Long-Term Soil Responses to Site Preparation Burning in the Southern Appalachians

Jennifer D. Knoepp, James M. Vose, and Wayne T. Swank

ABSTRACT. The mixed oak–pine ecosystems in the southern Appalachians are in decline because of a combination of drought and southern pine-beetle infestation. A commonly applied prescription for restoration of these degraded sites has been to fell all vegetation, allow it to dry, and conduct a site-preparation burn. However, there is little information on the mid- and long-term influences of this prescription on nutrient cycling. The fell-and-burn treatment was applied to three mixed oak–pine stands in the Nantahala National Forest in western North Carolina. Each stand had an untreated control area. Our objective was to determine the effects of this treatment on soil nutrient availability and potential nutrient loss. Exchangeable soil cations, pH, total carbon (C), and total nitrogen (N) were measured before and periodically for 5 years after treatment. Nitrogen transformations and nutrient availability in soil solution and in a stream draining one site were measured before and periodically for 3 years after burning. Exchangeable calcium and magnesium concentrations, soil pH, and N availability increased after treatment. There was no treatment effect on total soil C or N. Nitrogen mineralization rates were greater on burned versus control plots in 50% of the posttreatment measurements. This treatment increased nutrient availability and, although a significant amount of total site N was lost, there were no adverse effects on total soil nutrients or water quality. FOR. SCI. 50(4):540–550.

Key Words: Prescribed burn, nitrogen, nutrient availability, forest soil chemistry, mixed oak–pine.

THE MIXED OAK–PINE ECOSYSTEM occupies xeric south and southwestern ridges in the southern Appalachians. The pine component, mostly pitch pine (*Pinus rigida* Mill.), has declined by as much as 98% because of drought and insect attacks (Smith 1991). Dense understories of mountain laurel (*Kalmia latifolia* L.) have prevented pine regeneration, and these ecosystems have developed into a sparse oak–mixed hardwood overstory with a dense mountain laurel understory. One approach for restoring these sites has been to fell all vegetation, burn, and plant white pine seedlings at a wide spacing (Clinton et al. 1993). Little is known about how soil resources are affected by site-preparation burning of mixed oak–pine stands.

Short- and long-term effects of fire on soil are largely due to nutrient cycle alterations. Forest soils often have limited nutrient availability. Nitrogen (N) is often the most limiting nutrient. Native forests rely on the internal cycling of nutrients to maintain plant growth (Perala and Alban

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Acknowledgments: Thanks to Lee Reynolds and Patsy Clinton for field and lab assistance. The USDA Forest Service and United Nations Educational Scientific and Cultural Organization (UNESCO) Man and the Biosphere program funded this research.

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1982, Cole 1995). In the absence of any major disturbance, this pattern of tightly controlled nutrient cycling reduces the loss of nutrients from the system. Prescribed burning or wildfire consumes and/or alters the forest floor and woody fuels. This changes both the quantity of nutrient-containing material and the patterns of nutrient release, which may indirectly affect soil nutrients. For example, forest-floor decomposition rates may increase after burning, releasing NH_4 and other nutrients (Schoch and Binkley 1986, Raison et al. 1990). This response may be short-lived. As readily available organic matter diminishes, decomposition rates decrease (Raison et al. 1990).

During combustion of aboveground organic materials (fuels), some material becomes ash and some volatilizes. Raison et al. (1990) suggest that relatively soluble cations in the forest floor such as potassium (K) and magnesium (Mg) can be washed into the soil from ash and altered forest-floor material. Once in the soil, they are either held by the soil or leached. In contrast, soil calcium (Ca) moves more slowly, and inputs from ashes and the forest floor may increase surface soil concentrations for many years after burning. Fire effects on total soil carbon (C) and N are variable and also depend on site conditions and fire characteristics (Raison et al. 1990, DeBano 1990b, Binkley et al. 1992, Vose et al. 1995, Johnson and Curtis 2001). Johnson and Curtis (2001) did an extensive meta analysis of forest-management effects on soil C and N and found that fire rarely influences total C and N. However, individual studies have found both increases (Wells et al. 1979) (Lynham et al. 1998) and decreases (Groeschl et al. 1993) in total soil C and N following burning.

The amount of organic material volatilized is proportional to the temperature of the fire and the volatility of chemicals in the forest floor. Most volatilized material leaves the site. However, some moves vertically into the remaining forest floor and mineral soil, condensing in the cooler and wetter layers below (DeBano 1990a). Condensation plus increased N transformation rates resulting from changes in soil moisture and temperature often result in increased N availability after burning, although the magnitude is related to fire severity. Most burns in the mixed forests of the Eastern United States are low- to mid-severity, increasing soil-extractable N between 1 and 8 mg N kg $soil^{-1}$ (Groeschl et al. 1993, Knoepp and Swank 1993). Variations in N response among studies may be attributable to differences in burning frequency, site quality, and organic matter quality. Although burning may increase N availability, N leaching may degrade the site and negatively affect water quality. Little information is available concerning the effects of burning on stream N concentrations. However, most studies have shown that burning without cutting does not affect streamwater quality in Southeastern ecosystems (Douglass and Van Lear 1983, Clinton et al. 2003).

Information is lacking on the mid- and long-term responses of degraded mixed oak–pine ecosystems to the fell-and-burn prescription. Our objectives were to measure changes in soil nutrient availability and examine the potential for nutrient losses resulting from this treatment. This information is especially important for evaluating the affects of prescribed fire on long-term site productivity. We measured soil nutrients, including exchangeable cations, total C and N and indices of N availability, net mineralization, and nitrification. We examined the potential for nutrient loss due to leaching by measuring soil-solution nutrients within and below the main rooting zone and from a stream draining one of the sites.

Materials and Methods

Site Description

Three study sites—Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD)—were located on the Wayah Ranger District of the Nantahala National Forest in western North Carolina. All sites were at least 5.25 ha in total area and had similar vegetation (Swift et al. 1993) and soils (Knoepp and Swank 1993). Sites extended from the ridge downward on west to southwestern facing slopes. Elevations at midslope were 765 m on JE and JW and 1,040 m on DD. Soils were classified in the Cowee–Evard complex, which include fine loamy, mixed, mesic Typic Hapludults, with a sandy clay loam Bt horizon between 30 and 60 cm. Overstory vegetation was scattered pitch pine, scarlet oak (*Quercus coccinea* Muenchh.), and chestnut oak (*Quercus prinus* L.) with basal area ranging from 9 to 19 m^2 ha^{-1}. The shrub understory of mountain laurel had a basal area of 18 to 35 m^2 ha^{-1}. Vose and Swank (1993) describe in detail the stand structure and biomass before burning.

