Quantifying the coarse-root biomass of intensively managed loblolly pine plantations

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Abstract: Most of the carbon accumulation during a forest rotation is in plant biomass and the forest floor. Most of the belowground biomass in older loblolly pine (*Pinus taeda* L.) forests is in coarse roots, and coarse roots persist longer after harvest than aboveground biomass and fine roots. The main objective was to assess the carbon accumulation in coarse roots of a loblolly pine plantation that was subjected to different levels of management intensity. Total belowground biomass ranged from 56.4 to 62.4 $Mt \cdot ha^{-1}$ and was not affected by treatment. Vegetation control and disking increased pine taproot biomass and decreased hardwood taproot biomass. Pines between tree coarse roots were unaffected by treatment, but hardwoods between tree coarse roots were significantly reduced by vegetation control. Necromass was substantially lower than between-tree biomass, indicating that decomposition of coarse-root biomass from the previous stand was rapid for between-tree coarse roots. Total aboveground biomass was increased by vegetation control, with the lowest production on the least intensively managed plots (180.2 $Mt \cdot ha^{-1}$) and the highest production on the most intensively managed plots (247.3 $Mt \cdot ha^{-1}$). Coarse-root biomass ranged from 19% to 24% of total biomass. Silvicultural practices increasing aboveground pine productivity did not increase total coarse-root biomass carbon because of the difference in root/shoot allocation between pine and hardwood species.

Résumé : La majeure partie du carbon accumulé au cours de la période de révolution d'une forêt se retrouve dans la biomasse de la plante et dans la couverture morte. La majeure partie de la biomasse souterraine dans les vieilles forêts de pin à encens se trouve dans les grosses racines qui persistent plus longtemps après la récolte que la biomasse aérienne et les racines fines. L'objectif principal consistait à évaluer le carbone accumulé dans les grosses racines dans une plantation de pin à encens soumises à différentes intensités d'aménagement. La biomasse souterraine totale variait de 56,4 à 62,4 $Mt \cdot ha^{-1}$ et n'était pas affectée par les traitements. Le contrôle de la végétation et le disquage ont augmenté la biomasse de la racine pivotante du pin et diminué celle de la racine pivotante des feuillus. Les pins situés entre les grosses racines des arbres n'ont pas été affectés par les traitements mais les feuillus situés entre les grosses racines des arbres ont été significativement supprimés par le contrôle de la végétation. La masse de matière morte était substantiellement plus faible que la biomasse entre les arbres, indiquant que la décomposition de la biomasse des grosses racines du peuplement précédent était rapide pour les grosses racines situées entre les arbres. La biomasse aérienne totale a augmenté avec le contrôle de la végétation de telle sorte que les parcelles les moins intensivement aménagées étaient les moins productives (180,2 $Mt \cdot ha^{-1}$) alors que les parcelles les plus intensément aménagées étaient les plus productives (247,3 $Mt \cdot ha^{-1}$). La biomasse des grosses racines représentait 19 à 24 % de la biomasse totale. Les pratiques sylvicoles qui contribuent à augmenter la productivité aérienne du pin n'ont pas augmenté le carbone total de la biomasse des grosses racines à cause de la différence dans l'allocation vers les racines et les pousses entre le pin et les espèces feuillues.

[Traduit par la Rédaction]

Introduction

Atmospheric concentrations of CO_2 are expected to continue increasing because of 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 carbon (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, 1999; Laiho et al. 2003). Nearly all (>98%) stand-level 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

Received 14 April 2005. Accepted 28 September 2005. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 12 January 2006.

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 doi:10.1139/X05-229

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 12.1×10^6 ha in pine plantations are intensively managed, and that land area is expected to increase to 6.1×10^6 ha 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 because of 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 because of 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 (Whittaker et al. 1974; 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 that provided by fine roots, which tend to decompose more quickly (Fahey et al. 1988; 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, constituting 90% of the total living root biomass (Laiho and Finer 1996; Ehman et al. 2002). The ability to quantify coarse-root C is important because of the emerging need to accurately quantify storage and flux associated with C budgets as well as the potential to increase C 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 C accumulation in managed pine forests, hardwood coarse-root biomass estimates are also needed (Brown 2002).

