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Forest Management Effects on Surface Soil Carbon and Nitrogen

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ABSTRACT

Changes in surface soil C and N can result from forest management practices and may provide an index of impacts on long-term site productivity. Soil C and N were measured over time for five watersheds in the southern Appalachians: two aggrading hardwood forests, one south- and one north-facing, undisturbed since the 1920s; a white pine (*Pinus strobus* L.) plantation planted in 1956; and two regenerating hardwood forests, a whole-tree harvest in 1980, and a commercial sawlog harvest in 1977. Soils on harvested watersheds were sampled before and for ≈15 yr after harvest. Surface soil C concentration on the undisturbed watersheds varied significantly among sample years. Concentrations fluctuated on the south-facing and decreased on the north-facing watershed. The pattern for total N was similar. Total N decreased significantly on the north-facing but was stable on the south-facing watershed. In the white pine plantation, C increased while N concentrations decreased during the 20-yr period. Soil C and N concentrations generally declined the first year following whole-tree harvest. Fourteen years after cutting, C remained stable, while N was greater compared with reference watershed soils. The commercial sawlog harvest resulted in large increases in surface soil C and N concentrations immediately after cutting. Carbon levels remained elevated 17 yr following cutting. Our data suggest that the forest management practices examined do not result in long-term decreases in soil C and N. However, the high interannual variation on all watersheds suggests that care must be taken in selecting control sites to determine long-term treatment impacts.

Vegetation and soils are inextricably linked (Jenny, 1941). As a result, soil properties are partially dependent on forest type (Alban, 1982; David et al., 1988; Grigal and Ohmann, 1992). Forest management practices directly affect vegetation and may also change soil properties such as soil organic matter. Powers (1989) suggested that forest productivity is directly related to soil organic matter content. Soil organic matter content can change due to normal site processes with time such as succession and biomass accumulation (Snyder and Harter, 1984). Changes can also occur through anthropogenic manipulations such as species conversion (Richter et al., 1994; Alban, 1982), or harvesting (Mueller-Harvey et al., 1985; Mroz et al., 1985; Kraske and Fernandez, 1993). Soil C or N increases or decreases may correspond to changes in potential site productivity.

The objective of this study was to measure the long-term trends in soil C and N on undisturbed mixed hardwood forests and to examine the effects of several forest management practices on soil C and N. Sample periods range from 14 to 20 yr and management regimes included: (i) undisturbed, south- and north-facing reference watersheds; (ii) species conversion, a white pine plantation planted after felling all hardwood vegetation, all logged material was left on site; (iii) even-aged management, a commercial whole-tree harvest, all above-ground woody material was felled and no logging residue remained; (iv) even-aged management, a commercial sawlog harvest using cable-yarding technique, logging residue was left in place and disturbance to the forest floor was minimized.

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MATERIALS AND METHODS

Site and Treatment Description

All study sites are in the Coweeta Hydrologic Laboratory, a 2180-ha USDA Forest Service facility in the southern Appalachians of western North Carolina. The climate is characterized by 1900 mm of precipitation annually with most months receiving at least 100 mm. The growing season extends from early May to early October. Highest mean monthly temperatures are in June through August (20°C) and lowest in December through January (5°C).

North-Facing Reference Watershed

North-facing reference watershed 18 is 13 ha, with mixed-hardwood vegetation. The NREF was selectively logged in the 1920s and subsequently has not been disturbed by humans. Basal area of the forest was ≈26 m^2 ha^{-1} and the overstory is dominated by three *Quercus* spp., red maple (*Acer rubrum* L.), tulip-poplar (*Liriodendron tulipifera* L.), and pignut hickory [*Carya glabra* (Miller) Sweet]. Rosebay rhododendron (*Rhododendron maximum* L.) and mountain laurel (*Kalmia latifolia* L.), both evergreen species, are the dominant understory species. They make up 7.4 and 5.1% of the total basal area, respectively (Day et al., 1988).

Elevation ranges from 726 to 993 m, and slope averages ≈50%. Two soil series were sampled that represent ≈90% of the watershed: the Saunook series, a fine-loamy, mixed, mesic Humic Hapludult, found at streamside positions, and Cowee–Evard complex soils, fine-loamy, mixed–oxidic, mesic, Typic Hapludult, found on ridge positions.

South-Facing Reference Watershed

South-southeast-facing reference watershed 2 is 12 ha, with mixed-hardwood vegetation. The SREF was selectively logged in the 1920s and subsequently has not been disturbed by humans. Vegetation is similar to the NREF described above.

Elevation ranges from 709 to 1004 m with slope average of 60%. Soil series on the watershed include the Fannin series (fine-loamy, micaceous, mesic Typic Hapludult) in side-slope position and the Cullasaja–Tuckasegee complex (loamy-skeletal/fine-loamy, mixed, mesic Typic Haplumbrept) at streamside. All plots were on the Fannin soil type, which occupies ≈60% of the watershed.

