Effect of Harvest Residue Management on Tree Productivity and Carbon Pools during Early Stand Development in a Loblolly Pine Plantation

Chris A. Maier, Kurt H. Johnsen, Phillip Dougherty, Daniel McInnis, Pete Anderson, and Steve Patterson

Abstract: Soil incorporation of postharvest forest floor or logging residues during site preparation increased mineral soil carbon (C) and nitrogen (N) concentration and had a differential effect on early stand growth in a clonal loblolly pine (*Pinus taeda* L.) plantation. Incorporating 25 Mg ha^{-1} of forest floor (FF) (C/N ratio $\approx$ 112:1) or 25 (1LR) or 50 (2LR) Mg ha^{-1} masticated logging residues (C/N ratio $\approx$ 856:1) increased soil C concentration by 24−49% in the top 60 cm of soil compared with that for a nontreated control or a raked (R) treatment where the forest floor (−25 Mg ha^{-1}) was removed. Although the long-term treatment effects on soil C are unknown, increased macro-organic matter C (150–2,000 μm) in the recalcitrant heavy fraction coupled with an estimated 20- to 35-year turnover rate for the incorporated residues suggests that soil C will be elevated in the FF, 1LR, and 2LR treatments through the current rotation. There was a treatment $\times$ age interaction on stand volume growth ($P = 0.03$) caused by a differential response to FF and LR treatments. Relative to the control, the FF treatment increased stem volume growth and stand homogeneity, resulting in 18% more stand volume at age 6. In contrast, the LR treatments initially suppressed volume growth; however, at age 6 there were no significant differences in stem volume among control and LR treatments. Six-year stand volume was 116.6, 112.6, 135.1, 116.0, and 112.3 (SE 3.6) m^3 ha^{-1} in the control, R, FF, 1LR, and 2LR treatments, respectively. Whereas the efficacy of organic matter management will be site-dependent, our results suggest that soil incorporation of forest residues during site preparation can have positive benefits for productivity and building soil C on sites with relatively high inherent soil C stocks. FOR. SCI. 58(5):430–445.

Keywords: biomass, ecosystem carbon, soil carbon, carbon sequestration, nitrogen

PINE PLANTATIONS IN THE ATLANTIC COASTAL PLAIN are some of the most productive forests in the United States and provide much of the nation's supply of wood and fiber (Fox et al. 2007). These forests sequester large amounts of carbon (C) in products and in plant biomass and may provide a negative feedback to atmospheric accumulation of CO_2 (Johnsen et al. 2001). Increased C storage that persists across rotations is thought to be mainly through increased productivity of coarse woody lateral and taproots (Johnsen et al. 2001) rather than in enhanced mineral soil organic matter C. Soil C is clearly linked to site productivity (Vance 2000), and increasing soil C is an important objective for the sustainable use of forest soil resources (Lal 2005). However, the effect of intensive management on belowground biomass and C storage is not well understood. Frequent harvesting (e.g., whole-tree) followed by intensive site preparation practices such as bedding, disking, or subsoiling can promote soil C loss (Johnson and Curtis 2001, Laiho et al. 2003). Chemical weed control during site establishment often results in substantial reductions in soil C and nutrients that can persist throughout the rotation (Carlyle 1993, Shan et al. 2001, Echeverría et al. 2004, Rifai et al. 2010, Vogel et al. 2011). These C losses may be offset somewhat by increased productivity. For example, fertilization can increase soil C input through greater root growth and litterfall, but it may (Rifai et al. 2010, Vogel et al. 2011) or may not (Johnson and Curtis 2001, Shan et al. 2001, Leggett and Kelting 2006, Sartori et al. 2006) result in increased mineral soil C. Determining the fundamental relationship between soil C accumulation and productivity is critical for determining whether intensive forest management represents a viable C sequestration strategy.

Fifty to 85 Mg ha^{-1} of logging residues, composed of foliage, branches, and forest floor remain on site after whole-tree harvesting of loblolly pine plantations (Eisenbies et al. 2009). These materials represent a large reservoir of C and nutrients (Morris et al. 1983, Pye and Vitousek 1985, Tew et al. 1986). For example, Carter et al. (2002) found an average of 126.0, 7.2, and 37.8 kg ha^{-1} of nitrogen (N), phosphorus, and potassium, respectively, in forest logging residues in whole-tree-harvested loblolly pine plantations. Numerous studies show that retaining these residues on-site

Manuscript received May 31, 2011; accepted March 22, 2012; published online May 10, 2012; http://dx.doi.org/10.5849/forsci.11-069.

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Acknowledgments: The USDA Forest Service Agenda 2020 program supported this research. We thank John Johnson with MeadWestvaco for field installation of the treatments and site support. We also thank Karen Sarsony for laboratory analysis and Bob Eaton, Tom Christensen, and Joel Burley for field support.

benefits growth of the regenerating stand (Olsson et al. 2000, Smith et al. 2000, Egnell and Valinger 2003, Mendham et al. 2003, Tutua et al. 2008). Scott and Dean (2006) found that whole-tree harvest, in which foliage and branches were removed, compared with stem-only harvest, caused an 18% reduction in loblolly pine stem biomass growth by age 10 on 15 of 19 study sites in the Gulf Coastal Plain. Likewise, Zerpa et al. (2010) showed that retaining the forest floor after harvest resulted in increased N availability and tree growth in 10-year-old loblolly pine plantations. In contrast, 10-year results from a Long-Term Soil Productivity Study installation in North Carolina found that complete removal of aboveground biomass, including the forest floor, had no effect on loblolly pine productivity (Sanchez et al. 2006).

Forest residue management effects on mineral soil C are equivocal. Some studies have found little or no response to manipulating forest residues on soil C (Olsson et al. 1996, Johnson and Todd 1998, Mendham et al. 2003, Busse et al. 2009, Zerpa et al. 2010), whereas others have found early but ephemeral decreases or increases in soil C that disappear after a few months or years (Knoepp and Swank 1997, Tiarks et al. 2004, Powers et al. 2004, Chen and Xu 2005). In a meta-analysis of forest management effects on soil C, Johnson and Curtis (2001) found that retaining forest residues during stem-only harvest resulted in an 18% increase in soil C whereas whole-tree harvesting caused a 6% reduction in soil C. It may be that forest floor and logging residues left on the soil surface decompose quickly after harvest, returning C as CO_2 back to the atmosphere (Richter et al. 1999, Schlesinger and Lichter 2001), while contributing little to the soil (Johnson and Todd 1998).

Buford and Stokes (2000) hypothesized that incorporating masticated logging residues into the soil during site preparation would increase nutrient mineralization and enhance soil C, potentially increasing site productivity and soil C. The long-term fate of incorporated forest residues will probably depend on the quantity and quality of residues, soil chemical and biological retention or loss mechanisms, and the growth response of the regenerating stand (Harrison et al. 1995). Soil incorporation of forest residues during site preparation led to early increases in soil C, nutrient contents, and tree growth in *Pinus radiata* plantations (Smethurst and Nambiar 1990, Pérez-Batallón et al. 2001). Jones et al. (1999) also observed increased early productivity of planted and coppiced *Eucalyptus globulus* plantations when harvest residue was tilled into the soil compared with when it was either left on the surface or removed. Sanchez et al. (2000, 2003) found that tree growth and soil C after incorporation of logging residues in loblolly pine plantations varied with site quality. Residue treatments led to early increases in soil C on all sites, but the effect was ephemeral, disappearing after 6–8 years and in some cases leading to a reduction in soil C, presumably from increased decomposition resulting from tillage (Busse et al. 2009, Sanchez et al. 2009).

We investigated how manipulating the quantity and quality of forest residues during site preparation affected early stand growth, soil C and N pools, and ecosystem C storage in a clonal loblolly pine plantation. Nutrient pools and fluxes are linked inextricably with C; thus, any activity that alters the C cycle will affect nutrient cycling and availability. Logging residues typically have low nutrient concentrations and high C/N ratios (100–800:1). Incorporation of large quantities of this low-quality organic matter could induce N immobilization, decreasing N availability and growth of the regenerating trees (Pérez-Batallón et al. 2001). Alternatively, proper management of residual biomass after harvest may dampen N mineralization (Vitousek and Matson 1985) and leaching loss, making it available later for stand growth. Based on these potential N availability dynamics, we hypothesized that incorporating forest harvest residues (i.e., forest floor or logging debris) into the soil during site preparation would increase pine productivity and mineral soil C stocks. We further hypothesized that the timing and magnitude of the response would vary with the quantity and quality of the material. We used a single fast-growing clone for this study to minimize genetic $\times$ environmental interactions (Martin et al. 2005).

Materials and Methods

Site Description

The site is located in Berkeley County, South Carolina (33°16′ N, 80°10′ W). The soils are classified predominately as a Seagate series (sandy over loamy, siliceous, active, thermic Typic Haplohumods) (US Department of Agriculture, Natural Resources Conservation Service 2012), which typically have moderate levels of organic matter (0.5–2%) and are devoid of rocks. The soils are somewhat poorly drained and have a fluctuating water table that approaches the surface after harvest. Annual rainfall is 1,358 mm, and average January and July temperatures are 8 and 27°C, respectively.

