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RESEARCH ARTICLE

Soil carbon storage and nitrogen and phosphorous availability in loblolly pine plantations over 4 to16 years of herbicide and fertilizer treatments

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Abstract The impact of extended herbicide (H) and annual fertilizer (F) treatments on the mineral soil carbon (C) pool and nitrogen (N) and phosphorous (P) availability were analyzed in managed loblolly pine (*Pinus taeda* L.) plantations in the Piedmont of Georgia in stands ranging from 4 to 16 years old. Mineral soil C, N, P, and extractable P were measured in 66 plots in three locations comparing H, F, and their combination HF to the Control plots. Soils were sampled in January 2000 near Eatonton ($n = 40$), in August 2001 near Athens ($n = 12$), and in March 2003 near Dawsonville ($n = 14$). In addition, twelve plots (two H and two HF at each location) were measured on 17 dates using a mixed bead resin core technique to estimate mineral soil N availability. At all three study locations the H treatment tended to deplete the mineral soil C pool while, overall, the F treatments did not determine any significant mineral soil C increase. The soil C pool (0- to 50-cm depth) was depleted by about 5 Mg C ha^{-1} under the H-treated plots near Eatonton. The HF plots had much higher resin-extractable N than the corresponding H plots in all months of the year. At a plot level, HF values ranged from about 9 to 3,195 μg N g^{-1} resin while H values ranged from about 4 to 858 μg N g^{-1} resin. The corresponding annual cumulative resin-extractable N ranged from about 13 kg N ha^{-1} in the H to about 372 kg N ha^{-1} in the HF. Extractable P values were also elevated in all F-treated plots. Fertilization and herbicide treatments favored C sequestration only in the aboveground biomass. No significant change was observed in the mineral soil C pool, despite the generally observed increases in soil available N and P.

Keywords Soil carbon sequestration · Fertilization · Herbicide control · Soil available nitrogen · Soil extractable phosphorous

Introduction

Intensively managed pine plantations in the southeastern United States have been studied to identify the relationship between tree growth and silvicultural practices such as fertilization and aggressive competition control (Albaugh et al. 2004; Borders et al. 2004; Jokela et al. 2004).

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Understanding the potential of southern pine plantations to serve as carbon (C) sinks to counteract the greenhouse effect has become another important focus of recent research (Lee and Dodson 1996; Johnsen et al. 2001; Sanchez and Eaton 2001; Shan et al. 2001). Because of the net C increase in the atmosphere (3.2 Pg C yr^{-1} (Janzen 2004)) there is strong interest in understanding what land uses and management practices enhance terrestrial C sequestration (Lee and Dodson 1996; Post and Kwon 2000; Heath et al. 2003; Giardina et al. 2004; Johnson et al. 2006; Niu and Duiker 2006). The literature on the mechanisms that favor C storage as soil organic matter (SOM) is currently expanding to better quantify the impact of afforestation of marginal lands and forest management on the global C cycle and the potential of forest soils to serve as a C sink (Johnson and Curtis 2001; Paul et al. 2002; Heath et al. 2003; Gough and Seiler 2004; Johnson et al. 2006). Carbon present in SOM is a significant component of the terrestrial C pool. SOM dynamics can strongly impact the atmospheric C pool because small changes in SOM concentration following land-use change can impart measurable changes in atmospheric CO_2 (Harrison et al. 1993).

In this article we will frequently refer to soil C as the C-mass equivalent of the predominant C-containing components of the mineral soil. Soil C is the mass of C in SOM, which is the sum of all organic fractions of the mineral soil. It includes plant, animal, and microbial residues, fresh and at all stages of decomposition, and the relatively resistant soil humus—all of which accompany soil mineral particles able to pass through a 2-mm sieve (Nelson and Sommers 1996).

Enhancing the soil C pool results in long-term net-C gains and improves site fertility (Ingram and Fernandes 2001; Sanchez and Eaton 2001; Paul et al. 2002). Conversely, intensive forest management practices may deplete soil C by reducing the amount of aboveground and belowground litter inputs (Morris et al. 1983; Vitousek and Matson 1985; Carlyle 1993; Shan et al. 2001; Echeverria et al. 2004). In intensively managed pine plantations of the southeastern United States, large quantities of organic matter—in some cases the whole tree components—are removed in merchantable wood products at harvest. Similarly at site preparation, the degree of organic matter removal depends upon the practices being used to improve site conditions for planting, seedling survival, and tree biomass production. These practices also reduce the competition from woody and herbaceous vegetation (Butnor et al. 2006). One of the most common practices at site preparation is windrowing or spot piling, by which tree residues (comprised of bark, wood, and foliage) are raked or bulldozed into rows or piles located outside the planting area (Morris et al. 1983; Vitousek and Matson 1985; Piatek and Allen 2001). The accumulated residues are generally left in place to decompose or burned with consequent oxidation of C as CO_2 efflux to the atmosphere. Other important macronutrients (i.e., N and P) may also be lost through this process. The loss of nutrients contained in SOM due to windrowing of organic residues may produce a decline of the site productivity (Morris et al. 1983). Under this type of management regime, long-term C sequestration may result more from C accumulations in long-lived wood products, created from harvesting wood, than in the mineral soil (Johnsen et al. 2001).

Forest soils studies suggest that, after agricultural utilization, the soil C pool recovery within the mineral soil under loblolly pine secondary forests is relatively slow (from 0.075 to 0.79 Mg ha^{-1} yr^{-1}, Huntington 1995; Richter et al. 1995; Van Lear et al. 1995; Schlesinger and Lichter 2001) and C is allocated primarily to aboveground tree biomass (4.1 Mg ha^{-1} yr^{-1}, Richter et al. 1995; Shan et al. 2001; Johnson et al. 2003; Gough and Seiler 2004). One of the management operations that may enhance mineral soil C accumulations is fertilization. In general, proper fertilizer use is considered a “managed/improved” situation (Ingram and Fernandes 2001) that favors soil C accumulations in both forest and agricultural soils (Paustian et al. 2000; Johnson and Curtis 2001; Paul et al. 2002; Lal 2004). Such practice carries a C cost related to fossil-fuel emission during fertilizer production that may nullify any net soil C gains (Markewitz 2006). In pine plantations, fertilization typically enhances C sequestration in the aboveground biomass rather than in the soil (Shan et al. 2001; Johnson et al. 2003). For example, in loblolly pine plantations re-sampled 18 years after establishment, Johnson et al. (2003) observed no significant soil C increase on Hapludults in Tennessee despite fertilization applied from age 1 to 3 years.

It has been clearly demonstrated in different physiographic regions of the Southeast that loblolly pine growth responds primarily to N and P fertilization (Vose and Allen 1988; Maimone et al. 1991; Jokela et al. 2004). Extremely high growth responses, in particular, to the combination of extended Herbicide plus annual Fertilizer (HF) treatment have been reported (Borders and Bailey 2001; Borders et al. 2004). These relevant aboveground biomass growth responses may have important implications for soil C sequestration as well as SOM processes related to nutrient or N availability (Johnson 1995).

Many of the above cited soil studies have typically monitored soil C and nutrient changes in response to one-time fertilizer applications. In this article we report on the effects of sustained competition control with herbicide treatments and repeated annual fertilizer applications for periods as long as 12 years. The main objectives of this work were to describe the decadal effects of the long-term Herbicide (H) and Fertilizer (F) treatments on the (1) C, N, and P pools and (2) on N and P availability of the mineral soil.

Fig. 1 Research locations near Athens (A), Eatonton (E), and Dawsonville (D), Georgia within the Piedmont (shaded area) of the southeastern United States. The Dawsonville site is located in a floodplain of the Etowah River, Georgia

Materials and methods

Research locations

Three research sites were located in the Piedmont of Georgia and were part of the Consortium for Accelerated Pine Productivity Studies (CAPPS) (Borders and Bailey 2001) (Fig. 1). The location of these study sites, based on the eco-region classification developed by McNab and Avers (1994), are in the Southern Appalachian Piedmont, consisting of an intensely metamorphosed, moderately dissected plain formed of thick saprolite, continental sediments, and accreted terrains. Elevation ranges from 100 m to 400 m. The potential vegetation is oak-hickory-pine forest and southern mixed forest (Kuchler 1964). Predominant vegetation form is evergreen forest. The loblolly-shortleaf pine (*Pinus echinata* Mill.) cover type is common on disturbed areas and usually has an understory component of dogwood (*Cornus florida* L.) and sourwood (*Oxydendrum arboreum* (L.) DC.). The growing season lasts about 205 to 235 days (Tables 1, 2).