White Pine Plantation

The white pine plantation occupies a north-facing watershed adjacent to NREF. The 13-ha hardwood forest was clear-

Abbreviations: SREF, south-facing reference watershed; NREF, north-facing reference watershed; WP, white pine plantation watershed; CSH, commercial sawlog harvest watershed; WTH, whole-tree harvest watershed; GLM, general linear models; TKN, total Kjeldahl nitrogen; PEN, total N determined using Perkin-Elmer 2400 CHN analyzer; DON, dissolved organic nitrogen.

cut in 1940, and regrowth was cut annually until 1955 with all material left in place as part of a water yield experiment. White pine was planted in 1956, and pines were released from hardwood competition as necessary by both cutting and chemical means until 1970. Basal area of WP in 1990 averaged ≈50 m^2 ha^{-1} (Knoepp and Swank, 1994).

Elevation ranges from 760 to 1021 m with an average slope of 50%. Soil series present on the watershed include the Saunook series and the Cowee–Evard complex; both were previously described for NREF. Plots were located on both soil series.

Whole-Tree Harvest

The whole-tree harvest site is a 0.67-ha area with a southeast aspect. Elevation is 990 m with slopes averaging 30%. The mixed-hardwood stand had 34 m^2 ha^{-1} basal area before harvest (Swank and Reynolds, 1986) and was composed of tulip-poplar, black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Muenchh.), northern red oak (*Quercus rubra* L.), and red maple. These species made up 63% of the total basal area. The remaining basal area was made up by nine additional tree species. Aboveground woody biomass was estimated at 178 Mg ha^{-1} (dry weight) before harvest in March 1980.

Soils on the site are in the Chandler (coarse-loamy, micaceous, mesic Typic Dystrochrept) and Tuckasegee (fine-loamy, mixed, mesic Typic Haplumbrept) series. Sample plots were located on both soil types.

Commercial Sawlog Harvest

The commercial sawlog harvest area is on a 59-ha south-facing watershed adjacent to SREF. Elevation ranges from 720 to 1065 m with slopes of 20 to 80%. Three vegetation community types were within the watershed: (i) cove hardwood, at lower elevations and adjacent to the stream at intermediate elevations, (ii) chestnut oak (*Quercus prinus* L.), at intermediate elevations on mesic southeast- and north-facing slopes, and (iii) scarlet oak–pine, at intermediate and upper elevations and ridgetops on xeric southwest- and south-facing slopes (Swank and Caskey, 1982). Before harvest, the basal area was 25 m^2 ha^{-1} (Boring et al., 1988). Logging took place between January and June 1977. Stems remaining after logging were felled in October. Most log removal was conducted from the roads with a mobile cable system. Tractor skidding occurred only on gentle slopes in a small portion of the watershed. Minimal surface soil compaction occurred, and the forest floor was generally undisturbed.

Soil series on the watershed include the Chandler and Fannin series and the Cullasaja–Tuckasegee complex. Sample plots were on all soil types.

Sample Collection and Analysis

The four 100-m^2 plots were established on SREF in 1977 to serve as long-term reference plots for CSH. The four plots were divided into two groups. Each group of two was sampled alternately every 2 wk from July 1977 through November 1978. Subsequently, collection frequency decreased, but this sampling design was continued until 1985. All four plots were resampled in 1992, 1993, and 1994. Soils were collected from two depths, 0 to 10 cm and 10 to 30 cm. In 1992 and before, soil samples were collected from a randomly selected point on each plot with a 7.5-cm-diameter auger. Composite samples were collected after 1992 from the entire plot using a 1.8-cm soil probe.

Initial sample collection on NREF and WP took place in 1970. Sampling was conducted at two positions on four sample transects established in the watersheds by Yount (1975). The four transects on NREF were at mid-watershed elevation, two near a perennial stream and two near an intermittent stream. On WP, two transects were in the lower third and two in the upper third of the watershed. Both transects began near a single perennial stream channel. Two plots (2 by 15 m) were established on each transect, for a total of eight plots per watershed. Transects began ≈10 m from the stream and led to a point 60 m upslope with one transect on each opposing slope. Triplicate 0.25-m^2 quadrants were randomly selected for sample collection on each plot.

In 1990, samples were collected in March and November for comparison with samples collected in the same months in 1970. Sample collection techniques used in 1990 were based on Yount's personal notes written in 1970. Notes included written and illustrated descriptions of the soil profile for accurate soil and forest floor horizon definition. Soil samples were collected with a 1.8-cm-diameter soil probe sampler. The top two soil surface horizons were sampled and the depth of the A horizon, which was present on all plots, was recorded. The second horizon varied from an AB to a BA and is therefore called AB/BA. Average A horizon depths in 1970 were 5.4 and 5.8 cm for NREF and WP, respectively. In NREF, A horizon depth increased significantly ($P < 0.05$) to 7.3 cm in 1990, while in WP, A horizon depth also increased (6.4 cm) but the change was not significant ($P < 0.05$) (Knoepp and Swank, 1994).

Ten 25-m^2 plots were randomly located on the WTH treatment area in late 1979. The SREF served as a control for WTH. The WTH soils were collected twice before harvest, in the fall and winter of 1979. The site was logged in March 1980. Soils were sampled every three months for one year following harvest. Sample collection then became less frequent, ranging from every six months to once per year through 1985. All plots were resampled in January 1992 and January 1994. Soils were collected from two depths, 0 to 10 cm and 10 to 30 cm. In 1992 and before, soil samples were collected from one randomly selected point on each plot with a 7.5-cm-diameter auger. Composite samples were collected after 1992 from the entire plot using a 1.8-cm soil probe.

