Soil Nitrogen Transformations Under Alternative Management Strategies in Appalachian Forests

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Once subject to frequent fire and strongly N limited, the forests of the Appalachian Mountain region of eastern North America have experienced almost a century of fire suppression, and changes in tree species composition, understory density and composition, and accumulations of detritus have paralleled the changes in fire frequency. In an effort to restore these ecosystems and reduce wildfire hazard, alternative management strategies (prescribed fire, mechanical fuel reduction, and a combination of both) were implemented at study sites in Ohio and North Carolina as part of the Fire and Fire Surrogate Network Study. As changes in N cycling resulting from these treatments could have potential negative impacts on forest health that might limit their usefulness as management alternatives, we monitored treatment effects on extractable total inorganic N (TIN), net N mineralization, net nitrification, and proportional nitrification during the growing season before treatment, the first growing season after treatment, and the third or fourth growing season after treatment. Mechanical treatment resulted in increases in extractable TIN, N mineralization, and nitrification during the first post-treatment year in Ohio and TIN was greater in the mechanical treatment and the mechanical + fire treatment during the third post-treatment year in North Carolina. Net N mineralization was reduced by fire alone in Ohio, but not in North Carolina. Nitrogen transformation rates were 2- to 10-fold higher in Ohio than North Carolina, a difference that may partly result from of the ericaceous shrub understory present in North Carolina but not in Ohio. Impacts of these treatments on N transformations were modest and for the most part transient, and would therefore not eliminate these treatments as viable management strategies for wildfire hazard reduction or ecosystem restoration.

Abbreviations: FFS, Fire and Fire Surrogate; IMI, integrated moisture index; LEC, landscape ecological classification system; TIN, total inorganic nitrogen.

FOREST, RANGE & WILDLAND SOILS

Humans have been actively managing the deciduous forests of the central and southern Appalachians of eastern North America for at least two millennia (Mann, 2005). These cultures used fire, clearing, and arboriculture to manipulate the forests around them (Mann, 2005), and paleontological studies on the Cumberland Plateau of the Appalachian Mountains indicate that fire has been common in the forests of the region for at least four millennia (Delcourt and Delcourt, 1997). Analyses of charcoal and pollen assemblages indicate that the average fire return interval was relatively stable until the rapid decline of Native American populations after European contact (Delcourt and Delcourt, 1997). The fire return interval remained relatively unchanged in the Appalachian Mountains and plateaus through the early 20th century, despite rapid Euro-American agricultural intensification in the region. Fire return intervals of 7.5 yr for extensive fires in mixed-oak forests in the Allegheny Plateau of Ohio (Sutherland, 1997) and 10 to 12 yr in the Great Smoky Mountains (Harmon, 1982) during the 19th and early 20th centuries have been documented.

Effective fire suppression was established as early as 1930 in Ohio (Sutherland, 1997) and 1940 in the Blue Ridge Mountains of North Carolina (Harmon, 1982). Fire return intervals increased significantly after that time; for example, Sutherland (1997) reported a post-suppression interval of 57 yr in southeastern Ohio. As a consequence, the otherwise-unmanaged forests of the central and southern Appalachians have become denser, have increased detrital mass, and in some areas have experienced changes in tree species composition (e.g., Iverson et al., 1997).

Under the conditions that prevailed before the onset of organized fire suppression, the forests of the Appalachian Mountains and western plateaus were probably N limited (Aber et al., 1989). Although such an assertion is difficult to prove empirically, partial validation can be achieved through comparisons of the amounts of N fertilizer required to grow cereal crops on cleared Appalachian forest land in the early 1900s (100–200 kg N ha^{-1} yr^{-1}; Paschall et al., 1938; Taylor et al., 1938) with the in situ rate of N mineralization in those soils under second-growth forest cover (22–56 kg N ha^{-1} yr^{-1}; Plymale et al., 1987). In addition, the historical dominance of species of trees dependent on ectomycorrhizal symbioses

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Table 1. Selected properties of the Ohio Hills (Ohio) and Green River (North Carolina) study sites of the Fire and Fire Surrogates Network Study. All soil data represent pretreatment conditions as reported to the national database of the Fire and Fire Surrogate Network (frames.nbii.gov/portal/server.pt?open=512&objID=363&mode=2&in_hi_userid=2&cached=true; verified 2 Dec. 2007). Soil taxonomy follows Lemaster and Gilmore (1993), Keenan (1998), and Hamilton et al. (2003). Soil properties are reported as site means followed by the range of unit means in parentheses.