For our research, we used plots within CAPPS, consisting of randomized complete block designs with equal number of replications of each treatment in different locations throughout the state of Georgia (Borders and Bailey 2001). In each block there are four 0.15-ha plots planted with 1660 trees ha^{-1}: a Control, extended H, annual F, and HF treatments (Borders et al. 2004). The H treatment consisted of a broadcast of sulfometheron methyl during early spring of the first three growing seasons following planting and subsequent application of glyphosate as needed in mid-summer each year thereafter. Fertilization rates were 78 kg N ha^{-1} yr^{-1}, 64 kg P ha^{-1} yr^{-1}, and 58 kg K ha^{-1} yr^{-1} as NH_4NO_3, triple super

Table 1 Minimum and maximum average monthly temperatures and annual precipitation of the three locations near Athens, Eatonton, and Dawsonville within the Georgia Piedmont, United States

Location	Average monthly temperature (°C)		Average annual precipitation[a] (cm)	Source
	January	July		
Athens	−0.1	32	126	(1961 to 1990, University of Georgia, http://climate.engr.uga.edu/info.html)
Eatonton	1.1	32.5	124	(1911 to 2003, University of Georgia, http://www.griffin.peachnet.edu/bae/)
Dawsonville	−0.1	30.7	140	(1911 to 2003, University of Georgia, http://www.griffin.peachnet.edu/bae/)

[a] In all three locations precipitation has a maximum in early March and minimum in October

phosphate, and KCl during the first two growing seasons applied in the spring and mid-summer. In subsequent growing seasons: 59 kg N ha^{-1} yr^{-1} as NH_4NO_3 early to mid-spring. At age 10 years, 118 kg N ha^{-1} and 36 kg P ha^{-1} as NH_4NO and triple super phosphate. At age 11 years, 92 kg N ha^{-1}, 179 kg P ha^{-1}, and 45 kg K ha^{-1} as NH_4NO_3, and super rainbow® with micronutrients. At age 12 years and forward 118 kg N ha^{-1} yr^{-1} as NH_4NO_3 applied in early spring.

For all studies tree volume data were computed from the inventories conducted by CAPPS at the D.B. Warnell School of Forestry and Natural Resources (Borders and Bailey 2001). Tree biomass was calculated based on annual individual tree measures of diameter and height. Each tree was identified by a unique tag number and repeatedly measured yearly. The corresponding volume outside bark was calculated using an allometric equation (Harrison and Borders 1996). Plot level estimates were computed by adding up individual tree volumes and expressed on a per hectare basis.

Soil samples

Mineral soil samples were collected from each stand using a stainless steel probe (diameter: 2.5 cm; length 60 cm) with removable internal liners and a slide hammer, after removal of the O horizon. The O horizon was not sampled because this material does not serve as a long-term sink for C sequestration—we assumed that it is removed at site preparation. Fourteen soil cores in each stand were divided into three different depth increments from the surface: 0 to 10, 10 to 30, and 30 to 50 cm and composited by depth within a plot. Samples for physical and chemical analysis were returned to the laboratory, air dried, and passed through a 2-mm sieve prior to analysis. Soil C and N concentrations were measured after pulverization with a dry combustion technique using a CE Elantech (NJ) NC 2100 analyzer (Bremmer and Mulvaney 1982). Total P concentration was measured on an Alpkem autoanalyzer (OI Analytical, College Station, TX) using the Murphy-Riley chemistry after digestion with H_2SO_4-H_2O_2 and H_2SeO_2 as a catalyst (Kuo 1996). Extractable P concentration was estimated via a double-acid (H_2SO_4-HCl) extraction (Kuo 1996).

For bulk density collections, a 7.5-cm diameter by 7.5-cm high brass core with a slide-hammer driven sampler was used. After collection, samples were returned to the laboratory, dried at 105°C to constant weight, and weighed. In the Eatonton sites bulk density was measured within each plot for the 0- to 7.5-cm depth ($n = 40$). In the 10- to 30- and 30- to 50-cm depths bulk density values were estimated for the blocks ($n = 10$) by collecting cores from the 15- to 22-cm and from 35- to 42-cm depth. In the Athens site bulk density was measured in the 0- to 7.5-cm horizon of the Control and H plots ($n = 4$). The bulk density data for H and Control plots in Athens and Eatonton have been reported previously (Echeverria et al. 2004). Soil bulk density was not measured in the Dawsonville site and a bulk density of 1.4 g cm^{-3} was assumed based on the United States Department of Agriculture-Soil

Table 2 Site characteristics, time of planting, and time of sampling in the experimental plots located in three locations near Athens, Eatonton, and Dawsonville within the Georgia Piedmont, United States

Sampling sites	Nearest location in the state of Georgia, USA	Soil types[a]	Slope ranges	Time of planting	Time of sampling	Number of sampled plots[b] (number of blocks is in parethesis)
Whitehall Forest (33° 57′ N, 83° 19′ W)	Athens	Cecil (fine, kaolinitic, thermic Typic Kanhapludults) Pacolet (fine, kaolinitic, thermic Typic Kanhapludults)	6 to 13 %	2 blocks in 1989 2 blocks in 1993	July and August 2001	*n* = 12 (2 complete and 2 incomplete blocks with only H and C)
B.F. Grant Forest (33° 20′ N, 83° 23′ W)	Eatonton	Appling (fine, kaolinitic, thermic Typic Kanhapludults) Davidson (fine, kaolinitic, thermic Rhodic Kandiudults) (USDA-SCS 1968)	6 to 13 %	4 blocks in 1988 4 blocks in 1990 2 in 1995	December 1999 and January 2000	*n* = 40 (10 blocks)
Georgia Forestry Commission Site (34° 21′ N, 84° 08′ W)	Dawsonville	Congaree series (fine-loamy, mixed, active, non-acid, thermic Typic Udifluvent) (USDA-SCS 1972)	<2 %	2 blocks in 1987 2 blocks in 1989	March 2003	*n* = 14 (4 blocks)

[a] Soils near Athens and Eatonton had an A or Ap horizon that ranged from sandy to sandy loam in texture and was absent in the most eroded sites due to severe erosion related to the cotton farming era. The Dawsonville site is on the floodplain of the Etowah River and as such has younger soils. The Congaree series includes a shallow A (loam) and three subsurface C horizons (from loam to very fine sandy loam) (USDA-SCS 1972)

[b] Four treatments (Herbicide, Fertilizer, Herbicide plus Fertilizer, and Control) were replicated in time and space in experimental blocks. In total, N = 66 stands were sampled. Near Dawsonville, two Fertilizer plots were not sampled because seedlings were suppressed by the vigorous understory vegetation competition. In this location the Herbicide and Fertilizer treatments were applied only until 1996

Conservation Service for the Congaree soil series of Dawson, Lumpkin, and White counties, GA (USDA-SCS 1972).

Temporal soil available N measurements

Twelve plots (two H and two HF at each location) were repeatedly sampled 17 times, with 10 monthly (from July 2002 to May 2003) and 7 bi-weekly (from June to September 2003) collections. These data are part of a more extensive soil-site productivity study (Sartori 2004). In this article we summarize and report only the monthly N availability estimates, to compare temporal patterns of N availability in the H and HF plots for the three different locations. We only investigated these two treatments assuming that the difference between the two would be greatest. We assumed that on N-limited sites the presence of the understory vegetation would reduce the difference in N availability between the F and Control plots. The understory vegetation creates a multi-strata system with higher inter- and intra-species competition for soil available N in the surface soil. This may result in higher rates of N uptake and translocation of soil N into understory-vegetation-biomass N.

Field collections were made using six polyvinyl chloride tubes with a 3.5-cm internal diameter following approximately a 3 × 3 m regular grid. Tubes were driven to a 12-cm soil depth and removed with the internal soil core intact. A small portion of the soil core at the base of the tube was removed and replaced with a mixed-bead resin bag (Binkley and Matson 1983), to capture available N derived from the soil solution percolating through the soil core. During each field collection a new 3 × 3 m grid within each plot would be selected and new soil cores set in place as described above. Two sets of 70 bags were available for this study: at each collection date one set of bags would be collected from the field and replaced with the freshly recharged set of bags.

The 4 × 4 cm resin bags were constructed using Nitex® 03-80/37 nylon material and sewed using nylon thread. Four grams of 20–50 mesh ion exchange resin from BIO-RAD (2 g of AG® 1-X8 chloride form and 2 g of AG® 50W-X8 hydrogen form) were placed within each bag. Each resin bag collected from the field was placed in separate centrifuge tubes with 40 ml of 1 M HCl solution and recharged by shaking it on a reciprocating shaker at 200 RPM for at least 24 h. Resin bags were extracted using a 1 M KCl solution in a reciprocating shaker (Mulvaney 1996). Resin-extractable NO_3-N and NH_4-N concentrations were measured on an Alpkem autoanalyzer (OI Analytical, College Station, TX) and on a Technicon segmented flow analyzer (Nicholson 1984), using the cadmium reduction column and the indophenol blue method for NO_3-N and NH_4-N concentrations, respectively. Because the resins were initially recharged with HCl, the KCl extracts had low pH (i.e., about 1 to 2) that could cause interference for the analysis of NH_4-N concentration. Therefore, samples were neutralized by addition of a drop of a 5 N NaOH solution prior to analysis. During each collection the soil within the PVC tube was collected and composited by plot in a plastic bag, returned to the laboratory, air dried, and passed through a 2-mm sieve for further analysis (Sartori 2004).

Atmospheric mineral N deposition

At each location one automated solar powered dry fall-wet fall collector (Aerochem Metrics, Kissimee, FL) was placed in an opening to collect wet-fall only precipitation samples. Intervals between collection dates were the same as those of the resin bag collections. The rain samples were taken to the laboratory and stored frozen in a scintillation vial until analysis. Atmospheric NO_3-N and NH_4-N concentrations were measured on a Dionex DX 500 Ion Chromatograph (Dionex, Sunnyvale CA).

