ECOSYSTEM RESTORATION TREATMENTS AFFECT SOIL PHYSICAL AND CHEMICAL PROPERTIES IN APPALACHIAN MIXED OAK FORESTS

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Abstract—This study presents an analysis of the effect of ecosystem restoration treatments on soil properties in the oak forests of southern Ohio. The treatments were (1) prescribed fire, (2) mechanical thinning, (3) fire and thinning, and (4) passive management (control). Fire and thinning resulted in increased mineral soil exposure, with the effect decreasing by the fourth post-treatment year. No significant effect on soil compaction was observed. Soil pH increased after fire and thinning+fire, but not thinning alone, and this effect persisted. P availability was lower in burned areas, whereas available Ca, K, and Al were not significantly affected. Ca:Al ratios were higher in burned areas the first year after treatment; this effect was greatly reduced by the fourth post-treatment year. These results suggest that prescribed fire and restoration thinning can be applied to this forest type without significant negative effects on the soil resource.

INTRODUCTION

The mixed oak forests of the Midwestern U.S. are far different from those encountered by early settlers and land surveyors. In addition to periodic harvesting, most of the oak forest region has been subjected to effective fire suppression for most of a century and to chronic deposition of the by-products of fossil fuel consumption for even longer. The result of these factors has been the development of forests that have greater stem density (especially in the understory and midstory), greater basal area, and greater fuel accumulations than those present prior to Euro-American settlement.

The Fire and Fire Surrogate Network Project was initiated in the late 1990's in an effort to evaluate the efficacy of four approaches for simultaneously reducing wildfire hazard and facilitating ecosystem restoration (Weatherspoon 2000). The four approaches are (1) passive management, (2) restoration of ecosystem function through the reintroduction of low intensity, dormant season fire at historic intervals, (3) restoration of community structure through mechanical treatment, involving thinning from below to approximately historic basal area, stem density, and tree species composition, and (4) the combination of those functional and structural approaches (Weatherspoon 2000).

Within this context, the specific objectives of this study were to assess the effect of these four ecosystem restoration approaches on soil nutrient status and physical properties in Ohio oak forests, and to evaluate the impact that any effects might have on decisions to implement one or more of these management approaches more broadly.

SITES

The three experimental blocks comprising the Ohio Hills Site of the National Fire and Fire Surrogate Network are located on the unglaciated Allegheny Plateau of southern Ohio. The climate of the region is cool, temperate with mean annual precipitation of 1024 mm and mean annual temperature of 11.3 °C (Sutherland and others 2003). The forests of the region developed between 1850 and 1900, after the cessation of cutting for the charcoal and iron industries (Sutherland and others 2003). The current canopy composition differs little from that recorded in the original land surveys of the early 1800's. The most abundant species in the current canopy are white oak (*Quercus alba* L.), chestnut oak (*Q. prinus* L.), hickories (*Carya* spp. Nutt.), and black oak (*Q. velutina* Lam.)(Yaussy and others 2003).

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Each of the three replicate blocks is composed of four treatment units of 19-26 ha, each of which is surrounded by a buffer of approximately 10 ha. Both the core treatment unit and its corresponding buffer receive the experimental treatment. These treatment units were designed to include all combinations of elevation, aspect, and soil, and approximated the local watershed scale in area. The replication within the Raccoon Ecological Management Area (39°11′ N, 82°22′ W) and the replication within Zaleski State Forest (39°21′ N, 82°22′ W) are both located in Vinton County, OH. They are underlain by sandstones, siltstones, and shales of Pennsylvanian age (Boerner and Sutherland 2003). The soils were formed in place from residuum and colluvium, and are dominated by Steinsburg and Gilpin series silt loams (typic hapludalfs) (Boerner and Sutherland 2003). The replication within Tar Hollow State Forest (39°20′ N, 82°46′ W) is located in Ross County, OH. Tar Hollow is underlain primarily by sandstone of Pennsylvanian age, and the soils are dominated by Muskingum series sandy loams (typic dystrochrepts). Some of the Tar Hollow ridgetops are capped by loess deposits in which Wellston series silt loams (alfic hapludults) have developed.

