2013

# Soil carbon and nitrogen content and stabilization in mid-rotation, intensively managed sweetgum and loblolly pine stands

Kurt H. Johnson
*USDA Forest Service, Southern Research Station*, kjohnsen@fs.fed.us

Lisa J. Samuelson
*School of Forestry and Wildlife Sciences, Auburn University*

Felipe G. Sanchez
*USDA Forest Service*

Robert J. Eaton
*USDA Forest Service, Southern Research Station*

Forest Ecology and Management 302 (2013) 144–153

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Soil carbon and nitrogen content and stabilization in mid-rotation, intensively managed sweetgum and loblolly pine stands

Kurt H. Johnsen [a,*], Lisa J. Samuelson [b], Felipe G. Sanchez [c], Robert J. Eaton [a]

[a] USDA Forest Service, Southern Research Station, 3041 Cornwallis Road, Research Triangle Park, NC 27709, United States
[b] School of Forestry and Wildlife Sciences, Auburn University, 3301 SFWS Building, Auburn, AL 36849, United States
[c] USDA Forest Service, 201, 14th Street SW, Mail Stop 1120, Washington, DC 20250, United States

ARTICLE INFO

*Article history:*
Received 15 October 2012
Received in revised form 11 March 2013
Accepted 14 March 2013
Available online 27 April 2013

*Keywords:*
Soil C
Soil N
Stabilization, forest productivity
Loblolly pine
Sweetgum

ABSTRACT

Intensive forestry has resulted in considerable increases in aboveground stand productivity including foliar and belowground biomass which are the primary sources of soil organic matter. Soil organic matter is important for the maintenance of soil physical, chemical and biological quality. Additionally, sequestering carbon (C) in soils may provide a means of mitigating increasing atmospheric carbon dioxide concentrations. In this study, we examined soil C and nitrogen (N) contents and stabilization in 12-year-old, intensively managed sweetgum (*Liquidambar styraciflua* L.) and loblolly pine (*Pinus taeda* L.) stands. The treatments examined include: (1) complete weed control; (2) weed control plus drip irrigation; (3) weed control plus drip irrigation and fertigation; and (4) (pine only) weed control plus irrigation, fertigation, and pest control. C and N stabilization was analyzed sequentially by fractionating the soil samples into six fractions using solutions of increasing density. These fractions represented increasingly stable organic matter pools. There was a trend towards increasing C and N contents with increasing management intensity that increase stand productivity; however, these differences were only significant for soil C content in sweetgum. Across all the sweetgum plots, soil C content generally increased with basal area (BA); no such relationship was found in loblolly pine although its BA was equal or higher than that of sweetgum. Generally, across all depths most C was found in the two lightest and in the heaviest fractions. These results suggest that changes to soil C due to increased forest management intensity which increases forest productivity, when they did occur, mostly did not change the percentages of C among soil density fractions over the 12 years of the experiment suggesting minimal inputs of recalcitrant C into the soil; however, even these transient changes may be still be important if intensive management is maintained over subsequent rotations.

Published by Elsevier B.V.

## 1. Introduction

Forests sequester carbon (C) occurs both *ex situ* and *in situ* (Johnsen et al., 2001). *Ex situ* C sequestration largely stems from the lifespan of products produced from harvested biomass (Skog and Nicholson, 1998; Skog, 2008). *In situ* C sequestration takes place above- and below-ground and is related to management activities that increase productivity and/or alter C allocation (Johnsen et al., 2001). Such intensive management strategies include activities such as cultivation, understory control, irrigation, fertilization and pest control. These strategies have resulted in considerable gains in forest productivity (Samuelson et al., 2008; Vance and Sanchez, 2006). However, the impact of these forest management strategies on belowground C dynamics is still unclear. In particular, the effect on C contained in soil organic matter is largely unstudied and can be difficult to detect (Johnsen et al., 2004). Besides its role in C sequestration, soil organic matter is critical for the maintenance of soil physical, chemical, and biological quality (Doran and Parkin, 1994; Stevenson, 1994; Jurgensen et al., 1997; Nambiar, 1997; Grigal, 2000). However, the mechanisms that control the internal cycling of soil organic matter are complex with multiple factors acting independently and in concert to impact C sequestration (Stevenson, 1994). Forest soil C levels are predicated by the balance between inputs and losses, which vary by climate, disturbance regime, plant and microbial community composition and activity, soil parent material, and time (Raich and Schlesinger, 1992; Jenny, 1994; Hanson et al., 2000; Ågren et al., 2001).

In forested ecosystems, soil organic matter primarily originates from two sources, forest floor leachates and belowground roots, and their subsequent turnover, both of which are directly affected by the net primary productivity (NPP) of the stand. Generally, with regards to mineral soil C, belowground C inputs outweigh the

* Corresponding author. Tel.: +1 919 549 4012; fax: +1 919 549 4047.
*E-mail address:* kjohnsen@fs.fed.us (K.H. Johnsen).

0378-1127/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.foreco.2013.03.016

contributions from the forest floor. As the forest floor decomposes, C tends to be lost as $CO_2$ and consequently is a minor contributor to mineral soil C pools (Richter et al., 1999; Sanchez et al., 2006). What primarily determines forest soil organic C levels are contributions from roots via fine root turnover. Estimates of the net annual carbon budget of a tree relegated to root growth and maintenance are disputed but range from 20% to 65% (Persson, 1979). Any changes in the amount of C allocated to the root system will coincidently affect the amount of fine root material entering the soil organic matter pool. Fertilization has been shown to decrease loblolly pine fine root biomass (Maier and Kress, 2000) but increase turnover (King et al., 2002) on a nutrient deficient site. Coleman (2007) reported increases in fine root biomass with increasing resource availability for loblolly and sweetgum. Samuelson et al. (2004a, 2008) demonstrated that increasing management intensity on loblolly pine (*Pinus taeda* L.) stands in Georgia increased above- and belowground (coarse root) biomass and foliar biomass in loblolly pine. Similar results were detected by Coleman (2007) in a study examining the effects of irrigation and fertilization on four woody crop species (sweetgum (*Liquidambar styraciflua* L.), loblolly pine, American sycamore (*Platanus occidentalis* L.) and eastern cottonwood (*Populus deltoidies* Bartr.). Thus, any land management that increases NPP, also potentially increases the organic matter input into the soil.

In contrast to mineral soil C, the forest floor is a major contributor to mineral soil nitrogen (N) pools with fine root turnover being the other major contributor (Keeney, 1980; King et al., 2002). Nitrogen can be sequestered in the forest floor (Gholz and Fisher, 1982; Piatek and Allen, 2001; Powers et al., 2005) and is an important nutrient source for forest soils as the litter layer decomposes (Raison et al., 1987; Stump and Binkley, 1993). An exogenous nutrient supply, whether from the forest floor, throughfall, or applied through fertilization, can influence the rate of decomposition and the litter's nutrient release pattern. Fertilization has been found to increase litter decomposition rates (Prescott et al., 1992; White et al., 1988) and N accumulation in decomposing litter (Titus and Malcolm, 1987). Additionally, initial nutrient concentrations in litter, the endogenous nutrient supply, may also influence decomposition and nutrient dynamics. Berg et al. (1987) found that needles with higher initial nitrogen concentrations released N more rapidly but maintained higher N concentrations than needles with lower initial N concentrations. Thus, fertilization, besides increasing the growth of the current rotation, may increase productivity of subsequent rotations increasing C sequestration.

In addition to the simple quantity of soil C and N, its qualitative characteristics are important. By sequentially separating soil organic matter into fractions of increasing density, a profile of C and N stabilization emerges which can be used to better understand effects on soil organic matter in response to forest management activities. As Sollins et al. (2006) hypothesized and displayed, soil organic matter fractions with lower densities are more labile and transient than higher density fractions because higher density fractions "layer" organic matter onto an inner organic layer made up of peptidic and lignin-exchanged carboxylic compounds of which other organic compounds can sorb more readily onto. Using soil collected from a mixed Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) stand, carbon mean residence time increased from ranged from 150 to >950 years from the lightest to the heaviest fractions measured (Sollins et al., 2006). As such, increases in fraction densities represent a gradation from active to passive C pools as described by Parton et al. (1987). Thus, shifts in C and N to higher density soil organic matter fractions indicate a relative stabilization effect, namely increased recalcitrance.

