ABSTRACT

TAYLOR, ASHLEY ERIN. Quantifying the Coarse Root Biomass of Intensively Managed Loblolly Pine Plantations. (Under the direction of H. Lee Allen.)

Nearly all of the C accumulation during a typical forest rotation is in plant biomass and the forest floor. Most biomass studies focus on aboveground C accumulation, and there is little information about biomass-C accumulation belowground. In older, loblolly pine forests, the majority of root biomass is in coarse roots, and coarse roots persist longer after harvest than aboveground biomass and fine roots. The main objective of this research was to assess the belowground carbon accumulation in coarse roots of a managed loblolly pine (*Pinus taeda* L.) plantation, which was subjected to different levels of management intensities. Additional objectives included determining the depth of excavation required to sample a majority of the coarse roots, quantifying coarse roots that were not associated with the taproots of either hardwoods or planted pines, developing an inter-specific hardwood regression relating diameter at breast height to coarse root biomass, and estimating total coarse root biomass per hectare. Estimates of total belowground biomass ranged from 56.4 to 62.4 Mt $ha^{-1}$and were not affected by treatment. Pine and hardwood taproot biomass was affected by treatment, with vegetation control and disking significantly increasing pine taproot biomass and decreasing hardwood taproot biomass. Pine coarse roots not associated with the taproot were unaffected by treatment, but hardwood coarse roots not associated with the taproot were significantly reduced with vegetation control. Necromass was substantially lower than between-tree biomass, indicating that the decomposition of coarse root biomass from the previous stand is fairly rapid for coarse roots not associated with the taproot. Total

aboveground biomass was significantly affected by vegetation control, with the lowest production on least intensively managed plots (180.2 Mt ha^{-1}) and the highest production on plots receiving intensively managed plots (247.3 Mt ha^{-1}). Coarse root biomass ranged from 19 to 24% of total biomass. Silvicultural practices that increased aboveground pine productivity by reducing hardwoods did not increase total coarse root biomass C. Additionally, there is no evidence that coarse roots provide long-term C storage because they decompose rather quickly after harvest and during subsequent rotations.

QUANTIFYING THE COARSE ROOT BIOMASS OF INTENSIVELY MANAGED LOBLOLLY PINE PLANTATIONS

By

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APPROVED BY:

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Chair of Advisory Committee

Dedication

This thesis is dedicated to my parents, who have given me so many opportunities to succeed and thrive. Without their love and support, I never would have made it this far. Thanks Mom and Dad, I love you.

Biography

Ashley Taylor was born and raised in Charlotte, North Carolina. After completing high school in 1999, she briefly attended the University of North Carolina at Chapel Hill, before coming to her senses and transferring to North Carolina State University. Ashley always thought that her Dad had a cool job, so she decided to follow in her father's footsteps and become a forester herself.

After completing a year and a half of undergraduate forestry classes, Ashley accepted an internship with Forestal Mininco in Concepción, Chile. While in Chile, she helped install the research of a graduate student that was studying in the United States, and greatly improved her Spanish skills. After returning to the US in the fall of 2002, Ashley finished her final courses and graduated Magna Cum Laude in May 2003.

After graduation, Ashley began working with Lee Allen and the Forest Nutrition Cooperative towards her Master of Science in Forestry. She foolishly chose to pursue a project focused on belowground biomass, and spent much of her time in graduate school digging up roots.

Ashley recently became engaged to another NCSU forestry alum, Chris Miller. They are getting married on June 4, 2005 and will live in Charlotte, NC. Ashley has recently accepted a position with James W. Sewall Company as a Timberland Appraiser.

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Background

Atmospheric concentrations of CO_2 are expected to continue increasing due to the combustion of fossil fuels, outpacing the ability of the biosphere to sequester excess CO_2 in soils and vegetation (Schlesinger 1997). Although soil is the largest terrestrial C sink (Van Lear et al. 1995), most scientists believe that there is little potential to increase soil C sequestration through management (Schlesinger 1990; Richter et al. 1993; Richter et al. 1999; Laiho et al. 2003; Leggett and Kelting 2003). Nearly all (>98%) of C accumulation during a typical forest rotation is in plant biomass and the forest floor (Richter et al. 1993).

Model simulations of C storage over many land uses indicate that forests store the most C at the landscape level (Harmon and Marks 2002), and within forests, trees sequester 80% of C (Richter et al. 1999). Intensive forest management can increase net ecosystem productivity and C sequestration primarily through increases in net primary productivity (Johnsen et al. 2001). Currently the southeastern United States supplies over half of the nation's timber supply and is the largest forest products producer in the World (Prestemon and Abt 2002). Today one quarter of the 30 million acres in pine plantations are intensively managed and that land area is expected to increase to 15 million acres in the next 20 years (Conner and Hartsell 2002; Siry 2002).

Although aboveground biomass and C content have been widely studied (Giese et al. 2003; Rubilar 2003), belowground biomass is not frequently quantified due to inherent sampling difficulties. As a result, most analyses rely on allometric equations derived from limited data sets relating belowground biomass to aboveground measurements (Grier and Edmonds 1981; Keyes and Grier 1981; Grigal and Ohmann 1992; Laiho and Finer 1996; Law et al. 2001). Those studies that do sample belowground biomass directly often do not include many observations due to time and labor-intensive sampling methods (Kochenderfer 1973; Santantonio et al. 1977; Mou et al. 1995; Hart et al. 2003). Some studies ignore coarse root biomass altogether because of the difficulty of sampling. Because of the high spatial variability of coarse roots, the most accurate method for deriving estimates is through excavations (Shelton et al. 1984; Van Lear and Kapeluck 1995; Retzlaff et al. 2001).

In southern pine forests, most of the root biomass is in coarse roots (Kapeluck and Van Lear 1995; Laiho and Finer 1996; Johnsen et al. 2001). Coarse roots have a longer in situ residence time than either aboveground biomass or fine roots. Additionally, coarse roots persist longer after harvest (Johnsen et al. 2001; Ludovici et al. 2002), providing a longer-term C storage mechanism than fine roots, which tend to decompose more quickly (Black et al. 1998; King et al. 2002).