PROCEDURES

Experimental Design

Treatments were randomly allocated among treatment units within a replicate, and all treatments units were sampled through the pre-treatment year 2000. Treatments consisted of prescribed fire, mechanical treatment involving thinning from below to a basal area comparable to that present prior to Euro-American settlement, the combination of prescribed fire and mechanical treatment, and an untreated control.

The prescribed fires were applied during March and April of 2001. These dormant season fires were designed to be similar to the predominant mode of natural fires in the region. Flame lengths varied from <20 cm to approximately 2 m. Maximum temperatures recorded by thermocouples at 25 cm above the forest floor averaged 152 °C, and the single maximum temperatures recorded in individual treatment units averaged 318 °C (Iverson, and others 2003, 2004). These fires consumed unconsolidated leaf litter and fine woody fuels while leaving the majority of the coarse woody fuels charred.

Mechanical treatment was accomplished between September 2000 and April 2001, and focused on understory and midstory stems. The goal was a residual basal area of approximately 14 m^2/ha, but this goal was not achieved at any of the study sites. Thinning left an average of 21 m^2/ha in residual basal area. Units that were subjected to both mechanical treatment and burning were thinned at least two months prior to burning.

Field and Laboratory Methods

Within each treatment unit ten sample plots of 0.10 ha were established such that the suite of ten plots spanned the full range of landscape positions. Samples of approximately 400 g fresh mass of the top 15 cm of the A + Oa horizon were taken from opposite corners of each plot in May or early June 2000 (the pretreatment year), 2001 (initial post-treatment year), and 2004 (fourth year post-treatment). This yielded N = 20 per treatment unit and N = 60 for each treatment on each date.

The forest floor was examined for exposure of bare mineral soil and soil strength was determined by penetrometer on each sample date at 20 randomly selected points along one long axis of each sample plot. This yielded N = 200 per treatment unit per date and N = 600 per treatment per date. Soil was judged to be compacted if the soil strength was more than two standard deviations above the mean of the 800 pretreatment samples for that block. Both soil compaction and exposure of bare mineral soil were expressed on a proportional basis.

Each soil sample was air-dried and sieved to remove material >2 mm. Root and particulate organic matter fragments were then removed by hand. Soil pH was determined in a 1/5 soil slurry of 0.01 mol/L $CaCl_2$ (Hendershot and others 1993), available P by the ascorbic acid method (Watanabe and Olsen

1965), available Al^{3+} in 0.5 mol/L K_2SO_4 extracts by the ferron method (Bersillon and others 1980), and exchangeable Ca^{2+} and K^+ in 1 mol/L NaOAc extracts using Orion® ion specific electrodes. Ca:Al ratio was calculated on a molar basis.

Data Analysis

The experiment was a randomized complete block design with study sites as replicate blocks within which the four treatments were allocated randomly to treatment units. As there were time lags between mechanical treatment of units that received only mechanical treatment and those receiving mechanical treatment followed by prescribed fire, and as the prescribed fires appeared to vary in intensity, we considered the four treatments to be independent rather than a 2 x 2 factorial design.

All response variables were tested for normality prior to analysis of variance, and log transformed where necessary to achieve normality. We evaluated treatment responses using one-way analysis of covariance for the randomized complete block design with pre-treatment year conditions as the covariate. Means separation was achieved using least squares estimation with the Bonferroni adjustment for multiple comparisons. The exception to this analysis strategy was the molar Ca:Al ratio, whose exponential distribution defied attempts at normalization. Ca:Al ratio was analyzed by non-parametric analysis of variance using the Savage method, which is designed specifically for exponential distributions. All statistical analyses employed SAS release 8e (Statistical Analysis System 2004).

RESULTS

Soil Physical Properties

During the first growing season after treatment, the proportion of the mineral soil surface exposed ranged from approximately two percent in the control units to approximately 26 percent in the burn-only units (fig. 1, table 1). Mineral soil exposure was significantly greater in units that were burned (with or without mechanical treatment) than in units that were either thinned or untreated. By the fourth growing season after treatment, the magnitude of differences among treatments had decreased, though all three manipulative treatments still had greater mineral soil exposure than was present in the control. The proportion of the soil that was compacted averaged less than seven percent of the treatment units in both the first and fourth growing seasons after treatment (fig. 1, table 1), and there were no significant differences among restoration treatments. The coefficients of variation in soil exposure and compaction averaged 120 percent, but did not vary significantly among treatments or years.