The first objective of this study was to quantify soil C and nitrogen (N) contents in sweetgum and loblolly pine stands under varying degrees of intensive management to determine the impact of management intensity and tree species on soil C and N contents 12 years after planting. A second objective was to explore whether any changes in the soil environment brought on by the treatments resulted in a change in the stabilization of the soil C and N. To determine the relative stability of the C and N stocks for the different treatments and tree species, we sequentially fractionated the soil samples into six fractions of affording differing stability. The study site is unique in that physiology of above and belowground (coarse root) growth of loblolly pine have been monitored for 11 years (Samuelson, 1998; Butnor et al., 2003; Samuelson et al., 2001, 2004b, 2008; Samuelson and Stokes, 2006), but management effects on soil C and N have not been investigated in either species until this point.

## 2. Materials and methods

### 2.1. Site description

In January 1995, International Paper Incorporated established a 15 ha research site in the Upper Coastal Plain (30°82′N, 84°76′W) on previously agricultural land. Mean annual precipitation and 24 hour temperature for the region are 1257 mm and 18.9 °C, respectively (Ruffner, 1980). The soils at the site were classified as sandy loam, well-drained Grossarenic Paleudults. For the native site, site index at base age 25 years was 18 m for loblolly pine.

In August 1994, soils were ripped to a 45 cm depth with a single-shank subsoiler and disc-harrowed the following November to eliminate soil compaction. Herbaceous vegetation was controlled using a broadcast spray of 1.5% (v/v) aqueous glyphosate solution applied in July and September 1994. The sweetgum plots and loblolly pine plots were adjacent to each other and are considered separate experiments. Treatment plots were arranged in randomized complete block designs with four treatments (three for sweetgum) and three replicates (blocks) and, on separate sub-plots, four loblolly pine improved second generation families and two sweetgum provenances. Growth and physiology of loblolly pine family 7–56 has been studied since planting to age 11 (Samuelson et al., 2008) and growth and physiology of one sweetgum provenance was monitored until age 4 (Samuelson et al., 2001). These same sources were examined in this study. Loblolly pine and sweetgum seedlings were assigned to separate 0.20 ha treatment plots within a block and hand-planted at a 2.4 m × 3.7 m spacing in January 1995. The measurement plot per species, family and treatment consisted of 28 trees in pine and 56 trees in sweetgum. Four treatments were applied and randomly assigned to treatment plots within the three blocks. The treatments were:

1. W: complete weed control maintained using a broadcast application of sulfometuron (0.1 kg $ha^{-1}$) and repeated applications of a 15% (v/v) aqueous glyphosate solution.
2. WI: weed control plus drip irrigation (Netafim Irrigation Inc., Altamonte Springs, FL) from March through December. Drip lines ran along tree rows on the south side of each tree.
3. WIF: weed control plus drip irrigation and fertigation (addition of a fertilizer solution to the irrigation water). Addition of fertilizer to the irrigation water began in May and continued through October. Annual applications of water and fertilizer over the first 10 years of the study are shown in Table 1.
4. WIFP: (pine only) weed control plus irrigation, fertigation, and pest control. Fusiform rust (*Cronartium quercuum* f. sp. *Fusiforme* ((Berk.) Miy. *ex* Shirai)) was controlled with applications

**Table 1**
Annual water balance and irrigation additions in WI, WIF and WIFP treatments and fertilizer additions in WIF and WIFP treatments for both sweetgum and loblolly pine (from Samuelson et al., 2008).

| Year | PET (mm) | Precipitation (mm) | Irrigation (mm) | N (kg ha$^{-1}$) | P (kg ha$^{-1}$) | K (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| 1995 | | | 341 | 45 | 11 | 45 |
| 1996 | 944 | 938 | 210 | 87 | 22 | 87 |
| 1997 | 908 | 951 | 266 | 135 | 33 | 135 |
| 1998 | 961 | 997 | 310 | 112 | 20 | 112 |
| 1999 | 833 | 597 | 1127 | 79 | 20 | 79 |
| 2000 | 794 | 614 | 1127 | 79 | 20 | 79 |
| 2001 | 635 | 1014 | 1575 | 111 | 28 | 111 |
| 2002 | 964 | 927 | 1575 | 113 | 28 | 113 |
| 2003 | 876 | 985 | 1575 | 132 | 37 | 132 |
| 2004 | 958 | 927 | 381 | 49 | 12 | 49 |
| 2005 | 943 | 1306 | 1016 | 38 | 10 | 38 |

*Note*: Potential evapotranspiration (PET) and precipitation data were from the Georgia Automated Environmental Monitoring Network (www.GeorgiaWeather.com) for Attapulgus, Georgia, approximately 21 km from the study site. W, weed control; WI, weed control plus irrigation; WIF, weed control plus irrigation and fertigation; WIFP, weed control plus irrigation, fertigation and pest control. Nitrogen was supplied as $NH_4NO_3$ and urea; phosphorus was supplied as $H_3PO_4$; potassium was supplied as $K_2O$. WIPF was not imposed on sweetgum plots.

of triadimefon fungicide from 1995 to 2000. Nantucket pine tip moth (*Rhyacionia frustana* (Cornstock)) was controlled with applications of permethrin or acephate insecticides.

A stand inventory was conducted in 2006 at age 11 and height and diameter at breast height (DBH, 1.37 m) were measured on all sample trees per plot. Data for pine were adapted from Samuelson et al. (2008). For both species, height, DBH and basal area (BA) generally increased with increasing management intensity (Table 2). Cumulative mortality at age 11 was 39, 51, 51 and 141 trees ha$^{-1}$ in the W, WI, WIF and WIFP treatments, respectively (Samuelson et al., 2008). In the sweetgum plots, average cumulative mortality observed at age 11 was 0, 3 and 35 trees ha$^{-1}$ in the W, WI and WIF treatments, respectively. A greater relative impact of management intensity on basal area was observed in sweetgum with basal area nearly tripling from the lowest to highest management intensity. In pine, the WIF and WIFP treatments were not significantly different.

### 2.2. Soil sampling and analyses

Unfortunately, baseline (before the experiments were imposed) soil was not collected. Soil samples were collected in November 2007, when trees were 12 years-old, from the loblolly pine experiment and December 2007 from the adjacent sweetgum experiment. Soil samples were collected with a 2.5-cm corer at 0–5, 5–10, 10–20 and 20–30 cm depths. The samples were collected from five approximately equidistant locations along each of two diagonal transects in each plot. For each plot, the soil samples were composited by depth resulting in two samples (one for each transect) for each depth. All soil samples were air-dried, passed through a 2-mm sieve, and weighed (no coarse fragments were found). Subsamples of the composites were analyzed for total carbon and nitrogen by dry combustion with detection by thermal conductivity (NA 1500 Carlo-Erba CNS, Milan, Italy).

A set of subsamples from the composites were chosen so that each species, treatment, depth combination was represented by at least two different subsamples per composite and separated into six fractions of differing stability using a modification of the procedure described by Sollins et al. (2006). We decided to fractionate by depth as there were significant differences or strong trends in changes in% C and C:N ratio with depth (Tables 3 and 4), both of which can influence fractionation (Sollins et al., 2006). In the modified procedure, sodium polytungstate was substituted with LST Heavy Liquid solution (Central Chemical Consulting, Perth, Australia); however, the five densities used by Sollins et al. (2006) were used for consistency. The soil fractions were based on organic matter flotation in solutions of increasing density (1.65 g cm$^{-3}$, 1.65 g cm$^{-3}$, 1.85 g cm$^{-3}$, 2.00 g cm$^{-3}$, 2.25 g cm$^{-3}$, and 2.50 g cm$^{-3}$), and represent soil fractions with increasingly stable soil organic matter. Fractionation was sequential from lowest to highest density and each solution captures C from the previous density to its density (i.e. fraction 1.65 captures all C that floated in a solution of 1.65 g cm$^{-3}$, the next sequential fractionation captured all C that would float in a solution between 1.65 and 1.85 g cm$^{-3}$, etc.). The sixth fraction reported represents the C remaining following the fifth density fractionation.

A separate set of soil samples were collected for bulk density determinations. These samples were collected from two locations at approximately the center of each plot. The samples were collected with a hammer driven 6.3 × 30 cm soil sampler and soil cores were sectioned into 10 cm increments down to the 30 cm depth. Soil C and N content was estimated using the concentration data and bulk density measures and scaling to Mg ha$^{-1}$.