The main objective of this research was to assess belowground C 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 a generalized hardwood regression relating diameter at breast height (DBH) 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%–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 33.8 $m^2 \cdot ha^{-1}$. Average pine basal area from the previous stand was 23.9 $m^2 \cdot ha^{-1}$, and average hardwood basal area was 9.9 $m^2 \cdot ha^{-1}$. Average aboveground biomass for the previous rotation was 123 $t \cdot ha^{-1}$ (Tew et al. 1986).

The current stand was established in 1982 and was the second rotation since agricultural abandonment. The study was a 2 × 2 × 2 factorial experiment that was imposed as a split plot. Two levels of harvest (stem-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 1982, loblolly pine seedlings were planted on a spacing of 2 m × 3 m.

Each plot has an area of 450 m^2, with a buffer of 6 m between plots. In April 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 1982. Vegetation control included a combination of herbicide applications and mechanical vegetation control for the first 5 years followed by periodic manual removal of hardwood regeneration throughout the rotation. The VC treatment maintained the amount of non-pine aboveground biomass to around 1 t/ha, while without vegetation control non-pine biomass increased from 3 t/ha in the first year to 14 t/ha by year 5 (Allen et al. 1991). 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 in more intensive treatments than in those receiving vegetation control and (or) disking (Table 1). Throughout the study, there have been no significant differences as a result of harvest

Table 1. Means and standard errors (SE) for plant community differences at age 23 that resulted from combinations of different site preparation (chop and burn (CH) vs. shear, pile and disk (DI)) and vegetation control (none (NO) vs. complete control for the first 5 years (VC)).

Treatment parameter	CHNO	DINO	CHVC	DIVC	SE
Basal area ($m^2 \cdot ha^{-1}$)					
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 ($trees \cdot ha^{-1}$)					
Pine	963	1563	1544	1550	150.6
Hardwood	6170	2759	1278	1267	843.3
No. of hardwood species present	14	11	5	4	1.3
Avg. pine diameter (cm)	17.3	18.2	20.1	20.3	0.9
Avg. hardwood diameter (cm)	4.4	4.0	1.2	1.2	0.5

method. Because of this, harvest method was not included in this report.

Determination of between-tree root biomass

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, with two pits 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 four pines, at least 0.5 m from surrounding planted pines, to capture coarse roots outside of this taproot zone of either pines or hardwoods. Coarse roots (>2 mm) 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 (maximum 3 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 of pine and hardwood roots was primarily based on appearance, color, bark, and texture. Live pine roots were intact, flexible, and reddish. 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 mass at 70 °C and weighed.

The deep excavations revealed that root abundance declined with increasing depth (Fig. 1), with 91.9% (±0.08%) of the coarse-root biomass occurring in the upper 50 cm.

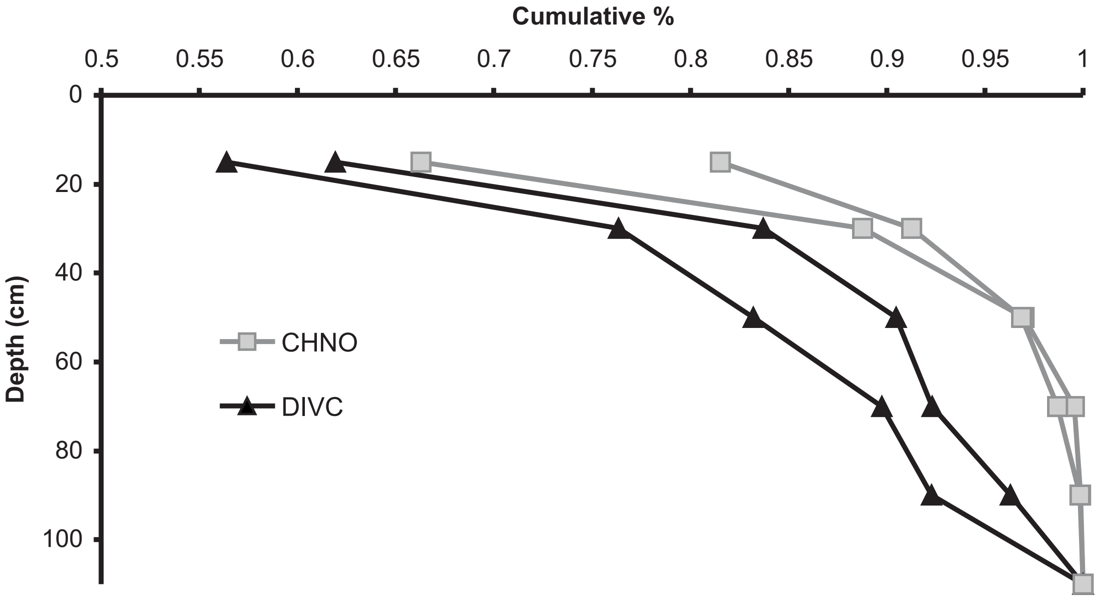
To reduce time and labor expenses, subsequent excavations were confined to the upper 50 cm of soil. Twenty 1.0 m^2 pits were excavated by hand to a depth of 50 cm in June 2004. These pits were placed in all plots not sampled during the initial round of sampling. Coarse roots (≥2 mm) were removed in incremental depths of 0–15, 15–30, and 30–50 cm and processed as outlined previously. 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 masses.