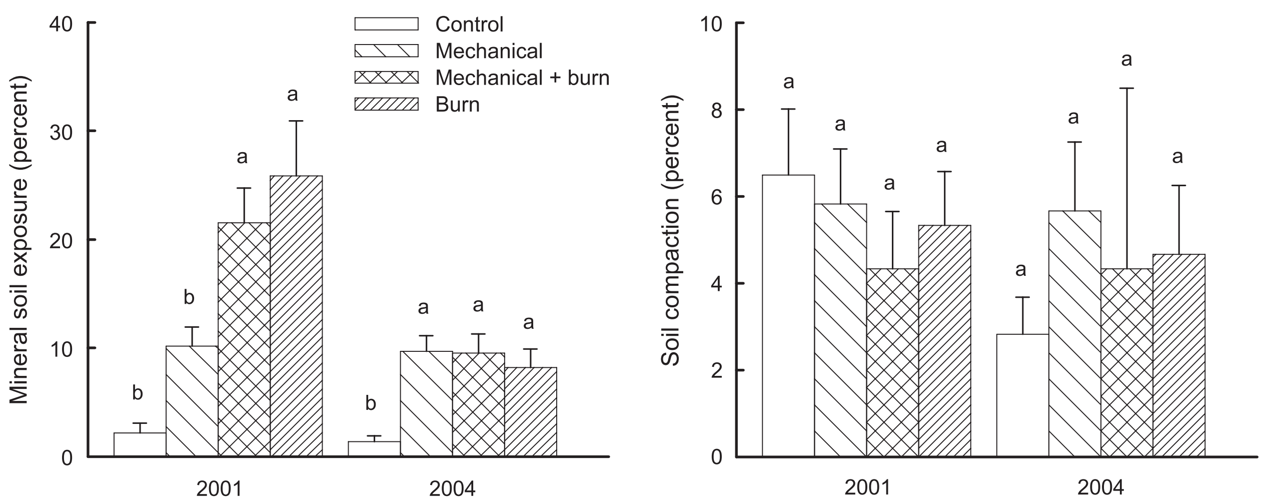

Figure 1—Effects of four ecosystem restoration treatments on the proportion of forest area with mineral soil exposed and the proportion of soil samples exhibiting significant compaction during the first growing season (2001) and the fourth growing season after treatment (2004). Means and standard errors of the means are indicated. Means labeled with the same lowercase letter were not significantly different at p<0.05 following analysis of covariance, with the pretreatment year (2000) as the covariate.

Table 1—Analysis of covariance for the randomized complete block design for the effects of four treatments on soil physical and chemical properties. Pretreatment (2000) conditions were used as the covariates. Shown are the F-statistic and corresponding p for the test of the treatment variance against the treatment-by-block interaction variance

Response parameter	Year	Treatment	Effect
Mineral soil exposure	2001	F = 4.87	p < 0.050
(proportion of area)	2004	F = 5.97	p < 0.032
Soil compaction	2001	F = 0.20	p < 0.895
(proportion of area)	2004	F = 2.49	p < 0.158
Soil pH	2001	F = 2.80	p < 0.013
	2004	F = 1.01	p < 0.045
Available P	2001	F = 0.26	p < 0.851
(μg/kg soil)	2004	F = 5.12	p < 0.044
Available Ca	2001	F = 1.26	p < 0.369
(mg/kg soil)	2004	F = 1.39	p < 0.334
Available Al	2001	F = 6.53	p < 0.026
(mg/kg soil)	2004	F = 0.93	p < 0.482
Available K	2001	F = 2.35	p < 0.172
(mg/kg soil)	2004	F = 0.99	p < 0.357

Soil Chemical Properties

During both years soil pH was significantly greater in the treatment units that were burned than in those thinned or untreated (fig. 2, table 1). The soil pH of the units that received both mechanical treatment and burning did not differ from those given any of the other treatments. During the first post-treatment growing season available P was not affected significantly by any of the treatments, and during the fourth growing season none of the manipulative treatments differed significantly from the control in available P (fig. 2, table 1). However, relative to the thinned units fourth growing season P was 46 percent lower in plots that were burned and 54 percent lower in plots that were burned and thinned.