As the loblolly pine and sweetgum plots were not interspersed but were located adjacent to each other they were analyzed as separate experiments. For each species, the effects of treatment, soil depth, and their interactions on soil C and N parameters and bulk density were tested by two-way analysis of variance (ANOVA) using PROC MIXED (SAS 2002). Means of subsamples per plot were used for statistical analyses. Tukey's Paired Comparison Procedure

**Table 2**
Effects of management treatment on stand structure of 12-year-old loblolly pine and sweetgum.

| | DBH (cm) | Height (m) | Basal area (m$^2$ ha$^{-1}$) |
|---|---|---|---|
| *Sweetgum* | | | |
| W | 10.5 (0.4) a | 9.3 (0.4) a | 11.4 (0.8) a |
| WI | 12.9 (0.7) b | 11.3 (0.7) b | 16.6 (1.8) b |
| WIF | 18.0 (0.2) c | 16.6 (0.2) c | 29.5 (1.0) c |
| $P > F$ | <0.001 | <0.001 | <0.001 |
| *Loblolly pine* | | | |
| W | 20.1 (0.2) a | 16.0 (0.2) a | 29.8 (0.8) a |
| WI | 22.1 (0.2) b | 17.8 (0.2) b | 35.5 (1.5) b |
| WIF | 23.8 (0.1) c | 18.0 (0.2) ab | 41.4 (2.0) c |
| WIFP | 24.2 (0.4) c | 18.6 (0.1) c | 38.4 (1.9) bc |
| $P > F$ | <0.001 | <0.001 | <0.001 |

*Note*: Values are means (SEs). Different letters within the same column indicate significant ($\alpha$ = 0.05) treatment differences. W, weed control; WI, weed control plus irrigation; WIF, weed control plus irrigation and fertigation; WIFP, weed control plus irrigation, fertigation and pest control. WIPF was not imposed on sweetgum plots.

**Table 3**
Means and *p*-values for effects of treatment and soil depth on 12-year-old sweetgum carbon (C) and nitrogen (N) parameters and bulk density.

| Source | Percent C<br>$\bar{X}$ (SE) | C content Mg ha$^{-1}$<br>$\bar{X}$ (SE) | Percent N<br>$\bar{X}$ (SE) | N content Mg ha$^{-1}$<br>$\bar{X}$ (SE) | C:N<br>$\bar{X}$ (SE) | Bulk density g cm$^{-3}$<br>$\bar{X}$ (SE) |
|---|---|---|---|---|---|---|
| *Treatment* | | | | | | |
| W | 4.81 (0.28) | 55.6a (5.3) | 0.20 (0.04) | 2.07 (0.51) | 143 (53.8) | 1.59a (0.03) |
| WI | 6.89 (0.74) | 78.6b (7.0) | 0.27 (0.04) | 2.95 (0.37) | 51 (17.7) | 1.62ab (0.02) |
| WIF | 6.66 (0.44) | 79.0b (7.5) | 0.28 (0.04) | 3.17 (0.37) | 44 (12.2) | 1.63b (0.02) |
| *Depth* | | | | | | |
| 0–5 | | | | | | |
| 5–10 | 7.94a (0.89) | 62.2a (7.1) | 0.37a (0.04) | 2.82ab (0.29) | 24 (2.8) | 1.56a (0.02) |
| 10–20 | 6.05b (0.44) | 47.4b (3.7) | 0.26b (0.04) | 2.00a (0.30) | 72 (49.0) | 1.56a (0.02) |
| 20–30 | 5.60b (0.43) | 90.8c (6.9) | 0.23b (0.04) | 3.56b (0.63) | 88 (38.8) | 1.62b (0.01) |
| | 4.88b (0.35) | 83.8c (6.7) | 0.16b (0.03) | 2.56ab (0.60) | 136 (49.5) | 1.70c (0.03) |
| *P > F* | | | | | | |
| Treatment depth | 0.18 | 0.045 | 0.18 | 0.121 | 0.285 | 0.098 |
| Treatment × depth | 0.001 | <0.001 | <0.001 | 0.02 | 0.12 | <0.001 |
| | 0.32 | 0.49 | 0.503 | 0.657 | 0.557 | 0.585 |

Different letters within the same column (within Treatment or depth effects) indicate significant ($\alpha$ = 0.05) differences between means. W = weed control; WI = weed control, irrigation; WIF = weed control, irrigation, fertilization. Note that estimates of the C:N ratio represent lower bounds as sample values of 0% were considered 0.01%, the detection limit of the C:N analyzer.

**Table 4**
Means and *p*-values for effects of treatment and soil depth on 12-year-old loblolly pine carbon (C) and nitrogen (N) parameters and bulk density.

| Source | Percent C<br>$\bar{X}$ (SE) | C content Mg ha$^{-1}$<br>$\bar{X}$ (SE) | Percent N<br>$\bar{X}$ (SE) | N content<br>Mg ha$^{-1}$ $\bar{X}$ (SE) | C:N<br>$\bar{X}$ (SE) | Bulk density g cm$^{-3}$<br>$\bar{X}$ (SE) |
|---|---|---|---|---|---|---|
| *Treatment* | | | | | | |
| W | 5.48 (0.45) | 64.5 (5.9) | 0.17 (0.05) | 1.77ab (0.61) | 190ab (52) | 1.67 (0.02) |
| WI | 5.34 (0.63) | 60.2 (6.9) | 0.10 (0.04) | 1.03a (0.35) | 316a (57) | 1.60 (0.02) |
| WIF | 5.82 (0.40) | 69.0 (6.7) | 0.18 (0.03) | 2.00ab (0.35) | 136ab (40) | 1.62 (0.02) |
| WIFP | 6.53 (0.67) | 74.4 (7.4) | 0.20 (0.04) | 2.26b (0.42) | 111b (32) | 1.61 (0.03) |
| *Depth* | | | | | | |
| | 7.25a (0.51) | | | | | |
| 0–5 | 6.04b (0.56) | 59.3a (4.3) | 0.25a (0.04) | 2.02 (0.36) | 141 (44.5) | 1.63 (0.01) |
| 5–10 | 5.35bc (0.48) | 49.5a (4.6) | 0.15ab (0.03) | 1.23 (0.24) | 166 (53.9) | 1.63 (0.01) |
| 10–20 | 4.52c (0.34) | 83.8b (7.5) | 0.15ab (0.03) | 2.41 (0.72) | 193 (63.0) | 1.57 (0.03) |
| 20–30 | | 75.5b (5.5) | 0.09b (0.02) | 1.40 (0.28) | 253 (37.6) | 1.68 (0.03) |
| | 0.618 | | | | | |
| *P > F* | <0.001 | 0.639 | | | | |
| Treatment depth | 0.817 | <0.001 | | | | |
| Treatment × depth | | 0.629 | 0.119 | 0.055 | 0.028 | 0.208 |
| | | | 0.005 | 0.144 | 0.327 | 0.093 |
| | | | 0.531 | 0.281 | 0.32 | 0.521 |

Different letters within the same column (within Treatment or depth effects) indicate significant ($\alpha$ = 0.05) differences between means. W = weed control; WI = weed control, irrigation; WIF = weed control, irrigation, fertilization. Note that estimates of the C:N ratio represent lower bounds as sample values of 0% were considered 0.01%, the detection limit of the C:N analyzer.

was used to compare treatment means. A similar ANOVA was conducted for each species to assess treatment effects and their interactions on the percentage of total C in each density fraction. For all ANOVA's effects were considered significant if $P \leqslant 0.05$. The relationships between plot BA and total soil C content were also explored. The relationship for sweetgum was analyzed using a 2 parameter exponential rise to a maximum function: $a(1-\exp(-bx))$ (Sigmaplot 9.01) where $a$ is the intercept, $b$ is the slope, and $x$ is BA. The relationship for loblolly pine was explored using linear and nonlinear regression.

## 3. Results

### 3.1. Sweetgum soil C and N and bulk density

In the sweetgum experiment, the only significant treatment effect was an increase in total soil C content with irrigation, although trends ($P < 0.20$) toward increases in soil C concentration, N and bulk density were observed in response to the addition of irrigation (Table 3). Soil percent C and N were highest at the shallowest depth and similar among deeper depths. Bulk density increased with depth. Carbon content decreased moderately with depth (note: 0–5 cm and 5–10-cm depths must be summed for valid comparisons with lower depths) and N content was lower in the 5–10 cm depth than in the 10–20 cm depth, although considerable total C (83.8 Mg ha$^{-1}$) and N (2.56 Mg ha$^{-1}$) was present at the lowest depth (20–30 cm, Table 3). No significant interactions between treatment and depth were observed for any parameter (Table 4). Across all plots, there was a general non-linear increase in soil C content with increasing BA (Fig. 1).