Sixteen 100-m^2 plots were established on CSH in 1975 at randomly selected points along four transects crossing the watershed. The plots were divided into two groups of eight. One group was sampled alternately every 2 wk. Soil samples were collected in this manner for 17 mo before watershed treatment. Post-treatment samples were collected on 10 plots, again divided into two groups, with alternate groups sampled every 2 wk. Plots selected for post-treatment soil sampling were also sites of intensive vegetation inventory and physiology studies. Sampling continued for 17 mo after completion of harvest. Subsequently, collection frequency decreased, but the alternate group sampling design was continued until 1985. All 10 plots were resampled in January 1992, June 1993, and January 1994. Soils were collected from two depths, 0 to 10 cm and 10 to 30 cm. In 1992 and before, soil samples were collected from one randomly selected point on each plot with a 7.5-cm-diameter auger. Composite samples were collected after 1992 from the entire plot using a 1.8-cm soil probe.

Soil C determinations before 1990 were made using the Walkley-Black method (Nelson and Sommers 1982) on samples for NREF, SREF, WP, and CSH. The Walkley-Black method was used on WTH samples until 1983 when combustion analysis using a Leco CR12 (Leco Corporation, St. Joseph, MI) began. Regression analysis showed a good correlation between Walkley-Black and the Leco carbon with a slope of 1.01 and $r^2 = 0.99$ ($n = 24$). Soil C determinations after 1990 were made on a Perkin-Elmer (Norwalk, CT) 2400 CHN analyzer also a combustion analysis. Comparisons of total percentage C determined with the Leco and the PE 2400 were conducted using an internal soil standard (4.8% C), standard $CaHCO_3$, and standard acetanilide; no significant differences were detected.

Total N concentrations were determined using the micro-Kjeldahl method (TKN) followed by analysis using the cyanurate–salicylate reaction with an autoanalyzer (Bremner and Mulvaney, 1982) for all pre-1990 samples. Soil samples collected between 1992 and 1994 were analyzed for total percentage N by the combustion method using a Perkin-Elmer 2400 CHN analyzer (PEN). Regression analysis between percentage N as determined with TKN and PEN was conducted to ensure appropriate data comparison. The PEN was determined on archived soil samples collected and analyzed for TKN in 1982. Analysis showed a good relationship between the TKN values obtained in 1982 and PEN data with a slope of 1.08 and r^2 = 0.98 (n = 24). Quality control during soil analysis in the 1990s was conducted for total N and C on each set of soil samples. Quality control samples included two internal soil standards and the CANMET standard soil sample SO-3 with 0.02% N and 6.6% C. The CANMET sample is not certified for C and N; however, these values were reached by a consensus of laboratories with coefficient of variation equal to 0.6% for C and 23% for N. These total C and N values are reproducible with our analytical procedure.

Statistical Analysis

Statistical analyses for SREF data examined the effect of year on soil C and N content using the GLM procedure in SAS (SAS Institute, 1985). Significant differences between annual means were determined using Tukey's mean separation (SAS Institute, 1985).

Statistical analyses of data from NREF and WP were conducted on the means of the three quadrants per plot (n = 8 plots × 2 dates = 16) in 1970 and 1990. Data were blocked by transect. Significant differences in soil C and N between years were determined with a split plot in time analysis using the GLM procedure in SAS (SAS Institute, 1985).

Analyses for CSH and WTH data examined the effect of year on soil C and N content using the GLM procedure in SAS (SAS Institute, 1985). The effect of soil type and the soil type by year interaction were included in the analysis of variance. Differences between pre- and post-treatment annual means were determined using Tukey's mean separation test (SAS Institute, 1985). The CSH and WTH were also compared with SREF in a split plot analysis using the GLM procedure in SAS (SAS Institute, 1985). Only plots within CSH (n = 7) and WTH (n = 7) on soil types similar to SREF were used in the analysis. The plot within watershed error term was used to test for significant differences between watersheds for each year. Differences between WTH and SREF were also examined with analysis of covariance using GLM procedures in SAS (SAS Institute, 1985). Pre-treatment WTH data and SREF data collected the same year were used as covariates for each plot.

Table 1. Analysis of variance tables, including source, degrees of freedom (DF), mean square, F-value, and probability of values greater than F (Prob > F). ANOVA tables used to test year effect on total C and total N (g kg^{-1}) in the A horizon or surface 0 to 10 cm of soil are included for all sites.