Parameter	Ohio Hills	Green River
Climate	cool, temperate	warm, temperate
Mean temperature, °C	11.3	17.6
Mean precipitation, mm	1024	1638
Canopy tree species	*Quercus alba* L. (white oak), *Q. prinus* L. (chestnut oak), *Carya* spp. (hickories), *Q. velutina* Lam. (black oak)	*Quercus rubra* L. (northern red oak), *Q. alba, Q. prinus*, *Q. velutina*, *Carya* spp., *Pinus echinata* Mill. (shortleaf pine)
Subcanopy or understory	subcanopy of *Acer rubrum* L. (red maple), *A. saccharum* Marshall (sugar maple), *Liriodendron tulipifera* L. (yellow-poplar)	shrub layer of *Kalmia latifolia* L. (mountain laurel), *Rhododendron maximum* L. (rhododendron)
Soil series and orders	Steinsburg (Typic Hapludalf) Gilpin (Typic Hapludalf) Shelocta (Typic Hapludalf) Brownsville (Typic Dystrochrept)	Evard (Typic Hapludult) Cliffield (Typic Hapludult) Ashe (Typic Dystrochrept)
Parent materials	shale, sandstone	gneiss, mica schist
Soil texture	silt loam, sandy loam	sandy loam, loam
Bulk density, g cm^{-3}	0.90 (0.86–0.92)	1.19 (1.10–1.25)
pH (0.01 mol L^{-1} $CaCl_2$)	3.67 (3.46–4.12)	4.58 (4.43–4.72)
extractable Ca^{2+}, mg kg^{-1}	130 (71–391)	265 (124–338)
Ca/Al molar ratio	0.12 (0.07–0.23)	0.08 (0.06–0.19)
Soil organic C, g kg^{-1}	33.8 (24.1–50.1)	22.2 (20.5–39.9)
Soil C/N ratio	18.9 (15.6–20.8)	23.6 (18.4–24.4)

(e.g., oaks, hickories, pines) is also consistent with an ecosystem whose soils are low in available inorganic N and high in relatively recalcitrant organic matter (Vogt et al., 1991).

It has been in this context of fire suppression that efforts to shift Appalachian ecosystems to structural and functional conditions more indicative of unstressed, well-functioning ecosystems have begun. Among those are the Fire and Fire Surrogate (FFS) Network Study (frames.nbii.gov/portal/server.pt?open=512&objID=363&mode=2&in_hi_userid=2&cached=true; verified 2 Dec. 2007), whose objective is to test alternative treatment modalities designed to facilitate both ecosystem restoration and wildfire hazard reduction in forests across the continent. The primary objective of the FFS Network Study is to determine the relative effects of low-severity fire at historical intervals (as a form of functional restoration), mechanical fuel reduction, understory manipulation, thinning of the canopy from below to presettlement structure, or some combination of the three (a form of structural restoration), and the combination of mechanical treatment and burning (a combined approach) in comparison with passive management. In this study, we assessed the effects of these alternative restoration strategies on soil N transformations and N availability, two attributes that we feel can give us insight into the ecosystem consequences of these alternative management strategies. In particular, we sought to determine whether any or all of the alternative treatments would result in these ecosystems becoming more like the N-limited, organic-C-driven systems that preceded the onset of organized fire suppression and atmospheric deposition.

The specific hypotheses we wished to address were:

- Prescribed fire, mechanical alteration of the understory and canopy, and the combination of the two will result in increased N mineralization, nitrification, and inorganic N pools.
- The effects of prescribed fire will be transient, whereas those produced by mechanical treatment will be persistent, at least during the 5-yr time frame addressed by this study.
- The combination of prescribed fire and mechanical treatment will differ between sites as a function of the intensity of the mechanical treatment. The combined treatment will parallel the fire-only treatment at the site where the mechanical treatment is primarily an understory removal (North Carolina) and will parallel the mechanical-only treatment at the site where significant thinning of the tree canopy is done (Ohio).

MATERIALS AND METHODS

Study Sites

This study took place in two of the 13 study sites that comprise the FFS Network study: the Ohio Hills site in Ohio (representing the central Appalachian plateaus) and the Green River site in North Carolina (representing the southern Appalachian Mountains). Each site consists of three replicate blocks, with each of the alternative ecosystem restoration treatments applied to a randomly chosen treatment unit within each block.

The Ohio Hills FFS site is located on the unglaciated Allegheny Plateau of southern Ohio (Table 1, Fig. 1). The forests of the region developed between 1850 and 1900, after the cessation of cutting for the charcoal and Fe industries (Sutherland et al., 2003). The current canopy composition differs little from that recorded in the original land surveys of the early 1800s (Table 1). The Ohio Hills FFS site is composed of three experimental blocks, with one each in the Raccoon Ecological Management Area, Zaleski State Forest, and Tar Hollow State Forest. The Raccoon Ecological Management Area block (39°11′