Coarse root production significantly increases with increasing resource availability (Albaugh et al. 1998), and pine coarse root and stump biomass has been found to increase with the age of the stand, comprising 90% of the total living root biomass (Laiho and Finer 1996; Ehman et al. 2002). The ability to quantify coarse root C is important due to the potential to increase carbon sequestration in coarse root biomass with more intensive management.

In addition to a general lack of belowground biomass data for pines, there is an even more striking lack of data to estimate the contributions of hardwood coarse root biomass to the belowground C pool. In order to accurately account for carbon accumulation in managed pine forests, hardwood coarse root biomass estimates are also needed (Brown 2002).

The main objective of this research was to assess the belowground carbon accumulation in the coarse root biomass of a managed loblolly pine (*Pinus taeda* L.) plantation, subjected to a range of management intensities that have resulted in very different levels of productivity and community structure. Additional objectives included determining the depth of excavation required to sample a majority of the coarse roots, quantifying coarse roots that were not associated with the taproots of either hardwoods or planted pines, developing an inter-specific hardwood regression relating diameter at breast height to coarse root biomass, and estimating total coarse root biomass per hectare.

Materials and Methods:

Site and Study Description

This work was conducted at the Henderson Site Productivity Study (36°25’N, 78°30’W), on International Paper land near Henderson, North Carolina. The study is located on gently sloping (2 to 10 %) piedmont terrain. The soils are predominately Cecil (fine, kaolinitic, thermic Typic Kanhapludult). Average temperatures are 2°C in January and 26°C in July, and average annual rainfall is 114 cm. The previous stand had an average total basal area of 33.4 m^2 ha^{-1}. Average pine basal area from the previous stand was 23.7 m^2 ha^{-1} and average hardwood basal area was 9.7 m^2 ha^{-1} (Blevins, D., personal communication 2005). Average aboveground biomass for the previous rotation was 123 tons ha^{-1}.

The current stand was established in 1982 and was the second rotation since agricultural abandonment. The study was a 2 x 2 x 2 factorial experiment that was imposed as a split plot. Two levels of harvest (stem wood only vs. whole tree removals) and two levels of site preparation (chop and burn vs. shear, pile and disk) made up the main plots. These main plots were then split into two levels of vegetation control (none vs. complete control for 5 years). The stem-only harvest removed all pines with a minimum diameter limit of 10 cm, and left tops above 3 cm on the site. The whole-tree harvest removed all pines with a minimum diameter limit of 7 cm, including the tops. The chop and burn site preparation treatment (CH) was conducted with a drum chopper, and a site preparation burn was conducted in November of 1981. The shear, pile and disk treatment (DI) sheared remaining trees at ground level with a horizontally mounted blade and piled the slash into windrows. The cleared ground was then tilled with large disks. In March of 1982, loblolly pine seedlings were planted on a spacing of 2 x 3 m.

Each plot had an area of 450 m^2, with a buffer of 6 m between plots. In April of 1982, half of these plots underwent vegetation control (VC), with a slow release treatment of Velpar (hexazinone), which was followed by Roundup (glyphosate) in September of 1982.

The other half of the treatments had no vegetation control (NO). Each treatment was replicated once in each of the three blocks, for a total of 24 plots

The stands resulting from the treatment applications showed significant differences in pine and hardwood productivity and stand composition (Pye and Vitousek 1985; Tew et al. 1986; Allen et al. 1995; Piatek and Allen 1999; Jeffries 2002). Pine productivity was significantly greater on more intensive treatments, those receiving vegetation control and/or disking (Table 1). Throughout the study, there have been no significant differences as a result of harvest method. Because of this, harvest method was not included in this report.

Determination of Between- Tree Root Biomass

In order to determine an appropriate depth for sampling coarse roots, four, 1.0 m^2 pits were excavated to a depth of 110 cm in May 2004. The pits were excavated in the most extreme treatments, two in the DIVC treatment and two in the CHNO treatment. The pits were located within the treated buffers but outside tree measurement plots. The pits were placed in the center of 4 pines, at least 0.5 m from surrounding planted pines, to capture coarse roots outside of this taproot zone of either pine or hardwood (Figure 1). Coarse roots (>2 millimeters) were removed in incremental depths of 0-15, 15-30, 30-50, 50-70, 70-90 and 90-110 cm and transported to the laboratory. Roots were stored in a refrigerator at 4°C for a maximum of three weeks to prevent decomposition until they could be processed in the lab.

In the laboratory, any remaining fine root segments (<2 mm) were removed at the point where the root tapered to less than 2 mm. All roots ≥ 2 mm were rinsed in tap water to remove mineral soil. The cleaned roots were separated into pine, hardwood, or dead roots.

The separation into pine or hardwood was primarily based on appearance; color, bark, and texture. Live pine roots were intact, flexible and reddish. The separation of dead roots was based on appearance and texture. Dead roots were brittle, discolored and/or irregularly shaped, often consisting only of an ectomycorrhizal sheath. Dead roots represented varying stages of decomposition. After roots were washed and separated, they were dried to a constant weight at 70° C and weighed.

The deep excavations revealed that root abundance declined with increasing depth (Figure 2), with 91.9% (+/- 0.08%) of the coarse root biomass occurring in the upper 50 cm. To reduce time and labor expenses, subsequent excavations were confined to the upper 50 cm of soil. Twenty 1.0 m^2 pits were excavated by hand to a depth of 50 cm in June 2004. These pits were placed in all plots not sampled during the initial round of sampling. Coarse roots (≥2 mm) were removed in incremental depths of 0-15, 15-30 and 30-50 cm and processed as outlined above. The amount of mineral soil remaining on washed roots was determined using the loss on ignition method for 20 randomly selected samples. These samples averaged 93.8 % (+/- 1 %) organic matter. This mass correction factor was applied to all reported dry weights.