We divided each site into a 4-ha treatment area, and the remaining area served as a control. In the summer of 1989, five 0.05-ha plots (15 × 33.3 m) were established in the treatment area and four in the adjacent control area. Plots had their long axes parallel to the slope contour; their location allowed sampling across the entire site. The three sites were clearcut using chain saws in June, July, and Aug. 1990; no materials were removed. Site preparation burning was done on Sept. 18, 19, and 21, 1990 at JE, JW, and DD, respectively (Swift et al. 1993).

Sample Collection and Analyses

Soil Chemical Analyses

Surface soils were sampled on all control and treatment plots before burning and at 6 weeks, 6 months, 1, 3, and 5 years after the fell-and-burn treatment. We collected composite samples from each plot, representing the upper two horizons. These were an A horizon (average depth 4 cm) and either an AB or BA horizon, (average depth 11 cm) hereafter referred to as B horizon. Samples were collected using a 2.54-cm soil sampling probe. Twenty-four to 36 individual samples made up each plot composite. Horizon depth was measured at each sampling point. Chemical analyses were conducted on air-dried and sieved (<2 mm) soil. Soil exchangeable cation concentrations were determined in NH_4-Acetate (pH = 7.0) extract solutions (Thomas 1982) using an atomic absorption spectrophotometer. Total soil C and N were determined on a finely ground subsample by

combustion on a Perkin Elmer 2400 CHN Analyzer (Perkin-Elmer Corp., Norwalk, CT). Soil pH was determined in a 1:1 0.01 M $CaCl_2$ solution to soil slurry.

Inorganic Nitrogen Concentrations and Nitrogen Transformations

On each plot, two transects were established parallel to the 33.3-m axis before prescribed burning. Transects were at 1 and 14 m along the 15-m axis; sampling points were chosen randomly on each transect. Monthly measurements of pretreatment in situ N transformations began in Apr. 1990, 5 months before the fell-and-burn treatment. Posttreatment measurements were made monthly in 1990, bimonthly in 1991 and 1992, and seasonally in 1993, for 38 posttreatment measurements.

We used a modified in situ closed-core method (Adams and Attiwill 1986) to measure net rates of N transformations. Two 15-cm long, 4.3-cm inside diameter PVC cores were driven 10 cm into the mineral soil within 25 cm of each randomly selected sample point. One PVC core was immediately removed and returned to the laboratory for time-zero determination of soil NH_4- and NO_3-N concentrations. The second core was capped and incubated in the field for 28 days before retrieval. All collected soil cores were kept cool until returned to the laboratory and then stored in a refrigerator at 4° C until analyzed, within 24 hours. Soils were moist sieved to <6 mm. One subsample (~20 g) was dried at 105° C for >12 hours to obtain oven-dry weight. One 5-g subsample was shaken with 20 ml of 2 M KCl for 1 hour to extract NH_4- and NO_3-N. The soil/KCl mixture was centrifuged for 15 minutes at 8,000 rpm. The supernatant was analyzed for NH_4- and NO_3-N concentration on an autoanalyzer using alkaline phenol and cadmium reduction techniques, respectively (USEPA 1983). Net N mineralization was calculated as soil NH_4 + NO_3-N concentrations at 28 days minus NH_4 + NO_3-N concentrations at time zero. Net nitrification equaled soil NO_3-N concentrations at 28 days minus NO_3-N concentrations at time zero. Calculations of seasonal N transformation rates were based on plant phenology: winter, dormant season (Dec., Jan., and Feb.); spring, bud break (Mar. and April); summer, full leaf (May, June, July, Aug., and Sept.); and fall, abscission layer formation and leaf fall (Oct. and Nov.). All soil N data are reported on an oven-dry-weight basis.

Soil Solution and Stream Sample Collection

We installed two tension lysimeters approximately 50 cm apart in the center of each 15 × 33.3-m plot one year before site treatment. One lysimeter was placed at 30 cm, the bottom of the major rooting zone, the other at 60 cm, the top of the Bt horizon [Evard soil series; Macon County Soil Survey (Thomas 1996)]. Soil solution collection began 6 weeks after installation to allow lysimeters to equilibrate, although all lysimeters were evacuated weekly. Each week after solution collections, lysimeter tension was set at 0.3 mPa. Weekly solution samples were composited monthly by volume before to analysis.

The headwater of a small stream was located in the lower portion of the treated area on JE. Stream water was sampled weekly using a 250-ml grab sample, beginning one year before treatment, approximately 5 m outside the treated area. Weekly stream samples were composited monthly before analysis.

Soil-solution and stream-chemical analyses included pH, anions (SO_4 and PO_4), inorganic nitrogen (NO_3 and NH_4), and cations (Ca, K, and Mg). Nitrate, SO_4, and PO_4 concentrations were determined with micro-membrane suppressed-ion chromatography. Other methods and instrumentation are as described above for soil analyses.

Statistics

Our experiment used a randomized block design with two treatments. The treatments are burn and control ($n = 2$), and the three sites are blocks ($n = 3$). We used an analysis of covariance (SAS 1985) to determine treatment effects using site means at each sample date. The covariate used was the pretreatment value of each variable. When the covariate was not significant, ANOVA was used to determine significant differences between treatment and control sites. We chose a significance level of ≤ 0.10 to determine both treatment effects and covariate significance. All analyses were conducted by sample date. The six posttreatment sample dates for soil chemical analyses (exchangeable cations, and total C and N) were analyzed using the pretreatment sample date (Apr. 1990) as the covariate. We analyzed rates of N mineralization and nitrification, initial NO_3 and NH_4 concentrations, and soil solution data, using seasonal means from each site. Spring and summer pretreatment data were covariates for N mineralization and nitrification rates and NO_3 and NH_4 analyses (spring and summer only). For soil-solution analyses, all seasons were used. One stream was available for sampling. Therefore, no statistical interpretation was possible.