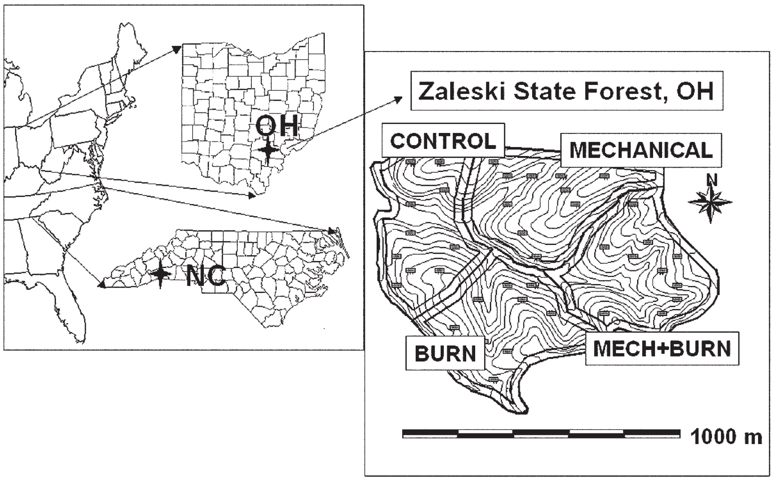

Fig. 1. Map of eastern North American showing the locations of the study areas in southeastern Ohio (OH) and western North Carolina (NC) (left) and topographic map of the Zaleski State Forest, OH block showing the placement of treatment units (right). Small solid rectangles represent the permanent sampling plots.

N, 82°22′ W) and the Zaleski State Forest block (39°21′ N, 82°22′ W) are both located in Vinton County, Ohio, and the Tar Hollow State Forest block (39°20′ N, 82°46′ W) is located in Ross County, Ohio. Analysis of fire scars in stems of trees that were cut as part of the establishment of the FFS experiment indicated that fires were frequent (return intervals of 8–15 yr) from 1875 to 1930; in contrast, few fires occurred after the onset of fire suppression activities in the early 1930s (Hutchinson et al., 2002).

The Green River FFS site is located in the Green River Game Lands in the Blue Ridge Physiographic Province, Polk County, North Carolina (Table 1, Fig. 1). The forests of the study area were 80 to 120 yr old, and no indication of past agriculture or recent fire was present, although the fire return interval before 1940 was approximately 10 yr (Harmon, 1982). Blocks 1 and 2 (35°17′ N, 82°17′ W) were adjacent but separated by Pulliam Creek. Block 3 (35°16′ N, 82°18′ W) was approximately 2.9 km southeast of Blocks 1 and 2, across the Green River.

Before treatment, the soils at Green River had somewhat greater bulk density and pH than did the soils in the Ohio Hills, whereas extractable Ca^{2+} and the molar Ca/Al ratio differed little between the two study sites (Table 1). The soils at the Ohio Hills site had more organic C and higher C/N ratios than did those at Green River (Table 1).

Experimental Design

Each of the three replicate blocks in each site was divided into four treatment units. At the Ohio Hills site, individual treatment units were 19 to 26 ha, whereas at the Green River site, they were approximately 10 ha in size. All treatment units were surrounded by buffer zones of approximately 4 to 10 ha, and both the treatment unit and its corresponding buffer received the experimental treatment. These treatment units were designed to include the prevailing combinations of elevation, aspect, and soil conditions (Fig. 1).

Ten 25- by 50-m (0.1-ha) sample plots were established randomly within each treatment unit (Fig. 1). The position of each sample plot was established by a geographic information system (GIS), and the landscape context of each was determined using the GIS-based integrated moisture index (IMI) developed by Iverson et al. (1997) at the Ohio Hills site and the Landscape Ecosystem Classification System (LEC) described by Carter et al. (2000) for the Green River site. These landscape classification metrics combine various combinations of elevation, slope angle, shape, and position, aspect, soil depth, and soil water-holding capacity into single measures and were used as covariates in analysis of experimental responses to help factor out the influence of landscape position on responses to fire and mechanical treatment.

Treatments were randomly allocated among treatment units within a site, and all treatments units were sampled through the pretreatment year (2000 at the Ohio Hills and 2001 at Green River). Treatments consisted of (i) prescribed fire, (ii) a mechanical thinning treatment, (iii) the combination of prescribed fire and thinning, and (iv) an untreated control.

Mechanical treatments were accomplished during September 2000 to April 2001 at the Ohio Hills and December 2001 to February 2002 at Green River. At the Ohio Hills, the mechanical treatment involved thinning from below to a basal area comparable to that present before Euro-American settlement. This was a commercial thinning operation that reduced basal area from 27.0 to 20.9 m^2 ha^{-1}. At Green River, the mechanical treatment was designed to create a vertical fuel break. Chainsaw crews removed all stems >1.8 m tall and <10.2-cm diameter at breast height as well as all *Kalmia latifolia* L. and *Rhododendron maximum* L. shrub stems, regardless of size. All detritus generated by the mechanical treatment was left on site at Green River; at the Ohio Hills, merchantable stems were removed for sale but all other detrital materials were left on site. At both sites, the mechanical treatments were designed to return forest structure to tree species composition, woody stem size and frequency distribution, and understory density consistent with what each site would have been like before fire suppression and other intensive management activities.