### 3.2. Loblolly pine soil C and N and bulk density

In the loblolly pine experiment, significant treatment effects were observed for soil N content and the C:N ratio; N content was lower in the WI then WIFP treatment and C:N was higher in the WI than WIFP treatment (Table 4). Soil percent C ($P < 0.0001$) and percent N decreased with depth as did total C content. Total N content decreased with depth. Considerable amounts of total C (75.5 Mg ha$^{-1}$) and N (1.40 Mg ha$^{-1}$) were present at the lowest depth (20–30 cm, Table 4). Soil bulk density generally showed no change with depth (Table 4). No significant interactions between treatment and depth were observed for any parameter (Table 4). Across all plots, there was no relationship between soil C and BA

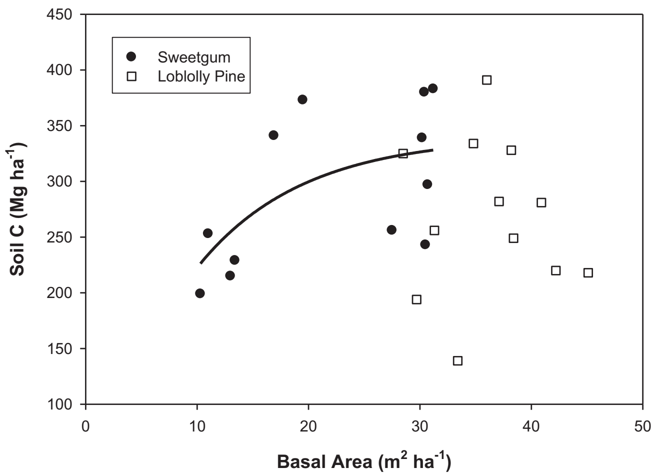


**Fig. 1.** Soil carbon (C) as a function of basal area for 12-year-old sweetgum and loblolly pine plots. The relationship for sweetgum was calculated using a 2 parameter exponential rise to a maximum function: Soil C = $a(1-\exp(-b(\text{basal area})))$. $a$(intercept): $P < 0.001$, $b$(slope): $P = 0.019$, regression $R^2 = 0.40$ and regression $P = 0.029$.

(Fig. 1). Note that virtually all of the lobolly plots have equal or higher BA than the highest BA observed in sweetgum plots.

### 3.3. Sweetgum C and N stabilization

In sweetgum, the percentage of C in the lightest soil fraction increased with management intensity in the 5–10 cm depth but decreased with management intensity in the 2.00–2.25 g $cm^{-3}$ density fraction at the same depth (Fig. 2). In the 0–5 cm depth, irrigation increased the percent of C in the 1.85–2.00 g $cm^{-3}$ density fraction. In the 20–30 cm depth, the percent of total C in the 1.85–2.00 g $m^{-3}$ density fraction was highest in the W treatment. Otherwise no significant effects of treatment on carbon stabilization were observed. Generally, across all depths most C was found in the two lightest and in the heaviest fractions. The only effect of treatment on N stabilization was an increase in percent of total N in the 1.85–2.00 g $cm^{-3}$ density fraction in the 0–5 cm depth in response to irrigation otherwise no clear patterns were observed among treatments in N stabilization (Fig. 3). Very little N was present in the >2.25 g $cm^{-3}$ density fractions across all depths (Fig. 3).

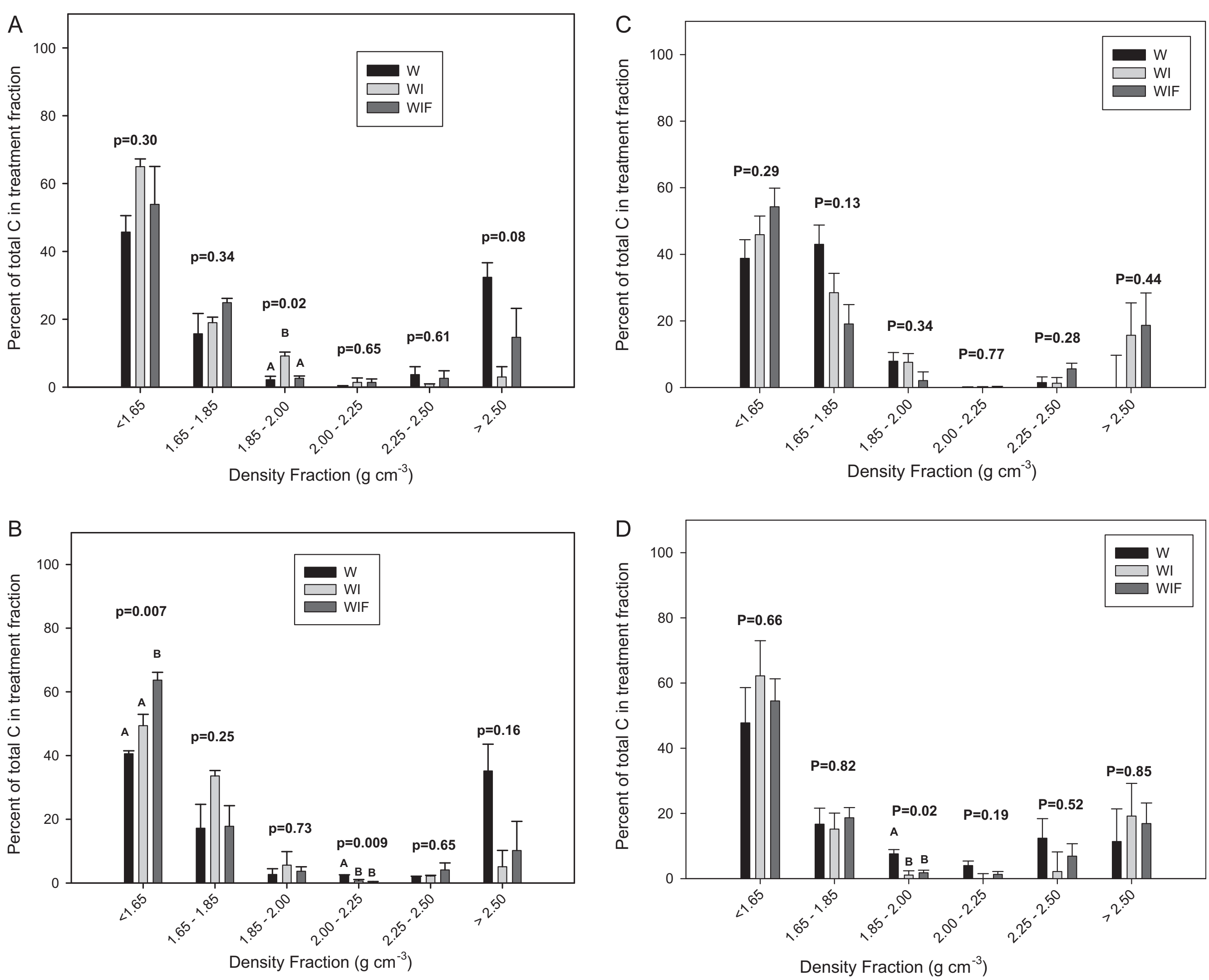


**Fig. 2.** Percentage of the total carbon (C) in six density fractions from soil samples collected from the 0–5 cm (A), 5–10 cm (B), 10–20 cm (C), and 20–30 cm (D) depths from 12-year-old sweetgum plots under different treatments. The treatments are: W = complete weed control; WI = weed control plus drip irrigation; and WIF = weed control plus drip irrigation and fertigation. Different letters within a fraction indicate significant ($\alpha = 0.05$) treatment differences.