Burn Prescription, Fire Characterization, and Fuel Consumption

All sites were burned using standard procedures by the Wayah Ranger District of the Nantahala National Forest of North Carolina Fire Team. Burning was conducted approximately 3 days after a soaking rain, in the afternoon following fog dissipation. Air temperature ranged from 22 to 25° C with relative humidity between 50 and 74% immediately before burning on the three sites (Swift et al. 1993). A fire line was burned across the ridgeline and down the flank of each burned site using a backing fire. The fire was ignited at the bottom of the slope using a drip torch, and a head fire proceeded upslope. Duff (Oe plus Oa layer) moisture content ranged from 59 to 99%.

We selected our sites based on similarities in vegetation and soils, and burned them over a 4-day period, yet observed a wide range in fire severity (Swift et al. 1993). Fire severity often determines soil responses to burning, with greater fire severity resulting in a greater response (Wells et al. 1979, VanLear and Danielovich 1988). Flame temperature was measured using a thermologger with attached thermocouples placed in the slash, 5 cm above the forest

Table 1. Fire characterization at three study sites: Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD). Shown are peak flame temperatures measured in the slash layer (5 cm), heat penetration into the forest floor/soil, total fuel consumption, total N loss, forest-floor consumption, and forest-floor N loss.

	JE	JW	DD
Peak flame temperature (°C)	812	694	630
60° C Heat penetration (mm)	45	37	44
Total fuel consumption (Mg ha^{-1})	129.7	86.3	62.2
Total N loss (kg ha^{-1})	480	376	193
Forest floor consumption (Mg ha^{-1})	15.6	12.6	6.6
Forest floor N loss (kg ha^{-1})	123.0	133.8	1.3

Data previously reported in Swift et al. (1993) and Vose and Swank (1993).

floor. Heat penetration into the duff (Oa plus Oe) and soil were measured using heat-sensitive paint on clay tiles. Peak flame temperatures in the slash ranged from 630 to 812° C and heat penetration (60° C) ranged from 37 to 45 mm into the forest floor (Table 1) (Ottmar and Vihnanek 1991).

Fuel loads were measured on four randomly selected 1-m plots on each of the five burn plots before and after site burning. Fuel components included foliage, smallwood, large wood, and forest floor separated into Oi and Oe plus Oa layers. Total fuel consumption was greatest on JE and least on DD (Vose and Swank 1993); total N loss on JE was 480 kg N ha^{-1}. Approximately half of the total aboveground N on the site was in the forest floor, consumption of the forest floor accounted for 6 to 36% of the total N loss (Vose and Swank 1993).

Results and Discussion

Exchangeable Soil Cation Responses

In the A horizon (average depth 4 cm), soil-exchangeable Ca, K, and Mg concentrations increased after treatment (Figure 1). Calcium concentrations were significantly

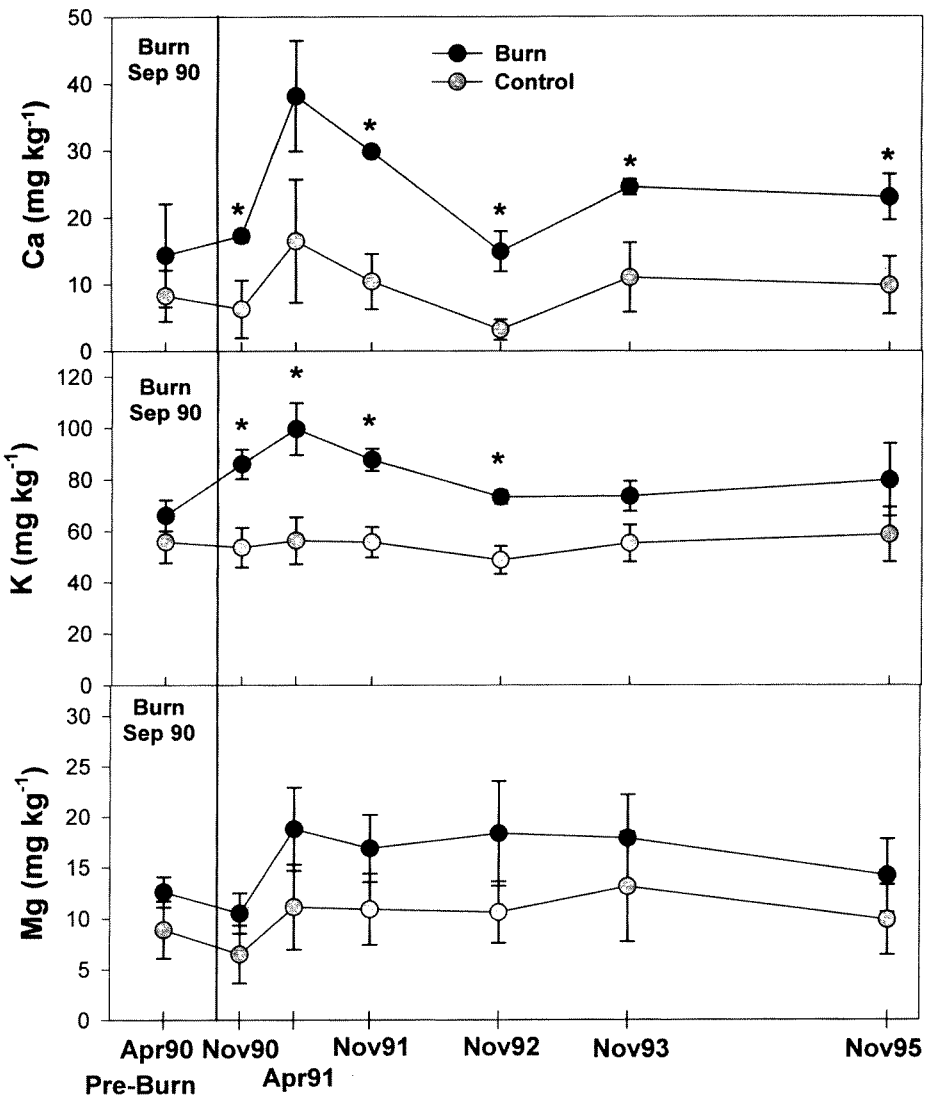

Figure 1. A-horizon soil exchangeable cation concentrations (mg kg^{-1}). Calcium, potassium, and magnesium, before and at six dates after fell-and-burn treatment. Plotted values are site means (n = 3). Error bars are standard error of the mean. (*) Indicates significant probability of a difference between control-and-burn sites ($P \leq 0.10$).