The previous stand was a 21-year-old second-rotation loblolly pine plantation. The site was sheared, raked, and bedded in 1983 and planted with superior loblolly pine in 1984. Stand management included two prescribed fire treatments at ages 10 and 12 and a fertilization at age 14 with 224 kg ha^{-1} nitrogen and 28 kg ha^{-1} phosphorus in urea and diammonium phosphate. Before harvest, the stand had 518 trees ha^{-1} and 43 m^2 ha^{-1} basal area (SI_{25} = 23 m). There was 11.0 $\pm$ 4.8 (SD) Mg ha^{-1} of forest floor litter (n = 30) and 43.1 $\pm$ 8.3 mg g^{-1} soil C (n = 12) in the top 20 cm. The stand was whole-tree harvested and chipped on-site in May 2004. Approximately 25 Mg ha^{-1} litter, including stems <0.5 cm diameter, and 22.1 Mg ha^{-1} woody material remained as forest floor residue.

Experimental Design

A range of soil organic matter conditions were created by adding or removing the postharvest forest floor (C/N ratio $\approx$ 112:1) or adding logging residue effluent (i.e., comminuted bark, branches, and foliage) (C/N ratio $\approx$ 856:1) left over from the chipping operation. Five organic matter residue treatments were installed in a fully randomized design in three blocks. Blocks were oriented parallel to a drainage ditch adjacent to the site to account for potential drainage differences across the site. The treatments were as follows: a control, where the residual forest floor ($\approx$25 Mg

ha^{-1}) was left intact; raked (R), where the residual forest floor was manually raked and removed; and three residue treatments consisting of the residual forest floor (≈25 Mg ha^{-1}) plus the addition of 25 Mg ha^{-1} forest floor from the R treatment (FF), 25 Mg ha^{-1} (1LR), or 50 Mg ha^{-1} (2LR) of logging debris residual from the chipping operation.

In November 2004, the material used in the FF, 1LR, and 2LR treatments was distributed in 1.75-m strips and then incorporated into beds using a Savannah plow pulled by a D-8 tractor. All plots were doubled-bedded to ensure good incorporation of residue material with the mineral soil. Containerized loblolly pine seedlings from a single clone (AA93; Arborgen, Inc.) were planted on a 1.8 m × 4.3 m (1,280 trees ha^{-1}) spacing in January 2005. Each treatment plot measured 48 m × 38 m and contained nine rows (248 trees). Measurement plots consisted of the four interior rows containing 130–135 trees. Understory vegetation was controlled during the first 2 years using aerial and direct spray applications with imazapyr and sulfometuron methyl.

Soil and Root Sampling

A stratified sampling approach was used to sample soil and roots. Bedding creates distinct soil micro-sites (Figure 1) that affect soil temperature and moisture, physical characteristics, and organic matter distribution. Beds were created by plowing and mixing soil excavated from the troughs with soil and added organic matter in the beds (zones A and B). Bed height, width, and width of the interrow and trough were measured near the end of the first growing season. There were no significant treatment effects on bed height ($P = 0.15$). Bed height ranged from 12.5 to 30 cm and averaged 20.5 ± 1.3 (SE) cm (Figure 1). There were also no significant treatment effects on bed ($P = 0.53$), interrow ($P = 0.95$), or trough ($P = 0.74$) width. Average widths of the beds, interrows, and troughs were 1.75 ± 0.08, 1.38 ± 0.40, and 0.57 ± 0.09 m, which accounted for 41, 27, and 32%, respectively, of the plot surface area (Figure 1).

Soil cores were collected in January 2005, 2 months after treatments were installed and then annually in winter (January–February) through 2008. Three locations were randomly selected in each treatment and at each location; the bed, trough, and interrow were sampled. On the beds, a 15.2-cm diameter (181.5-cm^2) steel auger was used to sample 0–20 and 20–40 cm depths. A 10.2-cm diameter (81.7-cm^2) steel auger was used to sample 40–60 cm. In 2008, soil from 60–80 and 80–100 cm was sampled using a 2.5-cm push tube auger. The 15.2-cm auger was used to sample 0–20 and 20–40 cm depths in the interrows and the 0–20 cm depth in the trough. Live roots, dead roots, coarse organic fragments (COF) (> 2 mm), and mineral soil were separated by first sieving through a 0.6-cm mesh screen to remove large live and dead roots and COF and then passed through a 2-mm mesh screen to separate smaller roots and COF from the mineral soil. Live pine roots were separated further into large roots >2 mm and small roots <2 mm. All components were dried at 70°C, weighed, and ground. Total C and N for each component were determined by combustion analysis using a Carlo Erba NA 1500 Series II C/N/S Analyzer (Fison Instruments, Danvers, MA).

Soil bulk density for the respective zones was used to estimate stand-level soil C and N content. Soil bulk density was measured in July 2007 at 0–20 and 20–40 cm in the beds (zones A and B), 0–20 cm in the interrow (zone C), and 0–20 cm in the trough (zone D) (Figure 1) using a 5-cm-wide × 5-cm-long lined AMS soil sampler (AMS, Inc., American Falls, ID) (Blake and Hartge 1986). The site had no rocks. Values are expressed as total soil bulk density and include >2 mm fraction.

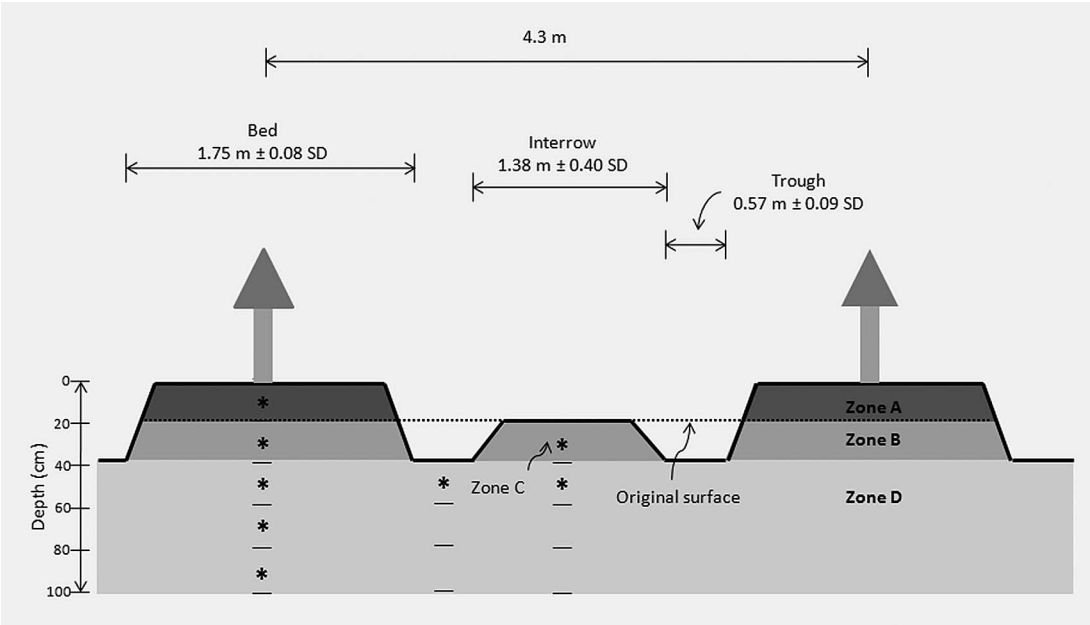

Figure 1. Schematic diagram of the cross-sectional area of bedded rows at the study site illustrating the microtopography of the beds, interrow, and trough. * Indicates a sampling point for soil carbon and root biomass. Zones represent areas of similar soil bulk density.

Soil Fractionation

Soil macro-organic matter (150–2,000 μm) was fractionated into three density fractions following the methods of Meijboom et al. (1995). One hundred-gram subsamples from the three 0–20 cm soil cores collected from beds were composited by block and treatment. Soil samples were air-dried and passed through a 2-mm sieve. A 100-g sample of sieved soil was placed in 1,000 ml of deionized water and stirred overnight. The dispersed soil sample was passed through a 150-μm mesh (no. 100) sieve. The sieved material was washed in pH 10 water and allowed to drain. The sieved material was then sequentially fractionated in silica suspensions (Ludox; Aldrich Chemical Company) into a light fraction (density <1.13 g cm^{-3}), medium fraction (density 1.13–1.37 g cm^{-3}), and a heavy fraction (density $>$ 1.37 g cm^{-3}). After each suspension, fractionated organic matter was washed in pH 10 water and drained. All fractions were washed in deionized water, dried at 70°C, and weighed. Carbon and N in each fraction was determined by combustion analysis using a Carlo Erba NA 1500 Series II C/N/S Analyzer.

Residue and Taproot Decomposition

FF and LR samples were collected immediately after harvesting. Samples were air-dried, and 50 and 100 g, respectively, of FF and LR were placed in 20 $\times$ 30 cm litterbags constructed from a 16-mesh fiberglass screen. Three sets of eight bags of FF litter were placed randomly in the control and FF plots in each block (144 bags). Similarly, three sets of eight bags of LR were placed randomly in the control, 1LR, and 2LR plots (216 bags). Bags were buried 5 cm in the beds between planted seedlings in April 2005. Litterbags from each set were collected periodically over the next 4.5 years. Litter was carefully separated from soil and roots and oven-dried at 65°C. Subsamples were measured for organic matter by loss-on-ignition by burning in a 450°C muffle furnace for 8 h (Council on Soil Testing and Plant Analysis 1992).