The prescribed fires were applied during March and April 2001 at the Ohio Hills and March 2003 at Green River. These dormant-season fires were designed to be similar to the predominant mode of natural fires in the region. These fires consumed unconsolidated leaf litter and fine woody fuels while leaving the majority of the coarse woody fuels only charred. At Green River, the fire prescription was also designed to kill ericaceous shrubs. At the Ohio Hills, these fires consumed an average of 79.3% of the unconsolidated litter, with a range among the three blocks of 64.1 to 88.3%. At Green River, an average of 86.9% of the litter was consumed, with a range of 85.1 to 90.1% among the three blocks. More details of fire behavior and prescriptions are given by Iverson et al. (2004) for the Ohio Hills and Tomcho (2004) for the Green River site.

Field Methods

Samples were taken from each plot during midsummer of the pretreatment year, the first post-treatment year, and the third or fourth post-treatment year (fourth for the Ohio Hills and third for Green River). We chose midsummer for sampling as our prior work in these systems (Decker et al., 1999; Boerner et al., 2000, 2004, 2005) indicated that the probability of committing a Type I error is minimized by comparing treatment effects during the time when microbial processes are at relatively low and temporally stable levels.

For determination of extractable inorganic N concentrations, samples of approximately 100 g fresh mass were taken at three (Ohio Hills) or four (Green River) random points in each of the 0.10-ha permanent sampling plots, yielding a sample size of n = 360 per year in the Ohio Hills and n = 480 per year at Green River. Geostatistical analysis of the spatial autocorrelation of soil properties at the Ohio

Table 2. Mixed model analysis of covariance of N transformations in forest soils in relation to wildfire hazard and ecological restoration treatments. *P* values associated with the variance components for treatment, the pretreatment covariate, and the landscape position covariate are shown. Variance components significant at $P < 0.05$ are shown in italic.

Parameter	Year	Site	Treatment	Pretreatment covariate	Landscape covariate
Total inorganic N, mg N kg^{-1} soil	Year 1	Green River	$P < 0.885$	$P < 0.962$	$P < 0.707$
	Year 1	Ohio Hills	*$P < 0.041$*	*$P < 0.001$*	$P < 0.612$
	Year 3	Green River	$P < 0.135$	$P < 0.256$	$P < 0.568$
	Year 4	Ohio Hills	$P < 0.139$	$P < 0.066$	*$P < 0.015$*
N mineralization rate, mg N kg^{-1} soil d^{-1}	Year 1	Green River	$P < 0.528$	$P < 0.861$	*$P < 0.018$*
	Year 1	Ohio Hills	*$P < 0.041$*	$P < 0.139$	$P < 0.133$
	Year 3	Green River	$P < 0.984$	$P < 0.079$	$P < 0.113$
	Year 4	Ohio Hills	$P < 0.153$	*$P < 0.009$*	*$P < 0.004$*
N mineralization rate, mg N kg^{-1} organic C d^{-1}	Year 1	Green River	$P < 0.619$	$P < 0.519$	*$P < 0.007$*
	Year 1	Ohio Hills	*$P < 0.006$*	$P < 0.566$	$P < 0.946$
	Year 3	Green River	$P < 0.592$	$P < 0.219$	$P < 0.088$
	Year 4	Ohio Hills	$P < 0.422$	*$P < 0.001$*	*$P < 0.049$*
Net nitrification rate, mg N kg^{-1} soil d^{-1}	Year 1	Green River	$P < 0.116$	$P < 0.650$	$P < 0.859$
	Year 1	Ohio Hills	*$P < 0.029$*	$P < 0.327$	$P < 0.354$
	Year 3	Green River	$P < 0.329$	$P < 0.303$	$P < 0.274$
	Year 4	Ohio Hills	$P < 0.123$	$P < 0.128$	*$P < 0.001$*
Proportional nitrification, %	Year 1	Green River	*$P < 0.040$*	$P < 0.202$	$P < 0.391$
	Year 1	Ohio Hills	*$P < 0.048$*	$P < 0.076$	*$P < 0.004$*
	Year 3	Green River	$P < 0.133$	$P < 0.404$	$P < 0.269$
	Year 4	Ohio Hills	$P < 0.075$	$P < 0.831$	*$P < 0.001$*

Hills site indicated that paired samples taken >5 m apart constitute spatially uncorrelated, statistically independent samples (Boerner and Brinkman, 2004, 2005). Soil samples were taken from the top 10 cm of the A horizon, after first removing the overlying O horizon (primarily an Oi horizon in these humid, mesic forests).

For estimation of N mineralization and nitrification potentials, soil samples of approximately 200 g fresh mass of the upper 10 cm of the A horizon were taken ~45 to 55 m apart, 1 to 2 m from the opposite corners of each permanently marked 0.10-ha sample plot. Each sample was split into one to four subsamples, of which one was returned to the laboratory for analysis and one (Green River) or three (Ohio Hills) were put into polyethylene bags then returned to the soil for incubation (Eno, 1960). Incubating bags were covered with the remaining soil from that sample point and the forest floor that was removed before sampling and allowed to incubate in situ for 25 to 30 d. Where multiple bags were incubated at a given point, results were averaged to give a single datum for each sampling point.