Determination of Hardwood Coarse Root Biomass

In December 2004, 16 pits were excavated centered on hardwoods representing a range of diameters and species found on the site. Species sampled included white oak (*Quercus alba*), red oak (*Quercus rubra, Quercus coccinea*), red maple (*Acer rubrum*), and sweetgum (*Liquidambar styraciflua*). Three of the red maples were not individual stems, but stump sprouts with several stems. Prior to felling, the diameter at breast height (1.4 m) was measured. The trees were felled, with the cut being made about 30 cm above the ground. This high stump was useful in moving the root ball around prior to excavation. After the root

ball was excavated, the stump was trimmed to ground level, with the litter layer representing the boundary between stump and bole, as in (Santantonio et al. 1977). The soil in the surrounding square meter centered on the stump was then excavated. Coarse roots ($\geq$ 2 mm) were separated from the soil over a large sieving table and transported back to the laboratory. If a distinct taproot was evident that surpassed 50 cm, the deep root was excavated but the soil was no longer sieved. On several of the larger oak species, roots extending to 60 cm were encountered and sampled. On the two sweetgums, taproots were encountered and excavated to 75 cm. It was not possible to extract the entire taproot, so both of these were cut at 75 cm. On the larger oaks, it was often necessary to dig a pit larger than one square meter to excavate the root ball. In these cases, only soil within the square meter was sieved, and lateral roots leaving the square meter were cut at the boundary, as these lateral roots were already estimated in the between-tree pits.

No pine roots were collected in the field during hardwood sampling. All hardwood roots occurring inside the square meter centered on the stump were collected, operating on the assumption that the amount of roots entering the pit from other hardwood trees was approximately equal to the amount of roots leaving the pit from the hardwood for which the regression was being constructed. This assumption has been found valid in other excavation studies (Jackson and Chittenden 1981; Resh et al. 2003).

Large root balls and structural roots were transported directly to a drying oven, where they were dried to a constant weight at 70°C. Once the roots were dry, mineral soil was removed from the roots by using a stiff brush. The clean, dry roots were then weighed and corrected for mass of mineral soil remaining, as described for the between-tree pits.

The dry weights of hardwood coarse roots were used to create a site-specific regression relating coarse root biomass to diameter at breast height for hardwoods. Diameter at breast height and basal area have been used as convenient predictor variables for total belowground biomass (Albaugh et al. 1998; Litton et al. 2003; Resh et al. 2003), and coarse root biomass has been found to correlate significantly with stem diameter in previous studies (Haynes and Gower 1995). For biomass conversions to C, coarse root biomass was assumed to be 50% carbon, as in other carbon studies (Richter et al. 1993; Vande Walle et al. 2001; Laiho et al. 2003; Resh et al. 2003).

Estimate of Total Coarse Root Biomass

A complete inventory of hardwood species and diameters was conducted in June 2004. Pine aboveground inventory of diameter and total height was performed in December 2003. In order to estimate total coarse root biomass per hectare, we scaled estimates of the coarse roots (including taproot) centered on planted pine stumps, coarse roots (including taproot) centered on hardwoods using pine and hardwood inventory, and between-tree coarse roots.

To estimate the biomass for the taproot of the planted pines, the following regressions were used. The regressions separately estimate the taproot and coarse roots contained in a square meter centered on the stump in two equations. The C term represents a correction factor needed because of the log transformation (Baskerville 1972).

$$\textbf{Weight (grams)} = C*e^{((\ln(d2h)*A)+B)}$$

Taproot	A= 0.95359411	Coarse root	A=0.791957123
	B=9.222988681		B=10.34463055
	$C=e^{(0.06059890/2)}$		$C=e^{(0.0185505112/2)}$

The above regression was developed from loblolly pine trees growing in clay soil, with a range in diameters of 8.6 to 17.0 cm (Albaugh, 2005, personal communication). The range of diameters to which the regression was applied is 6.6 to 31.5 cm.

Between-tree pine coarse root biomass per pit in each plot was applied to all m^2 on that plot not occupied by a planted pine. Between-tree hardwood coarse root biomass per pit in each plot was applied to all m^2 on a plot not occupied by a hardwood. The number of m^2 not occupied by a pine or hardwood tree was determined by totaling the number of trees (pines or hardwoods) on a plot, assuming each stem occupied one m^2 and then finding by subtraction the total number of m^2 not containing a pine or hardwood stump. Biomass estimate per plot (450 m^2) was scaled up to a kg ha^{-1} basis.

Estimate of Aboveground Biomass

Aboveground pine biomass was estimated using a site-specific regression relating aboveground biomass to diameter at breast height (Tew et al. 1986). Aboveground hardwood biomass was estimated using a multiple species hardwood regression compiled from many species on many sites relating aboveground biomass to diameter at breast height (Schroeder et al. 1997). All estimates of aboveground biomass include woody components as well as foliage. Because of the cost and labor-intensive methods involved in sampling belowground biomass, several regressions were developed to determine which, among the many aboveground measures, describes more of the variation in coarse root biomass.

Statistical Analysis

Above- and belowground biomass attributes were analyzed as a 2 x 2 x 2 split-plot design using the PROC GLM procedure (SAS Institute, Inc. 1985). One of the DIVC plots was not included in the analysis because of complications arising from a wildfire earlier in the rotation. Because of the unbalanced design, all means were reported as least square means (SAS). Standard errors were constructed as prescribed by (Steel and Torrie 1980) to allow for testing of the four treatment means . Regressions were also analyzed using the PROC GLM feature of SAS. An α-level of 0.05 was used to determine statistical significance.

Results

In order to correct for heteroscedascity, the data values for weight and diameter were log-transformed, and a correction factor (term C in following equation) was included to account for the error associated with re-transforming to get biomass in kg (Baskerville 1972). The resulting prediction equation that was applied to the hardwood inventory was of the form:

$$\textbf{Taproot weight (kg)} = C * e^{((\ln(d) * A) - B)}$$

Where **d**=diameter at breast height (1.4 m) in cm

A= 1.921950652 (0.212)

B=2.100356610 (0.564)

$C=e^{(0.09344710/2)}$

$R^2=0.88$

Equation 1. Regression coefficients and standard errors (in parenthesis) for the hardwood taproot biomass prediction equation.

The coarse root biomass of the three maple stump sprouts were substantially less for a given tree size than for other species so they were omitted from the regression (Figure 3). Because red maples accounted for less than 5% of total hardwood basal area, this omission resulted in only a slight overestimation of belowground hardwood biomass.