Source†	DF	Mean square	F-value	Prob > F
SREF	Carbon			
Year	11	430.35	3.49	<0.01
Error	133	123.38		
	Nitrogen			
Year	9	0.44	2.13	0.03
Error	71	0.20		
NREF	Carbon			
Block	3	83.16	2.82	0.13
Soil Type	1	41.53	1.41	0.28
B × S	3	20.27	0.69	0.59
Year	1	2 095.81	71.01	<0.01
Y × S	1	7.69	0.26	0.63
Error	6	29.51		
	Nitrogen			
Block	3	0.27	1.23	0.38
Soil Type	1	0.32	1.44	0.28
B × S	3	0.16	0.72	0.58
Year	1	19.06	85.60	<0.01
Y × S	1	0.35	1.58	0.26
Error	6	0.22		
WP	Carbon			
Block	3	26.22	0.56	0.66
Soil Type	1	7.06	0.15	0.71
B × S	3	41.60	0.88	0.50
Year	1	101.04	2.14	0.19
Y × S	1	0.01	0.00	0.99
Error	6	47.22		
	Nitrogen			
Block	3	0.08	1.13	0.41
Soil Type	1	0.07	0.91	0.38
B × S	3	0.08	1.21	0.41
Year	1	1.27	16.80	<0.01
Y × S	1	0.09	1.15	0.32
Error	6	0.08		
WTH	Carbon			
Year	8	319.03	1.63	0.12
Soil Type	2	12 375.50	63.28	<0.01
Y × S	16	100.13	0.51	0.94
Error	123	195.57		
	Nitrogen			
Year	8	1.31	2.57	0.01
Soil Type	2	41.89	81.94	<0.01
Y × S	16	0.38	0.75	0.74
Error	133	0.51		
CSH	Carbon			
Year	13	4 863.30	17.64	<0.01
Soil Type	1	1.34	0.00	0.94
Y × S	13	601.09	2.18	0.01
Error	588	275.63		
	Nitrogen			
Year	12	5.84	10.01	<0.01
Soil Type	1	12.57	21.55	<0.01
Y × S	12	0.70	1.20	0.28
Error	454	0.58		

† SREF = south-facing reference watershed; NREF, north-facing reference watershed; WP = white pine watershed; WTH = whole-tree harvest; CSH = commercial sawlog harvest watershed.

RESULTS AND DISCUSSION

Reference Watersheds

The effect of year on total soil C concentration of the 0- to 10-cm depth of SREF was significant (Table 1). However, this was due to high interannual variability, and soil C concentration did not increase or decrease with time (Table 2). Soil C also varied significantly with year at the 10- to 30-cm depth; again no trend was evident. Effect of year on total soil N was similar to total C on SREF. Sample years were significantly different at the 0- to 10-cm and 10- to 30-cm sample depth (Table 1). The interannual variability evident in SREF soil C and N could result from differences in rainfall and temperature, which would affect forest floor decomposition rates, fine root production, and turnover of soil N and C.

In the other reference watershed, NREF, only two years of soil data were available (1970 and 1990). Carbon concentration decreased significantly in the A horizon

Table 2. Carbon and nitrogen concentration in A and B horizon soils from a north-facing reference (NREF), south-facing reference (SREF), and white pine plantation (WP) watersheds. A horizon represents the first surface soil layer sampled, actual A horizon for NREF and WP and 0 to 10 cm of mineral soil for SREF. B horizon designates second surface soil layer sampled AB/BA horizon for NREF and WP and 10 to 30-cm depth for SREF. Values presented are annual means with standard error of the mean in parentheses. The probability of values greater than *F* for the effect of year are also presented for C and N in each horizon.

	Total C		Total N	
Year	A horizon	B horizon	A horizon	B horizon
SREF	g kg^{-1}			
$P > F$	<0.01	<0.01	0.04	0.02
1977	35.5 (2.1)	21.4 (1.0)	ND	ND
1978	45.7 (1.9)	26.9 (1.3)	2.15 (0.14)	1.38 (0.08)
1979	40.5 (1.8)	25.7 (1.0)	1.85 (0.07)	1.39 (0.09)
1980	32.3 (1.9)	22.0 (2.2)	1.83 (0.13)	1.21 (0.12)
1981	29.5 (5.0)	19.3 (3.2)	1.50 (0.27)	1.16 (0.18)
1982	45.6 (11.2)	16.6 (1.8)	1.85 (0.34)	0.99 (0.16)
1983	50.7 (7.8)	13.0 (3.2)	ND	ND
1984	37.9 (5.8)	18.4 (2.2)	2.50 (0.30)	0.95 (0.05)
1985	37.0 (7.5)	21.9 (9.2)	1.50 (0.20)	1.00 (0.30)
1992	32.6 (2.7)	14.7 (2.3)	1.55 (0.17)	0.80 (0.13)
1993	35.0 (3.4)	13.9 (2.2)	1.65 (0.10)	0.84 (0.07)
1994	27.9 (0.8)	12.7 (0.7)	1.40 (0.07)	0.84 (0.04)
NREF				
$P > F$	<0.01	0.78	<0.01	0.01
1970	61.1 (4.2)	20.4 (1.3)	3.89 (0.21)	1.22 (0.05)
1990	38.2 (1.7)	19.6 (0.7)	1.71 (0.07)	0.88 (0.04)
WP				
$P > F$	0.19	<0.01	<0.01	0.62
1970	44.5 (2.1)	20.7 (1.7)	2.51 (0.07)	1.25 (0.05)
1990	39.5 (1.4)	26.7 (1.2)	1.95 (0.07)	1.31 (0.05)

while the AB/BA horizon soils did not (Table 1 and 2). Soil N also decreased, 56% in the A horizon and 28% in the AB/BA horizon. Given the interannual variability in soil N noted in SREF, the magnitude of this decrease based on only two sample years is tenuous. However, soil cation concentrations also decreased in this watershed (Knoepp and Swank, 1994) supporting the trend for decreased soil nutrients as they are sequestered above ground.