Decomposition was assessed by determining the percent mass remaining over time and by calculating the decay rate constant (k) using an exponential decay model ($X_t/X_0 = e^{-kt}$), where X_t is the litter sample weight at time t and X_0 is the sample weight at $t = 0$. The decay constant was assessed for the entire measurement period. The mean residence time or turnover time for 99% of the litter mass to disappear was calculated as $5/k$ (Olson 1963).

Taproots from the previous stand were mapped, and diameters were measured at harvest. Residual taproots were excavated at the time of harvest and five times over the course of the study. Residual taproot biomass C and decomposition rates were assessed as described above.

Tree Growth and Biomass Sampling

Tree height and diameter growth were measured in December of each year on all trees in the measurement plot. Height (H) was recorded with either a height pole to the nearest cm (years 1–3) or a hypsometer to the nearest 0.1 m (years 4–6). Stem diameter (D) was measured to the nearest mm at groundline (year 1) using calipers or at 1.4 m using a diameter tape (years 2–6). Stem wood volume was calculated as

$$V = 0.00748 + (0.0000353D^2H) \quad (1)$$

where V is outside bark volume (m^3) (Shelton et al. 1984). Volume was calculated for each tree in the measurement plot and then summed to the plot level (1,024 m^2) and scaled to m^3 ha^{-1}. Annual volume increment was estimated as the difference between current and previous year V.

Destructive biomass harvests were conducted annually during December–January for each plot and year (years 1–4). One to three trees per treatment plot were selected from the buffer rows, cut at 10 cm aboveground line, and separated into foliage, stem, and live and dead branch components. The diameters of selected trees were within 1 SD of the plot mean. The taproot and coarse roots (>2 mm) were excavated down to 60 cm in a 1-m^2 area around the stem. Component material was dried at 70°C and weighed. Total C and N for each component were determined by combustion analysis using a Carlo Erba NA 1500 Series II C/N/S Analyzer.

Stand-level biomass (foliage, branch, stem, taproot, and lateral roots) was calculated for each plot and year using allometric equations. Separate equations were developed for year 1 and years 2–4 using the equation

$$\ln(Y) = B_0 + B_1\ln(X) + \varepsilon \quad (2)$$

where Y is dry weight (g per tree), X is groundline stem diameter or D, and ε is the error term. Covariance analysis showed that there were no significant differences among treatments; therefore, the data were pooled and common regression equations were developed. Corrections to biomass estimates were made for logarithmic bias (Baskerville 1972). Stand-level biomass (Mg ha^{-1}) and biomass increment (Mg ha^{-1} year^{-1}) were estimated using inventory data for each plot. Component biomass was calculated for each tree, summed to the plot level, and then scaled to area. Small roots (<2 mm) and coarse roots in the beds outside the 1-m^2 soil pit, troughs, and interrows were estimated from soil cores as described previously and scaled to the stand level based on core volume. Stand-level biomass C was estimated by multiplying plot-level biomass by component C concentration. Annual production was calculated as the difference between initial and final biomass C for each component.

Statistical Analysis

Treatment effects on tree growth, COF, total mineral and fractionated soil C and N, litter C, and component biomass C were tested using a randomized complete block design analysis of variance (ANOVA). Each plot served as the experimental unit. Repeated-measures analysis was conducted using PROC MIXED (SAS Institute, Cary, NC) to determine the treatment, stand age, and interaction effects on independent variables measured over time. Mineral soil C, COF, and root data used a three-way ANOVA with block and treatment as the main effects and soil depth as a split-plot. Treatment, stand age, and soil depth (where applicable) were fixed effects, and block was a random effect. The

Table 1. Summary of statistical significance (P > F) from ANOVA analysis on C in COF and mineral soil C and N concentration and content in the 0–60 cm soil profile in the beds.

	T	D	T × D	A	T × A	D × A	T × D × A
COF C (kg m^{-2})	<0.0001	<0.0001	<0.0001	0.8936	0.1521	<0.0001	0.5387
C (mg g^{-1})	<0.0001	<0.0001	0.0056	0.0045	0.4876	0.0006	0.6456
C (kg m^{-2})	0.0027	<0.0001	0.8079	0.0035	0.3292	0.0006	0.5573
N (mg g^{-1})	0.0010	<0.0001	0.1711	0.2258	0.3416	<0.0001	0.4624
N (kg m^{-2})	0.0716	<0.0001	0.4923	0.2134	0.1605	<0.0001	0.3345
C/N	0.3851	0.6139	0.2532	0.1862	0.8875	0.3327	0.7852

T, treatment; D, depth; A, age.

appropriate covariance structure was selected based on the Akaike information criterion. Where necessary, log-transformed data were used to satisfy heterogeneity of variance assumptions. Nontransformed values are reported. Significance tests for main and interactive effects were conducted at the $P \leq 0.05$ significance level and Tukey's adjustment was used for pairwise comparison of treatment means. Data are reported as least-squares means (LSMEANS) and SE, where SE is the square root of the full model mean square error divided by the treatment sample size.

Results

COF

The application of forest floor or logging residue treatment was confined to the bedded rows (Figure 1). Residue treatment had a large effect on the amount and distribution of COF (Table 1). When summed over the 60-cm profile, the 1LR and 2LR treatments increased COF compared with the control and R treatments (Figure 2a). Total COF did not change with age ($P = 0.89$), and there was no treatment × age interaction ($P = 0.15$). Averaged across all years, COF was 1.78, 1.21, 3.19, 5.55, and 8.67 kg C m^{-2} (SE 0.52), in the control, R, FF, 1LR, and 2LR treatments, respectively. Increases in COF in the 1LR and 2LR treatments occurred at 0–20 and 20–40 cm sampling depths but not at 40–60 cm (treatment by depth interaction, $P < 0.0001$) (Figure 2b). There was a strong depth × age interaction ($P < 0.0001$), which was caused by a large increase in COF in the 0–20 cm depth and a decrease in 40–60 cm depth (Figure 2c). This interaction was probably due to beds settling over time, confounding comparisons between years at a particular depth.

Litterbag Decomposition

The decomposition of incorporated forest floor and logging residue was measured in the FF, 1LR, and 2LR treatments and compared with decomposition of similar material in the control. Within a residue type, there was no treatment (FF: $P = 0.76$; LR: $P = 0.67$) or treatment × age interaction (FF: $P = 0.19$; LR: $P = 0.03$) on percent carbon mass remaining. After 4.25 years, FF maintained 33% (Figure 3a) of the original C mass compared with 52% (Figure 3b) for LR. The decay rate constant (k) over the 4.5-year study was 0.23 ± 0.03 years for the FF treatment compared with 0.16 ± 0.01 years for the LR treatment. The ash-free mass

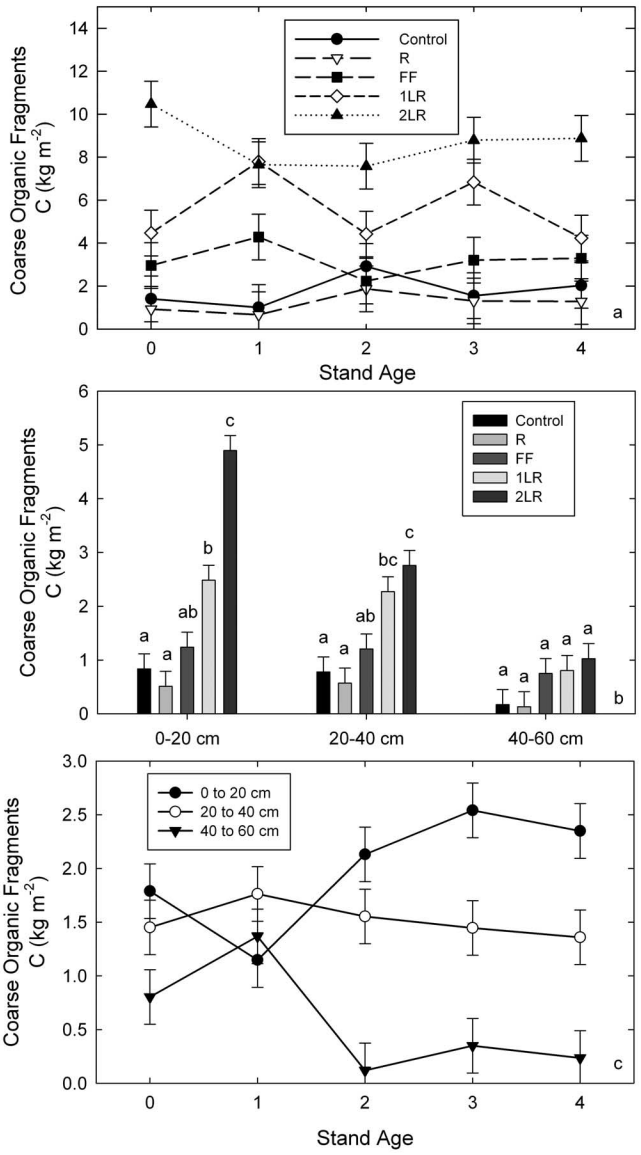

Figure 2. Variation in COF (> 2 mm) in the bedded rows for (a) mean annual total COF down to 60 cm, (b) mean COF by depth averaged across all years, and (c) mean annual COF by depth averaged over all treatments. Values are LSMEANS ± 1 SE ($n = 3$), where SE is the square root of the model mean square error divided by the treatment sample size. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added. In b, bars within a depth with a different letter are significantly different at $\alpha = 0.05$.

