Effects of fire at two frequencies on nitrogen transformations and soil chemistry in a nitrogen-enriched forest landscape

R.E.J. Boerner, J.A. Brinkman, and Elaine Kennedy Sutherland

Abstract: This study reports results of the application of dormant-season prescribed fire at two frequencies (periodic (two fires in 4 years) and annual) at four southern Ohio mixed-oak (*Quercus* spp.) forest sites to restore the ecosystem functional properties these sites had before the onset of fire suppression and chronic atmospheric deposition. Each forest site comprised three contiguous watershed-scale treatment units: one burned in 1996 and 1999, one burned annually from 1996 through 1999, and an unburned control. Soil organic matter, available P, net N mineralization, and nitrification were not significantly changed by fire at either frequency, though values for the latter two properties increased 4- to 10-fold from the period 1995–1997 to the period 1999–2000. Fire at both frequencies resulted in increased soil pH and exchangeable Ca^{2+}. Exchangeable Al^{3+} was reduced by fire at two of four sites, and the molar ratio of Ca/Al was increased by fire at three of four sites. In contrast to results in most studies of fire, N transformations and availability were not increased by fire in this N-enriched region (deposition of N averaged about 6 $kg \cdot ha^{-1} \cdot year^{-1}$ over the last 20 years). We hypothesize that the large observed increase in nitrification is an indication of the onset of N saturation. Although fire appears to offset the effect of atmospheric deposition in this region by increasing soil pH, Ca^{2+}, and Ca/Al ratio and reducing available Al^{3+}, increased NO_3^- fluxes through the soil from continued N deposition may negate the positive effect of fire.

Résumé : Cet article présente les résultats d'essais de brûlage dirigé pendant la période de dormance dans quatre stations occupées par une forêt mixte de chêne (*Quercus* spp.). Deux fréquences (périodique (deux fois en 4 ans) et annuelle) de brûlage dirigé ont été utilisées dans le but de restaurer les propriétés fonctionnelles de l'écosystème antérieures à la suppression des feux et aux dépôts atmosphériques chroniques. Chaque station forestière était constituée de trois unités correspondant à trois bassins versants contigus ayant chacun reçu un traitement : un bassin a été brûlé en 1996 et 1999, un autre a été brûlé à chaque année de 1996 à 1999 et le dernier a servi de témoin. Peu importe la fréquence, le feu n'a pas significativement affecté la matière organique du sol, le P disponible, la minéralisation nette de N et la nitrification même si la minéralisation nette de N et la nitrification ont augmenté de 4 à 10 fois de 1995–1997 à 1999–2000. Les deux fréquences de brûlage ont entraîné une augmentation du pH du sol et de la quantité de Ca^{2+} échangeable. Le feu a fait diminuer la quantité de Al^{3+} échangeable dans deux des quatre stations et augmenté le rapport molaire Ca/Al dans trois des quatre stations. Contrairement à la plupart des études sur le feu, le brûlage n'a affecté ni la transformation ni la disponibilité de N dans cette région enrichie en N où les dépôts atmosphériques ont atteint en moyenne 6 kg $N \cdot ha^{-1} \cdot an^{-1}$ au cours des 20 dernières années. Nous faisons l'hypothèse que la forte augmentation de la nitrification, que nous avons observée, est un indice d'un début de saturation en N. Bien que le brûlage semble pallier l'effet des dépôts atmosphériques dans cette région en augmentant le pH du sol, le contenu en Ca^{2+} et le rapport Ca/Al tout en réduisant la quantité de Al^{3+} disponible, l'augmentation des flux de NO_3^- dans le sol qui résulte des dépôts persistants de N pourrait annuler l'effet positif du brûlage.

[Traduit par la Rédaction]

Introduction

Analysis of long-term vegetation dynamics in eastern North America, based on pollen and macrofossils, indicates that species of oaks (*Quercus* spp.) were common and abundant in the region for millennia before European settlement (Davis 1989; Delcourt and Delcourt 1997). The study by Delcourt and Delcourt also supplies evidence that these areas experienced frequent fire over the last 3–4 millenia and that fires gradually shifted from large, regional ones to smaller, more frequent, local ones as native American populations increased (Delcourt and Delcourt 1997). Thus, the

Received 31 March 2003. Accepted 15 September 2003. Published on the NRC Research Press Web site at http://cjfr.nrc.ca on 15 March 2004.

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 doi: 10.1139/X03-221 © 2004 NRC Canada

forest ecosystems encountered by the earliest European explorers, trappers, and botanists would have already been shaped by fire.

Recent and ongoing studies indicate that dormant-season fires occurred frequently in this region from the late 1700s through the 1920s (Sutherland 1997; E.K. Sutherland and T.F. Hutchinson, unpublished data). On the unglaciated Allegheny Plateau of southern Ohio, such surface fires occurred at intervals of 3–4 years over that period, with few forested areas being fire free for more than 24 years (Sutherland 1997). Effective fire suppression in this region began in the early 1930s and has continued to the present day.

Over the last 23 years, atmospheric deposition of N has averaged 5.8–6.1 $kg \cdot ha^{-1} \cdot year^{-1}$ in southern Ohio (NADP 2003). Although the region has been receiving acidic deposition for over a century (e.g., over the past 30 years, average deposition of S = 11.0 $kg \cdot ha^{-1} \cdot year^{-1}$; average deposition of Ca + Mg + K = 2.4 $kg \cdot ha^{-1} \cdot year^{-1}$; NADP 2003), only in recent decades has N been a major component of atmospheric deposition. A comparison of the N deposition rate of the period 1980–2000 with estimates of annual net N mineralization in this region (Plymale et al. 1987) indicates that annual N deposition represents a subsidy equivalent to as much as 30% annual forest soil net N mineralization. Through their effects on soil properties and vegetation, both fire suppression and N deposition may have affected the functioning of these ecosystems.

Since the early 1960s the abundance of oaks and hickories (*Carya* spp.) have declined by >20%, whereas the abundance of maples (*Acer rubrum* L., *Acer saccharum* Marsh.), yellow-poplar (*Liriodendron tulipifera* L.), and black cherry (*Prunus serotina* Ehrh.) has increased by as much as 130% (Iverson et al. 1997). As these changes have occurred in unmanaged, uncut plots resampled periodically by the USDA Forest Service, they cannot be the result of harvesting practices. Our overarching hypothesis is that these changes in vegetation dynamics and composition are consequences of the long history of fire suppression and atmospheric deposition in this landscape.