A revised model of N cycling in the aggrading deciduous forests at Coweeta is in preparation (Swank et al., 1990, unpublished data). The model used N input and output data for the same period of record as the soil remeasurement data. The model estimated a net ecosystem accumulation of 9 kg N ha^{-1} yr^{-1} with 13 kg N ha^{-1} yr^{-1} sequestered in litter and vegetation. Thus, a small decline in soil N was expected but not the amount suggested by soil remeasurement data on NREF. The discrepancy could be attributed to several factors including analytical methods, errors of estimation, and/or unmeasured soil N pools. We addressed differences in analysis in the methods section of this study; discussing errors of estimation is beyond the scope of this paper. The presence of unmeasured pools of soil N is a very plausible explanation. Movement of N below the AB/BA soil horizon would remove it from the area sampled. Beyond the soil sampled is another 45 to 70 cm of soil that contains >36 Mg C ha^{-1} (Knoepp, 1989, unpublished data). This volume of soil also contains ≈17% of the total root biomass (McGinty, 1976) and >55% of the exchangeable cations (Knoepp, 1989, unpublished data). Richter et al. (1995) found ≈20% of the total C in a southeastern loblolly pine (*Pinus taeda* L.) forest at soil depths of 3 to 6 m. The presence of dissolved organic and inorganic C at all depths demonstrated biogeochemical activity. Research by Qualls and Haines (1991) and Qualls et al. (1991) in soils of SREF showed concentrations of DON declined as water moved down through the soil profile. However, DON concentrations were greater in B and C soil horizons than in stream water, indicating DON adsorption in these horizons.

The long-term response of surface soil N for the two aggrading reference hardwood stands at Coweeta differ considerably. Surface soil N decreased in NREF and while SREF showed significant variability, there was not a strong declining trend during the 20-yr period. Several reasons for such differences are possible. While the vegetative composition of the two reference watersheds was similar, net primary production and nutrient sequestration in biomass may have differed. Soil types and rainfall and water use patterns also differed. All plots on SREF were in a side slope position on Inceptisols with micaceous mineralogy. Plots on NREF were in both side slope and riparian positions on Ultisols with mixed mineralogy. Landscape position affects water movement through the soils and accumulation of organic materials and sediments. Inceptisols are usually on steep side slopes. These soils lack distinct horizons, such as a Bt horizon, probably due to the lateral movement of water through the soil profile. Ultisols occupy the less steep slopes and some cove positions. The vertical movement of water through these soils is indicated by the presence of a Bt horizon. Water movement patterns would increase the potential downward movement of nutrients in these forest systems. These sites also differ in their water use. The NREF received 20 cm more rainfall annually than SREF, increasing water movement within the soil profile. The SREF received greater solar inputs than NREF, especially in the winter. This difference in insolation resulted in less of the total rainfall leaving as streamflow on SREF compared with NREF (Swift and Knoerr, 1973; Douglas and Swank, 1975). These results emphasize the importance of reference sites that normalize factors that influence biogeochemical cycles such as climate, hydrology, and soils facilitating the interpretation of treatment effects.

Few studies have monitored changes in soil C and N with time in undisturbed hardwood forests. Johnson et al. (1988) resampled plots on Walker Branch watershed in eastern Tennessee to examine chemical changes during a 10-yr period. They found no significant change in total C and a general trend toward decreasing total N, although significant only in the B horizon (depth 45–60 cm). The decrease in N coincides with decreased soil base cation content at both Walker Branch (Johnson et al., 1988) and NREF (Knoepp and Swank, 1994). Decreases in both studies were attributed to sequestration in the biomass and leaching losses.

White Pine Plantation

Total soil C remained unchanged in the A horizon on WP but increased significantly in the AB/BA horizon

(Table 2). In contrast, total soil N increased in the A horizon and remained unchanged in the AB/BA horizon. Richter et al. (1994) found increases in soil organic matter in a loblolly pine plantation during a 30-yr period. While the response was similar, the loblolly plantation and Coweeta WP did not start with the same initial conditions. The loblolly pine plantation was established on an abandoned agricultural field with low initial soil organic matter. Coweeta WP was planted on a forested watershed repeatedly cleared without biomass removal. Both plantations are still aggrading and accumulating biomass.

Harvest Treatments

Total soil C on WTH declined slightly in the 0- to 10-cm depth following harvest (Table 1 and Fig. 1A). Soil C in the 10- to 30-cm depth showed no response to cutting ($P = 0.46$). Total N declined for 3 yr following harvest in the 0- to 10-cm depth (Fig. 1B). While the year effect was significant ($P = 0.01$; Table 1), mean separation tests found only the first post-treatment year was significantly different ($\alpha = 0.05$) from pre-treatment total N. No changes in N occurred at the 10- to 30-cm depth ($P = 0.60$). The C/N ratio in the 0- to 10-cm depth did not initially respond to treatment. Decreases in both C and N maintained a constant C/N ratio, between 20 and 22 for ≈4 yr. However, by years four and five following harvest, N levels increased and C remained low; thus, the C/N ratio dropped to ≈16, significantly lower than the high of 22 reached in 1982. When sites were resampled in 1992 and 1994, C/N ratios had remained low at 18.