greater in soils on treated compared to control sites in four of six posttreatment sample dates. Potassium increases were significant for three consecutive sample dates, representing 1 year after burning. Magnesium concentrations were significantly greater on treated sites at only one posttreatment sample date. B horizons (average depth 11 cm) also showed significant increases in exchangeable Ca and K posttreatment (Figure 2). Throughout the 5-year posttreatment period, Ca concentrations were significantly greater in burn soils than in the control in five out of six posttreatment sample dates. The response of soil K was brief, lasting just two years. Magnesium concentrations in B-horizon soil did not respond to the fell-and-burn treatment (Figure 2). Soil pH averaged 4.0 and 4.2 in the A and B horizons, respectively, across all sites (data not shown). A-horizon soil pH was significantly greater on the burn sites compared to the reference on three of the seven posttreatment dates. Soil pH in the B horizon did not respond to treatment.

Increases in soil extractable cations after burning have been observed in other studies. For example, Groeschl et al. (1993) found increases in cation concentrations 1 year after wildfire in table mountain pine (*Pinus pungens* Lamb.) stands in Virginia. Binkley et al. (1992) measured increased Ca concentrations after burning for 30 years in southern pine forests on an annual and biennial interval; other cations did not respond. Lynham et al. (1998) found that, after understory burns in boreal jack pine (*Pinus banksiana* Lamb.), K, Ca, and Mg all increased in the mineral soil; only K concentrations were greater than preburn levels 10 years later. Our responses differed. Calcium increases were long-lived, lasting for the 5-year duration of this study in the B horizon but not the A, K increased for only 2 years, whereas Mg did not respond. Differences in study results could be the result fire intensity, understory burning versus fell-and-burn, and soil properties. Spodosols and Ultisols, in boreal and temperate locations, respectively,

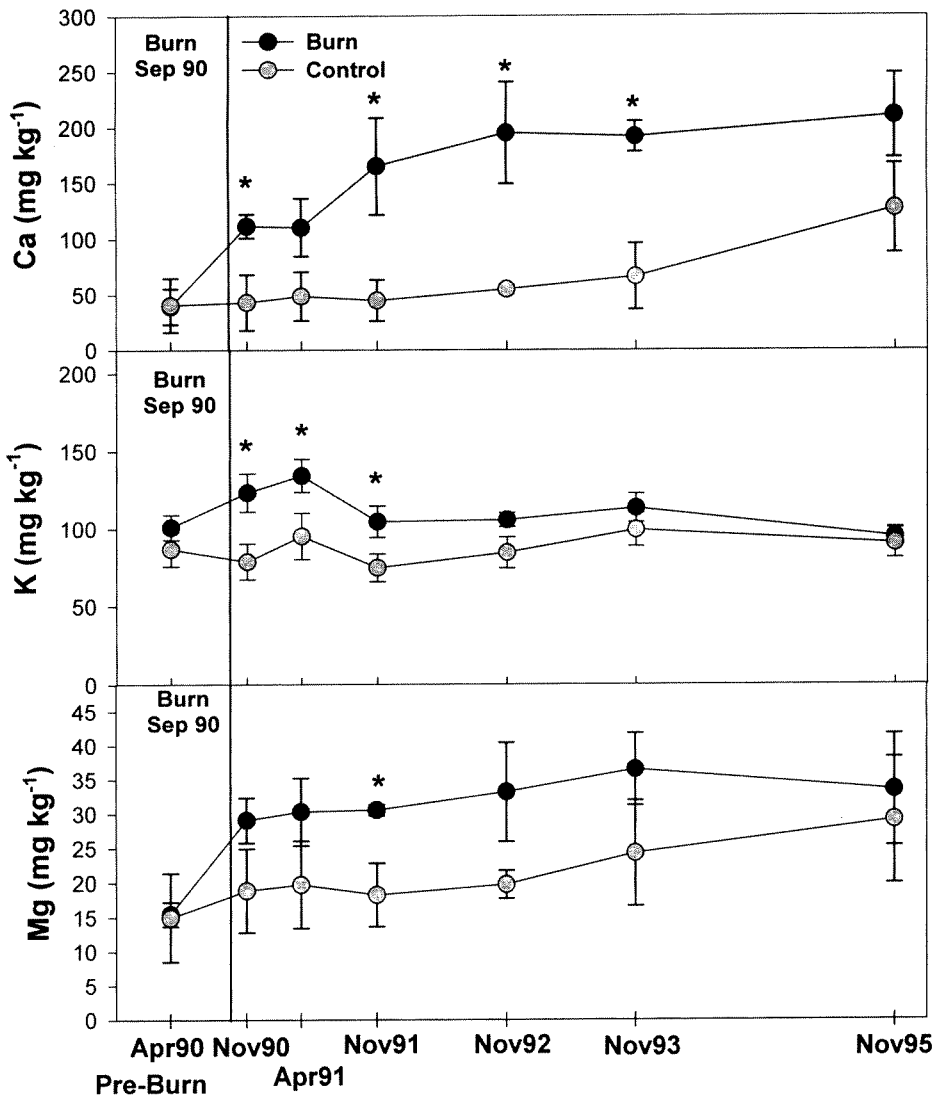

Figure 2. B-horizon soil exchangeable cation concentrations (mg kg^{-1}). Calcium, potassium, and magnesium, before and at six dates after fell-and-burn treatment. Plotted values are site means (n = 3). Error bars are standard error of the mean. (*) Indicates significant probability of a difference between control and burn sites ($P \leq 0.10$).

differ dramatically in organic matter content, texture, and chemical properties.

Other researchers have found soil responses to burning only in the upper surface soils. Grove et al. (1986) reported increases in Ca, Mg, and K immediately after fire, in the 0–3 cm depth of a eucalypt forest. At lower depths (3–10 and 10–20 cm) K was the only cation that increased. One year after burning, surface-soil cation increases were no longer significant. However, K concentrations in deeper soil remained greater than preburn concentrations. They ascribed responses in deeper soil to the leaching of cations from surface soils and ash deposits. In our study, increased cation availability in deeper soils and the long-lived response may be attributable to climatic conditions and soils. Our sites have high annual rainfall, which may increase cation movement deeper in the soil, and a higher clay content may increase cation retention capacity.