Coarse root biomass

Above- and belowground biomass estimates generally differed for the four combinations of site preparation and vegetation control as indicated by the significant site preparation, vegetation control, and site preparation x vegetation control interaction effects for biomass attributes (Tables 2 and 3). Block differences were also evident for several variables. Pine taproot biomass was least on CHNO plots, and significantly greater but not different on DINO, CHVC, and DIVC plots, reflecting differences in measured aboveground pine productivity on these plots. In contrast, treatment effects on hardwood taproot biomass were opposite those of pine taproot biomass, with CHNO>DINO>CHVC=DIVC, mirroring the pattern of aboveground biomass (Table 3). The highest hardwood taproot biomass was in the CHNO treatment, with 21.4 Mt ha^{-1}, followed by the DINO treatment with 7.6 Mt ha^{-1} of hardwood taproot biomass. Not surprisingly, the treatments receiving vegetation control had significantly lower hardwood taproot biomass. The CHVC treatment had 0.3 Mt ha^{-1} and the DIVC treatment had no hardwood taproot biomass.

Between-tree pine coarse root biomass was not significantly increased by any treatments (Tables 2 and 3). However, between-tree hardwood coarse root biomass exhibited significant site preparation, vegetation control, and site preparation by vegetation control interaction effects. Increasing the intensity of vegetation control, whether by disking or direct vegetation control, decreased the between-tree hardwood coarse root biomass.

Estimates of root necromass were very small and were significantly reduced by disking (Table 3). The highest value for necromass was found in the CHVC treatment, which had 0.08 Mt ha^{-1}. Estimates of total belowground biomass ranged from 56.4 to 62.4 Mt ha^{-1}and were not affected by treatment. In contrast, total aboveground biomass was significantly affected by vegetation control, with the lowest production on CHNO plots (180.2 Mt ha^{-1}) and the highest production on plots receiving complete vegetation control, DIVC (247.3 Mt ha^{-1}). As a result, the proportion of total biomass that was belowground was significantly less on plots receiving vegetation control. Total above- and belowground production was almost 30% higher on plots with complete vegetation control (DIVC) than on the CHNO plots.

Various regressions were developed to determine which, among several aboveground components, describes more of the variation in between tree pine coarse root biomass. All regressions take the form:

$$\text{Dependent variable} = \beta_0 + \beta_1 * (\text{independent variable})$$

Total basal area predicted between-tree pine coarse root biomass the best, explaining 43% of the variation, with the slope regression coefficient significant at the 95% confidence level (Table 4). Total aboveground biomass explained 27% of the variation in between-tree pine coarse root biomass. The positive slopes of these regressions indicate that between-tree pine coarse root biomass increased as aboveground production increased.

The same regression form was used for predicting between tree hardwood coarse root biomass (Table 5). Hardwood basal area and the percentage of basal area in hardwoods each explained 17% of the variation in between-tree hardwood coarse roots. Aboveground pine biomass and aboveground hardwood biomass predicted 15 and 13%, respectively, of the variation in between-tree hardwood coarse root biomass. Using aboveground pine biomass and total aboveground as the independent variables, the negative slopes implied that between-tree hardwood coarse roots decreased as aboveground pine and total biomass increased. Conversely, the positive slope for hardwood basal area and the percentage of basal area in hardwoods suggested that as more basal area was composed of hardwoods, the amount of between-tree hardwood coarse roots increased.

Discussion

The observed pattern of decreasing root density with increasing depth has been well documented for pine (Coile 1936; Harris et al. 1977; Kinerson et al. 1977; Sainju and Good 1993; Kapeluck and Van Lear 1995; Van Lear and Kapeluck 1995; Parker and Van Lear 1996; Retzlaff et al. 2001; Resh et al. 2003) and for other species (Symbula and Day 1988; Tufekcioglu et al. 1999). An increase in the clay fraction of soil and the associated higher mechanical resistance may contribute to this decline in root biomass with depth.

During the excavation of hardwood taproots, the assumption was made that the amount of hardwood roots from the target tree leaving the pit was approximately equal to the amount of hardwood roots from other hardwood trees entering the pit. During sampling, large hardwood lateral roots were noted exiting the pit in several of the trees, but rarely was a large lateral root from another hardwood encountered entering the pit. This observation casts doubt on the validity of the assumption. However, this is not likely to affect stand level estimates of total coarse root biomass since large lateral hardwood roots extending beyond the pit were estimated with the between-tree pit.

Stand level estimates of coarse root biomass ranged from 56.4 to 62.4 tons ha^{-1} and are higher than other reported values. Previous studies of loblolly pine have reported a range of belowground biomass estimates from 35.4 to 39 tons ha^{-1}(Pehl et al. 1984; Shelton et al. 1984; Van Lear and Kapeluck 1995). Applying the pine taproot regression from (Pehl et al. 1984) to the inventory data from this study resulted in a 31% lower estimate of pine taproot biomass. Comparing values from the Pehl regression to values obtained from another regression (Albaugh et al. 2005) that estimates taproot biomass based on diameter, the Pehl regression resulted in 25% lower taproot biomass.

It is possible that the pine tap regression used for this study overestimated pine taproot biomass. It was created from a group of destructively sampled pines with a smaller diameter range than the trees to which it was applied. Applying the regression to diameter values outside the range of data from which it was created can cause uncertainty because of the behavior of the regression at higher or lower diameter values. However, the regression used in this study was compared with another pine taproot regression that was developed from fertilized pines growing in a deep sandy soil (labeled ‘Sand’ in Figure 4) that had a similar diameter range to the trees in this study (Albaugh et al. 1998). When comparing these regressions, they appear to follow the same growth trajectory throughout the combined range of diameters (Figure 3). This lends confidence to the regression used in this study that the behavior of the regression does not appreciably change at diameter values outside of the range from which it was developed.

The difference in values for total coarse root biomass between this study and (Van Lear and Kapeluck 1995) might be due to differences in stand and site productivity. Their stand was located on an eroded site that was twice-thinned and had 145 Mt ha^{-1} aboveground pine biomass at 48 years. In contrast, our stand had 247.3 Mt ha^{-1} aboveground pine biomass at 23 years in the most productive plots (DIVC). Our greater aboveground biomass will also lead to greater belowground biomass because aboveground measures were used to estimate belowground biomass.