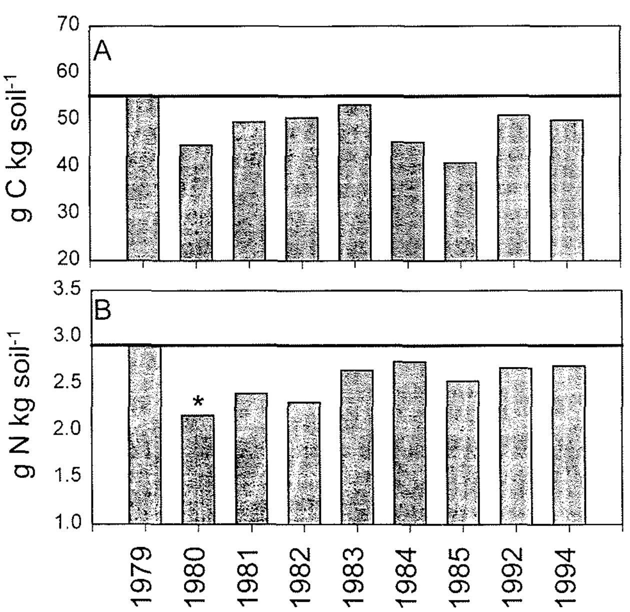

Fig. 1. (A) Total C (g kg^{-1}) and (B) total N (g kg^{-1}) at 0- to 10-cm depth for whole-tree harvest watershed. Data represent annual means for the watershed. 1979 represents pre-treatment data. The horizontal line represents the mean pre-treatment value. Site harvest took place in 1980. The 1980 data represent only post-treatment data. * designates soil C and N values significantly different from the pre-treatment mean as determined using Tukey's mean separation test ($P < 0.05$).

Total soil C and N concentration changed significantly in CSH following harvest (Table 1 and Fig. 2). In the 0- to 10-cm layer, soil C concentration increased more than 50%, from 37 g kg^{-1} before treatment to 55 and 63 g kg^{-1} the first and second year following watershed harvest. Carbon in the surface 10 cm remained elevated for 18 yr after treatment, though not significantly different from pre-treatment levels. Carbon in the 10- to 30-cm depth did not respond significantly to the stand harvest, although the year effect was significant ($P = 0.02$). Total N content at 0 to 10 cm increased significantly for 3 yr following treatment compared with pre-treatment levels. Nitrogen content at the 10- to 30-cm depth did not respond to forest harvest. The C/N ratio differed significantly among years ($P = 0.0001$); however, treatment response was not consistent.

The WTH responded similarly to other whole-tree harvest sites where soil C and N remained unchanged or decreased following cutting (Hendrickson et al., 1989; Mann et al., 1988; Alban and Perala, 1990; Edwards and Ross-Todd, 1983; Mroz et al., 1985; Johnson et al., 1991). On the other hand, soils on CSH increased in both total C and N, which contrasts with other studies that found either decreases or no change in soil C and N (Kraske and Fernandez, 1993; Hendrickson et al., 1989; Mueller-Harvey et al., 1985; Alban and Perala, 1990; Mattson and Smith, 1993; Edwards and Ross-Todd, 1983; Mroz et al., 1985; Johnson et al., 1991). The difference in soil C and N responses between harvest treatments on WTH and CSH must be largely associated with differences in the amount of woody material removed from the two

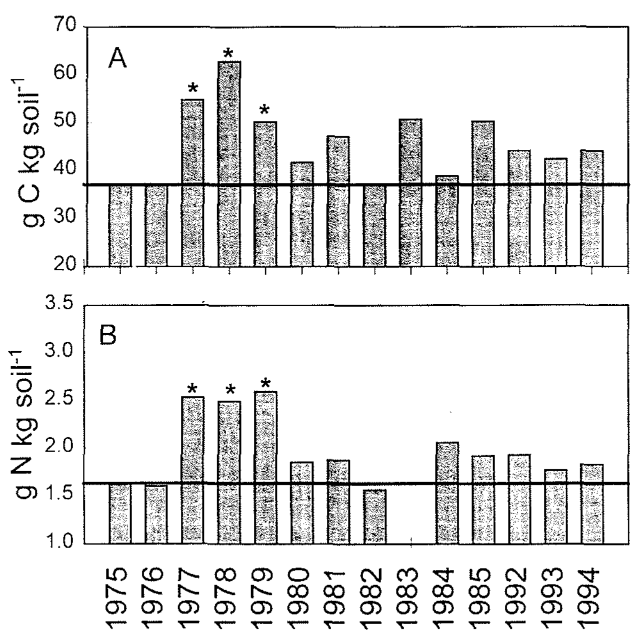

Fig. 2. (A) Total C (g kg^{-1}) and (B) total N (g kg^{-1}) in the upper 0 to 10 cm for commercial sawlog harvest watershed. Data represent annual means for the watershed. 1975 and 1976 represent pre-treatment data. Site harvest took place in early 1977. The 1977 data represent only post-treatment data collected October through December 1977. The horizontal line represents the pre-treatment mean value. * designates soil C and N values significantly different from the pre-treatment mean as determined using Tukey's mean separation test ($P < 0.05$).