As the judicious use of prescribed fire in the oak–hickory forests of our region has the potential to both restore the fire regime present before this century and ameliorate the impact of atmospheric deposition (by volatilizing N and (or) changing soil organic matter quantity or quality), we began in 1994 a long-term study of the use of prescribed fire in the restoration of Appalachian mixed-oak forest ecosystems. The specific objective of the research reported here was to quantify the effect of prescribed, dormant-season fire at two frequencies (annual and periodic) on soil chemistry and N transformations.

Materials and methods

Study sites and sampling design

The four sites chosen for this study were located in Vinton and Lawrence counties on the unglaciated Allegheny Plateau of southern Ohio. Each site was a contiguous block of 75–90 ha occupied by mixed-oak forests that developed following cutting for charcoal production in the second half of the 19th century. The Vinton County study sites, Arch Rock (39°11′N, 82°22′W) and Watch Rock (39°12′N, 82°23′W), and the Lawrence County study sites, Young's Branch (38°43′N, 82°41′N) and Bluegrass Ridge (38°36′N, 82°31′W), were separated by about 40 km (see Sutherland and Hutchinson (2003) for a complete description of the study and study sites).

The parent materials underlying the study sites were sandstones and shales of Pennsylvanian age. The soils of all four sites were silt loams formed from colluvium and residuum and were predominantly Alfisols (Boerner and Sutherland 2003). Except on ridgetops, the forest floor consisted of an unconsolidated litter layer overlying a mull of mixed-mineral soil, organic matter, and roots. A discontinuous layer of humified organic matter, roots, and fungal hyphae was present between the unconsolidated leaf litter layer and the mixed-mineral soil, organic matter layer on the ridge tops and in other fairly xeric microenvironments. The climate of the region is cool, temperate, and continental, with mean annual temperature and precipitation of 11.3 °C and 1024 mm for the Vinton County sites and 12.9 °C and 1059 mm for the Lawrence County sites (Sutherland and Hutchinson 2003). Microclimatic gradients generated by the steep, dissected topography of the region included the tendency for the south-, southwest-, and west-facing slopes to be drier and warmer than the northwest-, north-, and east-facing ones (Wolfe et al. 1949; Hutchins et al. 1976).

The study sites were chosen from a larger pool of candidate sites on the basis of the following criteria: (*i*) they met the age and land-use-history criteria, above; (*ii*) they each provided three topographically and geologically similar watershed-scale treatment units; and (*iii*) they showed no indications of significant disturbance since timber harvest in the late 1800s.

Soil analysis indicated that soil chemical properties varied significantly across the study sites (Morris and Boerner 1998; Boerner et al. 2003). The soils at Young's Branch and Bluegrass Ridge had significantly greater inorganic-N pool size, proportional-nitrification rate, organic-C content, pH, Ca^{2+}, Mg^{2+}, and molar ratio of Ca/Al than the soils of Arch Rock and Watch Rock did (Boerner et al. 2003).

The experimental design included two fire-frequency treatments. The periodic-burn treatment was intended to re-establish the temporal pattern of fire that was present before 1850: fires every 3 or 4 years. The annual-burn treatment was intended to remove as many of the small and medium-sized stems of fire-intolerant tree species and as much of the accumulated organic matter and fine fuel as possible; this treatment consisted of annual burns for 4 years, followed by fires imposed on a 3- to 4-year rotation. In April 1996 and 1999, two of the three treatment units in each study site were burned (periodic-burn units), and one treatment unit in each study site was burned in 1997 and 1998 as well (annual-burn units).

The fires of 1996 were of low intensity, with mean temperatures at 10 cm above the forest floor averaging 157–210 °C, depending on study site and fire (Boerner et al. 2000). These fires consumed 35%–80% of the unconsolidated leaf litter and other fine fuels but little or none of the underlying humified material (where present) or coarse woody debris (Boerner et al. 2000). Details of fire design,

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implementation, and behavior are given by Sutherland and Hutchinson (2003) and Iverson and Hutchinson (2002).

Within each of the treatment units, nine stratified random sample plots of 0.125 ha were established, with the stratification based on a long-term integrated moisture index developed for this region (Iverson et al. 1997). The experiment had a balanced, randomized-block design, with study areas as blocks (Iverson and Prasad 2003).

Field methods

Samples of about 400 g of fresh mass of the top 15 cm of the A + O_a horizon were taken from opposite corners of each of the 27 sample plots in each study site in May or early June from 1995 through 2000 (except 1998) at Arch Rock and Young's Branch; and in 1995 (prefire) and 1999 (postfire) at Watch Rock and Bluegrass Ridge. This sampling intensity yielded n = 18 per treatment unit and n = 54 for each study site on each date. All subsequent samples were taken within 50 cm of the initial 1995 sampling points, and all samples were returned to the laboratory under refrigeration. The lack of 1998 samples from all four study sites and of samples in other years from Watch Rock and Bluegrass Ridge was the result of limitations in funding that significantly reduced our ability to sample all sites in all years.

Laboratory methods

Each soil sample was air-dried and sieved to remove material >2 mm. Root and particulate organic matter fragments were then removed by hand. A subsample of about 15 g of soil was extracted with 2 mol/L KCl and analyzed for NH_4^+ and NO_3^- using colorimetric methods and a Lachat Quik-Chem autoanalyzer. Soil pH was determined in a 1/5 soil slurry of 0.01 mol/L $CaCl_2$ (Hendershot et al. 1993); available P, by the ascorbic acid method (Watanabe and Olsen 1965); available Al^{3+} in 2 mol/L KCl extracts, by the ferron method (Bersillon et al. 1980); exchangeable Ca^{2+} in 1 mol/L NH_4OAc extracts, by atomic absorption spectrophotometry (Lanyon and Heald 1982); and soil organic matter, by the Walkley–Black method (Allison 1965), with an organic matter to organic-C conversion derived empirically for this site.

A subsample of about 50 g of the sieved soil was placed in an incubation chamber, and artificial rainwater was added to bring the soil to 70% of field capacity. The soil samples were incubated for 27–29 days at 22–28 °C. Every third day, each soil sample was weighed and sufficient rainwater was added to bring the moisture content back to a randomly chosen level within the range of 50%–70% of field capacity (Morris and Boerner 1998). Laboratory incubations were chosen for use in this study because the manner in which the moisture regime for the incubating samples was maintained recreated the frequent fluctuations in soil moisture characteristic of the growing season in our ecosystems reasonably well (Morris and Boerner 1998).

At the end of the incubation period, 15 g of the incubated soil was extracted and analyzed for NH_4^+ and NO_3^-, as above. Net N mineralization was determined by subtracting the NH_4^+ and NO_3^- content of the initial samples from that of the incubated samples. Proportional nitrification was calculated by determining the proportion of the total NH_4^+ available for nitrification (initial NH_4^+ + NH_4^+ made available by ammonification) that was converted to NO_3^-.