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* L.), red oak (*Quercus rubra* L.), scarlet oak (*Quercus coccinea* Meunchh.), red maple (*Acer rubrum* L.), and sweetgum (*Liquidambar styraciflua* L.). Three of the red maples were not individual stems, but stump sprouts with several stems. Prior to felling, the DBH (1.4 m) was measured. An "equivalent diameter" was calculated for the maple stump sprouts by summing the individual stem diameters. 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 (Santantonio et al. 1977). The soil in the surrounding 1 m^2 centered on the stump was then excavated. Coarse roots (≥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 a depth of 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 1 m^2 to excavate the root ball. In these cases, only soil within the 1 m^2 was sieved, and lateral roots leaving the 1 m^2 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 1 m^2 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. In Jackson and Chittenden (1981), this assumption was used for excavations of root systems from *Pinus radiata* D. Don that were grown in trenches.

Fig. 1. Cumulative percentage of coarse-root biomass captured in deep excavations for the most extreme treatments. Two deep excavations each were placed in the most intensively managed treatments, those receiving shear, pile, and disc with vegetation control (DIVC), and in the least intensively managed treatments, those receiving chop and burn, with no vegetation control (CHNO).



Large root balls and structural roots were transported directly to a drying oven, where they were dried to a constant mass 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 masses of hardwood coarse roots were used to create a site-specific regression relating coarse-root biomass to DBH for hardwoods. In order to correct for heteroscedasticity, the data values for mass and diameter were log transformed, and a correction factor (term C in following equation) was included to account for the error associated with retransforming to get biomass in kilograms (Baskerville 1972). The resulting prediction equation that was applied to the hardwood inventory was of the following form:

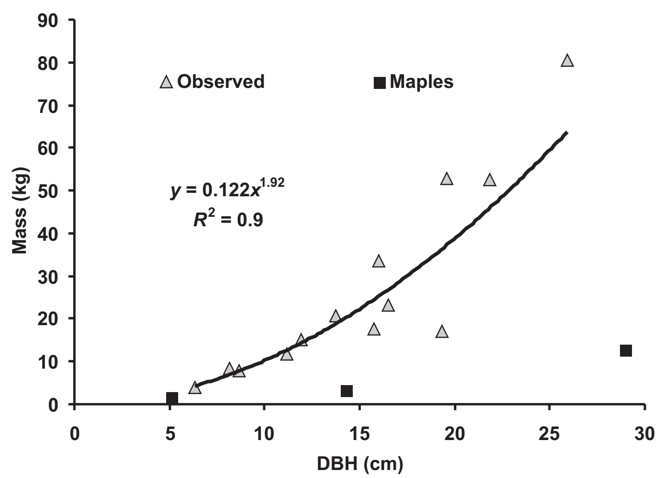
[1]
$$\text{Hardwood taproot mass} = Ce^{[(\ln d)A]-B} \qquad R^2 = 0.88$$

where
taproot mass is in kg;
d is DBH (at 1.4 m) in cm;
A = 1.921950652 (0.212);
B = 2.100356610 (0.564);
$C = e^{(0.09344710/2)}$.

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 (Fig. 2). 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.

DBH 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% C, as in other C studies (Richter et al. 1993; Vande Walle et al. 2001; Laiho et al. 2003; Resh et al. 2003).