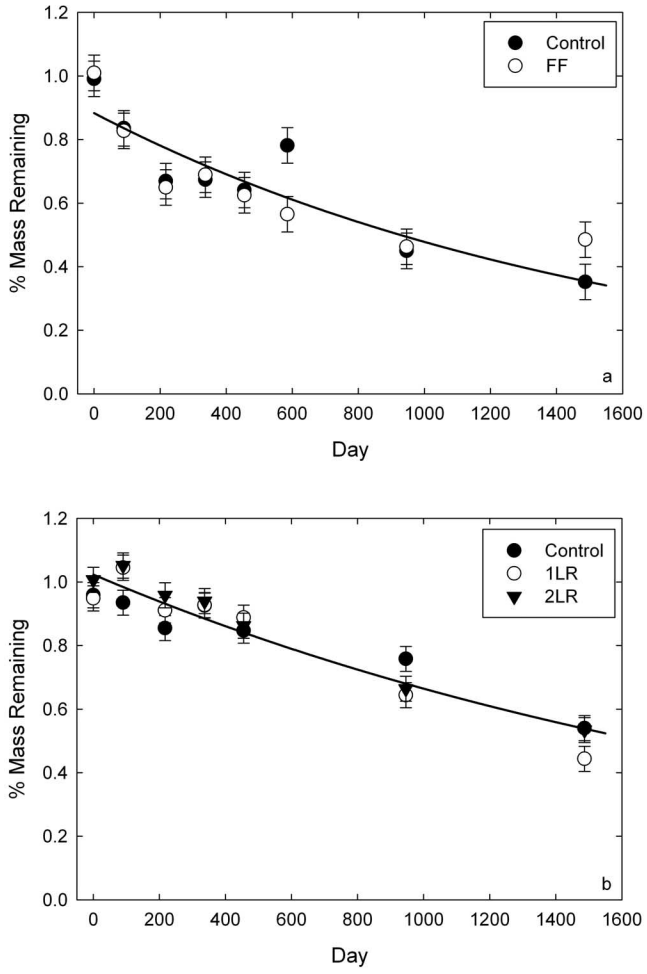

Figure 3. Decomposition of incorporated (a) forest floor (FF) and (b) logging residues (LR) in loblolly pine as measured by %C mass remaining during the first 4.5 years of stand establishment. Values are LSMEANS ± 1 SE ($n = 3$), where se is the square root of the model mean square error divided by the treatment sample size. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

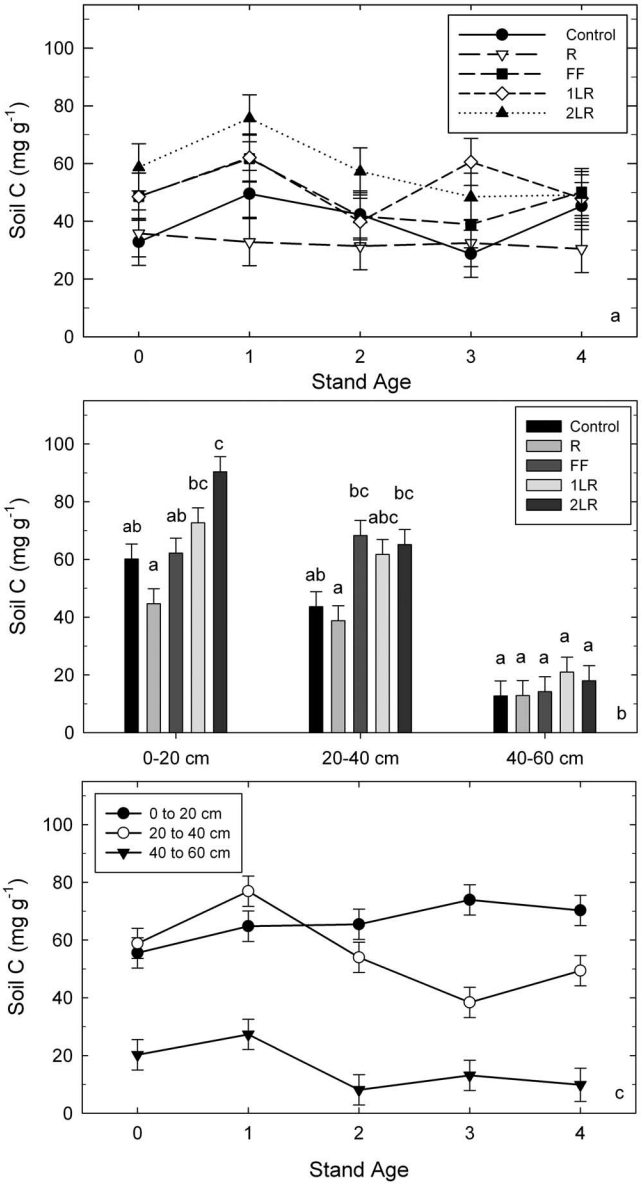

Figure 4. Variation mineral soil carbon (C, < 2 mm) in the bedded rows for (a) mean ($n = 3$) annual total soil C down to 60 cm, (b) mean soil C by depth averaged across all years, and (c) mean annual soil C by depth averaged over all treatments. Values are LSMEANS ± 1 SE ($n = 3$), where SE is the square root of the model mean square error divided by the treatment sample size. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added. In b, bars within a depth with a different letter are significantly different at $\alpha = 0.05$.

mean residence time for 99% of the original litter mass was 20.4 and 35.4 years for FF and LR, respectively.

Bed Mineral Soil C and N

Residue treatments had a significant effect on total soil bulk density in the beds ($P = 0.003$); however, there was no significant depth ($P = 0.54$) or treatment × depth interaction ($P = 0.56$). Soil bulk density, averaged across the 0–40 cm depth in the beds (zones A and B), was 1.21, 1.21, 0.95, 1.06, and 0.95 g cm^{-3} (SE 0.05), in the control, R, FF, 1LR, and 2LR treatments, respectively. There were no significant treatment effects on bulk density in the interrow ($P = 0.97$, 1.10 g cm^{-3}) or trough ($P = 0.09$, 1.38 g cm^{-3}).

The FF, 1LR, and 2LR treatments significantly increased mineral soil C concentration relative to that with the control and R treatments (Table 1). Soil C concentration varied with stand age, but there were no treatment × age (Figure 4a) or treatment × age × depth interactions. Soil C concentration decreased with soil depth, and there was a significant treatment × depth interaction (Figure 4b). Most of the response in FF, 1LR, and 2LR treatments occurred in the 0–20 and 20–40 cm depths. When averaged over the 5-year sampling, the FF, 1LR, and 2LR treatments increased soil C concentration in the 60-cm soil profile by 24–49% compared with the control and R treatments (Table 2). The R treatment reduced soil C concentration 17% relative to the control; however, this difference was not significant ($P = 0.25$). Similar to COF, there was a depth × age interaction for soil C concentration (Figure 4c). This was caused in part by an increase in C content in the 0–20 cm depth and a

Table 2. Mineral soil C and N concentration and content in the 0–60 cm profile in the beds.

	C		N	
Treatment*	mg g^{-1}	kg m^{-2}	mg g^{-1}	kg m^{-2}
Control	38.8 ab	27.7 ab	1.23 ab	0.88 a
R	32.1 a	22.9 a	1.03 a	0.73 a
FF	48.2 bc	27.9 ab	1.51 b	0.87 a
1LR	51.8 c	33.1 b	1.51 b	0.97 a
2LR	57.8 c	33.5 b	1.57 b	0.92 a
SE	3.1	2.3	0.10	0.08

Data are averaged over the first 5 years (years 0–4) of stand development. Values within a column followed by a different letter indicate significant difference at $\alpha = 0.05$. Data are LSMEANs and SE, where SE is the square root of the model mean square error divided by the treatment sample size.
* Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

decrease in the 20–40 and 40–60 cm depths. After correction for treatment effects on soil bulk density, the 1LR and 2LR treatments increased bed soil C content ≈45% relative to that with the R treatment; however, there were no differences in soil C content among control, FF, 1LR, and 2LR treatments (Table 2).

There was a significant residue treatment, depth, and depth × age effect on soil N concentration (Table 1). The FF, 1LR, and 2LR treatments increased soil N concentration, but the increase was only significant relative to that with the R treatment ($P < 0.05$) (Table 2). Relative to the R treatment, the FF, 1LR, and 2LR treatment increased soil N concentration by 47, 47, and 52%, respectively. Similar to soil C, soil N increased in the 0–20 cm depth and decreased in the 20–40 and 40–60 cm depths (data not shown). There were no significant treatment effects on soil N content (Tables 1 and 2). Despite large treatment effects on soil C and N, there were no treatment, age, depth, or interaction effects ($P > 0.05$) on soil quality as measured (Table 1) by soil C/N ratio. Treatment mean soil C/N ratio was 34.6, 36.8, 40.5, 58.8, and 42.3 (±9.4) for control, R, FF, 1LR, and 2LR, respectively.