Data analysis

All response variables except the molar ratio of Ca/Al either were normally distributed or could be transformed to normality with the use of a log transformation (PROC UNIVARIATE; SAS Institute Inc. 1995). These variables were analyzed by mixed-model analysis of variance using an unbalanced randomized complete-block design (PROC MIXED; SAS Institute Inc. 1995). The molar ratios of Ca/Al were analyzed by nonparametric analysis of variance using the Savage algorithm to calculate rank distances (PROC NPAR1WAY ANOVA, EXACT = SAVAGE; SAS Institute Inc. 1995). For all post-treatment years, the pretreatment conditions were used as a covariate in the analysis.

Significant block-by-treatment interactions occurred for all the soil parameters we measured, indicating that the effects of the various fire treatments differed among study sites (blocks). To resolve these differences, we considered each study site independently, using a nested, completely randomized design (PROC GLM; SAS Institute Inc. 1995) (except for Ca/Al ratio, which was analyzed as above). As the fires were patchy in intensity and duration within a treatment unit, each permanent sample plot within a burned-treatment unit was essentially subjected to a different and somewhat random fire treatment; thus, sample plots within treatment areas could be considered replicates in a completely randomized design. Where main effects were significant, least-squares means were used to test differences among treatments.

Results

Soil organic matter

At Arch Rock, soil organic matter content varied significantly among treatment units, before and after fire (Fig. 1). The pattern of variation among treatment units was the same in the prefire year (1995) as in the initial postfire year (1996): that is, it was significantly greater in the periodic-burn unit than in the other two units. In 1999, the soil organic matter content of the Arch Rock periodic-burn unit was still significantly greater than that of the control unit but not significantly different from that of the annual-burn unit (Fig. 1). At Young's Branch, the pattern of variation in soil organic matter among treatment units did not differ in any of the sampling years (Fig. 1). At Watch Rock, in 1995, soils from the control unit had significantly more soil organic matter than did soils from the two units to be burned (Fig. 1); however, in 1999, after fire, there was no significant difference in soil organic matter among treatment units. At Bluegrass Ridge, pretreatment soil organic matter content increased in the following order: control < periodic burn < annual burn. However, in 1999, there were no significant differences in soil organic matter among treatment units at Bluegrass Ridge (Fig. 1). There were no significant differences among years in soil organic matter content in any of the treatment units at Arch Rock, Watch Rock, or Young's Branch or in the control unit at Bluegrass Ridge. There was

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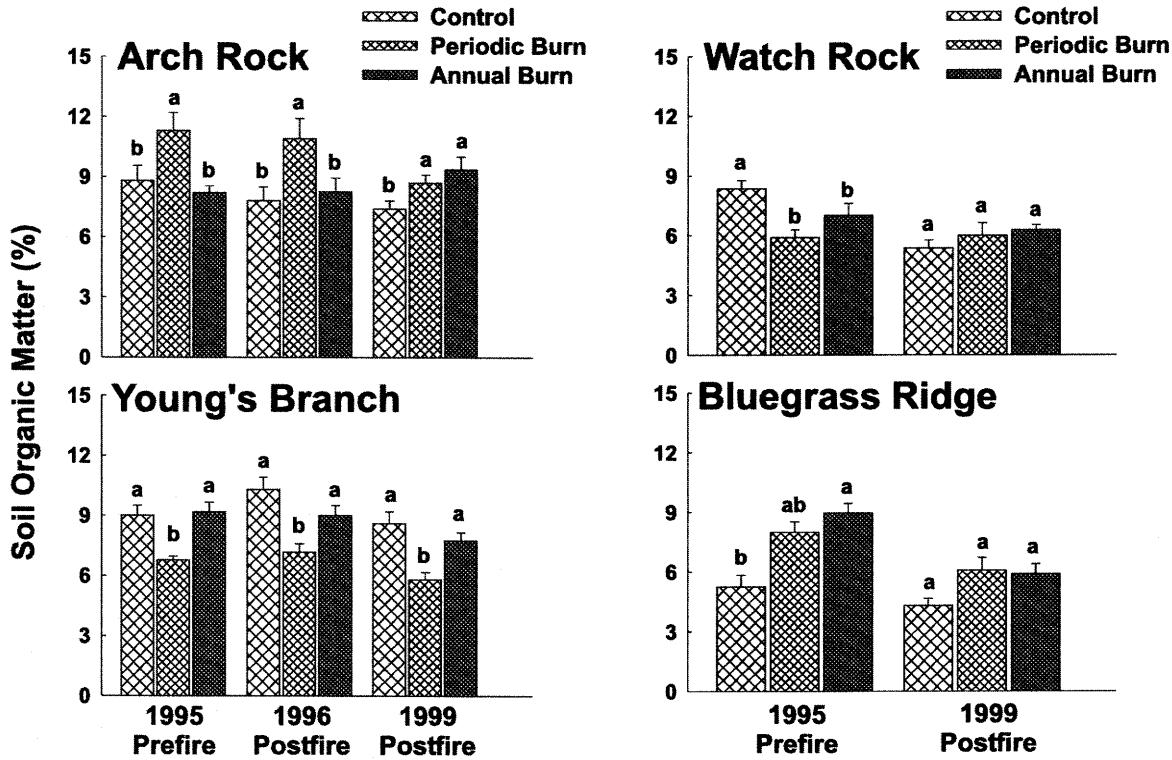
Fig. 1. Soil organic matter content (% by mass) in Ohio mixed-oak forest soils before and after the reintroduction of dormant-season fire. Each histogram bar represents the mean of n = 54, with the standard error of the mean indicated. Within a sample year, histogram bars labeled with the same letter were not significantly different at $p < 0.05$ following mixed-model analysis of variance (1995) or covariance using 1995 values as covariates (other years).



a significant decrease in soil organic matter from 1995 to 1999 in the two burned units at Bluegrass Ridge (Fig. 1).

Nitrogen mineralization and nitrification

The N mineralization rates did not differ significantly among treatment units at Arch Rock or Young's Branch in 1995 or 1996 (Fig. 2). Soils from the periodic-burn units did exhibit significantly greater N mineralization than those from the control and annual-burn units at Arch Rock in 1999 and at Young's Branch in 1997; however, neither of those differences persisted through 2000 (Fig. 2). At Watch Rock and Bluegrass Ridge, there were no significant differences among treatment units in net N-mineralization rate, either before or after fire (Fig. 2). Variations in total inorganic-N content of soils paralleled the variations in N-mineralization rates in all four study sites (data not shown).