sites. Whole-tree harvest removes more biomass and nutrients from a site than commercial sawlog harvest (Johnson et al., 1982; Federer et al., 1989). Total biomass removed from CSH and WTH was 43 and 178 Mg ha^{-1}, respectively (Mann et al., 1988). The CSH had 121 Mg ha^{-1} of logging residue remaining following sawlog removal (Mattson et al., 1987). The decay rates for the 0- to 5-cm residue materials were not significantly different between SREF and CSH mesic sites, with ≈85% remaining after 1 yr (Abbott and Crossley, 1982). However, CSH xeric sites had significantly lower rates of decomposition than SREF, indicating a decrease in decomposition across the entire watershed (Mattson and Swank, 1989). Logging residue therefore represents a large and long-term addition of C and N to the surface soil and probably accounts for most of the increase in soil C and N in CSH. The lack of this material on WTH contributes to the decrease in soil C and N.

Another important source of soil C and N following harvest is root mortality (Fahey et al., 1988). Root biomass in the 0- to 10-cm depth for hardwood forests at Coweeta was estimated at 10.5 Mg ha^{-1} (McGinty, 1976). Six years after cutting, fine root biomass on CSH was only 65% of SREF, the adjacent control watershed (Mattson and Swank, 1989). This decrease could be the result of extensive root mortality and/or changes that occurred in vegetation composition and age after stand harvest.

Hardwood sprouts, herbaceous plant growth, and the sprouting of black locust (*Robinia pseudoacacia* L.), a symbiotic N_2-fixing tree species, are other C and N sources contributing to the maintenance or increase of soil C and N after site disturbance. The first 3 yr following cutting, 80% of the total N present in the aboveground biomass was leaf and herbaceous plant material, which turn over quite rapidly (Boring et al., 1988). By year three, foliar net primary productivity, another important C and N source, was ≈75% of a mature hardwood forest. Black locust is an early successional species that can contribute a considerable amount of N to a recently disturbed site. Black locust sprouts made up ≈2% of the total woody stem density on CSH and 11% of the total stems 40 cm in height on WTH (Boring et al., 1988; W.T. Swank, 1980, unpublished data). Nitrogen fixation inputs on CSH the fourth year after harvest were 30 kg N ha^{-1} yr^{-1} in areas with high black locust density and averaged 10 kg ha^{-1} yr^{-1} across the entire watershed. Rates of N_2 fixation may have been greater on WTH where black locust density was greater. This suggests that initial total N losses on WTH may have been greater in its absence. The importance of N_2-fixing species has also been noted in early phases of other primary successional sequences (Bormann and Sidle, 1990). In these ecosystems, as in the southern Appalachians, the N_2 fixers are eventually removed through competition or insect infestation (Bormann and Sidle, 1990; Boring and Swank, 1984).

Collection of pre-treatment soils data is important in determining the initial soil responses to harvest treatment. However, for determination of long-term ecosystem responses, one must have a control or reference site for comparison. We saw significant differences in the long-term response of SREF and NREF, two control watersheds, and considerable year to year variation. Accounting for normal site processes in the interpretation of long-term treatment responses is important. We compared plots with similar soil types on WTH and CSH to SREF to consider these processes (Fig. 3). The initial patterns in soil C to treatment were similar while long-term responses differed. The CSH soil C content in 0 to 10 cm was greater than SREF for 5 yr following harvest. The CSH to SREF comparison suggests a longer lasting impact of harvest. Carbon levels on CSH are also greater than SREF 16 and 18 yr after harvest (Fig. 3b). The WTH shows a slight decrease in soil C initially, but 14 yr after site harvest, soil C is greater that SREF (Fig. 3c). The initial and long-term response of total N to harvest differed when harvested watersheds were compared with SREF (Fig. 4). The CSH total N is significantly greater than SREF only in 1979, 3 yr following harvest (Fig. 4b). Increases in total N on SREF, due to the interannual variation, coincide with the treatment response on CSH. Interannual variability in total N on SREF also affects the significance of response in WTH (Fig. 4b). Initially, the effect of harvest on WTH total N was not significant; 14 yr following harvest, WTH had significantly greater total N than SREF.