Soil samples from the 0–20 cm depths were analyzed further for C and N concentrations of macro-organic matter in the light, medium, and heavy density fractions (150–2,000 μm). Soil C in these fractions comprised 60–80% of total soil C, of which the heavy fraction contained the most C (47–58%). There were no significant treatment × age interactions for C or N in the light (C: $P = 0.50$; N: $P = 0.57$) and medium (C: $P = 0.51$; N: $P = 0.54$) fractions; however, there was a marginal interaction for C ($P = 0.08$) and a significant interaction for N ($P = 0.04$) in the heavy fraction as a result of large year-to-year variation (data not shown). When averaged across all years, the 2LR treatment increased soil organic C relative to that for the control by 148, 85, and 43% in the light, medium, and heavy density fractions, respectively (Table 3). The FF treatment elevated C in all fractions, but this was only significant compared with the R treatment in the medium density fraction. The R treatment reduced C by 38, 37, and 25% relative to that for the control in the light, medium, and heavy fractions, respectively, but the difference was not significant ($P > 0.05$). Similar treatment trends were observed for soil N; however, significant differences were only observed between 2LR, FF versus R, and 1LR, 2LR versus R in the medium and heavy fractions, respectively. The LR treatments significantly increased the C/N ratio (i.e., decrease in quality) in the light and medium fractions; however, there was a significant treatment × age effect for C/N ratio in all three density fractions (light: $P = 0.001$; medium: $P = 0.001$, heavy: $P = 0.025$). This was caused by increases in C/N ratio in the 1LR and 2LR treatments, which were most noticeable in the light fraction (Figure 5a); however, the LR treatments also increased C/N ratio in the

Table 3. Mass of C and N in light, medium, and heavy soil macro-organic matter (150–2000 μm) fractions in the top 20 cm of soil in the beds averaged over the first 5 years (years 0–4) of stand development.

Treatment*	Light	SE	Medium	SE	Heavy	SE
Carbon OM fraction (g C kg $soil^{-1}$)						
Control	3.89 ab		7.95 ab		16.45 ab	
R*	2.43 a		4.97 a		12.31 a	
FF	5.95 abc	1.04	11.75 bc	1.45	15.85 ab	1.84
1LR	7.03 bc		11.08 bc		21.32 bc	
2LR	9.65 c		14.68 c		23.58 c	
Nitrogen OM fraction (mg N kg $soil^{-1}$)						
Control	109.3 a		226.3 ab		500.1 ab	
R	57.3 a		126.8 a		375.2 a	
FF	149.0 a	23.9	333.3 b	34.7	488.0 ab	57.4
1LR	139.9 a		270.3 ab		653.6 b	
2LR	149.2 a		299.3 b		681.6 b	
C/N ratio						
Control	39.1 a		35.8 a		33.5 a	
R	43.2 a		39.1 ab		33.4 a	
FF	40.1 a	2.57	36.2 a	1.29	32.8 a	1.07
1LR	56.3 b		41.9 b		33.5 a	
2LR	69.2 c		49.4 c		35.9 a	

Values within a column followed by a different letter indicate significant difference at $\alpha = 0.05$. Data are LSMEANs and SE, where SE is the square root of the model mean square error divided by the treatment sample size. OM, organic matter.
* Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

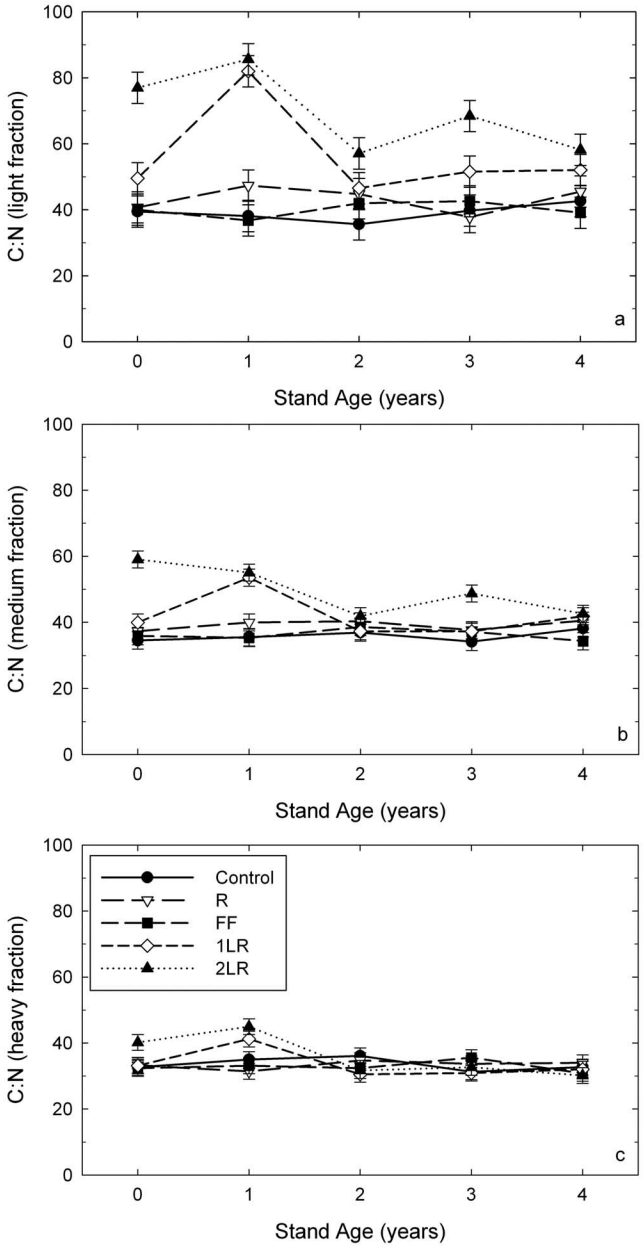

Figure 5. Variation in the mean annual C/N ratio of the (a) light, (b) medium, and (c) heavy macro-organic matter density fractions (150–2,000 μm). Values are LSMEANS ± 1 SE (n = 3), where SE is the square root of the model mean square error divided by the treatment sample size. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

medium and heavy fractions primarily during the first 2 years (Figure 5b and c).

Tree Growth

Treatment had no effect on seedling survival, which exceeded 95% on all plots after the first year. At age 6, mean height was 11.9, 11.9, 12.8, 12.1, and 11.6 m (SE ±0.18) and mean stem diameter was 13.6, 13.5, 14.5, 13.8, and 13.6 cm (±0.26) for the control, R, FF, 1LR, and 2LR treatments, respectively. There was a strong treatment × age interaction on tree height (P = 0.004), stem diameter (P = 0.007), stand volume (P = 0.013), and annual volume increment (P = 0.029) during the first 6 years of stand development. This interaction was caused by a differential growth response of the FF and LR treatments over time. Initially, the FF treatment had a large positive effect on volume growth, resulting in 18% more standing volume at age 6 than in the control treatments (Figure 6a and b); however, volume increment in the FF treatment declined with time and by age 6 was similar to that of the control (Figure 6c and d). In contrast, LR treatments initially decreased volume growth. In year 2, stem volume increment was 90 and 63% of control in 1LR and 2LR treatments, respectively (Figure 6b). Volume increment then increased with stand age relative to that for the control and at age 6, there was no significant difference in standing volume among 1LR, 2LR, and control treatments (Figure 6a and b). Removal of the forest floor had no effect on volume (R versus C, P = 0.89) or volume increment (P = 0.68), although volume increment appeared to be declining with time relative to that for the control (Figure 6d). At age 6, stand volume was 116.6, 112.6, 135.1, 116.0, and 112.3 (SE 3.6) m^3 ha^{-1} in the control, R, FF, 1LR, and 2LR treatments, respectively.

The FF treatment increased the number of trees in the larger size classes and decreased plot variation (Figure 7). Of stems, 55% were in the 15 cm or larger size classes in the FF treatment compared with 37 and 36% in the control and 2LR treatments, respectively. The average (n = 3) within-treatment coefficient of variation for stem diameter was 15.4, 12.8, 8.9, 12.2, and 14.0 cm for the control, R, FF, 1LR, and 2LR treatments, respectively.

Stand Biomass C and Production

As with tree volume response, there were treatment × age effects on stem (P = 0.006) growth and annual stem biomass C increment (P = 0.001). Stem biomass C was greatest in the FF treatment and lowest in the 2LR treatment (Figure 8a). In the first 2 years of stand growth, stem biomass C increment was greater in the FF and lower in the 1LR and 2LR treatments relative to that for the control (Figure 8b). By age 4, the FF treatment still had higher stem growth, but there was no significant difference in stem growth among the other treatments. Similar responses were observed in branch and foliar growth dynamics (data not shown). Age 4 total standing aboveground biomass C was 11.3, 11.1, 13.3, 10.6, and 10.0 (SE 0.67) Mg C ha^{-1} for control, R, FF, 1LR, and 2LR treatments, respectively (Table 4).