Total Soil C and N Responses

Our data showed no effect of the fell-and-burn treatment in A-horizon soils on either total C or N (Figure 3), although at one sample date, total N in burn-and-control sites differed significantly. A-horizon soil C ranged from 3.7 to 5.6% and varied considerably among sample dates, total N (A horizon) ranged from 0.10 to 0.18%. Total C also varied in the B horizon, ranging from 1.7 to 2.5%, total N ranged from 0.05 to 0.10% (data not shown). The C:N ratio at most sample dates was >30 in both A- and B-horizon soils and both treatments.

Unlike our study, other researchers have found significant effects of burning on total soil C and N at comparable soil depths. Groeschl et al. (1993) studied the effects of a wildfire on surface-soil (0–10 cm) total C and N in Shenandoah National Park. They found a relationship between fire intensity and soil response in areas with high fire severity, total C and N significantly decreased, whereas sites with low fire severity were largely unaffected. Other studies have shown increases in soil C and N after severe fires or after long-term frequent fires. For example, Wells et al. (1979) found increases in soil C after 20 years of periodic understory burning in a South Carolina pine plantation. Surface-soil (0–5 cm) total organic-matter content increased; but there was no effect on the 5–10-cm soil layer. Lynham et al. (1998) found that total soil N, in both 0–5- and 5–10-cm depths, was still increasing 10 years after burning in a boreal jack pine forest. Our site was burned once at low severity and retained most of the forest floor on all sites; it could be that a more severe fire or repeated burning would yield different results because of changes in vegetation and decomposition patterns. In addition, our study sites had A-horizon depths ranging from 2 to 10 cm in depth within a

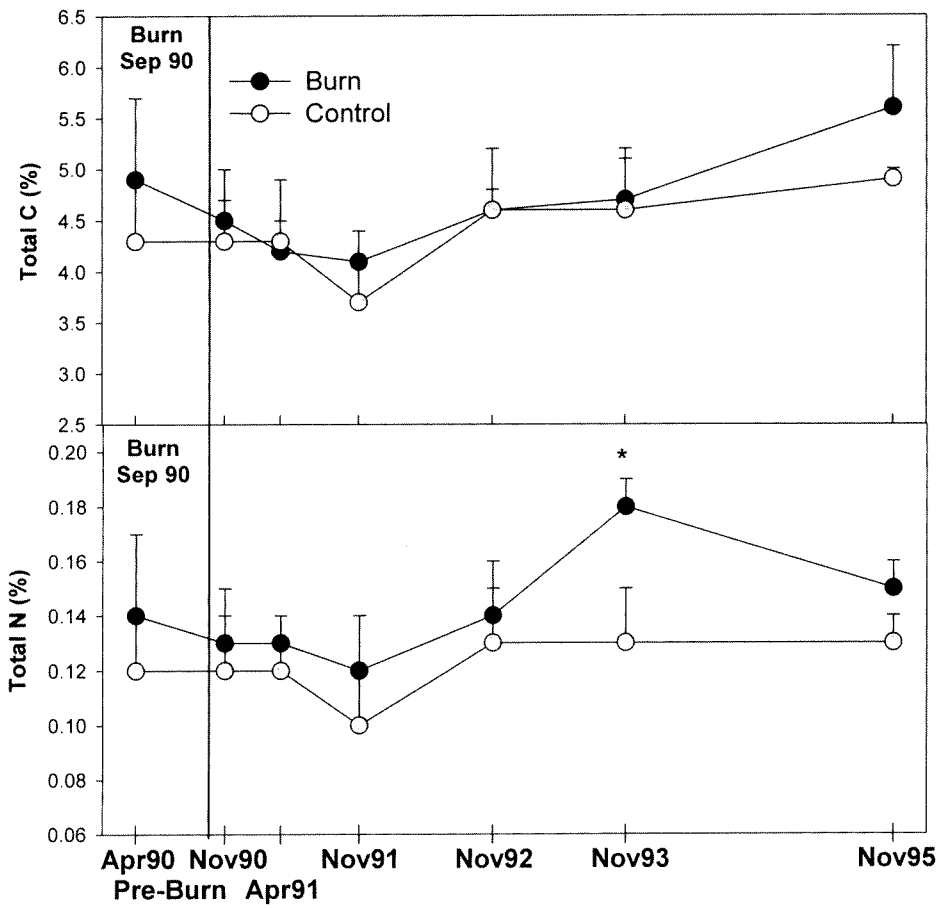

Figure 3. Total carbon and nitrogen in A-horizon soils in fell-and-burn and control plots. Plotted values are site means ($n = 3$). Error bars are standard error of the mean. (*) Indicates significant probability of a difference between control and burn sites ($P \leq 0.10$).

single plot. This high variability in soil organic materials could make detection of soil C and N burn responses extremely difficult without an intensive sampling scheme.

Inorganic Soil N and N Transformations

Soil NH_4-N concentrations increased significantly after the fell-and-burn treatment (Figure 4). Extractable soil NH_4 was greater on prescribed burn sites than on controls for 10 of the 13 seasonal means over 2.5 years of measurements. Summer NH_4-N concentrations were significantly greater in all 3 years after treatment. Nitrogen mineralization-rate responses to treatment were variable (Figure 4). A significant increase in N mineralization occurred after the felling of vegetation in summer 1990. After the prescribed burning treatment, there were significant differences in N mineralization between burn and control sites in 5 of the 13 seasonal means, all occurred in spring or summer. These data suggest that N availability increased after burning. Because of high variability soil NO_3 concentrations and nitrification rates showed few significant responses to treatment (data not shown).