Statistical analyses

Statistical analyses on the 2001 and 2003 single-time measured soil variables (i.e., soil C, total N, total P, and extractable P concentrations) for the comparison of all treatments were most concerned with soil differences among plot treatments by depth—statistical analyses were conducted only on the concentration data. The experimental design for these samples followed a randomized complete block design. We conducted a three-way MANOVA test (Wilk's Lambda) to test for an overall treatment effect using the SAS GLM procedure (SAS Institute 1990; Johnson and Wichern 1998), including as model variables soil C, N, total and extractable P concentrations.

If treatment was significant ($P < 0.05$) in the MANOVA, we conducted an *F*-test (univariate ANOVAs) for each individual variable by depth testing the effect of treatment, age, and block nested within age. If the univariate analysis was significant ($P < 0.05$), we then conducted Fisher's protected LSD ($P < 0.05$) to test the following orthogonal contrasts: A) Herbicide plots (H and HF) versus non-herbicide (Control and F), B) H versus HF, and C) Control versus F. In this study it was of interest to address specific questions in comparing H, HF, F, and Control plots with respect to the different soil nutrients, using specific orthogonal contrasts for pre-planned comparisons as suggested by Dean and Voss (1999). The questions of interest addressed using the selected orthogonal contrasts were: A) are the plots that received the H treatment significantly different from the non-H treated plots? B) In the presence of H application does fertilization have a significant effect? C) In the absence of H application does fertilization have a significant effect?

For the repeated soil available N measurements the effect of treatment, block, collection time, and the interaction between treatments and time were tested using SAS PROC MIXED (SAS Institute 1990). We used this SAS procedure considering a split-plot design for repeated measures having treatment, block, time, and the interaction of treatment × time as predictors of the log transformed available N response variable. Various different variance–covariance structures for the repeated measures through time were considered, but the split-plot in each case was found to be the most appropriate and therefore selected for analysis. The log was used as a variance stabilizing transformation because for many collection dates the HF had values 100-fold higher than the corresponding H treatment. The analysis was carried out by location considering that the study plots in the Dawsonville location had been treated differently over the years.

Results

Based on the MANOVA analysis, for the 0- to 10- and 30- to 50-cm depths near Athens and 0- to 10-cm depth in the Eatonton location there was an overall significant treatment effect ($\alpha = 0.05$). To the contrary in the Dawsonville location treatment had no overall significant effect at any depth. For descriptive purposes of comparison among sites results for the different variables have also been reported as average values by depth and treatment for each location.

Soil bulk density

Based on our analyses, there were no statistically significant differences in bulk density within location related to the use of the F treatment. The only significant differences were between H and non-H treatments. Therefore, the same results and conclusions referring to the comparison Control versus H, as discussed by Echeverria et al. (2004), can also be extended to the comparison F versus HF treatments for the Athens and Eatonton sites. Assuming the same bulk density for the entire soil profile in the Dawsonville location may have affected the pool estimates. Based on field observations, the Dawsonville site had fairly homogenous soil textural composition, structure, and color within the sampling depth. Possible changes in bulk densities may be due to the effects of periodic flooding and depth to the water table. The depth to the ground water table—measured during the winter months (data not shown)—increased with the distance from the adjacent Etowah River. This may create a bias in the estimation of bulk densities, which may vary with the distance from the river. However, we believe it was a realistic assumption for comparing the nutrient pools between treatments as discussed below. Likely it was not acceptable to test differences across sites based on element pool estimates.

Mineral soil C, N, and P concentrations

At the Athens site there was no statistically significant difference at any depth for soil C concentrations between H and non-H plots, although H-treated plots always had lower concentrations

Table 3 Total C, N, P, and extractable P concentrations (mean ± 1 SE) measured for replicate loblolly pine stands within the Consortium for Accelerated Pine Productivity Studies (CAPPS) in Georgia

Location	Depth (cm)	Treatment[a]	C (%)	N (%)	P ($\mu g\ g^{-1}$)	Ext-P ($\mu g\ g^{-1}$)
Athens	0–10	C	1.5 ± 0.2	0.05 ± 0.01	485 ± 71	1.7 ± 0.1
		F	2.0 ± 0.6	0.11 ± 0.04	566 ± 85	8.6 ± 1.9
		H	1.1 ± 0.1	0.04 ± 0.00	502 ± 29	1.4 ± 0.2
		HF	1.3 ± 0.3	0.06 ± 0.01	691 ± 55	14.0 ± 5.7
	Significant contrasts[b]:		NS	NS	NS	B, c
	10–30	C	0.6 ± 0.1	0.03 ± 0.01	455 ± 85	0.8 ± 0.1
		F	0.5 ± 0.1	0.03 ± 0.01	642 ± 82	2.0 ± 0.5
		H	0.5 ± 0.0	0.03 ± 0.00	451 ± 13	1.2 ± 0.5
		HF	0.6 ± 0.1	0.03 ± 0.01	576 ± 19	1.8 ± 0.1
	Significant contrasts[b]:		NS	NS	NS	NS
	30–50	C	0.3 ± 0.1	0.02 ± 0.00	446 ± 88	0.6 ± 0.1
		F	0.3 ± 0.0	0.01 ± 0.00	585 ± 74	0.9 ± 0.2
		H	0.3 ± 0.0	0.01 ± 0.00	516 ± 20	0.8 ± 0.2
		HF	0.3 ± 0.0	0.01 ± 0.00	435 ± 41	1.7 ± 0.0
	Significant contrasts[b]:		NS	NS	NS	NS
Eatonton	0–10	C	1.5 ± 0.2	0.07 ± 0.01	339 ± 48	1.2 ± 0.5
		F	1.5 ± 0.2	0.08 ± 0.01	389 ± 37	4.8 ± 1.2
		H	1.3 ± 0.1	0.06 ± 0.00	341 ± 30	0.8 ± 0.2
		HF	1.4 ± 0.1	0.07 ± 0.01	402 ± 36	3.9 ± 1.1
	Significant contrasts[b]:		NS	NS	NS	B, C
	10–30	C	0.8 ± 0.2	0.04 ± 0.01	319 ± 39	0.4 ± 0.2
		F	0.7 ± 0.1	0.04 ± 0.00	336 ± 22	1.3 ± 0.8
		H	0.6 ± 0.1	0.03 ± 0.00	361 ± 28	0.3 ± 0.1
		HF	0.6 ± 0.0	0.03 ± 0.00	340 ± 25	0.4 ± 0.1
	Significant contrasts[b]:		A	NS	NS	NS
	30–50	C	0.3 ± 0.1	0.02 ± 0.00	345 ± 36	0.3 ± 0.1
		F	0.4 ± 0.0	0.03 ± 0.00	335 ± 33	0.3 ± 0.1
		H	0.3 ± 0.0	0.02 ± 0.00	402 ± 40	0.3 ± 0.1
		HF	0.3 ± 0.0	0.02 ± 0.00	330 ± 29	0.3 ± 0.1
	Significant contrasts[b]:		NS	NS	NS	NS
Dawsonville	0–10	C	2.0 ± 0.0	0.12 ± 0.00	NA	34.0 ± 7.4
		F	2.1 ± 0.4	0.13 ± 0.03	NA	87.0 ± 37.0
		H	1.7 ± 0.1	0.10 ± 0.01	NA	51.0 ± 18.0
		HF	1.6 ± 0.0	0.09 ± 0.00	NA	58.0 ± 13.0
	Significant contrasts[b]:		NS	NS		C
	10–30	C	1.4 ± 0.1	0.08 ± 0.00	NA	19.0 ± 5.7
		F	1.4 ± 0.3	0.07 ± 0.02	NA	39.0 ± 18.0
		H	1.2 ± 0.2	0.07 ± 0.01	NA	25.0 ± 8.3
		HF	1.3 ± 0.1	0.07 ± 0.00	NA	18.0 ± 4.2
	Significant contrasts[b]:		NS	NS		C
	30–50	C	1.1 ± 0.2	0.06 ± 0.01	NA	2.8 ± 0.3
		F	0.7 ± 0.1	0.04 ± 0.01	NA	6.5 ± 4.5
		H	0.9 ± 0.2	0.05 ± 0.01	NA	5.0 ± 0.6
		HF	1.0 ± 0.2	0.06 ± 0.01	NA	4.3 ± 0.8
	Significant contrasts[b]:		NS	NS		

[a] The Control (C), fertilizer (F), herbicide (H), and HF treatments were sampled in December 1999 and January 2000 near Eatonton ($n = 40$), in July and August 2001 near Athens ($n = 12$), and in March 2003 near Dawsonville ($n = 14$)

[b] Orthogonal contrasts at each depth: letters beneath a column indicate significance at $P < 0.05$ (capitals) or 0.10 (lower case) for contrasts: A) Herbicide (H and HF) versus non-herbicide (C and F), B) Herbicide (H) versus Herbicide plus Fertilizer (HF), and C) Control (C) versus Fertilizer (F). Contrasts not shown were not significant (NS)

than the other treatments (Table 3). There was a general decreasing pattern in soil C concentration with depth having a maximum concentration of 2 % in the surface and a minimum of 0.3 % at 30- to 50-cm depth. Total N concentration showed a similar decreasing pattern with depth ranging from a maximum of 0.11 % to a minimum of 0.01 %. Total P concentration did not demonstrate a similar pattern with depth. Total P concentration was low, however, in the 0- to 10-cm depth for the Control, about 485 $\mu g\ g^{-1}$, but was not significantly different compared to the other treatments. Conversely, in the 0- to 10-cm depth, extractable P concentration tended to be lower ($\alpha = 0.1$) in the Control, 1.7 $\mu g\ g^{-1}$, compared to the F treatment, 8.6 $\mu g\ g^{-1}$, and was 10-fold lower ($\alpha = 0.05$) in the H, 1.4 $\mu g\ g^{-1}$, compared to the HF, 14 $\mu g\ g^{-1}$. Fertilized plots retained higher extractable P concentrations in the lower depths relative to the other treatments, although these differences were not statistically significant.