Although Ca availability varied by as much as 50 percent among treatments, there were no significant effects on Ca availability in either the first or fourth post-treatment growing season (fig. 3, table 1). In contrast, there was a strong and significant effect of the treatments on available Al, with all three manipulative treatments producing significantly lower Al availability than was present in the untreated controls (fig. 3, table 1). The patterns of Ca and Al availability among the four treatments were mirror images (fig. 3).

The molar Ca:Al ratio averaged 0.47 ($\pm$0.04) among the treatment unit groups during the pretreatment year (2000). During the first growing season after fire, the molar Ca:Al ratio was significantly greater than it was during the pretreatment year in the soils of treatments except the control. During the first post-treatment growing season there were significant differences among treatment units (χ^2=41.09, p<0.001) such that treatment units that were burned (either with or without mechanical treatment) had significantly greater Ca:Al ratio than did the thinned units, which in turn had significantly greater Ca:Al ratio than the untreated controls (fig. 4). There were also significant differences in Ca:Al ratio among treatments during the fourth growing season after treatment (χ^2=11.77, p<0.009). During 2004 the Ca:Al ratio of the thin+burn units was still significantly greater than that of the control, but the thinned units and burned units were no longer significantly different from the control (fig. 4).

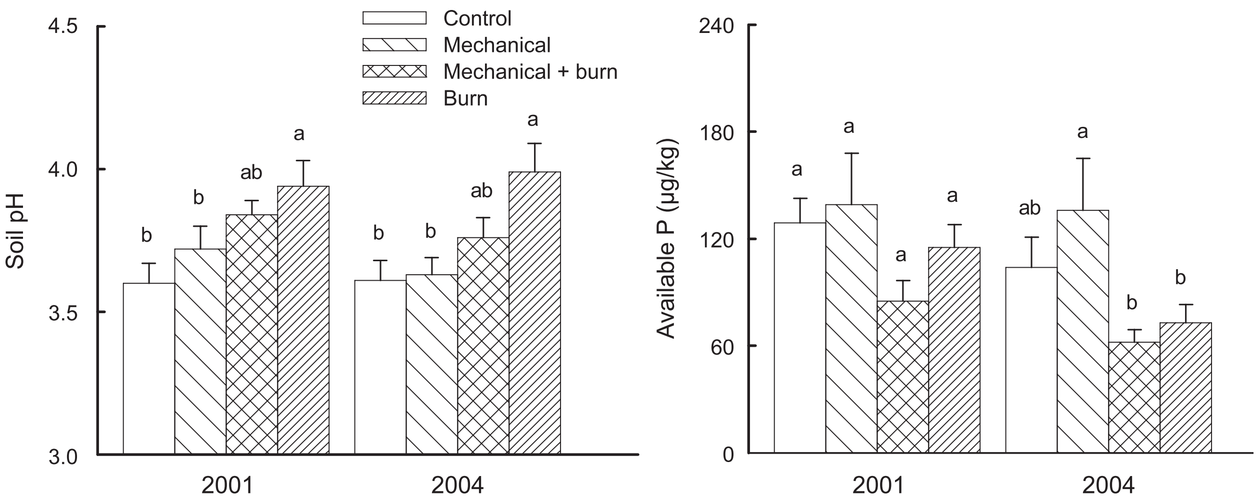

Figure 2—Effects of four ecosystem restoration treatments on soil pH and plant available P (format follows figure 1).