Treatment and treatment × age effects on taproot biomass were similar to those observed for stem biomass (data not shown). In contrast, there were no treatment or treatment × age effects on small or coarse root biomass. Treatment had a strong effect on root distribution in the beds (treatment × depth: $P < 0.0001$ for small and coarse roots) (Figure 9a and b). Small and coarse root biomass decreased with depth in the control and R treatments. However, in the FF, 1LR, and 2LR treatments, small and coarse root biomass in the 20–40 cm depth was equal to or exceeded

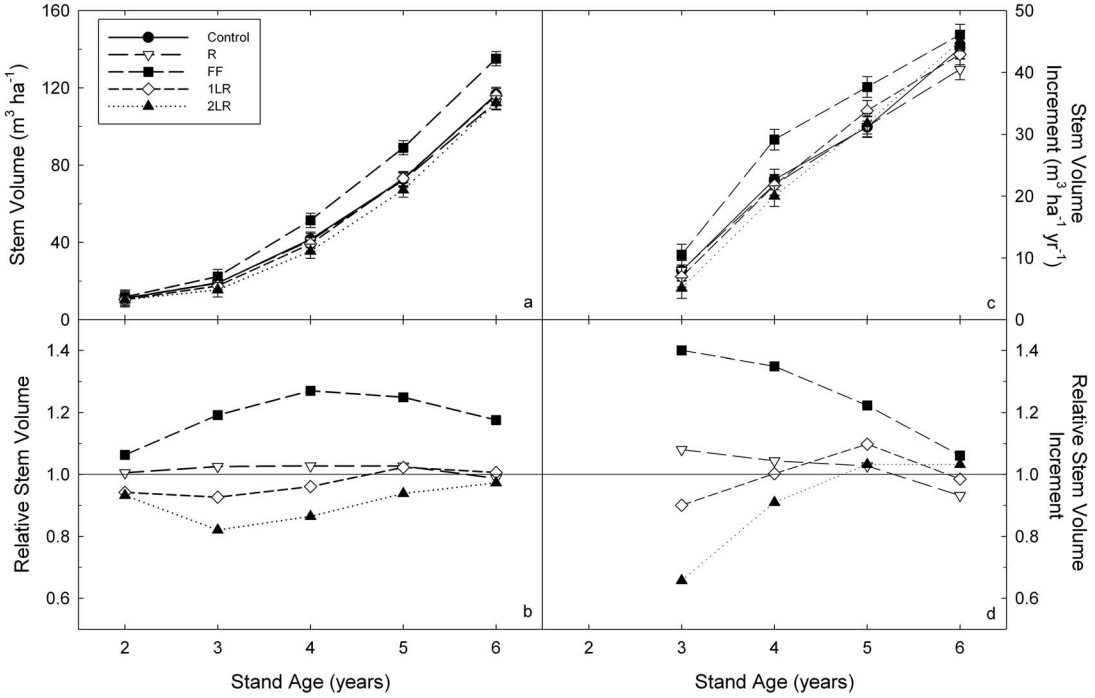

Figure 6. Influence of organic matter treatment on (a) annual stem volume, (b) treatment stem volume relative to the Control treatment, (c) annual stem volume increment, and (d) treatment volume increment relative to the Control. Values are LSMEANS ± 1 SE ($n = 3$), where SE is the square root of the model mean square error divided by the treatment sample size. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

biomass in the upper 20 cm for both root classes. At age 4, small root biomass at 20–40 cm depth was 33, 30, 44, 42, and 42% of total small root biomass for the control, R, FF, 1LR, and 2LR treatments, respectively. Treatment effects on coarse root biomass distribution at 20–40 cm depth were more evident, contributing 39, 19, 72, 64, and 51% of the total coarse root biomass.

At age 4, C in total tree biomass (above- and belowground) was 16.3, 15.1, 19.3, 15.9, and 13.9 (SE 1.08) Mg C ha^{-1} in the control, R, FF, 1LR and 2LR treatments, respectively (Table 4). Despite the large differences in biomass accumulation, treatment effects on above- and belowground biomass distribution were small. Averaged across treatments, foliage, stem, and branch composed 20, 61, and 18%, respectively, of total aboveground biomass. Taproot, coarse roots, and small roots made up 31, 43, and 25%, respectively, of belowground pine biomass. Belowground biomass comprised between 29 and 36% of total pine biomass.

Ecosystem Carbon at Age 4

Stand C stocks in living biomass, detritus, and soil were estimated for year 4 (Table 4). Belowground C in roots, detritus, and soil was estimated separately for beds, trough, and interrow and then was adjusted for the relative coverage for each region (Figure 1). There were no significant residue treatment effects on soil C in the 0–20 cm depth for the interrow ($P = 0.33$) or trough ($P = 0.34$). Soil C stocks were estimated for the 100-cm profile by taking additional soil samples at the 60–80 cm and 80–100 cm depths in the beds. There were no significant residue treatment effects on soil C at these depths (60–80 cm: $P = 0.71$; 80–100 cm: $P = 0.82$); therefore, these measurements were used to estimate C contents at the corresponding depths in the trough and interrow regions (Figure 1). Dead taproot biomass was ≈ 7.9 Mg C ha^{-1} at age 4 and is included in the detritus pool (Table 4).

Total ecosystem C ranged from 186 Mg C ha^{-1} in the R treatment to 265 Mg C ha^{-1} in the 2LR treatment, and this difference was significant ($P = 0.003$). There were significant treatment effects on living biomass C ($P = 0.039$) and detritus ($P = 0.002$), but not in the mineral soil ($P = 0.082$). Mineral soil C was the largest pool and ranged from 155 Mg C ha^{-1} in the R treatment to 194 Mg C ha^{-1} in the 1LR treatment and was 71 to 81% of the ecosystem C stock. Carbon in coarse organic fragments accounted for 4 to 18% of ecosystem C. Detrital C pools were similar among treatments and accounted for ≈10% of ecosystem C. At age 4, C in living vegetation accounted for only 5% of ecosystem C in the 2LR and 9% in the FF treatment. Of the vegetation C, 95% was in pine biomass.

Discussion

Soil Carbon and Nutrients

Incorporating forest residues into the beds resulted in a significant increase in mineral soil C concentration and content. Compared with the control, the FF and LR treatments increased bed soil C concentration and content 20–50%, with most of the response in the 0–20 and 20–40

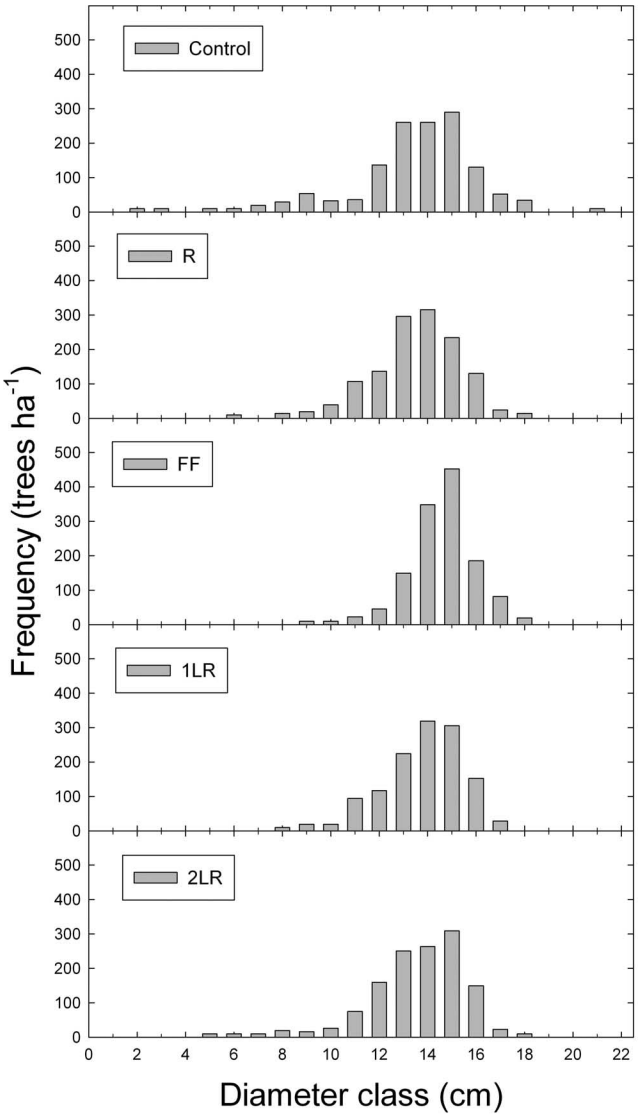

Figure 7. Diameter distribution of 6-year-old loblolly pine stands in response to incorporated organic matter treatment. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