At the Eatonton site (Table 3), there was a decreasing pattern with depth for soil C concentration with values ranging from 1.5 % to 0.3 %. In the 0- to 10-cm depth there were no significant treatment effects on soil C concentration, but the H and HF plots had the lowest values. In the 10- to 30-cm depth the same H and HF plots did have a significantly lower soil C concentration relative to the corresponding plots without H ($\alpha = 0.05$). There were no significant differences in soil C concentration at 30- to 50-cm depth. Soil total N concentration had a similar decreasing pattern with depth declining from 0.08 % to 0.02 % N. There were no significant differences between treatments. Total P concentration did not decline regularly with depth but in the 0- to 10-cm depth was lower (not significantly) in the Control, about 339 $\mu g\ g^{-1}$, compared to all the other treatments. Extractable P concentration in the 0- to 10-cm depth was significantly lower ($\alpha = 0.05$) in the Control, about 1.2 $\mu g\ g^{-1}$, compared to the F, about 4.8 $\mu g\ g^{-1}$, and in the H, about 0.8 $\mu g\ g^{-1}$, compared to the HF, about 4 $\mu g\ g^{-1}$. The same pattern of elevated extractable P concentration in the F and HF was maintained at lower depths, although again not statistically significant.

Although the overall MANOVA test for Dawsonville was not significant the univariate ANOVAs were carried out considering this initial overall result. Soil C concentration again declined with depth from a high of 2.1 % to a low of 0.7 % (Table 3). On average soil C concentration was higher in plots that did not receive any H treatments but such differences were again not statistically significant. Total N concentration had a general decreasing pattern ranging from a high of 0.13 % at the surface to a low of 0.04 % at 30- to 50-cm depth. Treatment had no significant effect on total N concentration. Total P concentration was not measured in these plots. Based on the univariate ANOVAs by depth, extractable P concentration was significantly lower ($\alpha = 0.05$) at 0- to 10-cm depth in the Control (34 $\mu g\ g^{-1}$) than in the F treatment (87 $\mu g\ g^{-1}$). Differences in extractable P concentration between these treatments were still significant at 10- to 30-cm depth, but were non-significant at 30- to 50-cm depth.

Temporal patterns in soil available N concentration

A seasonal pattern in soil available N concentration was observed for both the H and HF plots in all locations. In general, the highest N availability concentrations, for all three locations, were observed during September and October. The HF plots had much higher N availabilities than the corresponding H plots in all months of the year. HF plot averages across locations ranged from about 9 to > 1,700 $\mu g\ N\ g^{-1}$ while H values ranged from about 4 to < 860 $\mu g\ N\ g^{-1}$. In the Athens location (Fig. 2), based on the overall test using the split-plot model design for repeated measures, all three categorical variables (treatment, time, and treatment × time) were significant (i.e., $P < 0.0001$). On average HF resin-extractable N ranged from about 105 $\mu g\ N\ g^{-1}$ in January to about 3,195 $\mu g\ N\ g^{-1}$ in September, while H concentrations ranged from about 8 $\mu g\ N\ g^{-1}$ in May to about 77 $\mu g\ N\ g^{-1}$ in October. In the Eatonton location the only significant variables were treatment ($P < 0.05$) and time ($P < 0.001$). On average HF resin-extractable N concentrations ranged from about 128 $\mu g\ N\ g^{-1}$ (January) to about 1,286 $\mu g\ N\ g^{-1}$ (October), while H concentrations ranged from about 4 $\mu g\ N\ g^{-1}$ (November) to about 171 $\mu g\ N\ g^{-1}$ (August). In the Dawsonville location, treatment and the treatment × time interaction were not significant ($P = 0.95$ and $P = 0.77$, respectively), while time was significant ($P < 0.0001$). HF resin-extractable N concentrations ranged from about 9 $\mu g\ N\ g^{-1}$ (August) to about 322 $\mu g\ N\ g^{-1}$ (September), while H

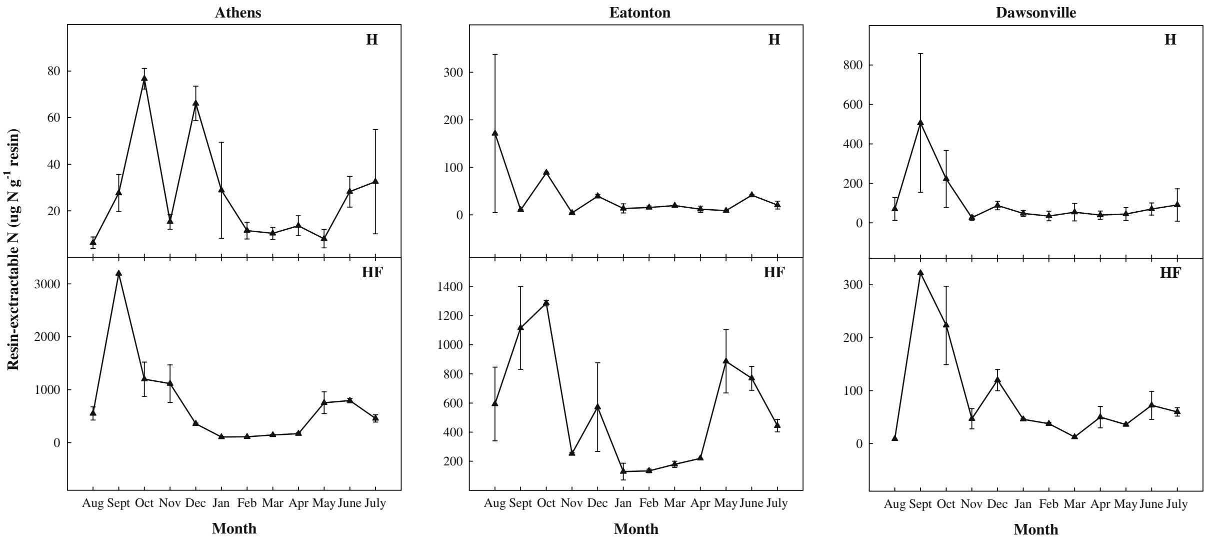

Fig. 2 Resin-extractable N (NO_3-N plus NH_4-N) concentration (mean ± 1 SE μg N g^{-1} resin, $n = 2$ plots) estimated using a mixed bead resin core technique in the 0–10 cm depth on a monthly basis during 2002–2003 for the Herbicide (H) and Herbicide plus Fertilizer (HF) plots located near Athens, Eatonton, and Dawsonville, GA

concentrations ranged from about 26 μg N g^{-1} (November) to about 506 μg N g^{-1} (September).

Atmospheric mineral N inputs

Athens and Dawsonville sites had the same volume weighted mean annual concentration of total inorganic N in wet-only deposition (0.7 mg L^{-1}), which was only slightly greater than inputs found near Eatonton (0.6 mg L^{-1}) (data not shown). Cumulative amounts of precipitation differed, however, with the Dawsonville sites (209.2 cm) exceeding those near Athens (165.4 cm) and Eatonton (173.4 cm). As a result, the sites near Dawsonville also had a higher total inorganic N deposition (12.6 kg ha^{-1}) during the period of collection compared to those near Athens (9.9 kg ha^{-1}) and Eatonton (11.4 kg ha^{-1}).

Discussion

Mineral soil C—response to fertilization

Long-term fertilizer application tended to enhance mineral soil C storage only in one location. In the Athens site (Fig. 3), at 0- to 50-cm depth, plots that received the F treatment in presence or in absence of the H treatment appeared to have a higher (but not significantly) soil C pool, being about 38.6, 42.6, 36.7, and 42.0 Mg C ha^{-1} for the Control, F, H, and HF treatment, respectively. Increased N inputs reduced the corresponding soil C:N ratio in both the F and HF plots compared to Control and H, respectively, in these N-limited sites. The corresponding C:N ratios were 30:1, 18:1, 27.5:1, and 21.6:1 for Control, F, H, and HF, respectively (0- to 10-cm depth). In the Eatonton location only soil total N and the C:N ratio in the fertilized plots (F and HF) were slightly greater and smaller, respectively, compared to the corresponding non-fertilized plots (Control and H). Near Dawsonville, where fertilization was truncated after 6 or 9 years (i.e., from 1987 or 1989 to 1996), no significant effects on soil C, N, or C:N ratio were observed (C:N varied between 16:1 and 18:1 in the 0–10 cm depth).

