34), increased initial planting density negatively affected taproot C within the 5-50 mm and total taproot mass in the PUCP. At the stand level belowground C was not affected by increased planting density. The results of this study are consistent with earlier research suggesting taproot growth was greater on sandier sites as opposed to more clay rich sites. Average taproot biomass in the Lower Coastal Plain (LCP) of 16.5 Mg ha^{-1} or 1.1 Mg ha^{-1} yr^{-1} was greater than taproot biomass in the Piedmont and Upper Coastal Plain (PUCP) of 13.5 Mg ha^{-1} or 0.9 Mg ha^{-1} yr^{-1}. There is also some evidence that belowground to aboveground ratio decreased with increasing aboveground biomass in the PUCP relative to the LCP. This could be a product of increasing compaction or resistance

to penetration with depth on the more clay rich sites in the PUCP. Decreased belowground to aboveground biomass could suggest that soil type (defined here by location) will have an increasing impact on the carbon sequestration potential of taproots with time. Furthermore, the decomposition of taproot carbon retained in the soil after harvest, at least in the LCP, appears to be rapid.

Effects of planting density and silvicultural treatments on soil (i.e., mineral and O horizons) carbon and nutrients was investigated in chapter 3. Hypothesis *i* that focused specifically on the forest floor, was partially supported since forest floor mass and carbon did increase with increased cultural management in the LCP, although this was not true in the PUCP. Planting density did not have an effect on forest floor mass or carbon. Nitrogen content was found to be significantly higher in forest floor but not in mineral soil agreeing with previous literature that suggested the forest floor is a nitrogen sink. Hypothesis *ii* was accepted as the soil carbon pool was not influenced by culture or planting density to a depth of 50 cm at either location. The results of this study suggest that the use of high planting densities within intensively managed forest stands may not have an effect on soil C (i.e., mineral and O horizon) pools despite growing more biomass with increasing density. As for nutrients, aside from a decrease in Mg within the 0-10 cm depth, nutrient concentrations in mineral soil were not impacted by planting density or increased silviculture.

The results of this study suggest that the use of high planting densities within intensively managed forest stands may not have an effect on soil (i.e., mineral and O horizon) or stand level taproot C pools despite growing more biomass with increasing density. This is positive in that C and nutrient pools are not declining and may be able to sustain multiple rotations. This is unfortunate, in that belowground C (forest floor, mineral soil, and taproots) do not appear as if

they will serve as a large C sink. Forest managers need to be driven by their principle objectives (e.g., maximizing growth or maximizing carbon storage) and recognize that varied management practices may have different effects on C and nutrients (e.g., those effects of harvesting cited above). As such, harvesting at a younger age (i.e., before age 12) may enable forest managers to better meet the increasing demand for wood bioenergy but will require continued monitoring.