Another possible explanation for the root biomass difference is that these studies did not include the contributions of hardwood roots to total belowground biomass. (Pehl et al. 1984) acknowledged only a sparse understory of yaupon (*Ilex vomitoria*) and American beautyberry (*Calicarpa americana*), neither of which were expected to contribute appreciably to total coarse root biomass. However, (Van Lear and Kapeluck 1995) encountered yellow-poplar (*Liriodendron tulipifera*) and oak (*Quercus* spp.) in the overstory of their stand, while the understory of their stand was similar in species composition to the present study.

Not surprisingly, the vegetation control treatment affected belowground biomass by increasing belowground pine taproot biomass, and decreasing hardwood taproot biomass. The pine taproot biomass increase was a reflection of increased aboveground pine productivity on these plots because larger trees have larger taproots. Disking, which also reduced hardwoods, increased the pine taproot biomass and decreased hardwood taproot biomass.

The biomass of the pine taproot and the hardwood taproot both showed significant interactions between site preparation and vegetation control. Aboveground hardwood biomass also exhibited significant interaction, but aboveground pine biomass did not. The interaction indicated that vegetation control was more effective at reducing hardwoods than disking. On the treatments receiving vegetation control, the site preparation had no effect on pine productivity or hardwood levels. However, without vegetation control, site preparation significantly increased pine productivity and decreased hardwood competition. The site preparation and vegetation control effects on between tree hardwood coarse root biomass reflected decreased hardwood production with more intensive treatment.

The increase in between-tree pine coarse roots for treatments receiving vegetation control was less than the increase in between-tree hardwood coarse roots for treatments not receiving vegetation control. There have been differences in rooting patterns reported for pines as compared to hardwoods. Hardwoods tend to have a greater percentage of roots in the upper layers of the soil, and immediately surrounding the tree (Brown and Woods 1968), whereas pines tend to have a greater percentage of roots in the taproot and large structural roots. A review of root distributions globally found that 52% of total root biomass was found in the upper 30 cm in temperate coniferous forests versus 65% in temperate deciduous forests (Jackson et al. 1996). Other studies have found a dense mat of surface roots in the top 10 cm of hardwood stands (Kochenderfer 1973).

The majority of total coarse root biomass was found in the square meter centered on a pine stump, which has been found in other studies as well (Kinerson et al. 1977; Van Lear and Kapeluck 1995; Resh et al. 2003). On a slightly older stand on a very similar soil type, the pine taproots were found to account for 55% of total belowground biomass (Van Lear and Kapeluck 1995). Loblolly pines growing in the Duke Forest of North Carolina had 50% of belowground biomass in the stump, with the rest in lateral roots (Kinerson et al. 1977). This rooting pattern has also been shown for other species, with 76% of total coarse root biomass in eucalyptus in the root ball (Resh et al. 2003) and over 75% in the taproots of ponderosa pine (Laclau 2003). The between-tree coarse root biomass encountered was very dependent on the placement of these excavation pits relative to existing trees, pine or hardwood. The between-tree pits were placed in the rectangular space between four planted pines, a placement that would minimize the amount of between-tree coarse roots encountered. In contrast, placing the between-tree pits between two adjacent pine trees, as opposed to between four planted pine trees, would be more likely to capture the coarse roots associated with those two pine trees, since the edge of the pit would be in closer proximity to the pine stems.

The limited data from the deep excavations suggested that a greater percentage of total biomass was found in the upper soil for stands with more hardwoods as compared to stands with fewer hardwoods. Extreme differences in root branching habit have been noted between pine and hardwood, with pine allocating more resources to growing large lateral roots and hardwoods investing more resources in smaller roots, which are typically found in the nutrient-rich upper layers of the soil (Harris et al. 1977). In a hardwood forest in the

Coweeta Basin, North Carolina, only 2.1% of total root biomass was located below 60 cm (McGinty (1976) in (Montague and Day 1980)). Belowground hardwood biomass decreased with increasing depth, with over three-fourths located in the uppermost 30 cm in a swamp in Virginia (Montague and Day 1980).

Root necromass was very small, but was significantly less on the shear, pile and disk plots. On the shear, pile and disk treatments, all stumps were sheared off and piled outside of the plot, and the remaining soil was double disked, breaking up the remaining belowground biomass into smaller pieces with larger surface to volume ratios, which would be expected to decompose at a faster rate. The chop and burn treatment only affected surface woody material, allowing the belowground biomass to remain whole and intact, which would be expected to slow decomposition.

Particularly striking about the dead material was how little of it there was, as compared to live biomass. On the treatment with the highest amount of dead material (CHVC), there was still less than one metric ton ha^{-1}, compared to 58.8 metric tons ha^{-1} of live coarse root material. The total coarse root biomass for the least intensive treatment (CHNO) may be a good estimate of the total coarse root biomass for the previous rotation. Therefore, the small amount of dead material encountered indicated that potentially over 55 Mt ha^{-1} of coarse root biomass from the previous rotation decomposed to the point where it was no longer readily evident.

From a C sequestration viewpoint, it would be interesting to know where the C stored in this biomass has gone. Previous work on soil C accretion indicates that there is little potential to appreciably increase soil C through different management practices (Schlesinger

1990; Richter et al. 1993; Schlesinger 1993; Richter et al. 1999; Leggett and Kelting 2003). Therefore it is unlikely that there will be a large (i.e. 50+ metric ton ha^{-1}) increase in soil C to explain the 'disappearance' of coarse root biomass from the previous stand.

Decomposition studies of loblolly pine roots in similar soils have shown that almost 20% of pine taproot biomass persisted 25 years after harvest (Ludovici et al. 2002). The amount remaining in the stands of this study, 23 years after harvest, is likely to be less than 20% due to differences in initial tree size (trees in this study were smaller). Additionally, the high spatial variability of coarse roots is compounded when only existing, partially decomposed root systems were considered. Therefore, there might actually be higher per hectare values for dead material in the present stands, but the number and nature of excavations were insufficient to capture this spatially heterogeneous material.