These results that demonstrate limited soil C accumulations in response to fertilization are in agreement with previous findings under pine plantations, underscoring that C sequestration occurs primarily in the aboveground biomass (Richter et al. 1995; Shan et al. 2001; Schlesinger and Lichter, 2001; Johnson et al. 2003). In other words the amount of sequestered C per unit of

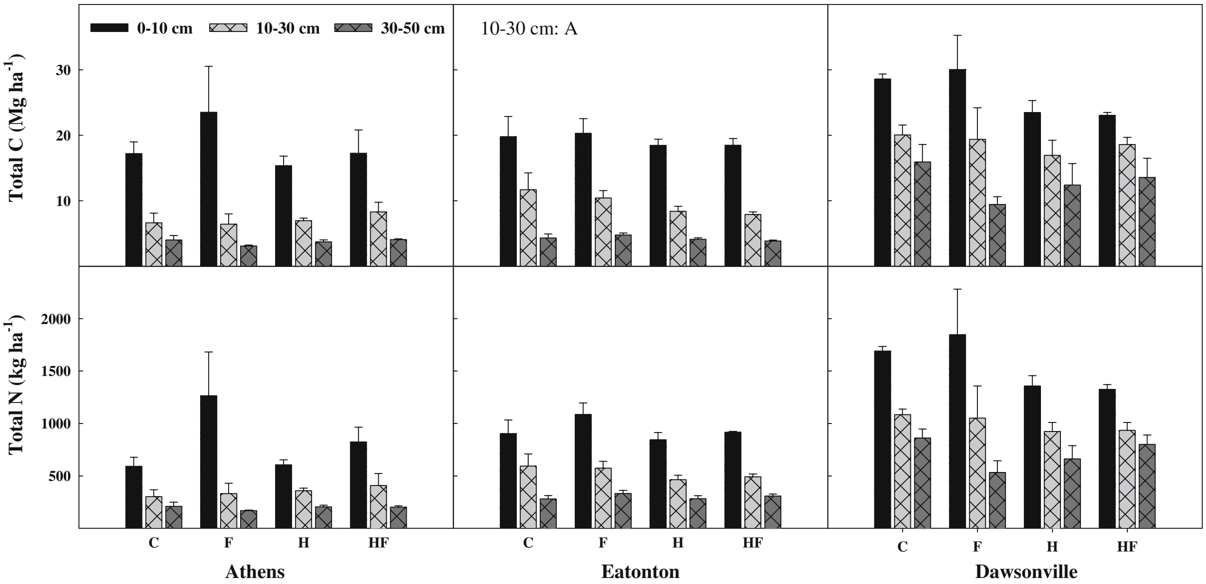

Fig. 3 Soil total C and N by location, treatment (Control (C), Fertilizer (F), Herbicide (H), and Herbicide plus Fertilizer (HF)), and depth (all element pools refer to a 10-cm soil depth increment) (mean ± 1 SE). Letters in the upper left corner of each graph indicate significance at $P < 0.05$ (capitals) or 0.10 (lower case) for contrasts: A) Herbicide plots (H and HF) versus non-herbicide ones (C and F), B) H versus HF, and C) F versus C (Only significant contrasts are presented by each depth. Contrasts not shown were not significant)

fertilizer added is much smaller in the mineral soil compared to above and belowground biomass C gains. On another CAPPS site in the Georgia Coastal Plain near Waycross, studies have demonstrated a similar shift from below to aboveground C allocation after 13 years of loblolly pine plantation management. Near Waycross, the F and HF treatments decreased the fine root C pools to 560 and 380 kg C ha^{-1}, respectively, relative to 925 and 540 kg C ha^{-1} in Control and H plots, respectively. Meanwhile, augmented aboveground allocation to foliage increased litter C accumulation (i.e., soil O horizons) from 8,900 and 10,050 kg C ha^{-1} in Control and H, respectively, to 16,400 and 19,700 kg C ha^{-1} in F and HF (Will et al. 2006). Similar allocation patterns have been reported by other authors for fertilized stands under 17-year-old slash pine (*Pinus elliottii* Engelm.) plantations in the Coastal Plain Flatwoods of Florida (Shan et al. 2001).

Other studies have observed relatively high rates of soil C accumulations under loblolly pine plantations even within a decade since planting (from 0.4 to 1.7 Mg C ha^{-1} yr^{-1}), underscoring that the rate of accumulation is highly variable with soil-site conditions (Van Lear et al. 1995; Garten 2002). Soil C accumulation under aggrading forest ecosystems varies widely (Post and Kwon 2000) and the time required to detect significant soil C accumulations is at least a decadal scale process (Paul et al. 2002). Land-use history, soil type, vegetation type, harvesting cycle, and other management practices influence rates of soil C accumulations (Sartori et al. 2006). The amount of soil C that can be stored in the mineral soil is determined by physicochemical limits. Formation of stable micro- and macro-aggregates in soils rich in silt and clay increases soil C protection (Jenkinson 1977; Tisdall and Oades 1982; Amato and Ladd 1992) as does the adsorption of C by silt and clay. Ingram and Fernandes (2001) defined the saturation of this adsorption capacity as the 'attainable" level of soil C relative to the "actual" soil C present. Increases in the soil C pool due to fertilization in pine plantations may be hard to detect if the actual soil C pool is already near or at the "attainable" level.

The three sites in the current study may well differ in the relative sizes of the "actual" and "attainable" soil C levels. In fact, the clay-rich

Hapludults in the Athens and Eatonton locations may offer relatively greater SOM protection than the sandy-loam textured Udifluvent in the Dawsonville site. However, in highly weathered soils, such as Hapludults, aggregate formation typically depends on the binding between 1:1 clay minerals and oxides and is less related to SOM (Oades and Waters 1991). Thus, low-activity 1:1 clay minerals (kaolinite) provide relatively low protection to soil C against microbial activity. The mechanisms of soil C sequestration in afforested soils are still not well understood. Physical or density fractionation methods may provide a better quantification of the more recalcitrant soil C fractions (Six et al. 2002; Echeverria et al. 2004).

The hypothesis that soil C increases with sustained fertilization is not well supported by this study, whose focus was on the C pool of the mineral soil. Carbon sequestration may derive more from accumulations in forest floor or tree biomass (Richter et al. 1995; Van Lear et al. 1995; Schlesinger and Lichter 2001). Unfortunately, the forest floor C pool may be removed during site preparation under many operations as currently applied in intensively managed pine plantations. Thus, the forest floor would represent only a short-term C sink (i.e., rotation length). The disposition of tree biomass whether as pulp for paper or saw logs for lumber will directly impact the longevity of sequestered C as aboveground biomass. These results suggest that other management practices that enhance C sequestration need to be considered, if/when C sequestration becomes an important externality to forest managers. The retention of the forest floor at site preparation and its inclusion with the forest slash into the mineral soil may prove effective to augment C sequestration in southern pine plantations. Some preliminary data suggest that these practices may also improve soil properties and seedling survival (Sanchez and Eaton 2001).

Mineral soil N and P—response to fertilization

Results for mineral soil N indicated no clear distinction between treatments based on soil total N (Fig. 3). In general, surficial soil total N near Athens and Eatonton was slightly higher (not significantly) for plots that received the F treatment, whereas near Dawsonville there were no clear patterns. Patterns in total N with management are consistent with data from the mixed bead resin core technique (i.e., low and high N values for the H and HF, respectively, for Athens and Eatonton sites) and confirm previous studies that found total N correlates to soil N availability indices (Binkley and Hart 1989). At greater depths these differences in N among treatments tended to disappear. In the Athens site, based only on the resin-extractable N estimates at 0- to 10-cm depth, the corresponding yearly cumulative N extracted was on average 13.5 kg ha^{-1} yr^{-1} for the H plots and about 370 kg ha^{-1} yr^{-1} for the corresponding HF plots. The cumulative contents were computed considering that each bag contained 4 g of resins and the soil core volume internal to the PVC tube was about 96.2 cm^3 (depth = 10 cm). Similarly, in the Eatonton site total resin-extractable N was on average about 18 and 270 kg ha^{-1} yr^{-1} for the H and HF plots, respectively. In the Dawsonville site, total cumulative resin-extractable N was on average about 53 and 43 kg ha^{-1} yr^{-1} for the H and HF plots, respectively. Clearly, the annual fertilization near Athens and Eatonton has sustained an increase in soil available N. Conversely near Dawsonville, where fertilization was discontinued, differences in N availability were absent, despite relatively high soil N availability.

The cumulative annual fluxes of N mineralization in the HF plots near Athens and Eatonton were much higher than the annual N fertilization rate—even if the rates of the H- are subtracted from the rates of the HF-treated plots (i.e., about 6-fold and 4-fold higher in the Athens and Eatonton sites, respectively). These results suggest that there was an overestimation of N fluxes using a mixed-bead resin core technique. There is no available method that can measure accurate rates of N mineralization in the field. All procedures that measure the accumulation of N in the absence of plant uptake alter to some degree soil moisture and the functional status of roots and mycorrhizae (Keeny 1980; Vitousek and Matson 1985; Adams et al. 1989; Hanselman et al. 2004). In general, the presence of any apparatus causes some modifications, whose degree varies upon its structure and with the time of in situ application.