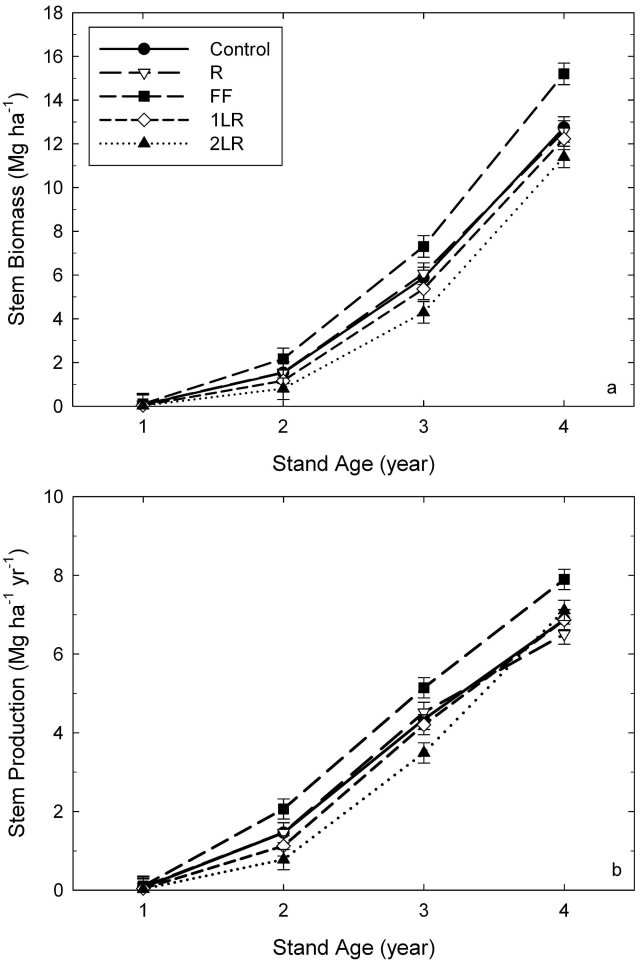

Figure 8. Influence of organic matter treatment on (a) standing stem biomass and (b) current annual increment. Values are LSMEANS ± 1 SE ($n = 3$), where SE is the square root of the model mean square error divided by the treatment sample size. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

cm soil depths. This was due to the bedding operation that concentrated residues (i.e., COF) in the top 40 cm. Although not significant, bed volume was approximately 26% larger in the 1LR and 2LR treatments, so the soil C content estimates are probably conservative. There was a significant depth × age effect, where soil C concentration increased in the 0–20 cm depth and decreased in the 20–40 and 40–60 cm depths. Carbon inputs from the litter treatments and developing root system probably contributed to soil C increases observed near the surface, whereas decomposition contributed to C loss at deeper depths. However, these patterns must be interpreted with caution because the beds probably settled over time, making interannual comparison for a particular depth equivocal.

Although the FF and LR treatments increased total soil C in the short term, it is not clear whether the treatments will lead to long-term retention in stabilized recalcitrant forms (Sanchez et al. 2007). Because of a warm and humid climate and highly weathered soils, forest soils in the southern United States are thought to have low potential to accumulate C (Richter et al. 1999) relative to that of soils in other regions and forest types (Busse et al. 2009). However, soil C dynamics are site-specific, influenced by soil drainage, texture, and mineralogy (Six et al. 2002) as well as management (i.e., species, site preparation, and vegetation control) (e.g., Vogel et al. 2011). If the exponential decay model is assumed to depict the long-term decay process, the mean residence time for incorporated FF or LR was 20 and 35 years, respectively, indicating that this material will affect soil C stocks for most of the rotation life of the current stand. Treatment had no effect on decomposition within a residue type (FF versus control or LR versus control); however, treatments did affect N and P mineralization (Tisdale 2008). The k value for FF (0.23 years^{-1}) is lower than the 0.29–0.47 year^{-1} reported for loblolly pine foliage and other needle conifers (Cortina and Vallejo 1994,

Table 4. Stand carbon stocks (Mg C ha^{-1}) at age 4 compared with the previous stand at harvest age 21 years.

Component	Treatment*					SE	Previous
	Control	R	FF	1LR	2LR		
Soil							
Bed	282.6 ab	236.6 a	286.4 ab	336.6 b	339.7 b	22.9	
Trough	44.5 a	50.0 a	52.8 a	57.2 a	49.1 a	6.6	
Interrow	135.2 a	131.5 a	135.5 a	126.7 a	115.9 a	12.5	
Total soil	171.1 a	154.6 a	175.0 a	194.0 a	189.6 a	10.3	136.5
Detritus							
COF	13.1 a	7.9 a	16.4 a	21.6 a	50.7 b	5.6	
Other detritus	10.0 a	9.1 a	10.1 a	10.2 a	11.0 a	0.46	
Total detritus	23.1 a	17.0 a	26.6 a	31.8 a	61.7 b	5.60	23.5
Living biomass							
AG pine	11.3 ab	11.1 ab	13.3 a	10.6 ab	10.0 b	0.67	
BG pine	5.1 a	4.1 a	6.0 a	5.3 a	3.9 a	0.6	
Total pine	16.3 ab	15.1 ab	19.3 a	15.9 ab	13.9 b	1.1	149.9
Other vegetation (AG + BG)	1.0 a	0.6 a	0.9 a	0.7 a	0.5 a	0.2	
Total living	17.3 ab	15.7 ab	20.2 a	16.6 ab	14.4 b	1.2	
Total stand	211.5 ab	185.6 a	221.8 abc	242.3 bc	265.7 c	10.8	309.9

Living biomass C is partitioned into aboveground (AG) and belowground (BG) pine and other vegetation. Soil C estimates are partitioned into bed, trough, and interrow and are the total based on 100-cm depth from the top of the beds. Total soil C estimates are adjusted for the relative coverage per hectare of the bed, trough, and interrow. Values within a row followed by a different letter indicate significant difference at $\alpha = 0.05$. Data are LSMEANs and SE (except for Previous), for which SE is the square root of the model mean square error divided by the treatment sample size.

* Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

Piatek and Allen 2001, Sanchez and Eaton 2001), but similar to that reported for early-rotation slash pine stands (Gholz et al. 1985). The difference was probably due to the bags being buried in the mineral soil rather than in the forest floor, suggesting that incorporating organic matter into the soil slowed its decomposition.

Laiho et al. (2003) found that forest floor and slash decomposition was greater after harvest for a poorly drained loblolly pine stand that experienced a wet growing season than for a well-drained site, drier site; however, the well-drained site had higher soil C loss. They concluded that sites with poor drainage and wet growing season conditions will impede soil C loss but may accelerate decomposition of residues left on the soil surface. Our study site had a high and fluctuating water table that approached the soil surface after harvesting (Pritchard et al. 2010). It is likely that poor drainage will impede the decomposition of incorporated residues at least during early stand development.

Reliance on total soil C as an indicator of environmental change may mask significant alterations in the labile and recalcitrant C pools that could have short- and long-term effects on nutrient supply, productivity, and C sequestration (Neff et al. 2002, Sarkhot et al. 2008). Carbon in macro-organic matter (i.e., 150–2,000 μm) made up 60–80% of total soil C. Most of the increases in mineral soil C in the FF, 1LR, and 2LR treatments came from large increases (>40%) in the light and medium density fractions. Although the turnover times for the labile lighter fractions are relatively short, increases in these fractions from mulching are important for nutrient cycling and stand productivity (Wander et al. 1994, Six et al. 2002) and for soil C sequestration. For example, in a coastal plain loblolly pine plantation mineral soil C in the top 30 cm of soil increased by 4-fold over preharvest levels within 5 years after planting before slowly decreasing back to baseline levels 12–16 years later (Powers et al. 2004, Johnsen et al. 2004). This temporary increase in soil C was probably a result of decomposition of fine and coarse roots rather than of decomposition of surface residues (Powers et al. 2004). Although this increase in "labile" soil C was ephemeral, it represented short-term C sequestration and should be considered when C budgets are developed (Maier and Johnsen 2010).

The increase in heavy fraction C in the 1LR and 2LR treatments suggests a potential to accrue C in partially stabilized organo-mineral complexes and aggregates (Meijboom et al. 1995) that could promote long-term C retention (i.e., decades to centuries) (Hassink 1995). The increase was associated with a large increase in soil calcium (Ca) in the LR treatments (unpublished data). The soil base cation concentration, especially Ca, helps stabilize soil C by protecting it from oxidation (Oades 1988). The increase in C in the heavy fraction also indicates that soils at our site are not C-saturated (Six et al. 2002). Soil texture has considerable control over the retention of organic C through chemical, physical, and biochemical stabilization (Six et al. 2002). Loamy or clay soils can stabilize C in organo-mineral complexes and aggregates, which is readably lost in sandy soils (Christensen 2001). Our results may not occur on sites with loamy or clay soils saturated in C or on sandy soils that have a low capacity to stabilize C (Busse et al. 2009).