Fig. 2. Regression for estimating belowground coarse-root biomass (>2 mm) for hardwood roots in 1 m^2 centered on the stump from 13 observations ($p < 0.0001$). Triangular data points represent maple stump sprout outliers that were not included in the regression.



Estimate of total coarse-root biomass

A complete inventory of hardwood species and diameters was conducted in June 2004. Pine aboveground diameter and total height were measured in December 2003. 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 the 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

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

Biomass attributes	Block	Site preparation	Herbicide	Site preparation × herbicide
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
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 biomass				
Pine	0.008	0.011	0.001	0.081
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 belowground biomass	0.026	0.210	0.001	0.652

1 m^2 centered on the stump in two equations. The *C* term represents a correction factor needed because of the log transformation (Baskerville 1972).

$$[2] \qquad \text{Mass} = Ce^{(\ln d^2 h)A + B}$$

where taproot values are defined as
$A = 0.95359411$;
$B = 9.222988681$;
$C = e^{(0.06059890/2)}$;
and coarse-root values are defined as
$A = 0.791957123$;
$B = 10.34463055$;
$C = e^{(0.0185505112/2)}$.

The eq. 2 regression was developed from loblolly pine trees growing in clay soil, with diameters ranging from 8.6 to 17.0 cm (T.J. Albaugh, personal communication, 2005). The range of diameters to which the regression was applied is 6.6–31.5 cm.

Between-tree pine coarse-root biomass per pit in each plot was applied to all of the 1 m^2 area in that plot not occupied by a planted pine. Between-tree hardwood coarse-root biomass per pit in each plot was applied to all of the 1 m^2 area in a plot not occupied by a hardwood. The number of square metres 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 1 m^2, and then finding by subtraction the total number of square metres not containing a pine or hardwood stump. Biomass estimate per plot (450 m^2) was scaled up to a kilogram per hectare basis.

Estimate of aboveground biomass

Aboveground pine biomass was estimated using a site-specific regression relating aboveground biomass to DBH (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 DBH (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 below-ground biomass attributes were analyzed as a 2 × 2 × 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. 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. Statistical significance was set at $\alpha = 0.05$.

Results

Coarse-root biomass

Above- and below-ground 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 × 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 $Mt \cdot ha^{-1}$, followed by the DINO treatment, with 7.6 $Mt \cdot ha^{-1}$ of hardwood taproot biomass. Not surprisingly, the treatments receiving vegetation control had significantly lower hardwood taproot biomass. The CHVC treatment had 0.3 $Mt \cdot ha^{-1}$, 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 ×

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

Biomass attributes	Biomass (t·ha^{-1}) CHNO	DINO	CHVC	DIVC	SE
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
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 biomass					
Pine	112.4	190.7	234.3	247.3	27.2
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 belowground biomass	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.

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

Note: Regressions take the following form: between-tree pine coarse-root biomass (kg) = $\beta_0 + \beta_1$(independent variable).

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 below-ground 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 following form:

[3] $$\text{Dependent variable} = \beta_0 + \beta_1(\text{independent variable})$$

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 biomass 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

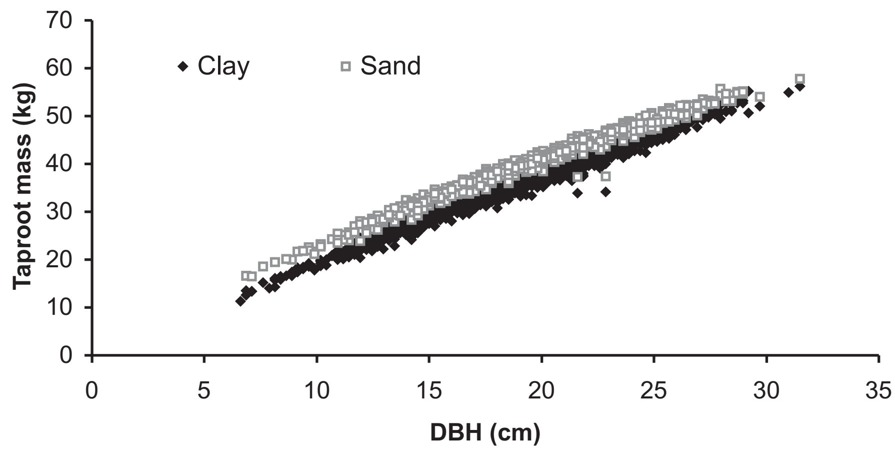
The observed pattern of decreasing root density with increasing depth has been well documented for pine (Coile 1936; Fahey et al. 1988; Harris et al. 1977; Kinerson et al. 1977; Sainju and Good 1993; Kapeluck and Van Lear 1995; Van Lear and Kapeluck 1995; Parker and Van Lear 1996;

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.