The specific PVC apparatus as used in our study may have produced (1) a reduction of the C input from litter decomposition and cessation of inputs from fine-root turnover, (2) an increase in C inputs from severed roots, and/or (3) a modification of the soil moisture and temperature regimes.

Mechanisms that increased C-inputs into the soil core's system likely increased N immobilization by the bacterial population. Thus, higher immobilization may have lowered soil N availability. At the same time, the cessation of N uptake by tree roots (in presence of the PVC tube) may have contributed to the larger-than-expected N accumulation in the resin bags. The mixed bead resin core technique as used in this study also demonstrated some other limitations discussed by Hanselman et al. (2004). During many collection dates, standing water was found on the top of the soil core internal to the PVC tubes indicating that water dynamics did not reflect that in the field and such prolonged water saturated conditions may induce denitrification. Such conditions may produce biased estimates of soil N availability (Hanselman et al. 2004). Denitrification would have resulted in lower estimates of N availability during the wettest months (i.e., March) (Fig. 2).

The temporal patterns in resin-extractable N concentrations indicate that there was a relative minimum in all locations during the winter months (including the wettest month, March). However, the low soil temperatures during the winter months (data not shown)—rather than denitrification losses—likely caused the relatively lower soil N availability. Low soil temperatures reduced the activity of the bacterial population and thus soil N mineralization processes. In the HF plots the annual fertilizer application of about 59 kg N ha^{-1} yr^{-1} has likely created the elevated spikes in N availability, despite fertilizer applications in April. Relative maxima were observed in both treatments in October (near Athens and Eatonton) and September (near Dawsonville) (Fig. 2). During the summer months there were dry soil moisture conditions (data not shown), which may have reduced N mineralization processes.

The above estimates for annual resin-extractable N in the H plots are within the range of previously reported data. For example, Vitousek and Matson (1984; 1985) and Vitousek et al. (1992) report that in the 0- to 15-cm depth layer net N availability under loblolly pine in the North Carolina Piedmont ranged from 80–90 kg ha^{-1} yr^{-1} at age 1 year to 40–50 kg ha^{-1} yr^{-1} at age 5 years. Vitousek and Matson (1985) studied the effects of harvest intensity, site preparation, and herbicide treatment in a clear-cut site under loblolly pine in the North Carolina Piedmont. These authors reported that net nitrogen mineralization followed a sinusoidal pattern, with a peak early in the growing season (April to June) in all plots during both 1982 and 1983. They also concluded that the peaks were accentuated by forest harvesting operations through their effects on soil temperature, moisture, and substrate litter quality.

Although available N is likely a major driver of growth among the treatments at all sites, the presence of readily available P is essential for sustained tree growth (Fig. 4). In the Athens location, P fertilization has significantly increased extractable P contents in the F and HF treatment plots at 0- to 10-cm depth (i.e., about 2, 10, 2, and 19 kg ha^{-1} for the Control, F, H, and HF plots, respectively) and a similar significant increase was detected in the lower 30- to 50-cm depth (i.e., about 5, 17, 7, and 28 kg ha^{-1} for the Control, F, H, and HF plots, respectively, at 0- to 50-cm depth). In all cases, however, available P only represents a small percentage of the corresponding soil total P that ranged between 2,653 kg ha^{-1} and 3,635 kg ha^{-1} (0- to 50-cm depth). Results near Eatonton were similar to the Athens sites where the extractable P was approximately 3-fold higher in plots that received the F treatment (i.e., about 3.5, 10.7, 3.0, and 7.3 kg ha^{-1} for Control, F, H, and HF plots, respectively) and represents only a small percentage of the corresponding soil total P that ranged from about 2,249 kg ha^{-1} to 2,649 kg ha^{-1} (0- to 50-cm depth). In the Dawsonville location, extractable P was higher in the F compared to the non-F plots only in the absence of the H treatment (i.e., about 78, 185, 113, and 113 kg ha^{-1} for Control, F, H, and HF plots, respectively, at 0- to 50-cm depth). The P fertilization in this study caused a long-term increase on the soil nutrient status since P was not applied annually like N. The retention of P fertilizer over

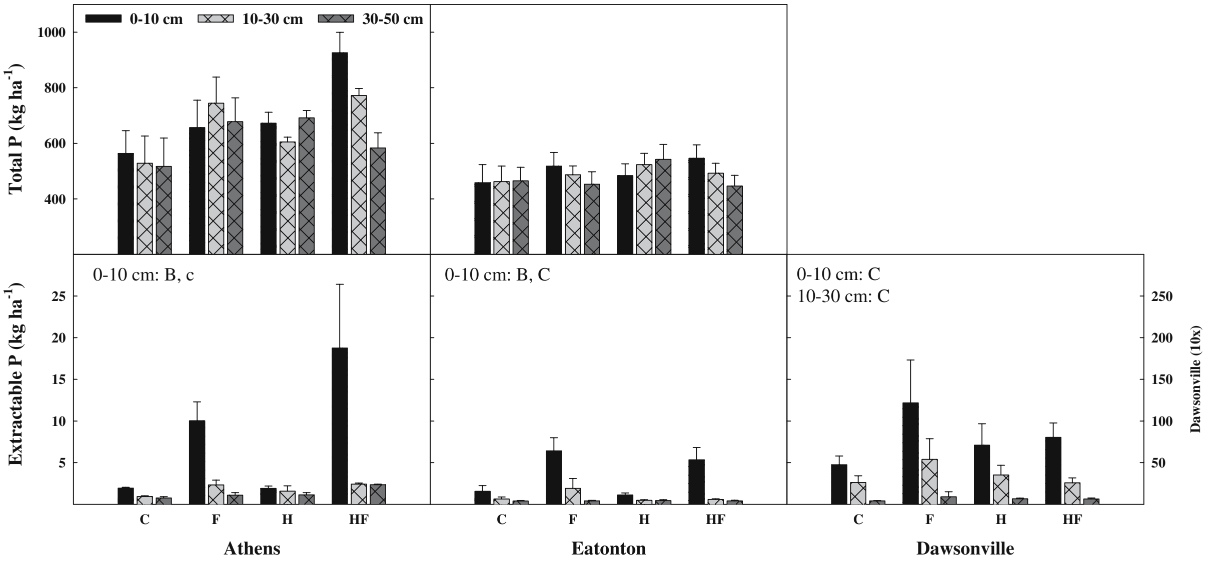

Fig. 4 Soil total and extractable P by location, treatment (Control (C), Fertilizer (F), Herbicide (H), and Herbicide plus Fertilizer (HF)), and depth (all element pools refer to a 10-cm soil depth increment) (mean ± 1 SE). Total P was not measured for the Dawsonville site. Letters in the upper left corner of each graph indicate significance at $P < 0.05$ (capitals) or 0.10 (lower case) for contrasts: A) Herbicide plots (H and HF) versus non-herbicide ones (C and F), B) H versus HF, and C) F versus C (Only significant contrasts are presented by each depth. Contrasts not shown were not significant)

decades or even centuries time scale has been observed by other authors (e.g., Fransson and Bergkvist 2000). The long-term recycling of P fertilizer inputs through organic residues was demonstrated in a north Florida pine plantation (Polglase et al. 1992) and would be important at these sites for the sustained availability of P with its subsequent effect on growth.

The soils in the Dawsonville site had an inherently higher extractable P (Control and H plots), which may depend on differences in parent material, biogeochemistry, or site history. The Typic Kanhapludults near Athens and Eatonton are highly weathered soils and likely contain less phosphate-rich minerals than the Typic Udifluvents near Dawsonville. The Dawsonville soils are also flood-prone soils that undergo anaerobic conditions for brief periods during winter or spring. In the Georgia Coastal Plain, Wright et al. (2001) studied the effects of artificial flooding on P availability in a forested floodplain ecosystem along the Ogeechee River, near Savannah, GA. These authors hypothesized that P availability would increase with flooding duration and periodicity, primarily because the flooded-induced release of P from Fe and Al phosphate, as observed for upland soils flooded for rice cultivation. Based on their results, they concluded that biological processes were the major cause for flooding-induced increases in P availability rather than solubilization of mineral phosphate. Finally, many of the floodplains of the Etowah River near Dawsonville are currently under agriculture and this study area may have had a similar agricultural history. Even in the absence of agriculture in vicinity of this site, in agricultural and urban areas higher P-availability may derive from the floodwaters, which can carry significant loadings of available P (Carpenter et al. 1998).