Laboratory Methods

Each sample was passed through a 2-mm sieve to remove stones and root fragments, extracted with 0.5 mol L^{-1} K_2SO_4 (Ohio Hills) or 1.0 mol L^{-1} KCl (Green River), then analyzed for NH_4^+ and NO_3^- using the microtiter methods of Sims et al. (1995). Total inorganic N (TIN) was defined as NH_4^+–N and NO_3^-–N. Net N mineralization was defined as the difference in TIN between individual preincubation samples and TIN in either the corresponding post-incubation sample where $n = 1$ or the mean of the post-incubation samples where $n = 3$. Net nitrification was defined as the difference in NO_3^-–N in preincubation and post-incubation samples. Proportional nitrification was calculated by dividing net nitrification by the total NH_4^+–N available to be nitrified (initial NH_4^+–N + net N mineralized). Soil organic C concentrations used to estimate N mineralization per unit soil organic C are from Boerner et al. (2007).

Data Analysis

This experiment was designed as a randomized complete block, with three blocks per site and four treatments allocated to each block. Responses were either normally distributed (e.g., N mineralization, net nitrification) or could be normalized by transformation (e.g., TIN, proportional nitrification). Differences in response parameters among treatments during each year were analyzed for each site by mixed model analysis of covariance for a completely randomized block design, using LEC/IMI and pretreatment TIN, N mineralization, or nitrification as covariates (SAS Institute, 2004). In this analysis, treatments and the two covariates were considered random factors and blocks were treated as fixed factors. Means separations were done by least squares estimation, using the Bonferonni adjustment for multiple comparisons at $P < 0.05$ (SAS Institute, 2004).

The LEC/IMI covariate was added to determine if the effects of the treatments varied among landscape positions, and a significant LEC/IMI covariate would be a clear indication that analysis of these treatments at finer spatial scales is necessary before broad generalizations are offered. The pretreatment TIN, N mineralization, and nitrification covariate was designed to separate the effects of preexisting variations in N cycling rates not associated with broad landscape features. Legacies of earlier land use and heterogeneous patterns of coarse woody debris and litter accumulation across the forest floor can have effects on N cycling components that must be separated from the effects of the treatments (Boerner and Koslowsky, 1989). The degree of significance of the pretreatment covariate could be considered a measure of the spatial heterogeneity in the process being measured.

RESULTS

There were significant effects of the treatments on TIN during the first post-treatment growing season in the Ohio Hills but not at Green River (Table 2). Soils from the Ohio Hills mechanical treatment had significantly greater TIN (by a factor of 1.5–2.7) than did soils from the other three treatments (Fig. 2).

There was no significant effect of the treatments on TIN during the later sampling year at either site (Table 2), although post hoc *t*-tests indicated that TIN was significantly greater in

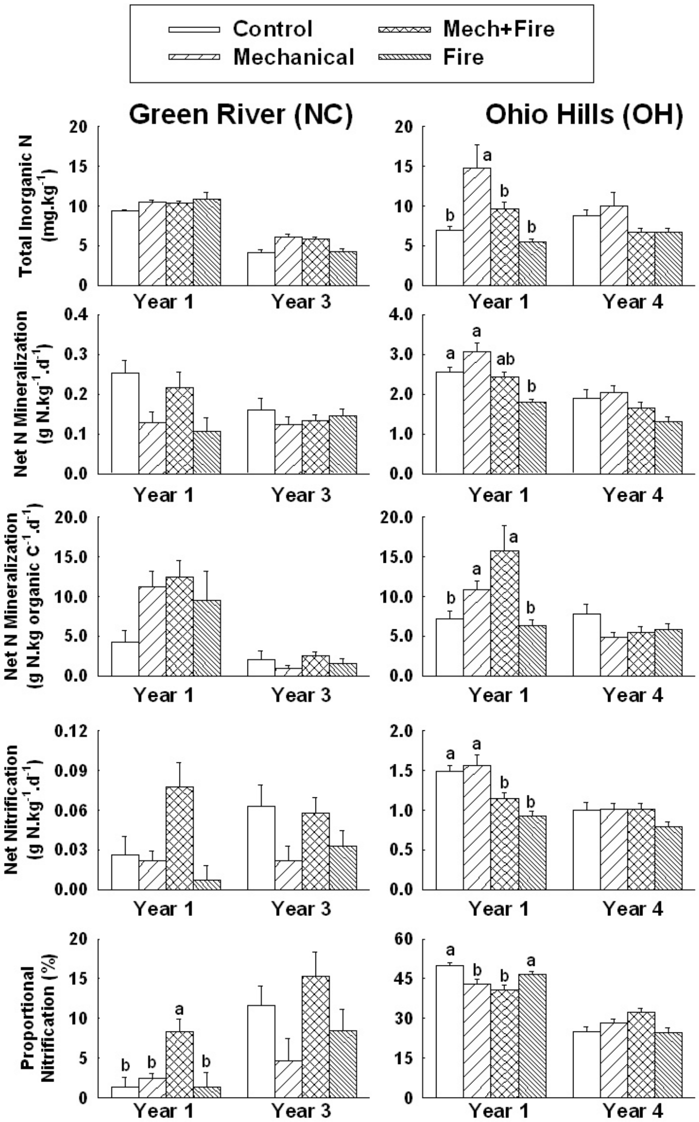

Fig. 2. Total inorganic N, net N mineralization, net nitrification, and proportional nitrification from in situ incubations of forest soils in the Green River (North Carolina) and Ohio Hills (Ohio) Fire and Fire Surrogate Network study sites in relation to forest management alternatives. Histogram bars represent means of *n* = 3 treatment units per site, with standard errors of the means indicated. Where analysis of covariance indicated significant treatment effects, histogram bars indicated by the same lowercase letter were not significantly different at *P* < 0.05.