The aboveground hardwood biomass trends are exactly opposite aboveground pine biomass trends, with more aboveground hardwood biomass on less intensively treated plots and virtually no hardwoods on plots receiving vegetation control. Values for belowground biomass as a percentage of total biomass were 19 to 24%, within the ranges reported by others. In similar stand and soil conditions, loblolly pine roots were 19% of the total loblolly pine biomass and the proportion for hardwood stands was found to stabilize around 20% as total biomass exceeded 30 tons ha^{-1} (Harris et al. 1977). Another estimate of proportional allocation in a loblolly pine stand to belowground components showed a decreasing allocation pattern with successive years, decreasing from 32% to 24% in three years (Albaugh et al. 1998). In a lodgepole pine stand the total root biomass was 20-28% of total biomass (Comeau and Kimmins 1988).

Another reporting of root: shoot allocation finds consistently that >70% is allocated to shoot tissue and <30% is allocated to root tissue. Fertilization treatments resulted in different total biomass values between treatments, but proportional allocation to different tissue types did not changed as a result of these treatments (Retzlaff et al. 2001). (Cairnes et al 1997) compiled data from many published root: shoot estimates of woody species and estimates that the mean root: shoot ratio for the temperate zone is 0.26, and for fine soil it is 0.24

The best prediction of pine between-tree coarse root biomass was total basal area. Overall, the aboveground variables were less successful at predicting hardwood between-tree coarse root biomass, probably due to the variation in hardwood distribution between the plots. North Carolina, along with Georgia, was found to have the highest biomass pools of all eastern forests, with 65 to 75% of the pool in hardwood forests (Brown et al. 1999). It is important that we are able to accurately quantify the biomass stored in hardwood forests. However, the fragmented landscape of the southeast is a potential impediment in large-scale estimations of total biomass. A wide range in total biomass per unit area has been reported for the southeastern states (Brown et al. 1999), which is most likely the result of a highly parcelized landscape with many small tracts of land subject to a wide range of silvicultural intensities.

We have presented a regression for estimating taproot biomass of common southern upland hardwoods and regressions to estimate the coarse root biomass outside of the 'sphere' of pines and hardwood stems to scale up total coarse root biomass estimates to a per hectare basis. Aboveground total biomass can be accurately predicted with several published aboveground biomass equations. Including a prediction of belowground biomass based on our regressions can increase the potential gain in carbon credit revenue.

Conclusions

The ability to confidently quantify coarse root C is important due to the potential of coarse roots to sequester larger amounts of C through increased intensive silvicultural practices that increase resource allocation to crop trees. Silvicultural practices that increased aboveground pine productivity by reducing hardwoods did not increase total belowground biomass C. Additionally, there is no evidence that coarse roots provide long-term C storage because they decompose rather quickly after harvest and during subsequent rotations.

Foresters must have access to the tools to estimate total on-site C in order to realize the potential gain in revenue possible by utilizing market-based emissions trading (i.e. carbon credits) and to facilitate carbon accounting. By estimating total biomass from aboveground biomass equations based on diameter, and belowground biomass from various regressions, foresters can convert easy to obtain measurements from a stand of timber into kg ha^{-1} of C for that stand.

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Table 1. Means and standard errors for plant community differences at age 23 that resulted from combinations of different site preparation and vegetation control silvicultural treatments. The two levels of site preparation were chop and burn (CH) and shear, pile and disk (DI); the two levels of vegetation control were none (NO) and complete control for the first five years (VC).

Treatment / **Parameter**	**CHNO**	**DINO**	**CHVC**	**DIVC**	**Standard Error**
Basal Area ($m^2\ ha^{-1}$)					
Total	38.8	42.4	45.7	45.2	3.2
Pine	23.2	37.0	45.5	45.2	5.1
Hardwood	15.6	5.4	0.2	0.0	3.0
Stand Density (trees ha^{-1})					
Pine	963	1563	1544	1550	150.6
Hardwood	6170	2759	1278	1267	843.3
Number of hardwood species present	14	11	5	4	1.3
Average pine diameter (cm)	17.3	18.2	20.1	20.3	0.9
Average hardwood diameter (cm)	4.4	4.0	1.2	1.2	0.5

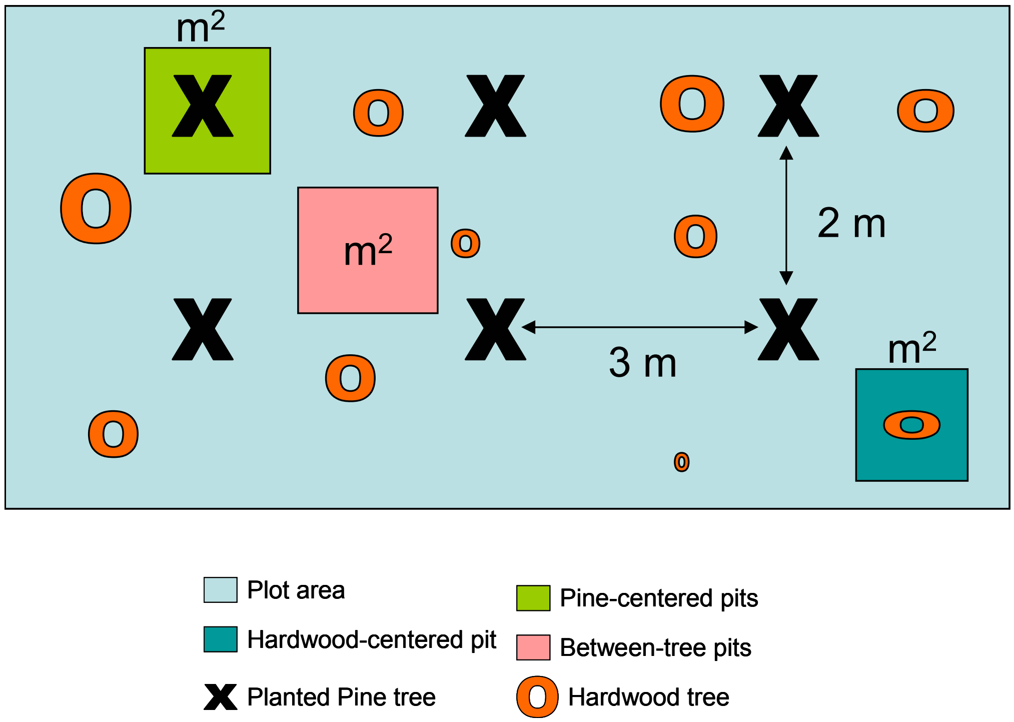

Figure 1. Diagram of excavation placement for pine-centered pits, hardwood-centered pits, and between-tree pits.