Mineral soil C, N, and P—response to herbicide treatment

Results relating to mineral soil C in response to herbicide treatments agree with those reported by Echeverria et al. (2004). These authors observed that soil C was significantly lower in the H compared to the Control plots, using some of the same stands—but working only in the Control and H plots—near Athens and Eatonton. The soil

C pool at all three study locations show decreasing patterns with the application of H treatments, although significant concentration differences occurred only in the 10- to 30-cm depth near Eatonton. For example, in the Eatonton site, plots under the H treatment had lower soil C pool (0- to 50-cm depth), being 50.2, 48.9, 43.6, and 41.1 Mg C ha^{-1} for the Control, F, H, and HF, respectively (Fig. 3). Similarly, near Dawsonville, the soil C pool was 64.6, 58.9, 52.8, and 55.2 Mg C ha^{-1} for the Control, F, H, and HF, respectively. The results from these two locations appear to indicate that declines observed in response to H treatments were not balanced by increases under F. In other words, the surface soil C pool in the HF plots was typically lower than in the Control plots and about the same in the H plots. Near Athens, reductions in the mineral soil C pool were only partially counterbalanced in the HF (42.0 Mg ha^{-1} yr^{-1}) compared to the H (36.7 Mg ha^{-1} yr^{-1}) and the Control (38.6 Mg ha^{-1} yr^{-1}). It is likely that over longer durations larger and significant differences between H- and non-H-treated plots may be detected similarly to other studies.

The above results also support findings reported by Shan et al. (2001), who observed a significant decrease in mineral soil C in a 17-year-old slash pine plantation. These authors also observed a reduction in fine-root turnover of 0.4 Mg C ha^{-1} yr^{-1} due to the H treatment. Reduction in mineral soil C in H-treated plots under pine plantations may well result from reduced fine-root litter inputs. In the 13-year-old CAPPS plots near Waycross, the H treatment had decreased the fine root biomass pool, which was 385 kg C ha^{-1} smaller than in the Control (i.e., 925 and 540 kg C ha^{-1} in Control and H, respectively), and increased the forest floor biomass (i.e., 8,900 and 10,050 kg C ha^{-1} in Control and H, respectively). Despite the presence of a thicker forest floor under the H treatments, the mineral soil C pool was generally lower under H compared to non-H-treated plots, although not statistically significant (Will et al. 2006). Similarly, Echeverria et al. (2004) found average reductions for C and N of 20 % and 19 % compared to the Control plots, respectively, and average declines found in the literature ranged from 18 % to 33 % for mineral soil C and 10 % to 30 % for N (Aust and Lea 1991; Polglase et al. 1992; Carlyle 1993; Munson et al. 1993).

The H treatment effects on the N pool were similar to those of F only near Athens. In fact, the H treatment lowered the soil C:N ratio compared to the Control. One possible hypothesis supporting lower C:N ratios in the H plots is that there are differences in quality of SOM inputs. Aboveground litter inputs are reduced and most SOM derives from belowground litter (e.g., fine roots) inputs with lower C:N ratios. Instead in the other two locations, C:N ratios in the H and Control were about the same and do not support such hypothesis.

The absence of any specific patterns of total or extractable P with application of the H treatments suggests that P availability in upland soils is not predominantly controlled by the cycling of soil C, although clearly depends on these sources over the long-term (Richter et al. 2006). Observed patterns in soil P depend primarily on the external fertilizer inputs as indicated by higher total and available P in the F and HF plots. Generally the amount of soil P available to plants, which is extremely low in piedmont soils, depends on the equilibrium among different soil P pools, including organic pools, which involve interaction with iron and aluminum and the ability of pine mycorrhizae to obtain P from insoluble forms (Humphreys and Pritchett 1971; Jorgensen and Wells 1986; Richter et al. 2006).

Tree growth response

Given the above responses in mineral soil C, N, and P one might infer clear tree growth increases in F or HF plots. Aboveground biomass was estimated using available growth data for the Athens, Eatonton, and Dawsonville sites (Borders and Bailey 2001; Borders, unpublished data), tree volume outside bark equations (Harrison and Borders 1996), and an assumed wood density of 0.249 Mg C m^{-3} (based on Birdsey 1992). Stands in the Athens and Eatonton locations showed a response to F, H, and particularly HF of about 2-fold higher compared to the Control. For example at age 10 years near Athens, standing biomass was about 19.2 and

34.5 Mg C ha^{-1} greater for the H and HF, respectively, than in the corresponding Control plot (about 28.7 Mg C ha^{-1}). At age 11 years near Eatonton, standing biomass was about 24.7 and 42.2 Mg C ha^{-1} greater for the H and HF, respectively, than the corresponding Control plot (about 25.5 Mg C ha^{-1}) (Borders and Bailey 2001). In the Dawsonville sites the response to H treatments was clear, but that to F was not so apparent likely due to the abandonment of annual fertilization in 1996 and higher site fertility. As an example, at age 12 years standing biomass was about 47.9 and 41.9 Mg C ha^{-1} greater for the H and HF, respectively, than the corresponding Control plot (about 27.2 Mg C ha^{-1}) (Borders et al., unpublished data).

Conclusions

In all three locations the decade-long treatments of competition control with herbicides and annual fertilizations (throughout stand life near Athens and Eatonton and for 7 to 9 years near Dawsonville) primarily enhanced C sequestration in the aboveground biomass in agreement with previous studies in pine plantations. The herbicide treatments appeared to deplete the soil C pool in all three locations—a significant depletion in mineral soil C was observed only in one location (near Eatonton). The fertilization treatment did not consistently increase the C pool of the mineral soil, suggesting that such treatments may not buffer and counter the possible negative effects of the herbicide treatment. It appears that within the mineral soil the potential belowground C losses—from fine root inputs—are not balanced by increased inputs deposited on the soil surface through increased aboveground litter inputs. In general, however, the H, F, and HF treatments in these pine stands increased tree growth. At present it still is not possible to predict mineral soil C response to plantation management activities and despite some declines in soil nutrient contents it does not appear that site productivity has diminished during the current rotation.

On the relatively nutrient poor Ultisols near Athens and Eatonton high values of soil available N and P were associated with high tree biomass growth responses. On the nutrient rich Udifluvents near Dawsonville it was not possible to find a clear correspondence between soil available N and extractable P and the response to F and H treatments in aboveground tree biomass. In fact, soil available N was about 100-fold higher in the HF compared to H plots near Athens and Eatonton but not near Dawsonville.

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References

Adams MA, Polglase PJ, Attiwill PM, Weston CJ (1989) *In situ* studies of nitrogen mineralization and uptake in forest soils; some comments on the methodology. Soil Biol Biochem 21:423–429

Albaugh TJ, Allen HL, Dougherty PM, Johnsen KH (2004) Long term growth responses of loblolly pine to optimal nutrient and water resource availability. For Ecol Manage 192:3–19

Amato M, Ladd JN (1992) Decomposition of ^{14}C-labeled glucose and legume material in soils: properties influencing the accumulation of organic residue C and microbial biomass C. Soil Biol Biochem 24:455–464

Aust WM, Lea R (1991) Site temperature and organic matter in a disturbed forested wetland. Soil Sci Soc Am J 55:1741–1746

Binkley D, Hart SC (1989) The components of nitrogen availability assessments in forest soils. Adv Soil Sci 10:57–112

Binkley D, Matson P (1983) Ion exchange resin bag method for assessing forest soil nitrogen availability. Soil Sci Soc Am J 47:1050–1052

Birdsey RA (1992) Carbon storage and accumulation in United States forest ecosystems. General technical report WO-59. United States Department of Agriculture, Forest Service, Washington, DC, USA

Borders BE, Bailey RL (2001) Loblolly pine—pushing the limits of growth. South J App For 25:69–74

Borders BE, Will RE, Markewitz D, Clark A, Hendrick R, Teskey RO, Zhang Y (2004) Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. For Ecol Manage 192:21–37

Bremmer JM, Mulvaney CS (1982) Nitrogen—total. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis. Part 2. Chemical and microbiological properties. Soil Science Society of America, Madison, WI, USA, pp 595–624

Butnor JR, Johnsen KH, Sanchez FG (2006) Whole-tree and forest floor removal from a loblolly pine plantation have no effect on forest floor CO_2 efflux 10 years after harvest. For Ecol Manage 227:89–95

Carlyle JC (1993) Organic carbon in forested sandy soils: properties, processes, and the impact of forest management. N Z J For Sci 23:390–402

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Applic 8:559–568

Dean AM, Voss DT (1999) Design and analysis of experiments. Springer-Verlag, New York, NY, USA, 740 pp

Echeverria ME, Markewitz D, Morris LA, Hendrick RL (2004) Soil organic matter fractions under managed pine plantations of the southeastern USA. Soil Sci Soc Am J 68:950–958

Fransson A, Bergkvist B (2000) Phosphorus fertilization causes durable enhancement of phosphorus concentrations in forest soil. For Ecol Manage 130:69–76

Garten Jr CT (2002) Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. Biomass Bioenergy 23:93–102

Giardina CP, Binkley D, Ryan MG, Fownes JH, Senock RS (2004) Belowground carbon cycling in a humid tropical forest decreases with fertilization. Oecologia 139:545–550

Gough CM, Seiler JR (2004) Belowground carbon dynamics in loblolly pine (*Pinus taeda*) immediately following diammonium phosphate fertilization. Tree Physiol 24:845–851

Hanselman TA, Graetz DA, Obreza TA (2004) A comparison of *in situ* methods for measuring net nitrogen mineralization rates of organic soil amendments. J Environ Qual 33:1098–1105