The proportion of NH_4^+ that was nitrified in soils from Arch Rock and Young's Branch was relatively low and similar among treatment units in 1995 and 1996 (Fig. 3). In 1997, proportional-nitrification rates did vary among treatment units at Young's Branch, with the annual-burn unit having significantly greater proportional nitrification than the soils from the other two treatment units (Fig. 3). Proportional-nitrification rates increased by an order of magnitude from 1997 to 1999 but did not differ significantly among treatment units in either site in 1999. The rates remained high in 2000, and at both sites the rate was significantly greater in soils from the periodic-burn unit than in soils from the control and annual-burn units (Fig. 3).

At Watch Rock, proportional-nitrification rates among the three treatment units varied by an order of magnitude before the introduction of fire (Fig. 3). The rates in all three treatment units in 1999 were significantly greater than observed in 1995 (Fig. 3). Although 1999 soils from the periodic-burn unit showed significantly greater proportional-nitrification rates than did soils from the control and annual-burn units, the absolute differences were small (Fig. 3). At Bluegrass Ridge, there were again significant differences among treatment units before fire, and proportional-nitrification rates were considerably higher in 1999 than in 1995; however, there were no significant differences among units at Bluegrass Ridge in 1999 (Fig. 3).

Soil pH, exchangeable Ca^{2+}, and exchangeable Al^{3+}

Soil pH did not vary among treatment units within Arch Rock or Young's Branch during the pretreatment year (Fig. 4). In contrast, in 1999 and 2000, soil pH was significantly greater in the two burned units within each of those sites than in soils from the corresponding control units (Fig. 4). The same was observed at Bluegrass Ridge in 1999 (Fig. 4). In contrast, pretreatment soil pH differed significantly among units at Watch Rock, but those differences were no longer apparent after fire (Fig. 4). No significant differences in soil-available P were found among treatment units within any of the four sites, either in 1995 or 1999 (data not shown).

At Arch Rock, prefire Ca^{2+} availability did not differ significantly among treatment units (Fig. 5). In both 1999 and

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Fig. 2. Net N mineralization (mg N·kg soil^{-1}·day^{-1}) in Ohio mixed-oak forest soils before and after the reintroduction of dormant-season fire. See Fig. 1 for explanation of the histograms.

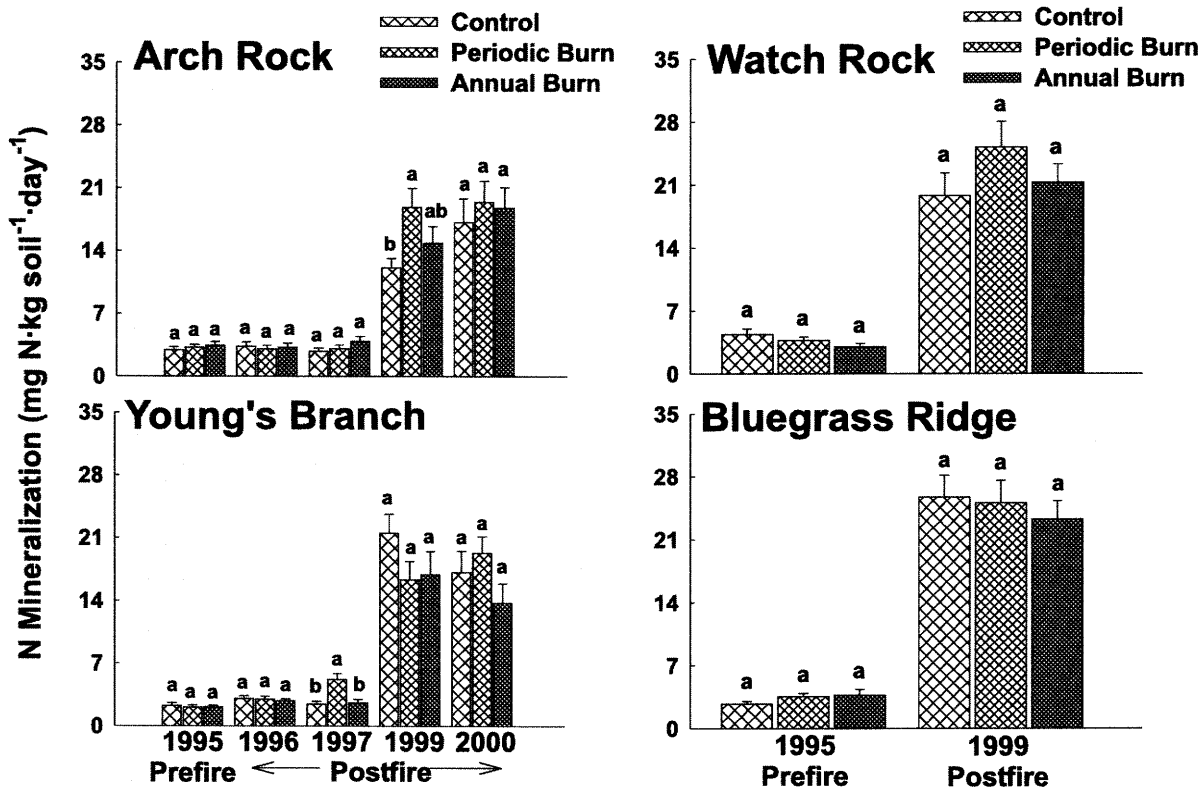

Fig. 3. Proportional nitrification (%) in Ohio mixed-oak forest soils before and after the reintroduction of dormant-season fire. See Fig. 1 for explanation of the histograms.