Changes in inorganic N concentrations measured after burning vary greatly among studies largely because of differences in fire severity. Burning results in the rapid oxidation of organic material on the forest floor and in soil organic matter. Some of the volatilized N moves into the mineral soil where it condenses as exchangeable NH_4 because of steep temperature gradients in the soil during burning (DeBano 1990a). In our study, pretreatment soil NH_4 concentrations averaged 0.55 mg kg^{-1}. After treatment, concentrations averaged 4.5 mg kg^{-1} for the next three seasons (Figure 4). Initial increases ranged from 1.7 to 9.5 mg kg^{-1} on the three sites studied (Knoepp and Swank 1993). Similar to the response in our sites, Covington and Sackett (1992) found that NH_4 increases in a ponderosa pine

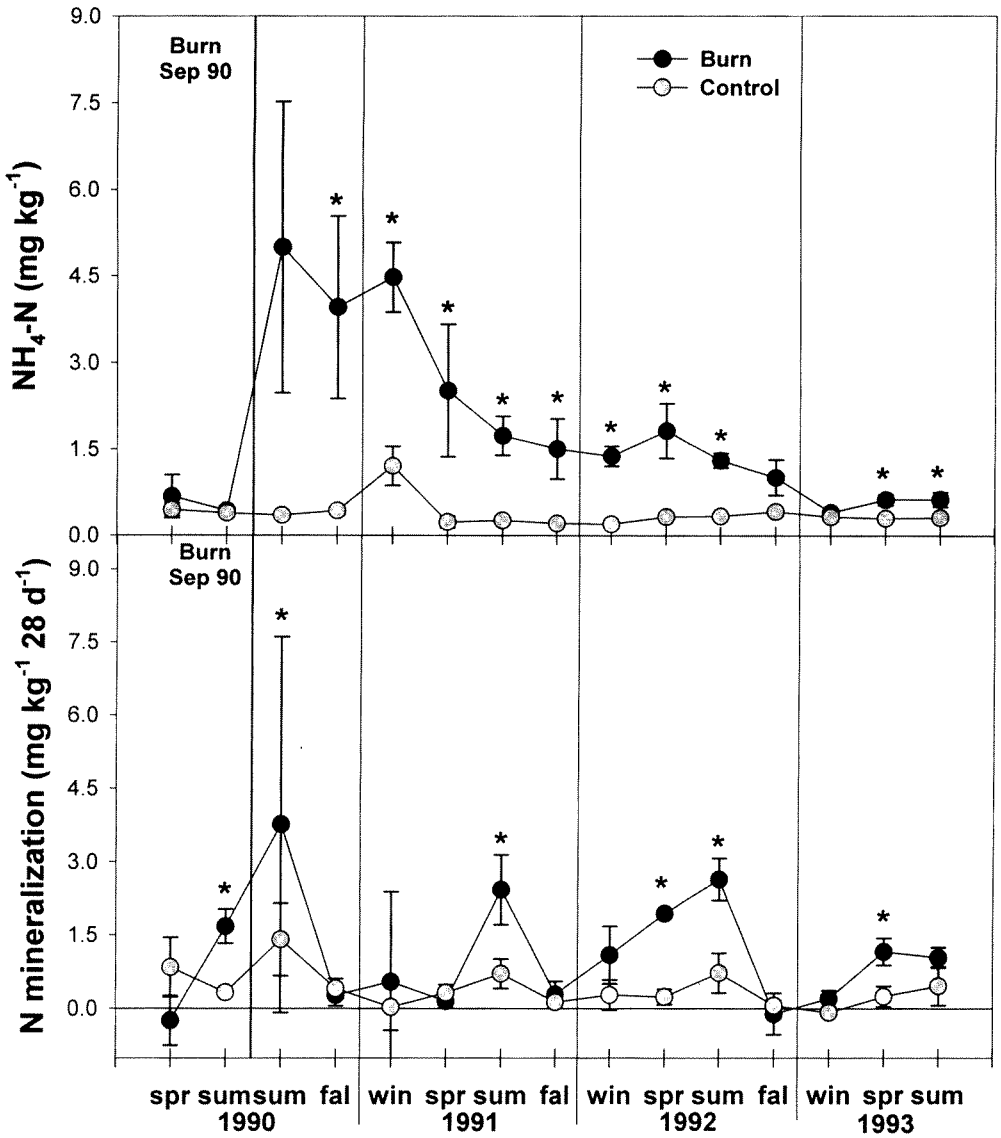

Figure 4. Surface soil (0–10 cm) KCl, extractable NH_4-N (mg kg^{-1}), and 28-day N mineralization rates (mg kg^{-1} 28 d^{-1}) before and 3 years after fell-and-burn treatment. Plotted values are seasonal site mean values (n = 3). Error bars are standard error of the mean. (*) Indicates significant probability of a difference between control and burn sites ($P \leq 0.10$).

stand were related to forest floor mass loss. Soil NH_4 responses vary in endurance, Covington and Sackett (1986) found that NH_4 concentrations remained elevated for 3 to 4 years, similar to our study. By contrast, DeLuca and Zouhar (2000) reported increased inorganic N for only 1 year after a cut-and-burn treatment in a Montana ponderosa pine stand, suggesting that this must have been a low-intensity fire.

Soil Solution Response

Soil solution chemistry responses from the 30-cm lysimeters were highly variable (Figure 5). There was a trend toward an increase in Ca and NO_3 after the fell-and-burn treatment. One date showed a significant difference in NO_3 only. Solution K had a significant response from the summer of 1991 (1 year after treatment) through the summer of 1992. The 60-cm lysimeter solutions (Ca, K, and NO_3) also tended to be greater after treatment (Figure 6). We observed increased concentrations in half of the posttreatment sampling seasons for all three of these nutrients. Before treatment, K and NO_3 concentrations were often greater on burn sites than on controls, demonstrating the importance of the covariate (pretreatment values) analysis.