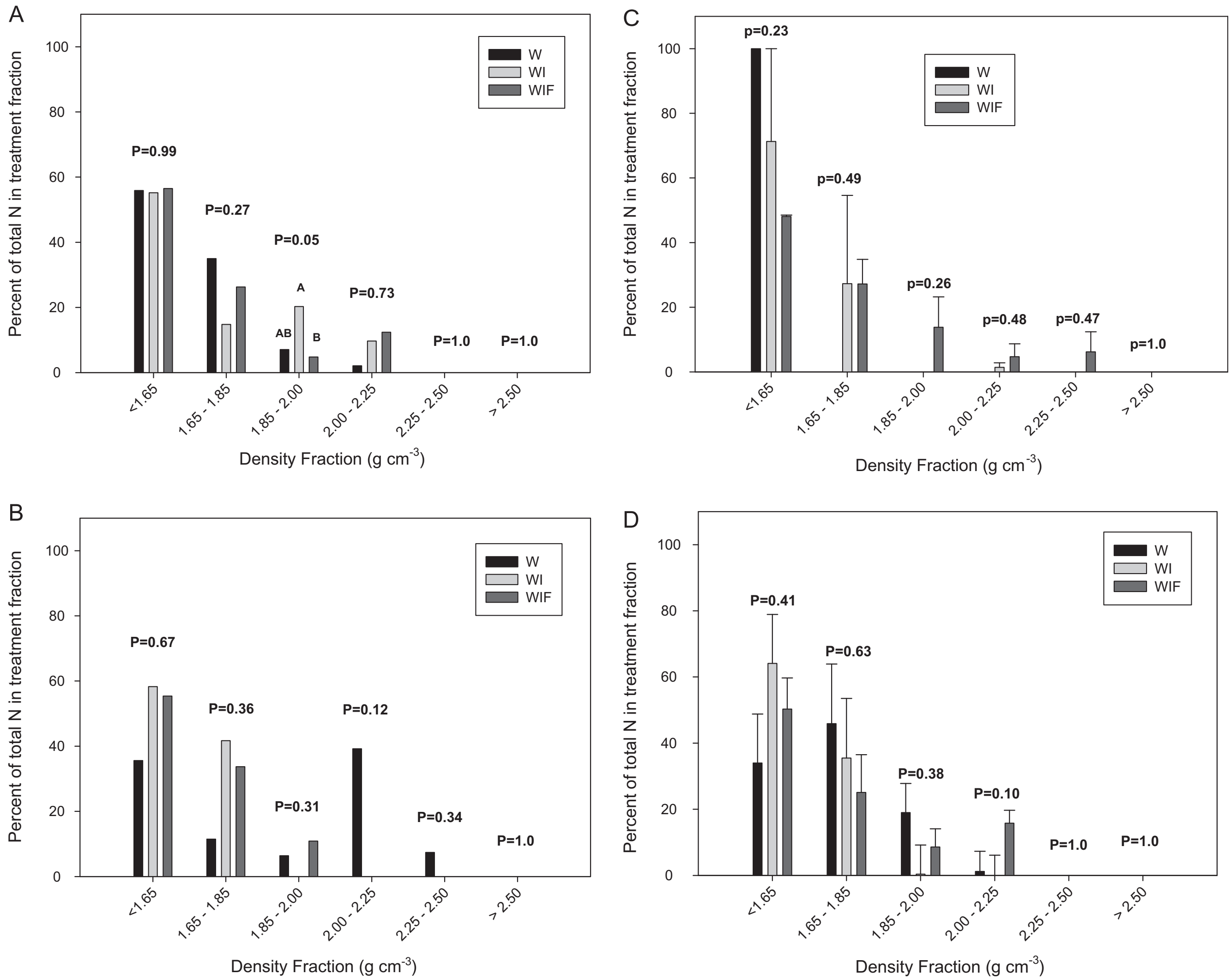


**Fig. 3.** Percentage of the total nitrogen (N) in six density fractions from soil samples collected from the 0–5 cm (A), 5–10 cm (B), 10–20 cm (C), and 20–30 cm (D) depths from 12-year-old sweetgum plots under different treatments. The treatments are: W = complete weed control; WI = weed control plus drip irrigation; and WIF = weed control plus drip irrigation and fertigation. Different letters within a fraction indicate significant ($\alpha$ = 0.05) treatment differences.

### *3.4. Loblolly pine C and N stabilization*

In loblolly pine, in the 0–5 cm depth, increasing management intensity increased the percentage of C in the 1.65–1.85 g cm$^{-3}$ density fraction but reduced the percentage of C to almost nil in the >2.25 g cm$^{-3}$ density fraction (Fig. 4). In the 5–10 cm depth, percentage of C in the 2.00–2.25 g cm$^{-3}$ density fraction was highest in the control treatment. Percent C in the 2.25–2.50 g m$^{-3}$ density fraction in the 10–20 cm depth was highest in non-fertilizer treatments. Similar to results found in sweetgum, most C was found in the two lightest and in the heaviest fractions. Treatments had no effects or trends towards effects on the stabilization of N, except that the WIFP increased the percentage of N in the 2.00–2.25 g cm$^{-3}$ density fraction in the 20–30 cm soil layer (Fig. 5). As in the sweetgum plots very little to no N was present in the heavier soil density fractions across all depths.

## 4. Discussion

Clearly, the C contents in the top 30 cm of soil in the sweetgum (284.2 Mg ha$^{-1}$) and loblolly pine (268.1 Mg ha$^{-1}$) experiments are very high across all treatments. This is due to both high soil C concentrations and relatively high bulk densities across the strata. This compares to 171 Mg ha$^{-1}$ in the top 60 cm in the control plots of a 6-year-old loblolly pine stand in the coastal plain of South Carolina (Maier et al., 2012) and 163 Mg ha$^{-1}$ in the top 60 cm of 32-year-old black spruce sites in Ontario (Major et al., 2012) although the latter study displayed extremely high soil C concentrations in the 0–10 depth due to a thick layer of organic matter and then soil C concentrations dropped precipitously with depth. One of the highest soil C contents (>400 Mg ha$^{-1}$ to a 70 cm depth) reported were by Gower et al. (1997) in old-growth boreal black spruce stands which had 20–50 cm of high C containing peat over mineral soil.

Early in stand development, Samuelson et al. (2004a) detected a significant treatment difference in stand-level loblolly pine fine root mass only between W and WIFP treatments. Although Samuelson et al. (2004a) did not measure root biomass for sweetgum, our analyses on the impact of treatments on soil C content indicated that differential (not statistically compared) effects of the treatments on the two species suggest that sweetgum allocated more C below-ground, perhaps as fine roots, than loblolly pine. Coleman (2007) found that sweetgum had a greater response in fine root biomass to resource availability than did loblolly pine.

Samuelson et al. (2004a) did not detect significant treatment effects on foliar N of loblolly pine after 6 years but at 10 years foliar N