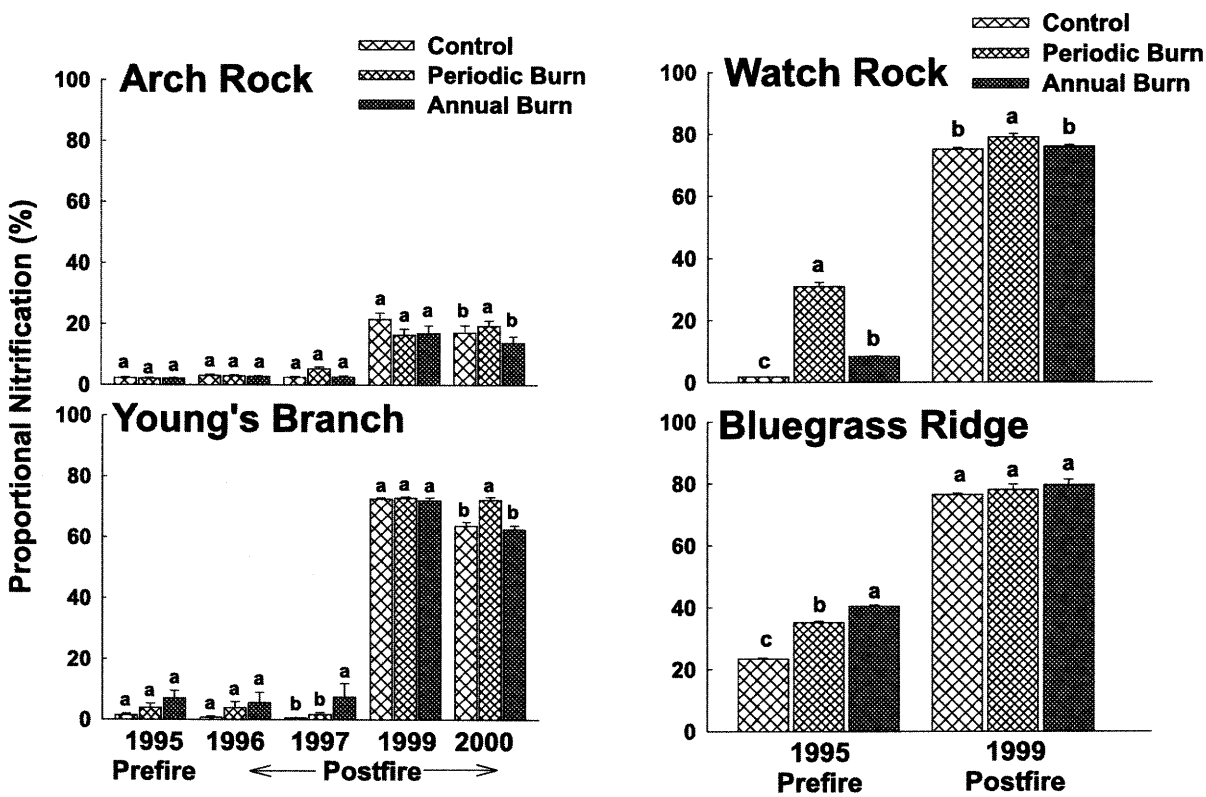

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Fig. 4. Soil pH in Ohio mixed-oak forest soils before and after the reintroduction of dormant-season fire. See Fig. 1 for explanation of the histograms.

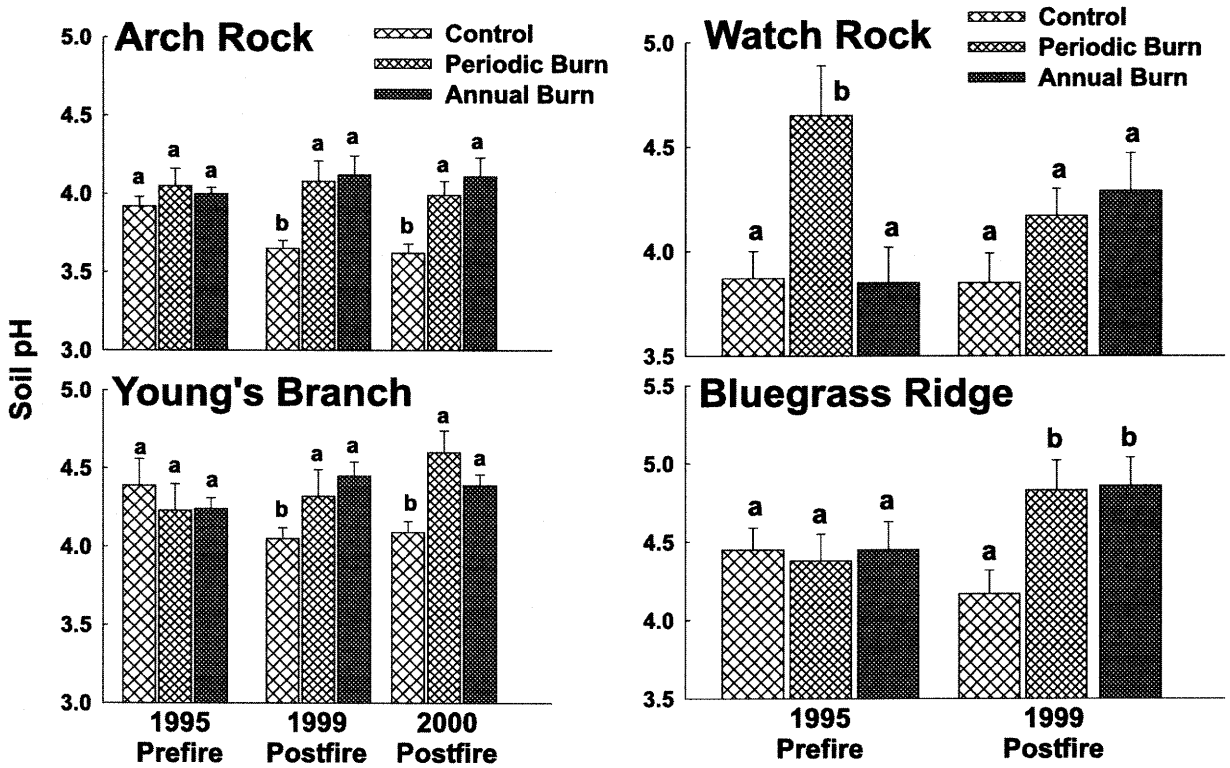

Fig. 5. Exchangeable Ca^{2+} (mg·kg soil^{-1}) in Ohio mixed-oak forest soils before and after the reintroduction of dormant-season fire. Ordinate for Bluegrass Ridge differs. See Fig. 1 for explanation of the histograms.