Chronosequence studies are often used to examine

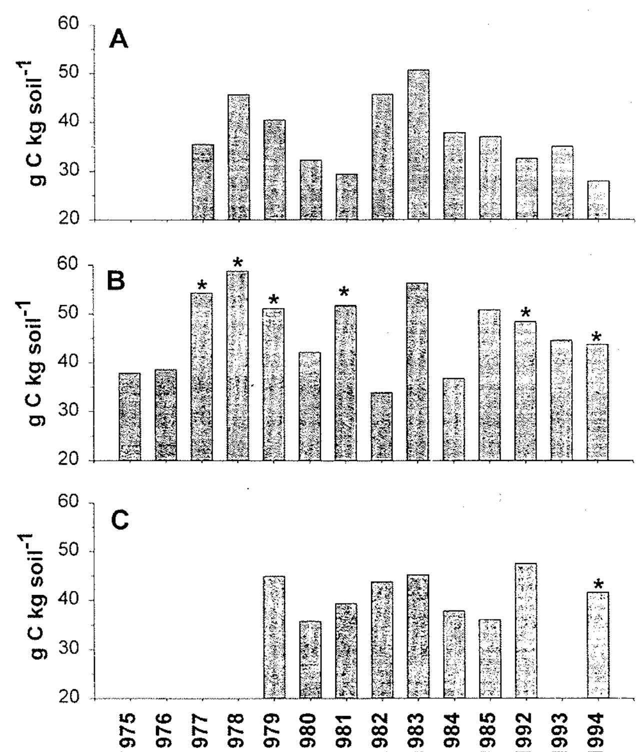

Fig. 3. Total C (g kg^{-1}) at 0- to 10-cm depth for (A) south-facing reference watershed (SREF); (B) commercial sawlog harvest watershed (CSH); and (C) whole-tree harvest sites (WTH). Data represent annual means for each watershed. Plots included from CSH and WTH are only those on soil types similar to SREF; n = 7 for both. * designates significant difference between harvested and reference watershed at that date (P < 0.05).

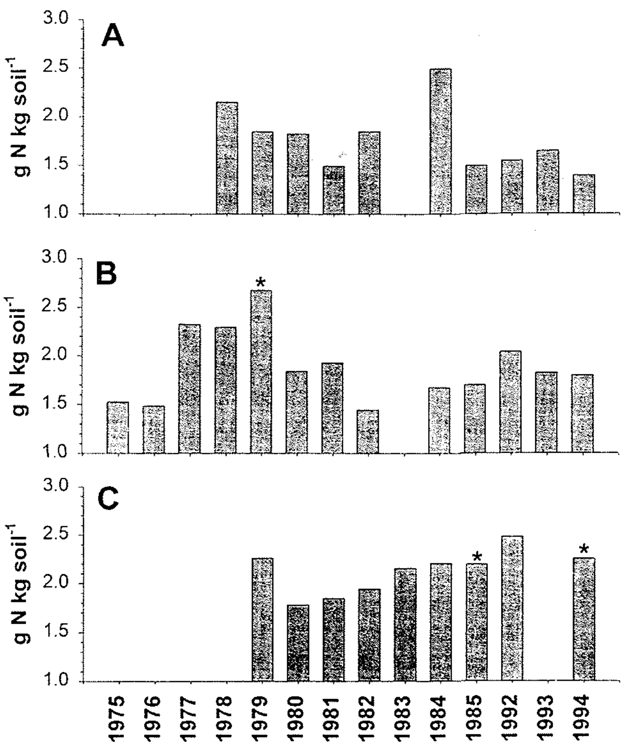

Fig. 4. Total N (g kg^{-1}) at 0- to 10-cm depth for (A) south-facing reference watershed (SREF); (B) commercial sawlog harvest watershed (CSH); and (C) whole-tree harvest sites (WTH). Data represent annual means for each watershed plots included from CSH and WTH are only those on soil types similar to SREF; n = 7 for both. * designates significant difference between harvested and reference watershed at that date ($P < 0.05$).

long-term changes in soil organic matter following cutting. In northern hardwood stands ranging from 3 to 93 yr, Snyder and Harter (1984) found soil C increased from 3 to 10 yr following disturbance. In their systems, soil C then decreased between 10-, 30-, and 93-yr-old stands. Mattson and Smith (1993) found another pattern. They examined stands representing a 25-yr chronosequence following cutting and found no changes in soil organic matter. Using data from SREF, NREF, and every 5 yr on CSH to represent a 70-yr chronosequence following clear-cutting, we found a similar response to the northern hardwood sites of Snyder and Harter (1984). Soil C concentrations initially increase but then decrease with time. Our data also suggest there may be some problems with chronosequence studies. First, the interannual variability noted on SREF and CSH suggest that sample year may affect the observed response. The second problem would be identifying comparable sites with similar soils and water use patterns.

CONCLUSIONS

All forest management practices examined in this study affect total soil C and N and so have the potential to alter site productivity (Powers, 1989). Soils in an undisturbed north-facing forested watershed showed substantial declines in soil N levels, while in a south-facing watershed, total N levels show considerable interannual variation but are generally stable. Decreasing or stable soil C in both reference watersheds resulted in an increased C/N ratio during a 17- to 20-yr period. Conversion of a mixed-hardwood site to white pine resulted in increased soil C content. The coincident decrease in soil N levels again resulted in an increased C/N ratio. Increasing C/N ratios may eventually lead to decreased N availability. Initial results showed that the whole-tree harvest resulted in decreased total soil C and N. However, long-term data suggest that total N is greater than reference watershed soils 14 yr after harvest. Immediately following a commercial sawlog harvest, both soil N and C increased. This response was attributable to the large amounts of logging residue left on site, root mortality, and a successional pattern that included N_2 fixers. Long-term data suggest that soil C remained elevated 17 yr following harvest. Maintenance of surface soil C and N levels in whole-tree harvested and clear-cut sites suggest that site productivity was probably not diminished. The C and N on these watersheds may have been redistributed from woody vegetation to more rapidly cycling pools in surface soil and early successional vegetation. This may help moderate negative impacts the harvest treatments have on soil C and N, at least in early forest rotations.

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