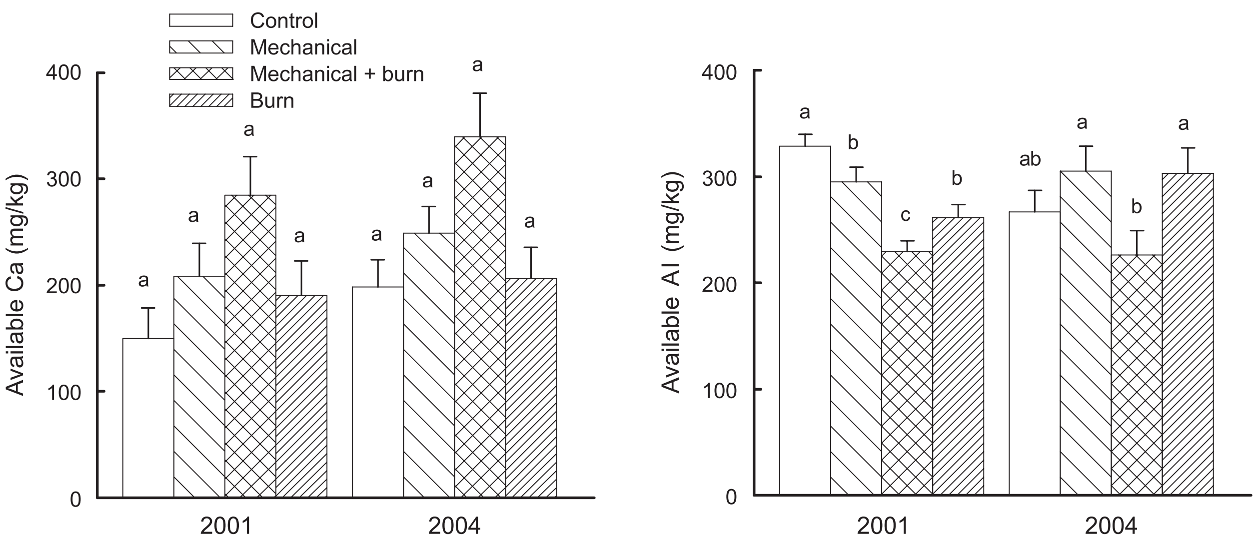

Figure 3—Effects of four ecosystem restoration treatments on extractable Ca and Al (format follows figure 1).

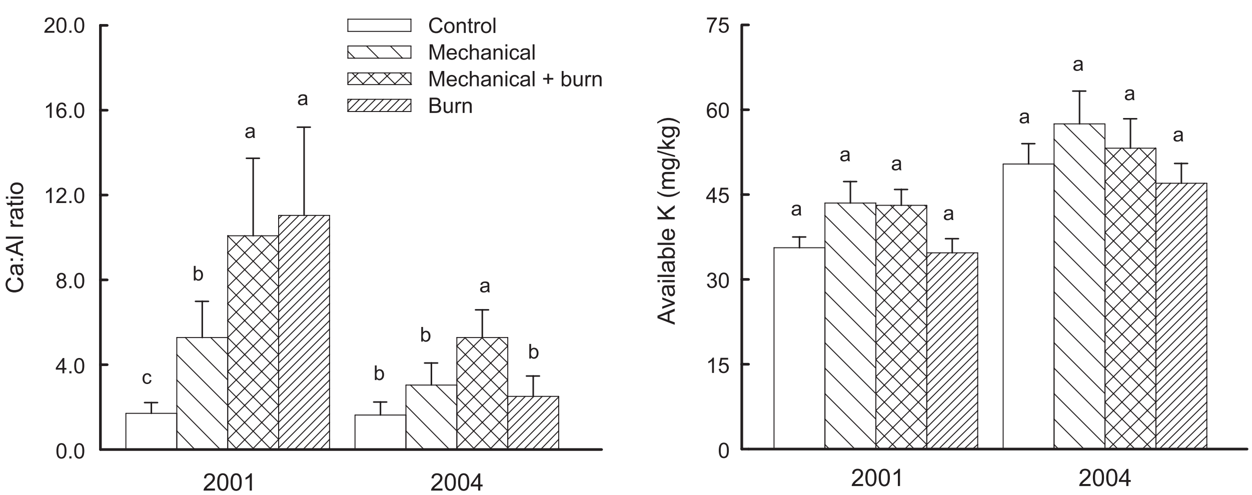

Figure 4—Effects of four ecosystem restoration treatments on molar Ca:Al ratio and extractable K (format follows figure 1).