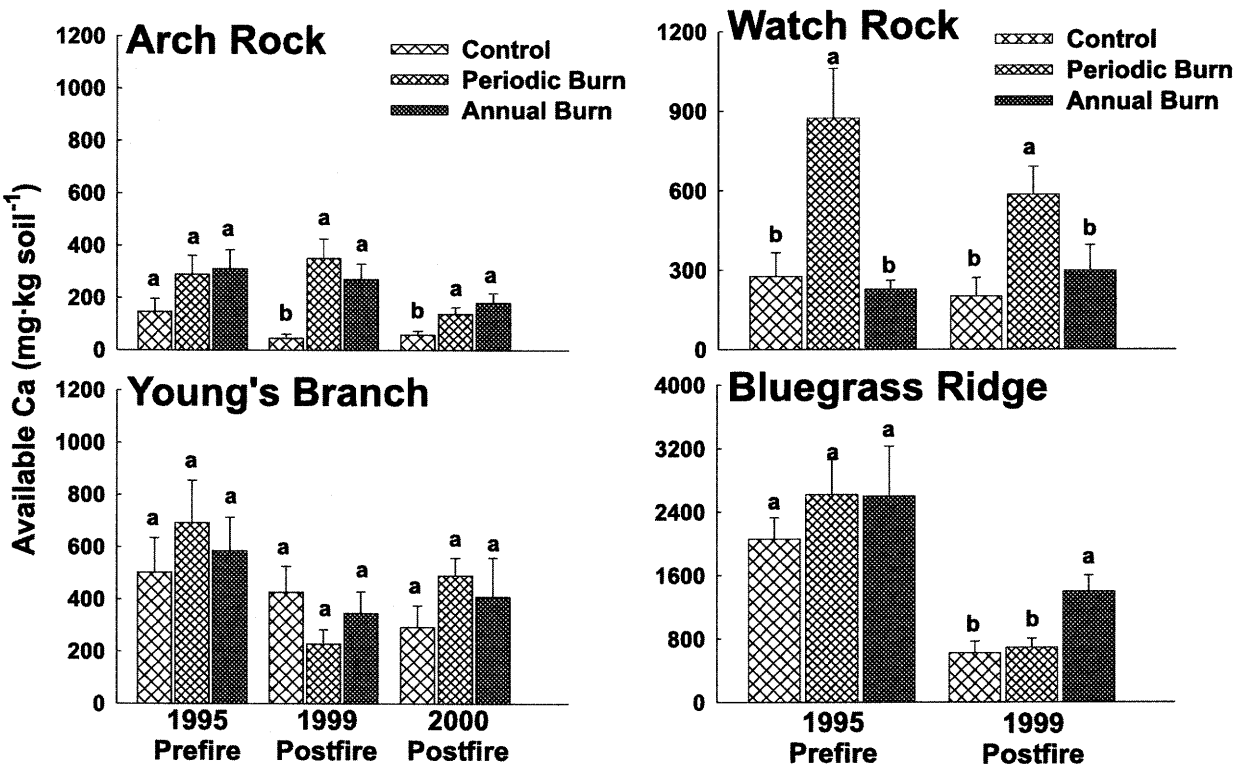

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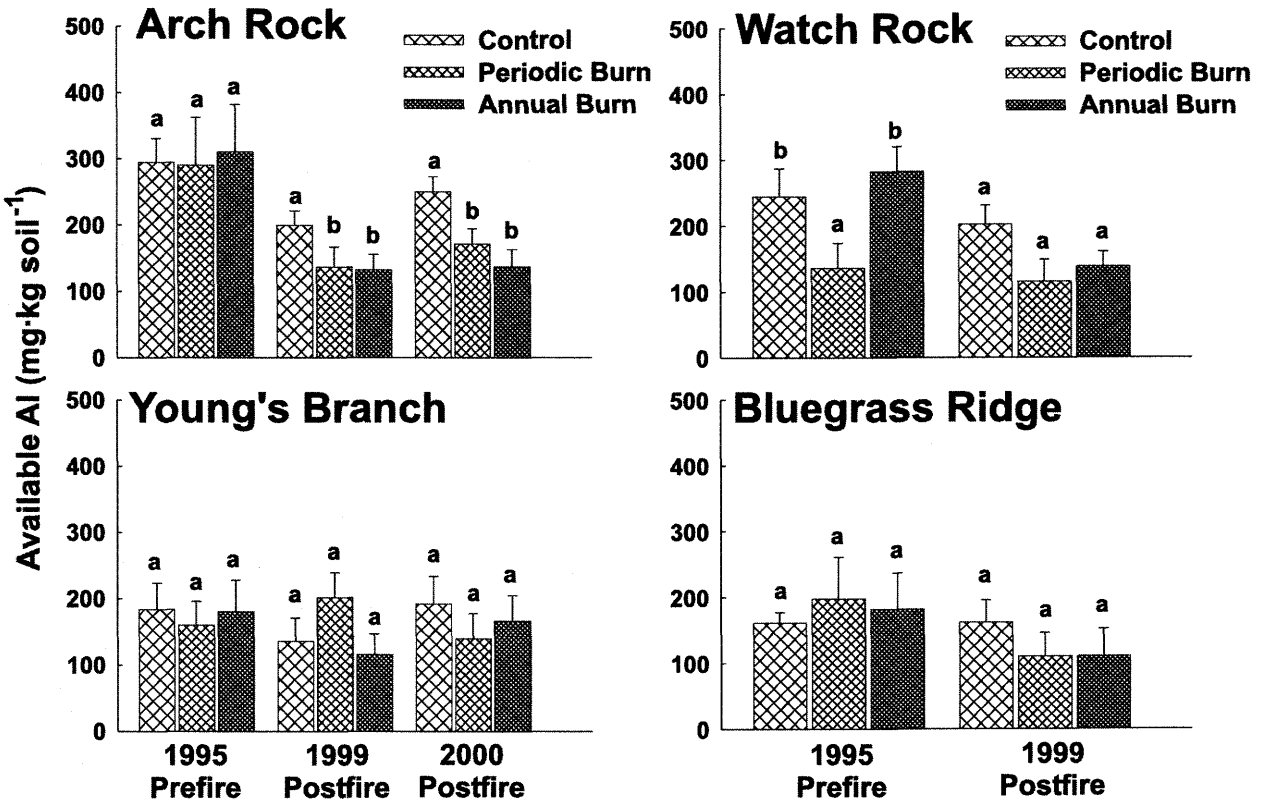
Fig. 6. Available Al^{3+} (mg·kg soil^{-1}) in Ohio mixed-oak forest soils before and after the reintroduction of dormant-season fire. See Fig. 1 for explanation of the histograms.



2000, Ca^{2+} availability among burned-treatment units was significantly greater than in the unburned control (Fig. 5). At Young's Branch, Ca^{2+} availability did not differ significantly among treatment units in any of the three sampling years (Fig. 5). Soils at Watch Rock differed in Ca^{2+} availability in the same manner in prefire 1995 samples as they did in postfire 1999 samples (Fig. 5). At Bluegrass Ridge, the three treatment units had similar Ca^{2+} levels before fire; after fire, the annual-burn unit had significantly greater exchangeable Ca^{2+} than the periodic-burn and control units (Fig. 5).

Available Al^{3+} content did not differ in soils of the three Arch Rock treatment units before fire (Fig. 6). After fire, burned units had significantly lower available Al^{3+} than the unburned control. At Young's Branch and Bluegrass Ridge, there were no significant differences in Al^{3+} availability among treatment units before or after fire (Fig. 6). Before fire at Watch Rock, the unit to be burned periodically had significantly lower Al^{3+} availability than the other two treatment units (Fig. 6). After fire, there were no significant differences among the three treatment units at Watch Rock. This was the consequence of a significant decrease in Al^{3+} from prefire to postfire in the annual-burn unit only.