Changes in cation availability and mobility after burning could explain the differences in exchangeable soil-nutrient concentration and soil-solution responses in our study. Extractable soil K gave a quick, short-lived response with the increase in soil solution K of the same duration. In contrast, Ca yielded a long-lived soil response, especially in the B horizon, but increased only sporadically in the soil solution. Nutrient increases in soil and soil solution after fire result from ash additions, forest floor leachates, and soil organic matter oxidation. Although the direct heating effect probably is limited to within a few cm of the surface, effects at greater depths are probably the result of the leaching of

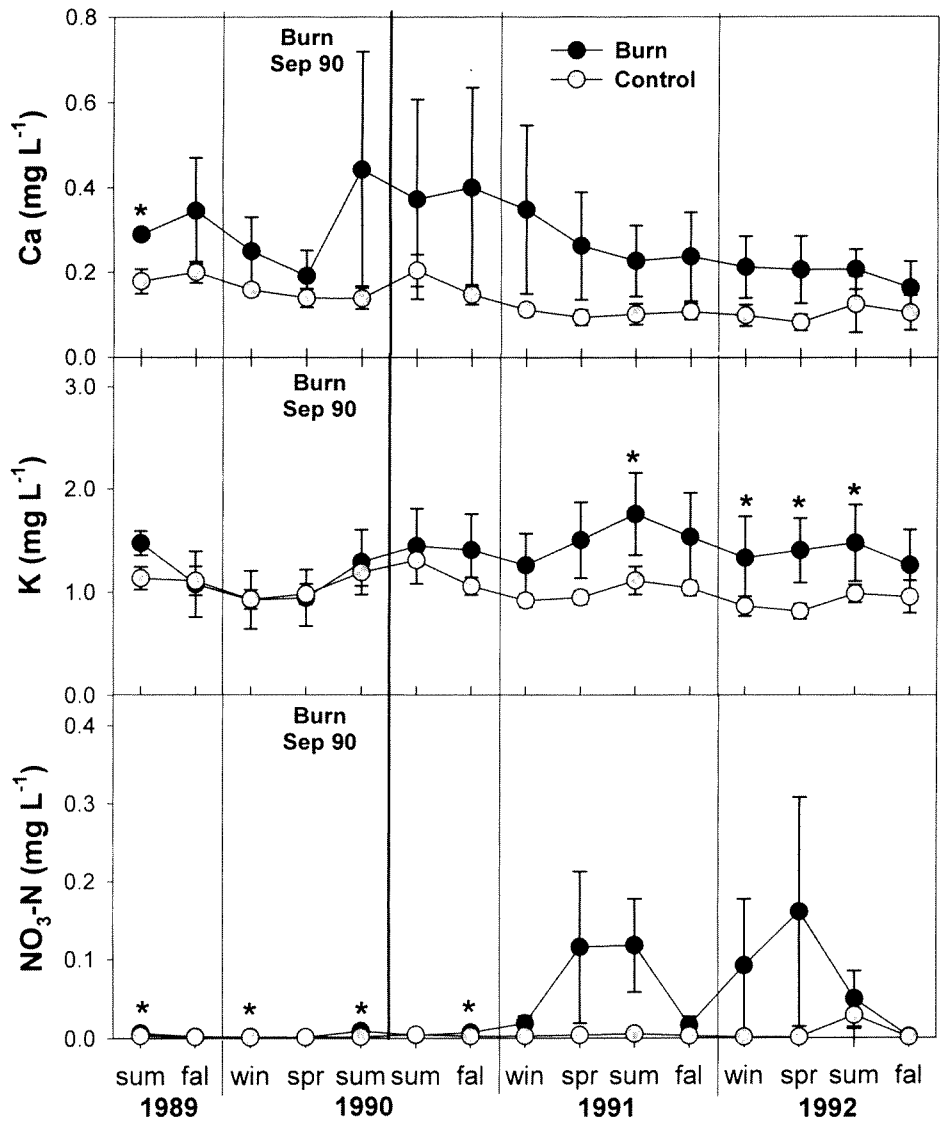

Figure 5. Thirty-cm lysimeter-collected soil-solution cation concentrations (mg L^{-1}) of calcium, potassium, and nitrate nitrogen. Plotted values are seasonal site mean values ($n = 3$). Error bars are standard error of the mean. (*) Indicates significant probability of a difference between control and burn sites ($P \leq 0.10$).