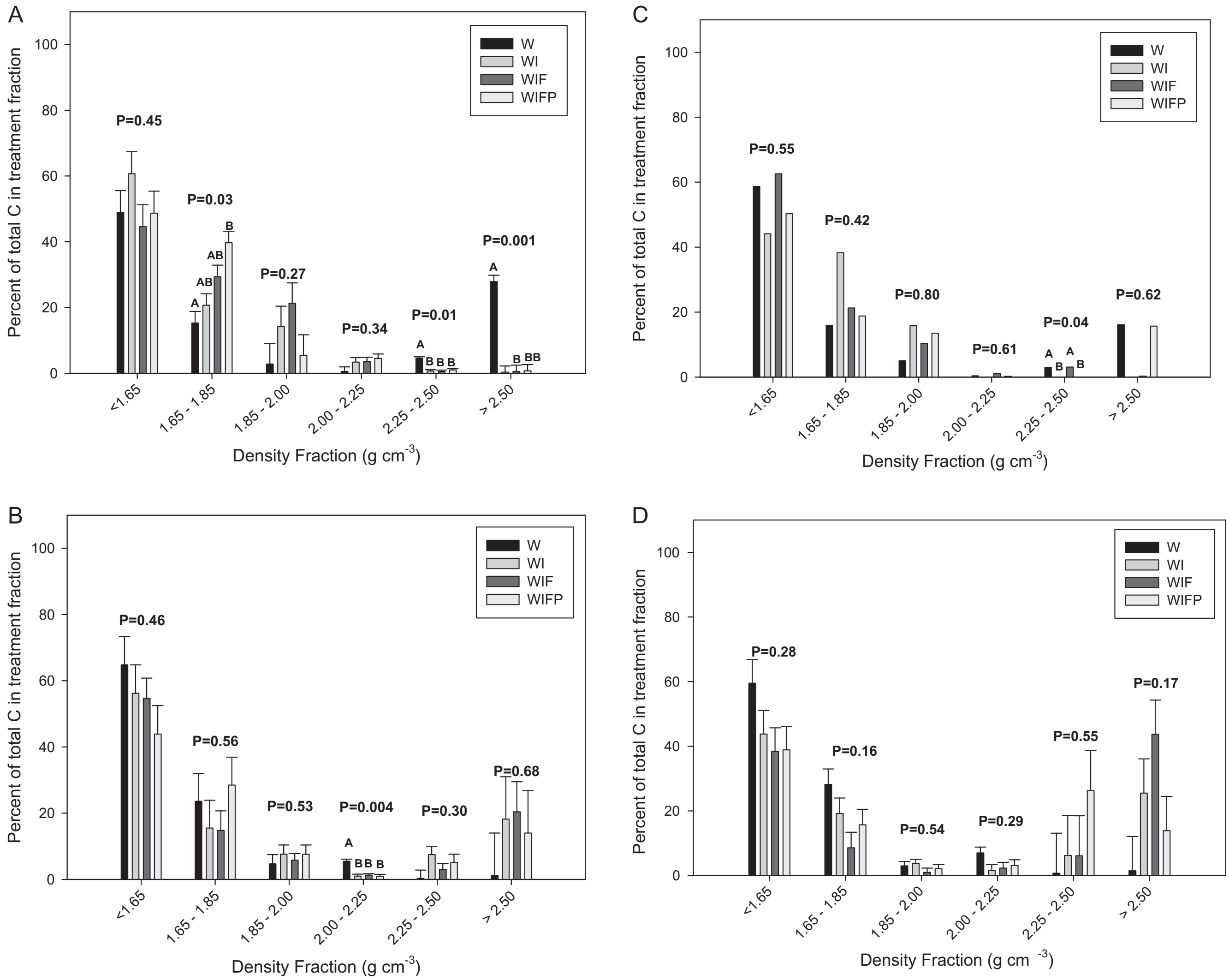


**Fig. 4.** Percentage of the total carbon (C) in six density fractions from soil samples collected from the 0–5 cm (A), 5–10 cm (B), 10–20 cm (C), and 20–30 cm (D) depths from 12-year-old loblolly pine plots under different treatments. The treatments are: W = complete weed control; WI = weed control plus drip irrigation; WIF = weed control plus drip irrigation and fertigation; and WIF = weed control plus drip irrigation and fertigation. Different letters within a fraction indicate significant ($\alpha = 0.05$) treatment differences.

was significantly higher in the WIFP and WIF treatments than in the W and WI treatments (Samuelson et al., 2008). At age 4, significant increases in foliar N concentrations with increasing management intensity were detected for sweetgum at this same site (Samuelson et al., 2001). After 6 years, Samuelson et al. (2004a,b) detected significant increases in leaf area index, and presumably increased litter biomass, with increasing management intensity in the loblolly pine plots, and at age 10 leaf biomass was higher in WI, WIF, and WIFP treatments (average of 24 Mg ha$^{-1}$) than in the W treatment (5 Mg ha$^{-1}$) (Samuelson et al., 2008). These increases in litter biomass, belowground biomass, and foliar N with management intensity could result in high levels of nitrogen entering the soil. However, only trends for increases in soil N content with management intensity were detected due to high variability. Nitrogen can be taken up by plants, lost in leachates, sequestered in the litter, or tied up in the soil humus. Although fertilization can increase forest floor decomposition and thus release more N, there is also an increase in biomass (above- and belowground) that can take up some or this entire added N. Interestingly, pine needles tend to accumulate in loblolly pine stands until a disturbance occurs (Authors-personal observation) while sweetgum litter tends to decompose quickly in aggrading and mature stands (P. Dougherty – personal communication), as do hardwoods in general (Scott and Messina, 2010). Finally, there can be considerable spatial variation in the amount of soil N within a site. Usher (1970) found that soil nitrogen measurements could vary four-fold within a 4-cm distance in a Scots pine (*Pinus sylvestris* L.) forest in the Scottish highlands. Soils in the southern United States may exhibit even more spatial variability (Worsham et al., 2010) than observed by Usher (1970) due to the previous land use history, warmer climate, and active decomposer organisms. Spatial variability, nutrient uptake, leaching losses, and variable inputs from the forest floor are all factors that generally contribute to the considerable variation observed in soil N measurements.

Management intensity increased soil C significantly in the sweetgum experiment but resulted in only minor trends in the adjacent loblolly pine experiment. The observed increase in soil C and N in the sweetgum plots may originate from differences in root biomass and density between the tree species, although these metrics were not determined in this or previous studies on this site. Root system morphology varies between species as does their response to resource availability (Pregitzer et al., 2002; Coleman, 2007). In an irrigation and fertilization study in South Carolina, Coleman (2007) found that loblolly and sweetgum fine root

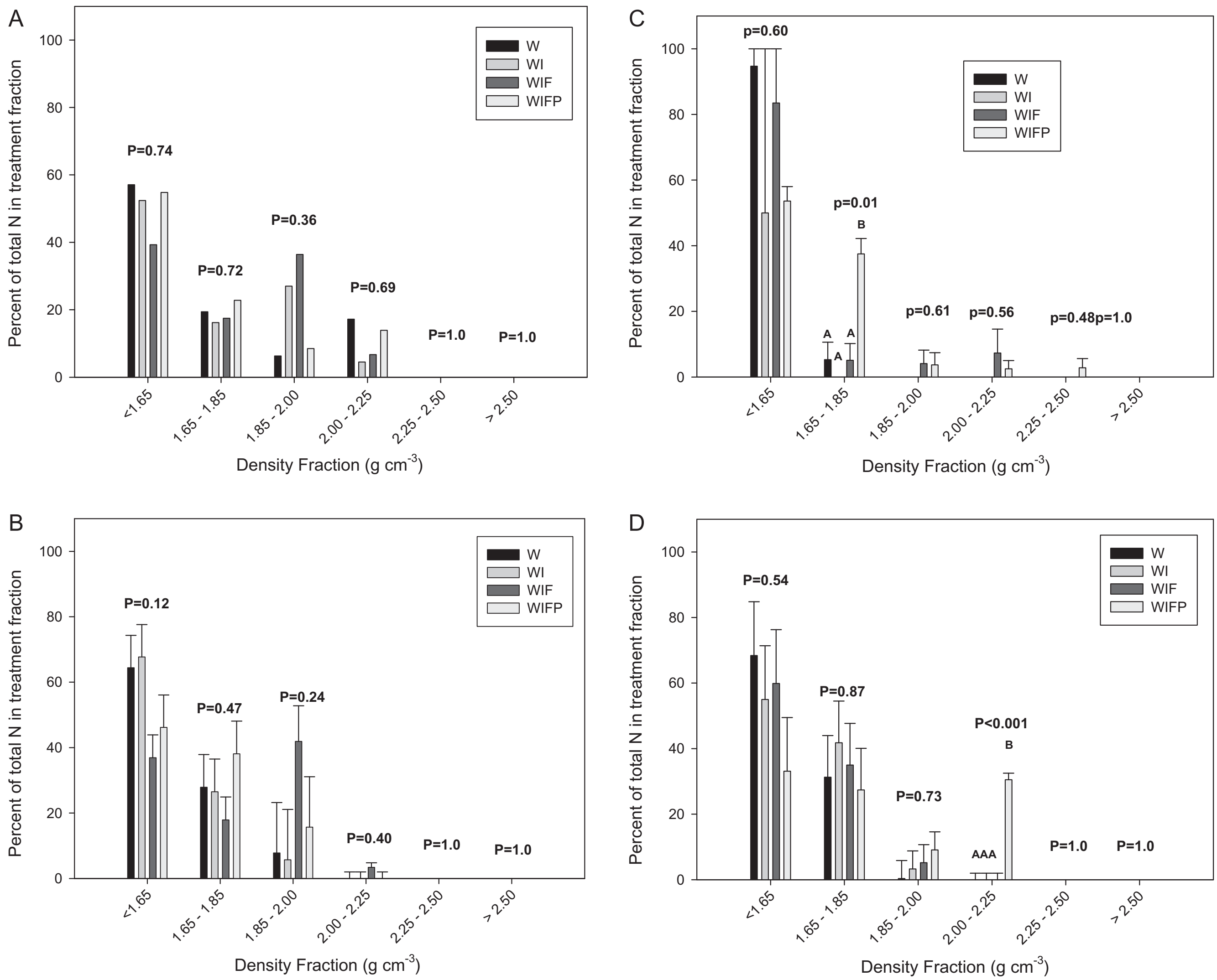


**Fig. 5.** Percentage of the total nitrogen (N) in six density fractions from soil samples collected from the 0–5 cm (A), 5–10 cm (B), 10–20 cm (C), and 20–30 cm (D) depths from 12-year-old loblolly pine plots under different treatments. The treatments are: W = complete weed control; WI = weed control plus drip irrigation; WIF = weed control plus drip irrigation and fertigation; and WIF = weed control plus drip irrigation and fertigation. Different letters within a fraction indicate significant ($\alpha = 0.05$) treatment differences.

biomass, root length density (RLD) and specific root length (SRL) increased with resource availability, especially nutrients, and the response was greatest for sweetgum (fine root biomass = 115 ± 15 and 99 ± 10 g $m^{-2}$; RLD = 1.43 ± 0.09 and 0.20 ± 0.03 cm $cm^{-3}$; and SRL = 24.8 ± 0.7 and 12.3 ± 1.3 m $g^{-1}$, for sweetgum and loblolly pine respectively). Contrarily, Iveresen and Norby (2008) found that additions of 200 kg $ha^{-1}$ (2 years in a row, applied in March) in a 17-year-old sweetgum stand reduced allocation to fine root biomass and thus, potentially, fine root turnover. We have no data on fine root growth or turnover in our study. However, increases in total soil C observed in sweetgum in our study were virtually identical between the WI and WIF treatments despite the fact that the WIF treatments had 78% greater BA than the WI treatment suggesting that fertilization decreased relative sweetgum fine root growth.