Equation	Independent variable	β_o	ρ	β_1	ρ	R^2
8	Pine basal area ($m^2 \cdot ha^{-1}$)	833.4	0.025	–13.288	0.148	0.097
9	Hardwood basal area ($m^2 \cdot ha^{-1}$)	177.4	0.167	28.474	0.051	0.170
10	Total basal area ($m^2 \cdot ha^{-1}$)	738.7	0.354	–9.354	0.608	0.013
11	% of basal area in hardwoods	189.9	0.127	9.887	0.048	0.173
12	Total aboveground biomass ($kg \cdot ha^{-1}$)	1225.3	0.032	–0.004	0.105	0.120
13	Aboveground pine biomass ($kg \cdot ha^{-1}$)	889.0	0.008	–0.003	0.067	0.151
14	Aboveground hardwood biomass ($kg \cdot ha^{-1}$)	207.0	0.109	0.005	0.093	0.129

Note: Regressions take the following form: between-tree hardwood coarse-root biomass (kg) = $\beta_0 + \beta_1$(independent variable).

Fig. 3. The regression titled "Sand" was developed from fertilized pines with a diameter range of 6.6–31.5 cm, growing in deep sand, and the regression titled "Clay" was used in this study and was developed from unfertilized pines growing in clay, with a diameter range of 8.6–17.0 cm.



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 pits.

The hardwood regression is a general regression that estimates coarse-root biomass for several species. This method of creating biomass regressions, combining several species of similar form, can yield similarly confident estimations as species-specific regressions (Whittaker et al. 1974).

Stand-level estimates of coarse-root biomass ranged from 56.4 to 62.4 $t \cdot ha^{-1}$ 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 $t \cdot ha^{-1}$ (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 taproot 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 that of 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 Fig. 3) that had a similar diameter range to that of 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 (Fig. 2). This lends confidence to the regression used in this study and suggests 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) appears to be due to differences in stand and site productivity. Their stand was located on an eroded site that was thinned twice and had an aboveground pine biomass of 145 Mt·ha^{-1} at 48 years. In contrast, our stand had an aboveground pine biomass of 247.3 Mt·ha^{-1} at 23 years in the most productive plots (DIVC). Greater belowground biomass was due to greater aboveground biomass.

A second factor that may have contributed to the root biomass difference is that these earlier 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* Ait.) and American beautyberry (*Callicarpa americana* L.), neither of which were expected to contribute appreciably to total coarse-root biomass. However, Van Lear and Kapeluck (1995) encountered yellow-poplar (*Liriodendron tulipifera* L.) and oak (*Quercus* spp.) in the overstory of their stand, while the understory of their stand was similar in species composition to the stands in 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.

Biomass of both pine taproots and hardwood taproots interacted with site preparation and vegetation control. Aboveground hardwood biomass also exhibited significant interaction, but aboveground pine biomass did not. On the treatments receiving vegetation control, 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. 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 1 m^2 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* spp. in the root ball (Resh et al. 2003) and over 75% in the taproots of ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) (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 pines and hardwoods, with pines 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 a swamp in Virginia, belowground hardwood biomass decreased with increasing depth, with over three-fourths located in the uppermost 30 cm (Montague and Day 1980).

Root necromass was very small, but was significantly less on the shear, pile, and disk plots. On these 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; the smaller pieces 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 1 t·ha^{-1}, compared to 58.8 t·ha^{-1} of live coarse-root material. Applying the same taproot regressions to inventory data from the previous stand, and assuming that the amount of between-tree coarse-root biomass was the same, the total coarse-root biomass for the least intensive CHNO treatment was 42 t·ha^{-1}. Therefore, the small amount of dead material encountered indicated that potentially over 40 Mt·ha^{-1} of coarse-root biomass from the previous rotation decomposed to the point where it was no longer readily evident as roots.