the Green River mechanical and mechanical + burn sites (by 44 and 38%, respectively) than in control soils (Fig. 2).

Net N mineralization was approximately fivefold greater in soils from the Ohio Hills than in Green River soils (Fig. 2). There were no significant effects of the alternative treatments on net N mineralization potential at Green River during either sampling year or at the Ohio Hills during the later sampling year (Table 2, Fig. 2). Net N mineralization was significantly lower in soils of the burn-only treatment than in soils from the control or mechanical treatment during the first post-treatment year at the Ohio Hills (Table 2, Fig. 2). The N mineralization rates in control and mechanical treatment soils exceeded those in the burn-only treatment soils by 42 and 71%, respectively.

As the soils at the Ohio Hills site had more soil organic C than the Green River soils (Table 1; Boerner et al., 2007), we also expressed the N mineralization rate on an organic-C basis. When expressed on this basis, the strong difference in the rate of N mineralization between the Ohio Hills and Green River sites was reduced (Fig. 2). Once again, there were no significant effects of the alternative treatments on net N mineralization potential at Green River during either sampling year or at the Ohio Hills during the later sampling year (Table 2, Fig. 2). During the first post-treatment year at the Ohio Hills, net N mineralization per unit organic C was significantly greater in the soils of the mechanical treatment units (with or without fire) than in those of the control or burn-only units (Table 2, Fig. 2).

Net nitrification was approximately 10-fold greater in Ohio Hills soils than Green River soils, regardless of year or treatment (Fig. 2). As was the case for net N mineralization, there was no significant treatment effect on net nitrification at Green River during either year or in the Ohio Hills during the later sampling year (Table 2, Fig. 2). At the Ohio Hills site, net nitrification during the first post-treatment growing season was significantly greater in the control and mechanical treatment soils than in the mechanical + fire and fire-only soils (Table 2, Fig. 2).

When nitrification was expressed on a proportional basis, there were significant treatment effects in soils of both study sites during the first post-treatment growing season (Table 2). At Green River, proportional nitrification in soils from the mechanical + fire treatment exceeded that of the other three treatments by an average of 79% (Fig. 2). In the Ohio Hills, proportional nitrification was significantly lower in the two treatments that included mechanical treatment than in the control and burn-only soils. The relative magnitude of the differences among treatments at the Ohio Hills was considerably smaller, however, than that present at Green River (Fig. 2).

DISCUSSION

Fire reduced net N mineralization and net nitrification during the first growing season after burning at the Ohio Hills site, but this effect had dissipated before the fourth post-fire growing season, and extractable TIN was not affected significantly in either year. At the Green River site, net N mineralization, net nitrification, and TIN were not affected significantly by fire during either sampling year.

In contrast to what we observed, many studies have demonstrated increases in TIN, N mineralization, and nitrification after single fires (reviews by Raison, 1979; Wan et al., 2001; Boerner, 2006). Based on a meta-analysis of the effects of fire on soil N availability, Wan et al. (2001) concluded that TIN is increased by fire in general. Ammonium availability peaks soon after fire, but returns to prefire levels in less than a year, and this is typically the result of a combination of liberation of NH_4^+ from organic matter degraded during the fire, activity of heterotrophic soil biota, and N_2 fixation by symbionts of newly colonizing plants (Wan et al., 2001). Nitrate availability peaks some months later (generally 6–12 mo after fire) and is the result of enhanced NH_4^+ availability and increased activity of nitrifying bacteria (Raison, 1979; Wan et al., 2001). When the meta-analysis results were stratified by fire intensity and ecosystem, however, Wan et al. (2001) concluded that high-intensity wildfires and slash fires in conifer forests resulted in increased NO_3^- and NH_4^+, whereas prescribed burning and other fires in hardwood forests did not. Whether this difference is driven by fire intensity or ecosystem type is unclear, as most of the western coniferous forest fires in that data set were wildfires and most of the fires in the eastern deciduous forest were planned, low-intensity prescribed fires.