Before fire, the molar ratios of Ca/Al in soils from the three treatment units at both Arch Rock and Young's Branch did not differ significantly, although they differed among sites by one to two orders of magnitude (Fig. 7). After fire, soils from burned-treatment units at Arch Rock had significantly higher Ca/Al ratios than did soils from unburned controls. Fire had no significant effect on Ca/Al ratio in soils from Young's Branch (Fig. 7).

At Watch Rock, the soils in the treatment unit designated for periodic-burn treatments had significantly higher Ca/Al ratios than soils in the other two treatment units, both before and after fire (Fig. 7). At Bluegrass Ridge, there was no significant difference in Ca/Al ratio before fire (Fig. 7). In contrast, after fire, the Ca/Al ratio varied significantly among all three treatment units and in the following order: control < periodic burn < annual burn (Fig. 7).

Discussion

Despite a rich and extensive literature on the effects of fire on vegetation and soils of coniferous forests, shrublands, and grasslands, few studies of the effects of fire on the soils of deciduous temperate forests exist, and most of those report only short-term effects of fire (Boerner 2000; but see Vance and Henderson 1984). If prescribed fire is to become a widely applied tool for restoration of forest structure and (or) sustainability in this region, validation of its use over a significant period is necessary. Although the data presented cover a 6-year period, this presentation is intended as an interim report on an experiment designed to last more than 20 years (Sutherland and Hutchinson 2003).

Soil organic matter content did not change significantly over time at any of our study sites, and none of the variations we observed among treatment units within a site could be attributed to the effects of fire. These results are consis-

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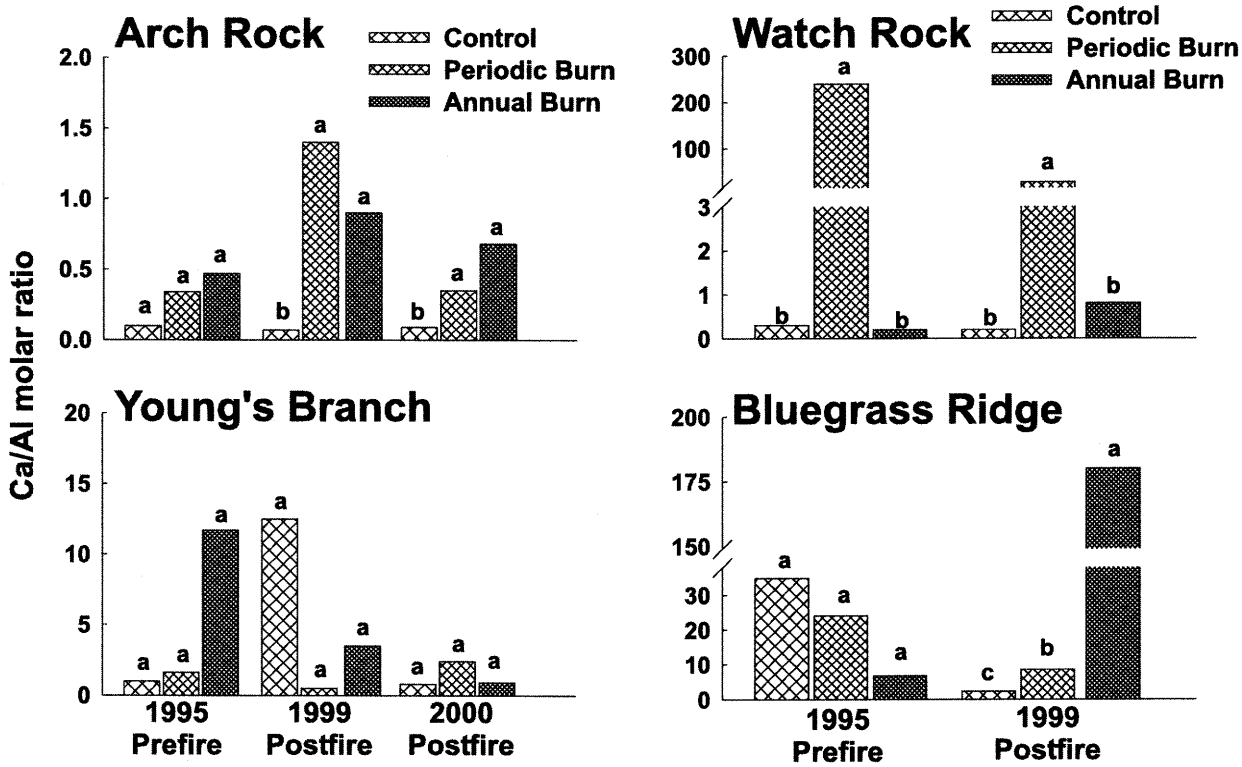
Fig. 7. Molar ratio of Ca/Al in Ohio mixed-oak forest soils before and after the reintroduction of dormant-season fire. Each histogram bar represents the median of n = 54. Within a sample year, histogram bars labeled with the same letter were not significantly different at p < 0.05 following nonparametric analysis of variance. Ordinates vary among panels. See text for details.



tent with those of Knighton (1977) and Eivasi and Bryan (1996), who respectively reported that one to three fires in a Wisconsin oak–hickory forest and ≥40 years of prescribed fire in a Missouri oak woodland had no observed effect on soil organic matter content.

Similarly, we observed few significant effects of fire on soil N transformations. We did observe transient increases in N-mineralization rates in periodic-burn treatment units in two of the sites, but neither difference was large, and neither persisted to the next sampling year. This was true whether mineralization was calculated on a soil-mass basis or on an organic-matter basis. Proportional nitrification also showed little response to fire at either frequency. This lack of a large and (or) persistent significant effect of fire on N availability at time scales ranging from 1 month to 2 years was similar to that reported for single and multiple prescribed burns in dry New Jersey oak–pine forests (*Quercus* spp. – *Pinus rigida*) (Burns 1952; Boerner et al. 1986). In contrast, the only published long-term study of prescribed fire and N availability in eastern hardwood forests reported a long-term decrease in available N following both annual and periodic fires (Vance and Henderson 1984).