Stand Development

Early tree height growth, 12–13 m at age 6, is one of the highest reported for nonfertilized loblolly pine in the southern United States (Borders and Bailey 2001, Samuelson et al. 2004). Residue treatment had a differential effect on early stand growth that was probably due to treatment

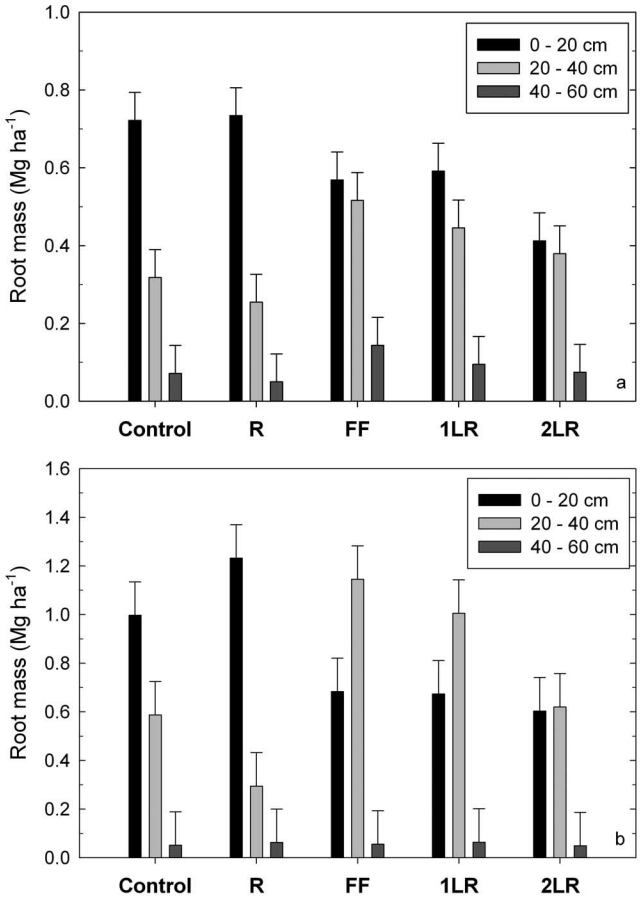

Figure 9. Distribution of (a) small (< 2 mm) and (b) coarse (> 2 mm) roots in the beds by soil depth and treatment at age 4. Values are LSMEANS ± 1 SE (n = 3), where SE is the square root of the model mean square error divided by the treatment sample size. Treatments: Control, forest floor left intact, R, 25 Mg ha^{-1} forest floor removed (raked), FF, 25 Mg ha^{-1} forest floor added, 1LR, 25 Mg ha^{-1} logging residue added; 2LR, 50 Mg ha^{-1} logging residue added.

differences in N availability. The doubling of forest floor in the FF treatment applied roughly 272 kg N ha^{-1} to the soil, similar to N fertilization rates at planting (McKeand et al. 1999). This additional N coupled with high N mineralization (Tisdale 2008) led to the FF treatment having 18 m^3 ha^{-1} more aboveground volume than the control at age 6. The benefits of adding forest floor were greatest during the first 3 years of stand growth, after which current annual increment began to decline. Increased volume growth in the FF treatments was accompanied by increased stand uniformity, i.e., more trees in the higher diameter classes. Although the benefits of the FF treatment on volume increment diminished with time, stand homogeneity with respect to size distribution allowed for high stand-level light use efficiency (Binkley et al. 2010), so these treatments will probably have greater stand-level production long after the direct treatment response has disappeared.

Reduced tree growth in the 1LR and 2LR treatments was probably a result of treatment-induced N immobilization (Tisdale 2008). Reduced N availability in the LR treatments was also reflected in increased C/N ratio of the light and medium macro-organic matter fractions above the level N mineralization occurs (30–40:1) (Janssen 1996) (Figure 5). The effect of N immobilization was short-lived because annual volume increment in the 1LR and 2LR treatment increased relative to that of the control and by age 6, there were no differences in stand volume between these treatments. The removal of forest floor in the R treatment had no significant effect on stand volume growth; however, annual volume increment in the R treatments declined relative to that of the control (Figure 6d). This result, coupled with 17% less soil C and 16% less soil N in the beds, suggests that soil N limitations may be beginning in R treatments. Collectively, these data highlight the importance of maintaining the forest floor intact for promoting early stand growth and sustaining productivity in intensively managed plantations (Smith et al. 2000, Laiho et al. 2003, Mendham et al. 2003, Zerpa et al. 2010).

In the control and R treatments, most of the small and coarse roots were distributed in the surface 20 cm of soil, which is consistent with other studies in young developing loblolly pine stands (Retzlaff et al. 2001, Adegbidi et al. 2004). In contrast, roots distribution in the FF, 1LR, and 2LR treatments in the 20–40 cm depth was equal to or greater than that in the top 20 cm. This corresponds with the distribution of COF and mineral soil C observed in these treatments (Figures 2 and 4). The long-term consequences of this differential root distribution on stand growth and soil C storage is unknown, but deeper root development may confer advantages in the future through increased nutrient and water availability (Sanchez et al. 2007). In addition, C mineralization declines with soil depth, so deeper belowground allocation and soil C input should prolong decomposition, resulting in a decrease in the decay rate for soil C (Jandl et al. 2007). Despite differences in root distribution, there were no treatment effects on above- and belowground partitioning, which was 64–71% and 29–36%, respectively, of total biomass. These values are consistent with those in other studies that had much larger treatment (i.e., fertilization)-induced differences in growth (Albaugh et al. 1998, Samuelson et al. 2004) and indicate that loblolly pine has a fixed structural biomass allocation that is only slightly affected by site resource availability (Retzlaff et al. 2001).

Ecosystem Carbon at Age 4

The lack of treatment effects on stand soil C is not surprising, given that the residue treatments were confined to the bedded rows, which covered only 41% of the surface area in the treatment plot (Figure 1). Residue treatments had no effect on soil C in the nontreated troughs and interrows ($P > 0.05$), so including these areas diluted the significant treatment response measured in the beds. Despite the lack of treatment effects on stand soil C, there were significant treatment effects on the distribution of C in detritus and biomass. Carbon in COF accounted for 5–20% of total soil C at age 4. Coarse organic fragments can account for a significant portion of soil C in forest soils (Bauhus et al. 2002, Busse et al. 2009, Zabowski et

al. 2011) and should be included in the stand C budget (Homann et al. 2004).

Harvesting or site preparation operations that remove or destroy the residual forest floor can reduce mineral soil C in the surface horizons (Powers et al. 2005, Jones et al. 2008). The decline in soil C generally occurs during first 5 years after harvest (Gholz and Fisher 1982, Smethurst and Nambiar 1990) and is thought to be a result of a combination of reduced input of labile C from living roots (Vogel et al. 2011) and increased decomposition (Johnson and Curtis 2001, Guo and Gifford 2002). In contrast, our study found that mineral soil C increased after harvest. Four years after harvest, soil C in the control and R treatment increased by 24 and 11%, respectively, over preharvest levels (Table 4), which was probably due to bedding operations that incorporated the residual forest floor into the soil and to inputs from decomposing root systems (Sanchez et al. 2003).

Accumulation of C in this fast growing clonal plantation over a 20- to 25-year rotation should exceed that of the previous stand. Using preharvest stand inventory and soil C measurements, we estimated that the C stock of the previous stand at harvest (age 21) was 310 Mg C ha^{-1}, of which 48% was in aboveground pine biomass (150 Mg C ha^{-1}) (Table 4). Based on early height growth, yield projections for the clone used in this study suggest that the control treatment will accumulate 150 Mg C ha^{-1} in aboveground biomass in 13–15 years, much sooner than achieved by the previous stand (unpublished data). Potential increases in forest floor litter and root biomass will increase soil C inputs. Even if not stabilized in organo-mineral complexes, increased C inputs should help sustain long-term site productivity (Zerpa et al. 2010). Although a possible long-term consequence is the gradual incorporation of C in the mineral-stabilized C pool (Jandl et al. 2007), we caution that the C dynamics explored here are based on one loblolly pine clone on one site. The clone used in this study is a fast-growing clone that is highly responsive to silvicultural treatment (Tyree et al. 2009). The potential gain in ecosystem C from accelerated growth may not be realized in a less responsive clone (McKeand et al. 1997).

Summary

Our results suggest that incorporating additional forest floor or masticated logging residues can have positive benefits to pine productivity and cause the buildup of soil C even on sites with relatively high inherent soil C stocks. The impact of the residue treatments on tree growth and ecosystem C storage changed over time and was linked to the quality and quantity of residue material. The addition of high-quality organic matter in the FF treatment increased early stand productivity. Although the benefits appear to be short-lived, the increase in early growth coupled with increased stand homogeneity will probably sustain increased volume well into the future. Addition of low-quality LR initially suppressed pine productivity in the 1LR and 2LR treatments, but by year 6, increment growth in these treatments very nearly equaled increment growth in the control. Increased mineralization of LR may continue to benefit growth in these treatments.

Although the long-term treatment effects on soil C are unknown, increased macro-organic matter in the recalcitrant heavy fraction and estimated 20- to 30-year turnover rate for incorporated residues suggest that soil C will be elevated in the FF and LR stands at least through the current rotation.

The efficacy of organic matter management will be site-dependent. Incorporation of large amounts of nutrient-poor biomass will have to be weighed against the inherent nutrient availability of the site and the nutrient requirements of the planted stock to prevent severe nutrient immobilization. Proper management of forest residues including chipping and incorporation could contribute to maintaining or increasing early productivity by limiting nutrient losses and facilitating better synchronization between stand nutrient uptake and nutrient release. However, the long-term impact of the residue treatments on productivity and soil C sequestration needs to be determined so that other forest management practices, such as fertilization, can be integrated with residue management.

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