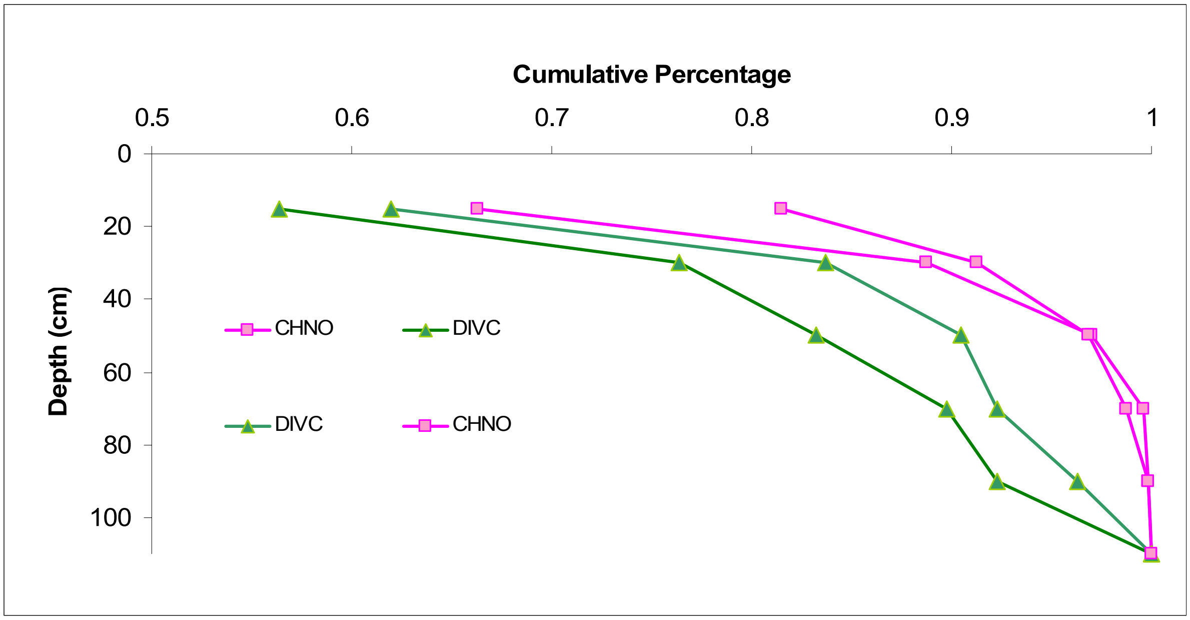

Figure 2. The cumulative percentage of coarse root biomass captured by depth in the deep excavations. Excavations were placed in the most extreme treatments, the least intensive CHNO, and the most intensive DIVC. Root density declined with depth, with over 90% of the roots captured in the upper 50 cm.

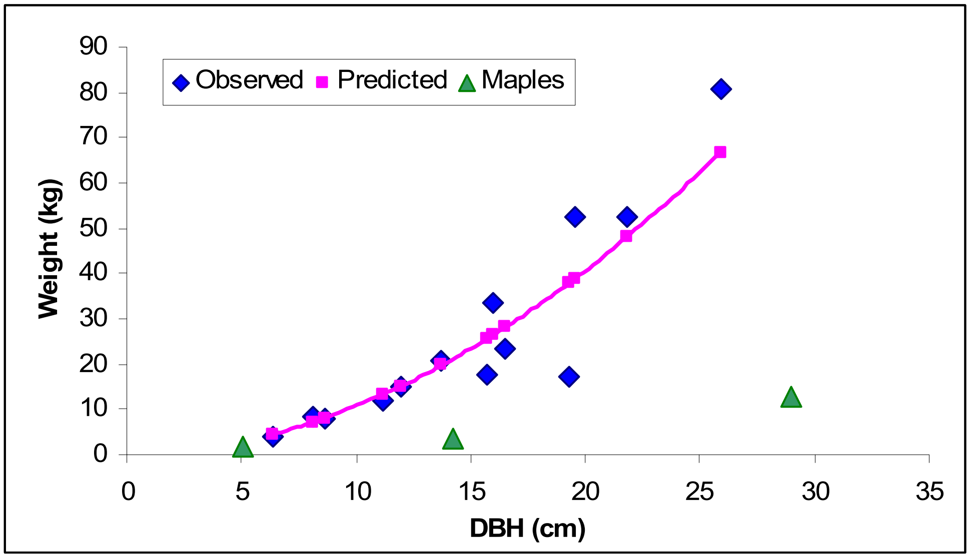

Figure 3. Regression for estimating belowground coarse root biomass (>2 mm) for hardwood roots in 1 square meter centered on the stump from 13 observations ($p<0.0001$). Diameter is in cm and weight is in kg. Triangular data points represent maple stump sprout outliers that were not included in the regression.

Table 2. Summary of ANOVA p-values for block and treatment effects on biomass in a 23-year-old loblolly pine plantation.

	---------------------------Effects---------------------------			
Biomass Attributes	**Block**	**Site Preparation**	**Herbicide**	**Site Prep*Herb**
Pine taproot	0.049	0.006	0.004	0.018
Hardwood taproot	0.608	0.017	0.000	0.015
Between tree- Pine	0.147	0.325	0.767	0.982
Between tree- Hardwood	0.179	0.004	0.008	0.040
Necromass	0.783	0.022	0.527	0.178
Total Belowground Biomass	0.010	0.065	0.658	0.109
Aboveground- Pine	0.008	0.011	0.001	0.081
Aboveground- Hardwood	0.561	0.024	0.001	0.027
Total Aboveground Biomass	0.006	0.089	0.002	0.307
Total Biomass	0.005	0.074	0.004	0.222
Proportion of Total Biomass Belowground	0.026	0.210	0.001	0.652

Table 3. Treatment means and standard errors for the four combinations of site preparation and vegetation control for biomass attributes in a 23-year-old loblolly pine plantation.