Available K averaged 39.2 (±0.88) mg K/kg soil during the first growing season after treatment and 52.3 (±2.4) mg K/kg soil during the fourth post-treatment growing season. K availability was not affected significantly by any of the treatments (fig. 4, table 1).

DISCUSSION

Physical disruption of the forest floor and upper mineral soil horizons can produce both acute and chronic impacts on soil nutrient status and subsequent tree growth (Agee 1993). During the first post-treatment growing season, prescribed fire (with or without mechanical treatment) resulted in the mineral soil surface being exposed over an average of 20-30 percent of the area of each burned treatment unit. In contrast, mechanical treatment resulted in approximately 10 percent soil exposure, and this degree of exposure was not significantly different from that of the controls. By the fourth post-treatment growing season, mineral soil was exposed on 8-10 percent in all three treatments. Although this degree of exposure was significantly greater than that observed in the controls (1-2 percent), it did indicate a relatively rapid reestablishment of forest floor cover, at least in the burned areas.

The proportion of the soil exposed by mechanical treatment in these Ohio forests was somewhat lower than that reported after harvesting in other regions. Rummer and others (1997) reported that soil exposure in upland hardwood forests in Alabama averaged 7-25 percent depending on cutting regime and Klepac and others (1999) observed soil exposure averaging 15 percent after mechanical treatment of conifer stands in Washington.

We observed no significant increase in the average or variance of the proportion of ground area with significant soil compaction as the result of fire, mechanical treatment, or the combination. Although it has been demonstrated in western conifer forests that severe and/or repeated burning has the potential to increase soil bulk density, such effects are typically less evident after low intensity fires, such as those typical of prescribed fire in Ohio oak forests (Agee 1993).

Harvesting operations also present the potential for significant effects on bulk density/compaction, especially in areas of heavy vehicle traffic. However, we observed no significant effect, either in average or variance, and Matson and Vitousek (1981) also reported no consistent changes in bulk density as the result of clear-cutting of mixed oak forests in Indiana. Other studies, however, do demonstrate significant effects of harvesting practices on soil compaction (e.g. Berger and others 2004, Rummer and others 1997). The lack of compaction we observed in our study may be the result of the relatively light intensity of the cutting in our Ohio sites. Another contributing factor may have been our random sampling scheme, as we did not single out skid trails when we sampled.

Changes in soil nutrient status as the result of management can have both short and long term effects on revegetation, as nutrients present in the mineral soil after fire are needed both for immediate plant needs and to replenish the nutrients lost from the site during fire or harvesting. In this study, fire alone resulted in an increase in soil pH while mechanical treatment had no significant effect on soil pH. The combination of mechanical treatment and burning produced soil pH that was not significantly different from fire or mechanical treatment alone or from the controls, and this pattern persisted through the fourth post-treatment growing season.

The increase in soil pH after fire we observed was consistent with that observed after single fires (Blankenship and Arthur 1999), multiple fires (Boerner and others 2004), and long term prescribed burning (Eivasi and Bayan 1996) in Midwestern oak forests. However, the lack of effect of mechanical treatment on soil pH in these stands was unexpected, as other studies have demonstrated that thinned stands often have significantly higher soil pH than reference stands. For example, a comparison of stands in Kentucky, Ohio, and Illinois that were experimentally thinned 30+ years before showed that thinned stands had soil pH on average 0.33 units higher than did paired reference stands (Boerner and Sutherland 1997).

We observed no significant effect of fire, mechanical treatment, or their combination on available K^+ at any time and no effect on available P during the first post-treatment growing season. However, by the fourth-post treatment growing season, available P in the burned and thinned+burned treatments was significantly lower than that in the thinned treatments (though none of the three were significantly different from available P in the untreated controls). Long term prescribed burning in a Missouri oak forest also resulted in a decrease of 24-35 percent in available P without a concomitant effect on K^+ (Eivasi and Bayan 1996). It is unclear whether the change in available P is a result of rapid uptake by post-fire regrowth depleting the local pool or the result of changes in P supply from parent material and organic matter.