Sweetgum plots had, in general, lower C:N ratios than the adjacent loblolly pine stand. Lower C:N ratios in the sweetgum plots compared with the loblolly plots was consistent at each depth measured. Soil C:N ratios have been used as an indicator of soil quality (Pritchett and Fisher, 1987; Ågren and Bosatta, 1987). This difference in the soil quality may result in higher N mineralization rates (Keeney, 1980) on the sweetgum plots compared with the loblolly pine plots and so the sequestered soil N may play a more important role in providing N for growth for subsequent sweetgum rotations than in loblolly pine.

Generally, for both species, across all depths, soil C mostly resided in the lightest and heaviest soil fractions. Again consistent for both species, across all depths N was predominately found in the light and intermediate fractions. Otherwise, only sporadic unexplainable significant treatment differences occurred among treatments in both C and N fractionation. These results suggest that higher these inputs of organic matter do not impact stabilization and thus relative recalcitrance of C and N in the soil, at least at this point in time which represents approximately half rotation age. This is consistent with the observations of Sanchez and Bursey (2002) who found that higher inputs of C did not result in increased C stabilization in the soil. These results call to question a basic assumption in many models on soil organic matter dynamics. A critical assumption in these models is that decomposition follows first-order kinetics and that a linear relationship exists between soil C content and C input (Six et al., 2002). This implies that soil C can increase indefinitely so long as there is a continual

C source. We suggest that a lack of a C saturation point for soils is not realistic. A more probable scenario is that stabilization of organic matter is primarily a function of the soil's mineralogy as proposed by Hassink and Whitmore (1997), Torn et al. (1997) and Six et al. (2002). Additional stabilization mechanisms include physical (aggregation, inclusion into small pore volumes) and biochemical (proportion of recalcitrant compounds such as lignin) protection (Balesdent et al., 2000; Swift, 2001; Six et al., 2002) which may account for up to 21% of a soil's protective capacity (Hassink and Whitmore, 1997). This concept of a C saturation point for soils is supported by our research here and also by long term agricultural research projects where there was little to no increase in soil C despite repeated inputs of organic matter (Campbell et al., 1991; Paustian et al., 1997; Solberg et al., 1997), although the recent study by Maier et al. (2012) represents a notable exception.

It is important to recognize that the largest and longest-lasting contributions to the soil organic matter pool may come at the times of thinning and after the stand is harvested. Residual root systems (coarse and tap roots) can persist in the soil (Ludovici et al., 2002) and their decomposition can impact C and nutrient release over several decades (Jenny, 1980; Vogt et al., 1991; Chen et al., 2001). Considering that tree roots in an unmanaged, mature stand may account for 20–30% of a tree's total biomass (Van Lear et al., 2000); this represents a considerable soil organic matter pool. Researchers have already demonstrated that belowground biomass increases with resource availability (Samuelson et al., 2004a,b; Coleman, 2007) and differs between tree species (Pregitzer et al., 2002; Coleman, 2007). Although our study only showed an increase in soil C concentration in sweetgum, the work of Samuelson et al. (2004a,b) and Coleman (2007) suggests that, after a harvest, C and N sequestration may be realized in these systems, in the form of persistent root systems, and will vary among tree species and resource availability.

## 5. Conclusions

Intensive management prescriptions have successfully increased the amount of wood fiber produced in both the sweetgum and loblolly pine experiments. These same prescriptions have also increased the amount of C and N entering the soil both through greater forest litter and belowground biomass production. This effect increased with the intensity of the management prescription and may vary between tree species. In our study, soil C and N in the sweetgum experiment increased more from intensive culture than in the loblolly pine experiment, although we could not statistically compare species differences. There was also a trend for differences between the tree species in the soil C:N ratio (sweetgum lower). This difference in soil quality may trigger a difference in nitrogen mineralization between the species. Finally, we found that in both tree species, treatment did not generally impact the stabilization of C and N in the soil. This suggests that although there may well be differences in soil C and N at rotation age, these differences will, at least, diminish once the site is disturbed such as by harvesting the stand. However, particularly in sweetgum at this point of only half rotation age, the large inputs of labile soil C may still impact total stand carbon sequestration if subsequent rotations employ intensive management.

## References


Ågren, G.I., Bosatta, E., 1987. Theoretical analysis of the long-term dynamics of carbon and nitrogen in soils. Ecology 68 (5), 1181–1189.

Ågren, G.I., Bossatta, E., Magill, A.H., 2001. Combining theory and experiment to understand effects of inorganic nitrogen on litter decomposition. Oecologia 128, 94–98.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Till. Res. 53, 215–230.

Berg, B., Staaf, H., Wessen, B., 1987. Decomposition and nutrient release in needle litter from nitrogen fertilized Scots pine (*Pinus sylvestris*) stands. Scand. J. For. Res. 2, 399–415.

Butnor, J.R., Doolittle, J.A., Johnsen, K.H., Samuelson, L., Stokes, T., Kress, L., 2003. Utility of ground-penetrating radar as a root biomass survey tool in forest systems. Soil Sci. Soc. Am. J. 67, 1607–1615.

Campbell, C.A., Bowren, K.E., Schnitzer, M., Zentner, R.P., Townley-Smith, L., 1991. Effect of crop rotations and fertilization on soil biochemical properties in a thick Black Chernozem. Can. J. Soil Sci. 71, 377–387.

Chen, H., Harmon, M.E., Griffiths, R.P., 2001. Decomposition and nitrogen release from decomposing woody roots in coniferous forests of the Pacific Northwest: a chronosequence approach. Can. J. For. Res. 31, 246–260.

Coleman, M., 2007. Spatial and temporal patterns of root distribution in developing stands of four woody crop species grown with drip irrigation and fertilization. Plant Soil 299, 195–213.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W. (Ed.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America Special Publication No. 35. Soil Science Society of America, Madison, WI, USA, pp. 3–21.

Gholz, H.L., Fisher, R.F., 1982. Organic matter production and distribution in slash pine ecosystems. Ecology 63, 1827–1839.

Gower, S.T., Vogel, J.G., Norman, J.M., Kucharik, C.J., Steele, S.J., Stow, T.K., 1997. Carbon distribution and aboveground net primary production in aspen, jack pine and black spruce stands in Saskatchewan and Manitoba. Canada. J. Geophys. Res. 102, 029–041.

Grigal, D.F., 2000. Effects of extensive forest management on soil productivity. For. Ecol. Manage. 138, 167–185.

Hanson, P.J., Edwards, N.T., Garten, C.T., Andrews, J.A., 2000. Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry 48, 115–146.

Hassink, J., Whitmore, A.P., 1997. A model of the physical protection of organic matter in soils. Soil Sci. Soc. Am. J. 61, 131–139.

Iveresen, C.M., Norby, R.J., 2008. Nitrogen limitation in a sweetgum plantation:implications for carbon allocation and storage. Can. J. For. Res. 38, 1021–1032.

Jenny, H., 1980. The Soil Resource. Springer-Verlag, New York.

Jenny, H., 1994. Factors of Soil Formation. In: A System of Quantitative Pedology. Dover Press, New York.

Johnsen, K.H., Wear, D., Oren, R., Teskey, R.O., Sanchez, F., Will, R., Butnor, J., Markewicz, D., Richter, D., Rials, T., Allen, H.L., Seiler, J., Ellsworth, D., Maier, C., Samuelson, L., Katul, G., Dougherty, P.M., 2001. Carbon sequestration via southern pine forestry. J. For. 99, 14–21.

Johnsen, K.H.B. Teskey, L. Samuelson, J. Butnor, F. Sanchez, D. Sampson, C. Maier, McKeand, S. 2004. Carbon sequestration in loblolly pine plantations: methods, limitations and research needs for estimating storage pools. In: Johnsen, K., Rauscher, H.M., Hubbard, W.G. (Eds.), Southern Forest Science Conference Proceedings. November 26–28. Atlanta, GA. pp. 373–381.