Boerner et al. (2000, 2004) quantified soil organic matter, N mineralization rate, and nitrification rate in four southern Ohio mixed-oak forests subjected to annual or periodic burning and found no consistent or persistent change in any index of microbially mediated N turnover. In that study, prefire conditions and landscape characteristics were more important in explaining changes in C and N dynamics at the plot scale than was fire behavior (Boerner et al., 2000). In a subsequent study of thinning + burning at a neighboring site, Boerner and Brinkman (2004) again found no significant effect of a single fire on N mineralization in an Ohio mixed-oak forest, and a similar lack of fire effect on N mineralization has been reported for oak–pine forests in Georgia and Tennessee (Hubbard et al., 2003) and oak–pine stands in North Carolina (Knoepp et al., 2004).

It is important to note that the results of single fires or relatively short-term studies may not scale linearly across longer time periods. Vance and Henderson (1984) measured rates of N mineralization in a Missouri oak flatwoods that had been burned either annually or periodically (3–4-yr rotation) for approximately 30 yr, and found that N mineralization was reduced by long-term burning. They concluded that this change was a consequence of a change in organic matter quality (measured as C/N ratio), not quantity. Similarly, Eivasi and Bayan (1996) resampled the same Missouri oak flatwoods a decade later and concluded that microbial biomass and activity had been reduced in proportion to fire frequency even though the amount of soil organic matter present had not been significantly affected. This would be consistent with what one would expect if long-term burning results in an accumulation of recalcitrant C forms, including black carbon, with time (Ponomarenko and Anderson, 2001).

When net N mineralization was expressed per unit soil organic matter available for consumption, the moderate reduction in N mineralization by fire at the Ohio Hills site during the first post-treatment year was no longer present. Although these fires did not produce a statistically significant reduction in soil organic matter content (Boerner et al., 2007) and studies in neighboring sites have documented only slight changes in soil organic matter in Ohio oak-hickory sites subjected to one to four prescribed fires (Boerner et al., 2000; Boerner and Brinkman, 2004), the changes that did occur were sufficient to shift what was a modest, although statistically significant difference in N mineralization when expressed on a soil-mass basis to a nonsignificant difference on an organic-matter basis.

Mechanical thinning of the understory and midstory trees at the Ohio Hills site had a significant, positive effect on soil TIN, net N mineralization, and nitrification during the first post-treatment growing season, and when N mineralization was expressed on an organic-matter basis both mechanical treatment and the combination of mechanical treatment and prescribed fire produced significant stimulation. Once again, these differences did not persist into the fourth growing season, and no such effects were present at the Green River site.

Changes in soil N transformations following pre-commercial thinning and other partial harvest practices may be the result of additions of leaf material and other low C/N ratio residues to the soil surface, changes in forest floor and soil microclimate due to canopy opening, and reductions in plant N uptake following harvest (Johnson and Curtis, 2001). For example, clear-cutting in a Virginia hardwood forest resulted in reduced plant N uptake and in increased microbial biomass, N mineralization rate, and TIN (Johnson et al., 1985).

At our study sites, the mechanical treatment produced only small and transient reductions in soil organic C at the Green River site, and the combined mechanical + prescribed fire treatment produced similar small and transient decreases in soil organic C content at both study sites (Boerner et al., 2007). Given the lack of a pronounced effect of the mechanical treatment (with or without prescribed fire) on soil organic C, the considerable stimulation of soil N transformations by mechanical treatment that we observed at the Ohio Hills site cannot have been the result of changes in soil organic C content.

It is difficult to separate the relative roles of the deposition of labile organic matter in logging residue, changes in forest floor microclimate, and changes in plant N uptake in the increase in N transformation rates observed after mechanical treatment. In a study of the effect of logging of a mixed-oak forest in Tennessee, Edwards and Ross-Todd (1983) found that total CO_2 efflux from the soil (i.e., root + microbial respiration) was significantly lower in the harvested stands than in the controls, despite lower temperature and humidity in the control; however, when live roots were sieved from the soils, the pattern of soil CO_2 efflux was reversed: 1.9- to 2.2-fold greater in the harvested sites than the controls. The results of this experiment demonstrate that the organic matter added to the soil by harvesting (i.e., deposition of leaf material and production of dead roots) can result in an increase in microbial respiration, which may affect rates of N transformations (Edwards and Ross-Todd, 1983).

As the majority of the shrubs and smaller trees at our study sites resprouted after fire and the changes in soil organic matter we observed were small and transient (Boerner et al., 2007), the differences in first-year N transformations between the Ohio Hills and Green River sites are probably not the result of differences in post-treatment N uptake or soil organic matter content. The largest difference between these two sites before treatment was the presence of the dense understory of the ericaceous shrubs *Rhododendron maximum* and *Kalmia latifolia* at Green River. In forests with dense ericaceous understories, such as those that develop at the Green River site when fire is suppressed, it is common to observe lower decomposition and soil organic matter consumption rates than are typical of forests that, like the Ohio Hills, lack a dense ericaceous shrub layer (DeLuca et al., 2002). The mechanism of this inhibition is thought to involve the accumulation of recalcitrant complexes composed of tannins (and other polyphenolics) derived from ericaceous litter (Waterman and Mole, 1994). Thus, cutting down the ericaceous shrubs would result in a sudden input of litter with high concentrations of polyphenolics, and this could result in an inhibition of N mineralization at the Green River site relative to the Ohio Hills site. As a result, mechanical treatment could produce a pulse of leaf and fine woody material to the forest floor and mineral soil surface of both sites but only stimulate soil N transformations at the Ohio Hills site. The inhibition of N mineralization (by polyphenolics) in the Green River soils, relative to the Ohio Hills soils, would then produce the observed differences in net nitrification and TIN in the soil. Furthermore, one would predict that these effects would be observed more in the mechanical-only treatment than in the mechanical + burn or burn-only treatments where the polyphenolic compounds would have been at least partially combusted. Thus, the nature of the shrub understory of these forests may be a key factor in determining the soil biochemical effects of pre-commercial thinning operations.