Harrison WM, Borders BE (1996) Yield prediction and growth projection for site-prepared loblolly pine plantations in the Carolinas, Georgia, Alabama and Florida. PMRC technical report 1. University of Georgia Warnell School of Forest Resources, Athens, GA, USA, 64 pp

Harrison KG, Broecker WS, Bonani G (1993) The effect of changing land use on soil radiocarbon. Science 262:725–726

Heath LS, Kimble JM, Birdsey RA, Lal R (2003) Chapter 23. The potential of U.S. forest soils to sequester carbon. In: Kimble JM, Heath LS, Birdsey RA, Lal R (eds) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. CRS Press, Boca Raton, FL, USA, pp 385–394

Humphreys FR, Pritchett WL (1971) Phosphorus adsorption and movement in some sandy forest soils. Soil Sci Soc Am Proc 35:495–500

Huntington TG (1995) Carbon sequestration in an aggrading forest ecosystem in the southeastern USA. Soil Sci Soc Am J 59:1459–1467

Ingram JSI, Fernandes ECM (2001) Managing carbon sequestration in soils: concepts and terminology. Agr Ecosyst Environ 87:111–117

Janzen HH (2004) Carbon cycling in earth systems—a soil science perspective. Agr Ecosyst Environ 104:399–417

Jenkinson DS (1977) Studies on the decomposition of plant material in soil. V. The effects of plant cover and soil type on the loss of carbon from ^{14}C labeled ryegrass decomposing under field conditions. J Soil Sci 28:424–434

Johnsen KH, Wear D, Oren R, Teskey RO, Sanchez F, Will R, Butnor J, Markewitz D, Richter D, Rials T, Allen HL, Seiler J, Ellsworth D, Maier C, Katul G, Dougherty PM (2001) Meeting global policy commitments: carbon sequestration and southern pine forests. J For 99:14–21

Johnson DW (1995) Role of carbon in the cycling of other nutrients in forested ecosystems. In: McFee WW, Kelly JM (eds) Carbon forms and functions in forest soils. Soil Science Society of America, Madison, WI, USA, pp 299–328

Johnson DW, Curtis PS (2001) Effects of forest management on soil C and N storage: meta analysis. For Ecol Manage 140:227–238

Johnson DW, Hoylman AM, Ball JT, Walker RF (2006) Ponderosa pine responses to elevated CO_2 and nitrogen fertilization. Biogeochemistry 77:157–175

Johnson DW, Todd Jr DE, Tolbert VR (2003) Changes in ecosystem carbon and nitrogen in a loblolly pine plantation over the first 18 years. Soil Sci Soc Am J 67:1594–1601

Johnson RA, Wichern DW (1998) Applied multivariate statistical analysis, 4th edn. Prentice Hall, Upper Saddle River, NJ, USA, 816 pp

Jokela EJ, Dougherty PM, Martin TA (2004) Production dynamics of intensively managed loblolly pine stands in the southern United States: a synthesis of seven long-term experiments. For Ecol Manage 192:117–130

Jorgensen JR, Wells CG (1986) Foresters' primer in nutrient cycling. A loblolly pine management guide.General technical report SE-37. United States Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC, USA, 42 pp

Keeny DR (1980) Prediction of soil nitrogen availability in forest ecosystems: a literature review. For Sci 26:159–171

Kuchler AW (1964) Potential natural vegetation of the counterminous United States. Special publication 36. American Geographical Society, New York, NY, USA, 116 pp

Kuo S (1996) Phosphorus. In: Sparks DL (ed) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America, Madison, WI, USA, pp 869–919

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627

Lee JJ, Dodson R (1996) Potential carbon sequestration by afforestation of pasture in the south-central United States. Agron J 88:381–384

Maimone RA, Morris LA, Fox TR (1991) Soil nitrogen mineralization potential in a fertilized loblolly pine plantation. Soil Sci Soc Am J 55:522–527

Markewitz D (2006) Fossil fuel carbon emissions from silviculture: impacts on net carbon sequestration in forests. For Ecol Manage 236:153–161

McNab WH, Avers PE (1994) Ecological subregions of the United States: section descriptions. Administrative Publication WO-WSA-5. United States Department of Agriculture-Forest Service, Washington, DC, USA, 267 pp

Morris LA, Pritchett WL, Swindel BF (1983) Displacement of nutrients into windrows during site preparation of a flatwood forest. Soil Sci Soc Am J 47:591–594

Mulvaney RL (1996) Nitrogen–inorganic forms. In: Sparks DL (ed) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America, Madison, WI, USA, pp 1123–1184

Munson AD, Margolis HA, Brand DG (1993) Intensive silvicultural treatment: impacts on soil fertility and planted conifer response. Soil Sci Soc Am J 57:246–255

Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. In: Sparks DL (ed) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America, Madison, WI, USA, pp 961–1010

Nicholson G (1984) Methods of soil, plant, and water analysis. Forest Research Institute Bulletin 70. New Zealand Forest Service, New Zealand

Niu X, Duiker SW (2006) Carbon sequestration potential by afforestation of marginal agricultural land in the Midwestern U.S. For Ecol Manage 223:415–427

Oades JM, Waters AG (1991) Aggregate hierarchy in soils. Aust J Soil Res 29:815–828

Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK (2002) Change in soil carbon following afforestation. For Ecol Manage 168:241–257

Paustian K, Six J, Elliott ET, Hunt HW (2000) Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48:147–163

Piatek KB, Allen HL (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

Polglase PJ, Comerford NB, Jokela EJ (1992) Mineralization of nitrogen and phosphorus from soil organic matter in southern pine plantations. Soil Sci Soc Am J 56:921–927

Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Glob Change Biol 6:317–327

Richter DD, Allen HL, Li J, Markewitz D, Raikes J (2006) Bioavailability of slowly cycling soil phosphorus: major restructuring of soil P fractions over four decades in an aggrading forest. Oecologia 150:259–271

Richter DD, Markewitz D, Dunsomb JK, Heine PR, Wells CG, Stuanes A, Allen HL, Urrego B, Harrison K, Bonani G (1995) Carbon cycling in a loblolly pine forest: implications for the missing carbon sink and for the concept of soil. In: McFee WW, Kelly JM (eds) Carbon forms and functions in forest soils. Soil Science Society of America, Madison, WI, USA, pp 233–252

Sanchez FG, Eaton RJ (2001) Sequestering carbon and improving soils: benefits of mulching and incorporating forest slash. J Forest 99:32–36

Sartori F (2004) Soil-site productivity indices and tree growth in loblolly pine (*Pinus taeda* L.) plantations. Ph.D. Dissertation. University of Georgia, Athens, GA, USA

Sartori F, Lal R, Ebinger ME, Parrish DJ (2006) Potential soil carbon sequestration and CO_2 offset by dedicated energy crops in the USA. Crit Rev Plant Sci 25:441–472

SAS Institute (1990) SAS/STAT User's Guide, Version 6, 4th edn. SAS Institute, Cary, NC, USA

Schlesinger WH, Lichter J (2001) Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO_2. Nature 411:466–469

Shan J, Morris LA, Hendrick RL (2001) The effects of management on soil and plant carbon sequestration in slash pine plantations. J Appl Ecol 38:932–941

Six J, Callewaert P, Lenders S, De Gryze S, Morris SJ, Gregorich EG, Paul EA, Paustian K (2002) Measuring and understanding carbon storage in afforested soils by physical fractionation. Soil Sci Soc Am J 66:1981–1987

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33:141–163

USDA-SCS (United States Department of Agriculture-Soil Conservation Service) (1968) Soil survey of Clarke-Oconee counties, Georgia. United States Department of Agriculture, Washington, DC, USA

USDA-SCS (United States Department of Agriculture-Soil Conservation Service) (1972) Soil survey of Dawson, Lumpkin, and White Counties, Georgia. United States Department of Agriculture, Washington, DC, USA

Van Lear DH, Kapeluck PR, Parker MM (1995) Distribution of carbon in a piedmont soil as affected by loblolly pine management. In: McFee WW, Kelly JM (eds) Carbon forms and functions in forest soils. Soil Science Society of America, Madison, WI, USA, pp 489–501

Vitousek PM, Andariese SW, Matson PA, Morris L, Sanford RL (1992) Effects of harvest intensity, site preparation, and herbicide use on soil nitrogen transformations in a young loblolly pine plantation. For Ecol Manage 49:277–292

Vitousek PM, Matson PA (1984) Mechanisms of nitrogen retention in forest ecosystems: a field experiment. Science 225:51–52

Vitousek PM, Matson PA (1985) Disturbance, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. Ecology 66:1360–1376

Vose JM, Allen HL (1988) Leaf area, stemwood growth, and nutrition relationships in loblolly pine. For Sci 34:547–563

Will RE, Markewitz D, Hendrick RL, Meason DF, Crocker TR, Borders BE 2006 Nitrogen and phosphorus dynamics for 13-year-old loblolly pine stands receiving complete competition control and annual N fertilizer. For Ecol Manage 227:155–168

Wright RB, Lockaby BG, Walbridge MR (2001) Phosphorus availability in an artificially flooded southeastern floodplain forest soil. Soil Sci Soc Am J 65:1293–1302