Jurgensen, M.F., Harvey, A.E., Graham, R.T., Page-Dumroese, D.S., Tonn, J.R., Larsen, M.J., Jain, T.B., 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of Inland Northwest forests. For. Sci. 43, 234–251.

Keeney, D.R., 1980. Prediction of soil nitrogen availability in forest ecosystems: a literature review. For. Sci. 26, 159–171.

King, J.S., Timothy, J., Albaugh, T.J., Allen, H.L., Buford, M., Strain, B.R., Dougherty, P., 2002. Below-ground carbon input to soil is controlled by nutrient availability and fine root dynamics in loblolly pine. New Phytol. 154, 389–398.

Ludovici, K.H., Zarnoch, S.J., Ritcher, D.D., 2002. Modeling *in situ* pine root decomposition using data from a 60-year chronosequence. Can. J. For. Res. 32, 1675–1684.

Maier, C.A., Kress, L.W., 2000. Soil $CO_2$ evolution and root respiration in 11-year-old loblolly pine (*Pinus taeda*) plantations as affected by moisture and nutrient availability. Can. J. For. Res. 30, 347–359.

Maier, C.A., Johnsen, K.H., Dougherty, P., McInnis, D., Anderson, P., Patterson, S., 2012. Effect of harvest residue management on tree productivity and carbon pools during early stand development in a loblolly pine plantation. For. Sci. 58, 430–435.

Major, J.E., Johnsen, K.H., Barsi, D.C., Campbell, M., 2012. Total belowground partitioning of mature black spruce families displaying a genetic x environment interaction in aboveground growth. Can. J. For. Res. 42, 1939–1952.

Nambiar, E.K.S., 1997. Sustained productivity of forests as a continuing challenge to soil science. Soil Sci. Soc. Am. J. 60, 1629–1642.

Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51, 1173–1179.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems. CRC Press, Boca Raton, FL, pp. 15–49.

Persson, H., 1979. Fine root production, mortality, and decomposition in forest ecosystems. Vegetatio 41, 101–109.

Piatek, K.B., Allen, H.L., 2001. Are forest floors in mid-rotation stands of loblolly pine (*Pinus taeda*) a sink for nitrogen and phosphorus? Can. J. For. Res. 31, 1164–1174.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D., Stone, D.M., 2005. The North American long-term soil productivity experiment. Findings from the first decade of research. For. Ecol. Manage. 220, 17–30.

Pregitzer, K.S., DeForest, J.L., Burton, A.J., Allen, M.F., Ruess, R.W., Hendrick, R.L., 2002. Fine root architecture of nine North American trees. Ecol. Monogr. 72, 293–309.
Prescott, C.E., Corbin, J.P., Parkinson, D., 1992. Immobilization and availability of N and P in the forest floors of fertilized Rocky Mountain coniferous forests. Plant Soil. 143, 1–10.
Pritchett, W.L., Fisher, R.F., 1987. Properties and Management of Forest Soils, 2nd Edition. Wiley, New York.
Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus 44B, 81–99.
Raison, R.J., Connell, M.J., Khanna, P.K., 1987. Methodology for studying fluxes of soil mineral-N *in situ*. Soil Biol. Biochem. 19, 521–530.
Richter, D.D., Markewitz, D., Trumbore, S.E., Wells, C.G., 1999. Rapid accumulation and turnover of soil carbon in a re-establishing forest. Nature 400, 56–58.
Ruffner, J.A., 1980. Climates of the states: NOAA, vol. 1. Gale Research, Detroit, Mich.
Samuelson, L.J., 1998. Influence of intensive culture on leaf net photosynthesis and growth of sweetgum and loblolly pine seedlings. For. Sci. 44, 308–316.
Samuelson, L.J., Stokes, T.A., 2006. Transpiration and canopy stomatal conductance of 5-year-old loblolly pine in response to intensive management. For. Sci. 52, 313–323.
Samuelson, L.J., Stokes, T., Cooksey, T., McLemore III, P., 2001. Production efficiency of loblolly pine and sweetgum in response to four years of intensive management. Tree Physiol. 21, 369–376.
Samuelson, L.J., Johnsen, K., Stokes, T., 2004a. Production, allocation, and stemwood growth efficiency of *Pinus taeda* L. stands in response to 6 years of intensive management. For. Ecol. Manage. 192, 59–72.
Samuelson, L.J., Johnsen, K., Stokes, T., Lu, W., 2004b. Intensive management modifies soil $CO_2$ efflux in 6-year-old *Pinus taeda* L. stands. For. Ecol. Manage. 200, 335–345.
Samuelson, L.J., Butnor, J., Maier, C., Stokes, T.A., Johnsen, K., Kane, M., 2008. Growth and physiology of loblolly pine in response to long-term resource management: defining growth potential in the southern United States. Can. J. For. Res. 38, 721–732.
Sanchez, F.G., Bursey, M.M., 2002. Transient nature of rhizosphere carbon elucidated by supercritical freon-22 extraction and $^{13}C$ NMR analysis. For. Ecol. Manage. 169, 177–185.
Sanchez, F.G., Tiarks, A.E., Kranabetter, J.M., Page-Dumroese, D.S., Powers, R.F., Sanborn, P., Chapman, W.K., 2006. Effects of organic matter removal and soil compaction on fifth-year mineral soil carbon and nitrogen contents for sites across the United States and Canada. Can. J. For. Res. 36, 565–576.
SAS Institute, 2002. SAS/STAT User's Guide. Version 9.2. SAS Institute, Cary, NC.
Scott, D.A., Messina, M.G., 2010. Soil properties in 35 y old pine and hardwood plantations after conversion from mixed hardwood forest. Am. Midl. Nat. 163, 197–211.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176.
Skog, K.E., 2008. Sequestration of carbon in harvested wood products for the United States. For. Prod. J. 58, 56–72.
Skog, K.E.G.A., Nicholson, G.A., 1998. Carbon cycling through wood products: the role of wood paper products in carbon sequestration. For. Prod. J. 48, 75–83.
Solberg, E.D., Nyborg, M., Izaurralde, R.C., Malhi, S.S., Janzen, H.H., Molina-Ayala, M., 1997. Carbon storage in soils under continuous cereal grain cropping: N fertilizer and straw. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 235–254.
Sollins, P., Swanson, C., Kleber, M., Filley, T., Kramer, M., Crow, S., Caldwell, B.A., Lajtha, K., Bowden, R., 2006. Organic C and N stabilization in a forest soil: evidence from sequential density fractionation. Soil Biol. Biochem. 38, 3313–3324.
Stevenson, F.J., 1994. Humus Chemistry. In: Genesis, Composition, Reactions. John Wiley and Sons, New York.
Stump, L.M., Binkley, D., 1993. Relationships between litter quality and nitrogen availability in Rocky Mountain forests. Can. J. For. Res. 23, 492–502.
Swift, R.S., 2001. Sequestration of carbon by soil. Soil Sci. 166, 858–871.
Titus, B.D., Malcolm, D.C., 1987. The effect of fertilization on litter decomposition in clearfelled spruce stands. Plant Soil 110, 297–322.
Torn, M.S., Trumbore, S.E., Chadwick, O.A., Vitousek, P.M., Hendricks, D.M., 1997. Mineral control of soil organic carbon storage and turnover. Nature 389, 170–173.
Usher, M.B., 1970. Pattern and seasonal variability in the environment of a Scots pine forest soil. J. Ecol. 58, 669–679.
Van Lear, D.H., Kapeluck, P.R., Carroll, W.D., 2000. Productivity of loblolly pine as affected by decomposing root systems. For. Ecol. Manage. 138, 435–443.
Vance, E.D., Sanchez, F.G., 2006. Perspectives on site productivity of loblolly pine plantations in the southern United States. For. Ecol. Manage. 227, 135–136.
Vogt, K.A., Vogt, D.J., Bloomfield, J., 1991. Input of organic matter to the soil by tree roots. In: McMichael, B.L., Persson, H. (Eds.), Plant Roots and their Environment. Development in Agriculture and Managed-Forest Ecology. Elsevier, Amsterdam, pp. 171–190.
White, D.L., Haines, B.L., Boring, L.R., 1988. Litter decomposition in southern Appalachian black locust and pine-hardwood stands: litter quality and nitrogen dynamics. Can. J. For. Res. 18, 54–63.
Worsham, L., Markewitz, D., Nibblelink, N., 2010. Incorporating spatial dependence into estimates of soil carbon contents under different land covers. Soil Sci. Soc. Am. J. 74, 635–646.