Previous work on soil C accretion indicates that there is little potential to appreciably increase soil C through different management practices (Schlesinger 1990, 1993; Richter et al. 1993, 1999). Therefore, it is unlikely that there will be a large (i.e., >40 t·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% because of 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%–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 $t \cdot ha^{-1}$ (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 3 years (Albaugh et al. 1998). In a lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stand, the total root biomass was 20%–28% of total biomass (Comeau and Kimmins 1989).

Retzlaff et al. (2001) reported on root/shoot allocation and found 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 change 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 estimated that the mean root/shoot ratio for the temperate zone is 0.26, and for fine soil it is 0.24. The proven consistency in pine root/shoot allocation implies that differences in belowground biomass cannot be explained by changing pine root/shoot allocation patterns. Therefore, since the proportion of total biomass belowground was higher for treatments with more hardwood vegetation (24% vs. 19%), it is implied that hardwoods allocate a higher proportion of total biomass belowground and through this mechanism alter the stand level root/shoot ratio. Since the presence of hardwoods decreases the productivity of the pines, above ground and therefore below ground as well (based on allometric equations), then the difference in root/shoot allocation between hardwoods and pines causes there to be no significant difference in belowground biomass between treatments.

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 because of the variation in hardwood distribution between the plots. Although there are many existing allometric equations that can be used to predict taproot biomass on a variety of species and soil types, there are fewer studies that predict coarse lateral roots. It is unfortunate that this study did not find any variables that explained a substantial portion of the variability in between-tree coarse-root biomass. Because the regressions presented to estimate between-tree pine and hardwood coarse-root biomass explain relatively little variation in total coarse-root biomass, the existing allometric equations are useful in estimating stand-level coarse-root biomass C.

North Carolina, along with Georgia, was found to have the highest biomass pools of all eastern forests, with 65%–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 (Whittaker et al. 1974). 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.

Conclusions

The ability to confidently quantify coarse-root C is important because of the potential of coarse roots to sequester large amounts of C through intensive silviculture. We assessed coarse-root distribution and biomass accumulation in loblolly pine plantations that were subjected to different levels of management intensity. Silvicultural practices that increased aboveground pine productivity by reducing hardwoods did not increase total belowground root biomass (i.e., the sum of pine and hardwood taproots and between-tree root biomass). This is because silvicultural treatments had offsetting effects on root/shoot allocation patterns of pine and hardwood species. The more intensive treatments increased pine root biomass and decreased hardwood root biomass, while in the less intensive treatments the presence of hardwood competition increased hardwood root biomass and decreased pine root biomass. The net result was no significant differences in total (pine and hardwood) coarse-root biomass between treatments.

The deep pit excavations (110 cm) revealed that treatments with more hardwoods had a higher proportion of total coarse-root biomass in the upper 30 cm, while intensively managed treatments with virtually no hardwoods had a more even vertical distribution of roots. Nevertheless, on these Piedmont soils 90% of the roots occupied the top 50 cm of soil.

Between-tree root biomass, that is, areas outside the 1 m^2 surrounding the pine or hardwood stem, contributed less than 3% to total belowground biomass. Predictive regression equations based on aboveground stand parameters explain only a small percentage of the total variation in total coarse-root biomass C. While the between-tree root regressions were useful for refining an estimate of total coarse-root biomass, allometric equations that predict taproot biomass C do a sufficient job of explaining most of the variation.

On the least intensive treatments, hardwood DBH explained 88% of the variation in hardwood taproot biomass. Since most coarse-root biomass is found centered on the stump, this regression is useful for estimates of landscape-level C in stands that contain a significant hardwood component. However, there was evidence that the relationship between stem diameter and root biomass differs for stumps with multiple stems; maple stumps with multiple stems had less root biomass for a given stem size than other species. Therefore, use of these equations on sites with significant "sprout" regeneration may grossly overestimate hardwood root biomass.

Foresters must have access to the tools to estimate total on-site C to realize the potential gain in revenue possible by using market-based emissions trading (i.e., C credits) and to facilitate C 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 kilograms per hectare of C for that stand.

Acknowledgements

Graduate assistantship and lab analysis support for the research came from the Forest Nutrition Cooperative. International Paper made considerable contributions by monitoring and measuring the study and providing additional financial assistance. The USDA Forest Service, Southern Research Station, contributed to the research by providing significant help with the fieldwork. Tim Albaugh contributed to the development of the methods.

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