	------------Treatments------------				
Biomass Attributes	**CHNO**	**DINO**	**CHVC**	**DIVC**	**Standard Error**
	-----------Metric tons ha^{-1}----------				
Pine taproot	33.8	54.3	57.7	57.9	4.0
Hardwood taproot	21.4	7.6	0.3	0.0	4.0
Between tree- Pine	0.4	0.4	0.5	0.4	0.1
Between tree- Hardwood	0.8	0.1	0.3	0.0	0.2
Necromass	0.03	0.02	0.08	0.01	0.04
Total Belowground Biomass	56.4	62.4	58.8	58.3	3.3
Aboveground- Pine	112.4	190.7	234.3	247.3	27.2
Aboveground- Hardwood	67.8	20.9	1.0	0.0	15.3
Total Aboveground Biomass	180.2	211.6	235.3	247.3	18.7
Total Biomass	236.6	274.0	294.1	305.6	19.9
Proportion of Total Biomass Belowground	0.24	0.23	0.20	0.19	0.01

Table 4. Regression coefficients and summary statistics for the relationships among between- tree pine coarse root biomass and several aboveground parameters for a 23-year-old loblolly pine plantation in the piedmont of North Carolina. Between-tree pine coarse root biomass was estimated based on 23 excavations, aboveground pine and hardwood inventories were conducted in 2003 and 2004 respectively. Aboveground biomass includes woody components and foliage. Biomass in kg ha^{-1}, basal area in m^2 ha^{-1}. The percentage of basal area in hardwoods is calculated as (Hardwood basal area/total basal area)*100%. Regressions take the form: between-tree pine coarse root biomass (kg)=$\beta_0 + \beta_1$*(Independent variable).

Equation #	Independent variable	β_o	ρ	β_1	ρ	R^2
1	**Pine basal area**	180.7	0.091	6.431	0.022	0.225
2	**Hardwood basal area**	448.4	0.000	-4.885	0.309	0.049
3	**Total basal area**	-321.2	0.103	17.272	0.001	0.430
4	**Percentage of basal area in hardwoods**	456.8	0.000	-2.405	0.139	0.101
5	**Total aboveground biomass**	-1.0	0.995	0.002	0.011	0.268
6	**Aboveground pine biomass**	219.1	0.029	0.001	0.033	0.199
7	**Aboveground hardwood biomass**	450.8	0.000	-0.001	0.235	0.067

Table 5. Regression coefficients and summary statistics for the relationships among between- tree hardwood coarse root biomass and several aboveground parameters for a 23-year-old loblolly pine plantation in the piedmont of North Carolina. Between- tree hardwood coarse root biomass was estimated based on 23 excavations, aboveground pine and hardwood inventories were conducted in 2003 and 2004 respectively. Aboveground biomass includes woody components and foliage. Biomass in kg ha^{-1}, basal area in m^2 ha^{-1}. The percentage of basal area in hardwoods is calculated as (Hardwood basal area/total basal area)*100%. Regressions take the form: between-tree hardwood coarse root biomass (kg)=$\beta_0 + \beta_1$*(Independent variable).

Equation #	Independent variable	β_o	ρ	β_1	ρ	R^2
8	**Pine basal area**	833.4	0.025	-13.288	0.148	0.097
9	**Hardwood basal area**	177.4	0.167	28.474	0.051	0.170
10	**Total basal area**	738.7	0.354	-9.354	0.608	0.013
11	**Percentage of basal area in hardwoods**	189.9	0.127	9.887	0.048	0.173
12	**Total aboveground biomass**	1225.3	0.032	-0.004	0.105	0.120
13	**Aboveground pine biomass**	889.0	0.008	-0.003	0.067	0.151
14	**Aboveground hardwood biomass**	207.0	0.109	0.005	0.093	0.129

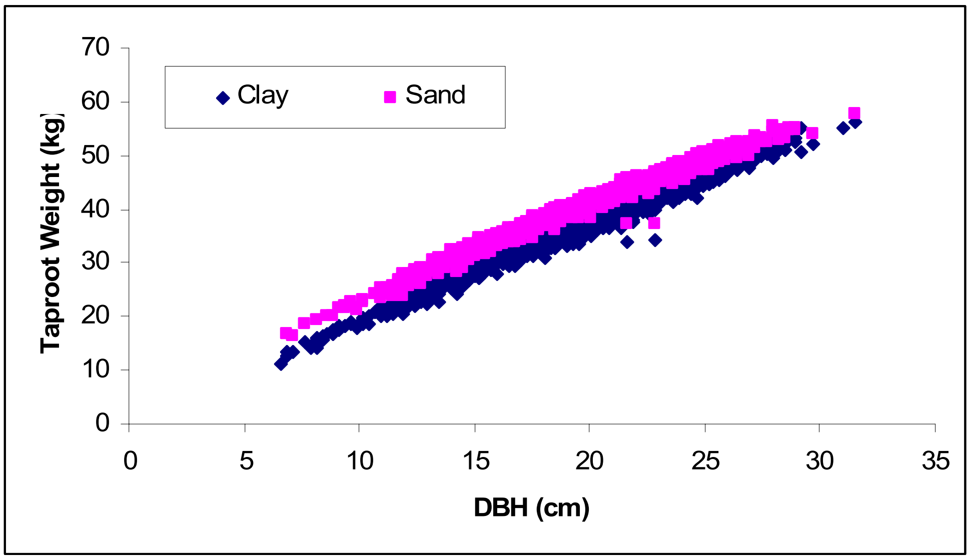

Figure 4. Two separate pine taproot regressions applied to individual pine trees in a 23-year-old loblolly pine plantation. The regression titled 'Sand' was developed from fertilized pines with a diameter range of 6.6 to 31.5 cm, growing in deep sand. The regression titled 'Clay' was used in this study, and was developed from unfertilized pines growing in a clay, with a diameter range of 8.6 to 17.0 cm. Although the 'Sand' regression was developed from a dataset with a similar diameter range as the data to which it was applied, both regressions follow the same trajectory.