Although the extractable TIN concentrations were similar between study sites regardless of treatment, N mineralization and nitrification rates were significantly greater in the Ohio Hills soils than the Green River soils. Expressing net N mineralization rate per unit soil organic matter removed any differences arising solely from differences in soil organic matter content between sites and eliminated almost all of the difference between sites. The same is true of net nitrification rates, although for brevity we did not present those data in our results. Differences in soil organic matter content, however, cannot explain the differences in proportional nitrification between sites. At Green River, an average of 3.4 and 10.0% of available NH_4^+ was nitrified during the first and third post-treatment growing seasons, respectively. In contrast, proportional nitrification averaged 45.1 and 27.6% during the two sampling years at the Ohio Hills site. Even in the treatment that tended to stimulate proportional nitrification the most, the mechanical treatment, the differences between sites were still large: 5.5-fold greater in the soils from the Ohio Hills than in the Green River soils.

These Appalachian forests are considered to have historically been N limited (Aber et al., 1989). A comparison of N deposition reported for the four National Atmospheric Deposition Program monitoring sites nearest to each of our study areas for the period 1995 to 2004 indicates that, over a decade, an Ohio Hills forested area receives 16.3 kg N ha^{-1} yr^{-1} more N than a similar site in western North Carolina (National Atmospheric Deposition Program, 2006). For comparison, average annual N mineralization rates in the soils of the Ohio Hills forested areas are 22 to 56 kg N ha^{-1} yr^{-1} (Plymale et al., 1987).

One of the earliest indicators of impending N saturation in formerly N-limited forests is a marked increase in nitrification (Aber et al., 1989), and increases in proportional nitrification from <10 to >40% over 15 yr have recently been reported in the Ohio Hills region (Boerner et al., 2004). In neighboring West Virginia, N saturation of hardwood watersheds has already been documented (Peterjohn et al., 1999). Assuming the differences in N deposition rates of 1995 to 2004 continue in the future, one would expect the forests of the Ohio Hills to become less responsive to management alternatives that affect deposition of N-rich organic matter and its subsequent turnover.

Our treatment units approximated the watershed scale at these study sites. Given the complex, dissected topography of these regions, it was reasonable to hypothesize that the magnitude and even the direction of the effects of the FFS treatments would vary among landscape positions within each treatment unit, and reports of such landscape-scale variations in responses to fire have been reported in the past (Boerner et al., 2000; Boerner, 2006). We used a dual-covariate approach to help account for variations at this scale. We used the landscape metrics (IMI of Iverson et al. [1997] at the Ohio Hills and the LEC of Carter et al. [2000] for Green River) as a covariate to determine if the effects of the treatments varied among landscape positions. We also utilized the pretreatment TIN, N mineralization, and nitrification rates of each sample plot to separate from the treatment effects the effects of preexisting variations in N cycling rates not associated with broad landscape features. For example, legacies of earlier land use and heterogeneous patterns of coarse woody debris and litter accumulation across the forest floor may have effects on N cycling components that must be separated from the effects of the treatments. At the Green River site, none of the pretreatment covariates were significant and only those landscape position covariates associated with the N mineralization rate in the later sampling year were significant. Thus, neither variations among landscape positions nor preexisting spatial variations at finer scales were particularly important in determining post-treatment responses at Green River. In contrast, at the Ohio Hills, pretreatment variations were a significant covariate in determining differences in TIN among sample plots in the first post-treatment year and marginally significant ($P < 0.066$) in the later sampling year. In addition, variations among landscape positions within a treatment unit were also significant at the Ohio Hills during the first post-treatment year for proportional nitrification and for TIN, N mineralization, and proportional nitrification during the fourth post-treatment year. Thus, landscape-level variations were more important in contributing to the overall effects of the treatments at the Ohio Hills site than at the Green River site, and became more important with time. The mechanisms for these differences between sites are unclear and are the subject of continuing research.

The effects of prescribed fire, mechanically thinning from below, and their combination on N transformations in hardwood forest soils in the Appalachian Mountains were, for the most part, modest and transient. Although qualitatively different responses might have been expected if the treatments were of greater intensity or severity (e.g., high-severity wildfire, whole-tree harvest), our results suggest that the impacts of treatments such as the ones we used should not present a barrier to innovation in either forest ecosystem restoration efforts or wildfire hazard management.

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