These results stand in stark relief when compared with the plethora of studies that have shown N availability increasing after fire (reviews by Raison 1979; Boerner 1982). In a meta-analysis of fire effects on N cycling, Wan et al. (2001) concluded that over all ecosystems and fire types, fire results in an average increase of 94% in NH_4^+ and 128% in NO_3^-. The increase in NH_4^+ was greatest within 1 month after fire, whereas the increase in NO_3^- reached a peak 0.5–1.0 years after fire (Wan et al. 2001). As we sampled at 1 month, 1 year, and 2 years after fire, we feel we would have detected any increased N availability. As further indication of the lack of effect of our fires on N availability, Dress and Boerner (2001) found little effect on root growth in these sites that could be attributed to changes in N availability and no detectable, fire-related changes in the [N] of fine roots or the rate of N released to the soil by decomposition of fine roots in these sites (Dress and Boerner 2003).

The most obvious trend in N transformation was temporal. From 1995 (the prefire year) through 1997, net N-mineralization rates were generally <5 mg N·kg soil^{-1}·day^{-1}, and proportional-nitrification rates were generally <10% (except at Bluegrass Ridge). In 1999–2000, N-mineralization rates were on average eightfold higher than those in 1995–1997, and proportional-nitrification rates had increased fourfold at Arch Rock and Bluegrass Ridge and eightfold at Watch Rock and Young's Branch.

In three of our four study sites, there was no significant difference in soil pH or exchangeable Ca^{2+} among treatment units before fire. At Watch Rock, the soils of the area designated for the periodic-burn treatment had pH values that were >0.5 units higher than the pH values of soils from the other two treatment units, and they also had three times more exchangeable Ca^{2+}. This difference in soil chemistry was paralleled by a somewhat unique assemblage of herbaceous understory species in this treatment unit (Hutchinson et al. 1999). As extensive review of property records and aerial photos showed no indication of cultivation or land-cover alteration (T.F. Hutchinson, personal commununication), we can offer no reasonable hypothesis to explain the uniqueness of this 30-ha area. We have sampled extensively in nine

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other watersheds in and around the Watch Rock periodic-burn unit and have not found any other areas like this one.

Soil pH was significantly higher in burned units than in controls at Arch Rock, Young's Branch, and Bluegrass Ridge following fire at both frequencies. In addition, the soil pH of the annually burned unit at Watch Rock exceeded that of the control by about 0.6 pH units. Blankenship and Arthur (1999) reported an increase of 0.2–0.3 pH units in response to a single prescribed fire in an oak–pine ecosystem in Kentucky. In contrast, no significant effect of fire on soil pH was found after eight annual or two periodic burns in an oak forest in Tennessee (Thor and Nichols 1973) or ≥40 years of annual and periodic fire in a Missouri oak flatwoods (Eivasi and Bryan 1996).

Exchangeable-Ca^{2+} levels were significantly greater following periodic and (or) annual burning at Arch Rock, Young's Branch, and Bluegrass Ridge. At Watch Rock, there were no differences in exchangeable Ca^{2+} that could be attributed to fire. These results were consistent both with the changes in soil pH we observed and with the increase in Ca^{2+} and Mg^{2+} that followed fire in Wisconsin (Knighton 1977). Exchangeable Al^{3+} decreased significantly in both burn treatments at Arch Rock, and such a trend might have been observed at Watch Rock and Bluegrass Ridge had variability within a treatment unit been lower. Young's Branch showed no indication of an effect of fire on exchangeable Al^{3+}.

Perhaps more important to ecosystem structure than Ca^{2+} and Al^{3+} in the soil solution is the relationship between the two. Al^{3+} is an effective competitor with Ca^{2+} for binding sites important to both structure (e.g., cellulose microfibrils) and function (Ca-dependent ATPases, calmodulin, oxalates) in both plants and fungi (McLaughlin and Wimmer 1999). Molar ratios of Ca/Al of <2 to <5 have been suggested as indicators of incipient forest decline (defined as reduced growth and increased mortality; Cronan and Grigal 1995).

Before the reintroduction of fire at these sites, we observed no significant difference in molar ratio of Ca/Al among treatment units at Arch Rock, Young's Branch, or Bluegrass Ridge. At Arch Rock and Watch Rock (except for the anomalous treatment unit), Ca/Al ratios were consistently <1.5 and often <0.4, a range typically associated with high risk for forest decline, according to Cronan and Grigal (1995). At Young's Branch and Bluegrass Ridge, the median Ca/Al ratio within treatment units ranged from 2 to 35, with the drier, more acidic landscape positions at these sites often having Ca/Al ratios of <1 and the more mesic, fertile landscape positions having Ca/Al ratios of >30. Thus, before the reintroduction of fire, all or part of each of our four study sites had Ca/Al ratios in the range cited by Cronan and Grigal (1995) as being of concern.

Following fire, the molar ratio of Ca/Al was significantly greater in soil of burned-treatment units than in soils of the unburned control at Arch Rock and Bluegrass Ridge. In 1999, median Ca/Al ratios in burned units at those two sites exceeded 1.0, but by 2000 the Ca/Al ratio in burned plots at Arch Rock was again <1.0. There were no statistically significant changes in Ca/Al ratio at Watch Rock or Young's Branch.

The combination of persistent, chronic deposition of N over several decades, low molar ratios of Ca/Al, and rapid increase in nitrification we observed over the 5-year period of this study raises the possibility that N saturation is present or incipient, as the earliest sign of N saturation is a significant increase in nitrification in ecosystems historically so limited in N that little nitrification was possible (Aber et al. 1989). The levels of proportional nitrification we observed in 1999 and 2000 in our four study sites were four to eight times higher than what we had observed earlier in this study; they also greatly exceeded estimates of nitrification that had been made about 15 years earlier in a site <25 km away (Plymale et al. 1987). Loss of base cations due to accelerated leaching of NO_3^- would lead to further reductions in the Ca/Al ratio in our sites, both from direct loss of Ca^{2+} to leaching and from increased Al^{3+} solubility resulting from increased acidity.

The regional soil-acidification model developed for European sites by DeVries et al. (1995) predicts that greatly reducing N input in precipitation would result in a return to net N retention, a decrease in Al solubility, and an increase in base saturation and pH. Our results suggest that in our region, fire can produce some of these beneficial effects, at least transiently, without having to overcome the technological and political barriers to reducing atmospheric deposition of N.

Acknowledgements

This study was funded by an Ecosystem Management grant from the USDA Forest Service, Northeastern Research Station. We thank Kelly Decker, Sherri Morris, Michael Fisher, Rachel Thiet, William Dress, Melissa Knorr, Beth Swinehart, Ryan Strachan, and Annemarie Smith for assistance in the laboratory and field. We also acknowledge the MeadWestvaco Corporation and the Wayne National Forest for their assistance in making the study sites available to us and for supplying key infrastructure support.

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