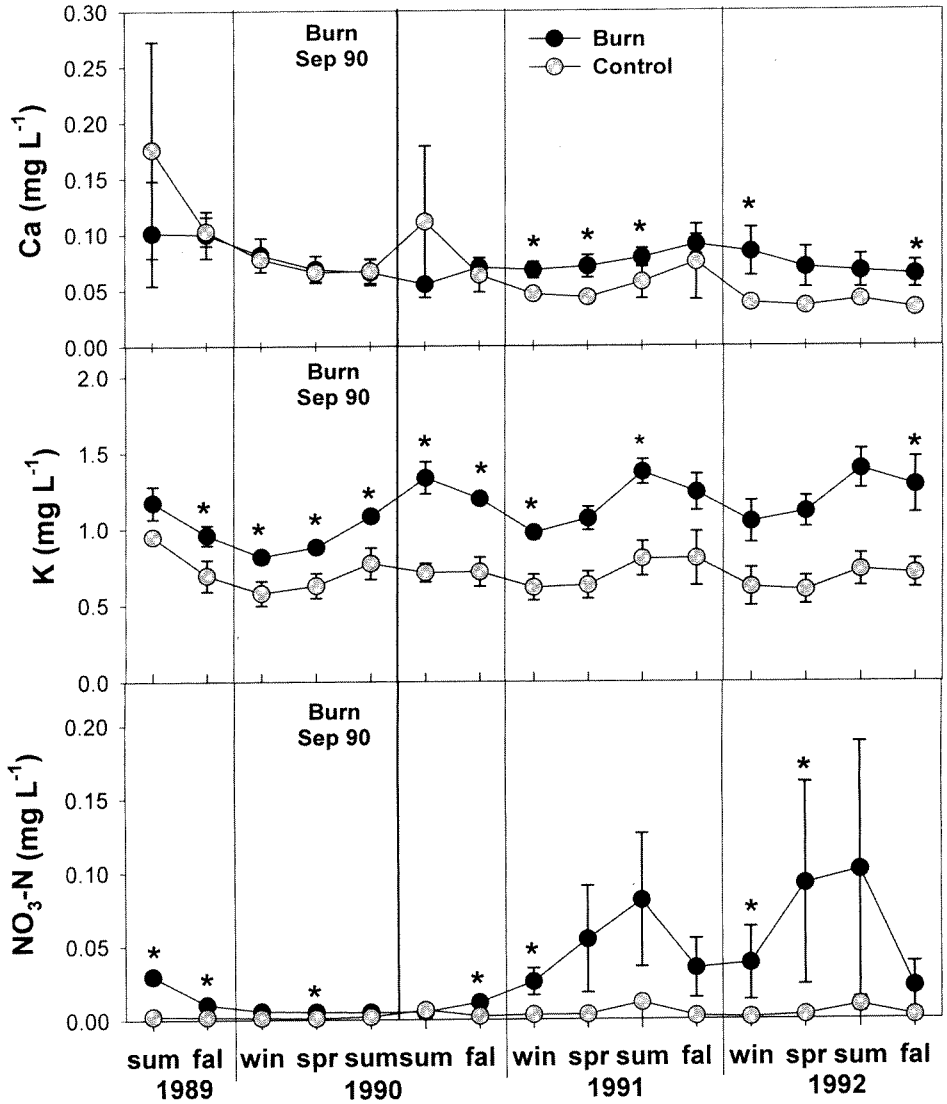

Figure 6. Sixty-cm lysimeter-collected soil-solution cation concentrations (mg L^{-1}) of calcium, potassium, and nitrate nitrogen. Plotted values are seasonal site mean values (n = 3). Error bars are standard error of the mean. (*) Indicates significant probability of a difference between control and burn sites ($P \leq 0.10$).

nutrients out of the forest floor and surface soil layers and decreased plant uptake. In a laboratory study, Soto and Diaz-Fierros (1993) measured changes in cation leaching patterns after burning at different temperatures for six soils representing six different parent materials. They found similar patterns to our results for all soil types. Movement of both divalent and monovalent cations was dependent on temperature. However, 89 to 98% of the nutrients leached from the forest floor and ash were adsorbed in the mineral soil. Lewis (1974) measured cation leaching from the forest floor in an understory burn of a Southern pine forest. Leaching increased two times that of unburned litter for monovalent cations Na and K, whereas divalent cations Mg and Ca increased 10–20 times. This differs from the soil cation responses reported by Raison et al. (1990), in which the mobility of K and Mg was greater than Ca after burning.

Stream Response

Our sample collections included a stream draining one of the sites, JE, the site with the greatest fire severity (Table 1). We examined stream-nutrient concentration during the same period as the soil solution collections, one year pretreatment, and 2 years posttreatment. Nitrate responded to treatment (Figure 7), immediately increasing to 0.08 mg L^{-1} in May 1991, and decreasing in June as microbial activity, plant growth, and nitrogen uptake began. During the dormant season (Nov.—Dec.), NO_3 concentrations increased in a pattern similar to the first year after treatment, reaching 0.04 mg L^{-1}. This pattern suggests a treatment response. However, these stream N concentrations are still low and indicate no biologically significant N losses or impairment of water quality. Stream Ca and K concentrations did not respond to fell-and-burn treatment. Both cations showed increases in the soil and in soil solutions, yet

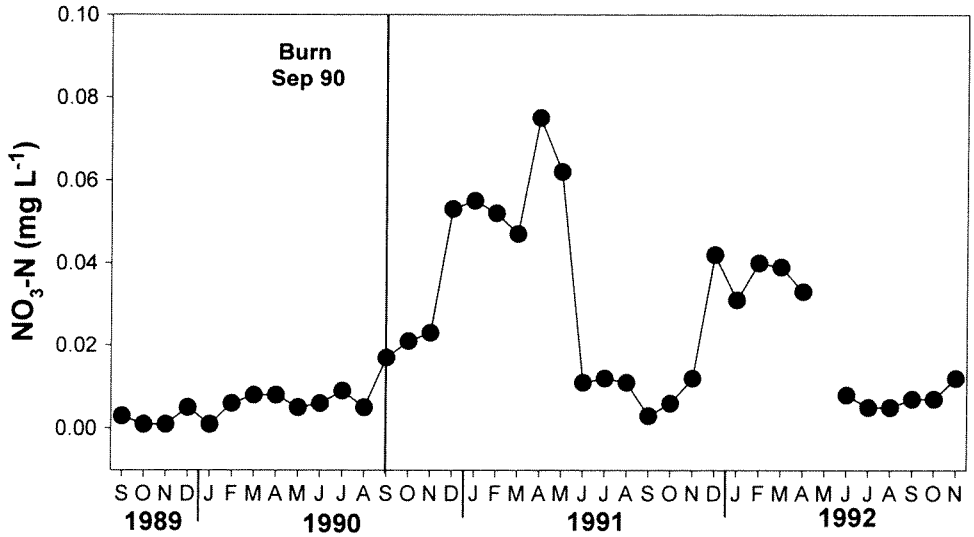

Figure 7. Nitrate concentration (mg L^{-1}) of stream draining one site (Jacob Branch East) before and after fell-and-burn treatment. Plotted values represent monthly concentrations as determined with a composited monthly sample.

did not increase in stream water. Many studies show an increase in cations along with NO_3 after disturbance or forest management. For example, in a clearcut watershed on similar soils, Ca and K concentrations increased in the stream water along with NO_3-N (Swank et al. 2001). Stream NO_3 increases after the fell-and-burn treatment were about half the concentration of the 59-ha clearcut, and apparently were not high enough to mobilize Ca and K.

Stream responses to burning vary among studies. Douglass and Van Lear (1983) studied stream responses to prescribed burning in the Piedmont of South Carolina. The study examined four paired watersheds and found no measurable response in stream NO_3 or any other nutrient. Clinton et al. (2003) compared stream NO_3 responses among fell-and-burn, stand-replacement burns, and a wildfire in an old-growth forest. They found a range of responses, from no change in stream NO_3 in the stand-replacement burn to a six-fold NO_3 increase in the old-growth wildfire, although concentrations remained low ($\leq$0.10 mg L^{-1}). Response differences were attributed to vegetation type (mixed oak–pine, mixed oak, and old-growth), effects on forest floor type, drainage size, type of the riparian zone, and type and season of burning.

Summary

We examined changes in soil nutrient availability and the potential for nutrient losses in a fell-and-burn treatment used to restore degraded mixed oak–pine ecosystems in the southern Appalachians. We found increased concentrations of N and base cations in both soils and soil solutions, with soil Ca increases extending for the duration of our study (5 years). The fell-and-burn treatment had no effect on total soil C and N concentrations. Measurements of stream nutrient content showed that losses via leaching were negligible and would not limit future site productivity or diminish water quality. The increase in soil nutrient availability may improve the productivity of these sites, suggesting that prescribed burning could be a useful tool for restoration of degraded mixed oak–pine ecosystems.

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