In a study of the consequences of clear-cutting on mixed oak forests in Virginia, Johnson and others (1985) found that rapid slash decay resulted in increased K^+ but not P in the mineral soil during the growing season after the harvesting. In contrast, Hendrickson and others (1989) reported no change in available K^+ after thinning of northern hardwoods and Frey and others (2003) observed a decrease in available K^+ after harvesting in an Alberta mixed forest. Given the high mobility of K^+ in the soil solution, post-treatment availability may be governed primarily by site- and situation-specific factors such as mineral soil exposure and post-fire precipitation patterns.

As was the case for K^+, we observed no significant effect of our treatments on available Ca^{2+}. This was an unanticipated result, as previous studies in nearby sites had shown significant, positive effects of 1-4 fires on available Ca^{2+} (Boerner and others 2004), and the significant increase we observed in soil pH suggested that Ca^{2+} would also have increased. Although prescribed burning over a longer term does not always result in increased Ca^{2+} in oak forests (e.g. Eivasi and Bayan 1996), shorter term studies typically do observe increases in the availability of Ca^{2+} (Boerner and others 2004). The lack of an effect of mechanical treatment on Ca^{2+} is equally unexpected. In their comparison of thinned and reference oak stands in Ohio, Kentucky, and Illinois, Boerner and Sutherland (1997) found that thinned stands had on average 55 percent greater Ca^{2+} availability than paired reference stands, and a number of studies have also demonstrated increases in Ca^{2+} after clear-cutting (e.g. Frey and others 2003, Hendrickson and others 1989).

Available Al^{3+} did decrease initially as the result of our treatments, but this change did not persist through the fourth post-treatment growing season. The patterns of Ca^{2+} and Al^{3+} among treatments were mirror images, as would be expected by their reciprocal responses to soil pH and base saturation. The Ca:Al molar ratio increased significantly after fire (with or without mechanical treatment), but once again these differences had begun to dissipate by the fourth-growing season after fire. Boerner and others (2004) observed similar post-fire increases in Ca:Al ratio in neighboring sites on similar, acidic parent materials. Based on an extensive literature survey, Cronan and Grigal (1995) concluded that forest decline symptoms were much more likely to develop in European forests after the Ca:Al molar ratio decreased to <2.0. As the pre-treatment Ca:Al ratios in our study sites averaged <2.0 and chronic N deposition continues to contribute to soil acidification in this region (Boerner and others 2004), management practices that have the potential to increase base saturation and Ca:Al ratio should be strongly considered.

MANAGEMENT IMPLICATIONS

Management practices designed to improve ecosystem health and sustainability must adhere to the same first principle as medicine: above all, do no harm. Although we commonly assess the impacts of our management activities in terms of trees, other plants, and animals, the impacts of management on the soil resource is one of the keys to long term sustainability.

The effects on the soil resource of the ecosystem restoration treatments we applied were relatively modest and, for the most part, positive. Although both fire and mechanical treatment resulted in disruption of the forest floor, neither had significant effects on soil compaction. Even the effects on mineral soil exposure were significantly reduced (at least for fire) by the fourth growing-season after fire.

Soil nutrient status was relatively unaffected by mechanical treatment and perhaps modestly improved by fire. Although the effect of the single fires we applied in this study produced effects that were transitory in nature, repeated application of fire at intervals might result in these changes becoming chronic (e.g. Eivasi and Bayan 1996). Given that chronic deposition of N onto these once N-limited ecosystems is unlikely to cease in the foreseeable future, multiple longer term studies of the relationships among fire frequency and forest soils are needed to bring the available database up to even the meager status of the thinning literature.

Studies of thinning at rates similar to the ones used here are uncommon; however, the longer term study of thinning in midwestern oak forests by Boerner and Sutherland (1997) suggests that the reduction in uptake demand that accompanies a reduction in basal area may help retard soil acidification, even in a region with heavy chronic N deposition. This conclusion must, however, be considered preliminary, given the sparseness of the available data and the concerns raised by studies of more intensive harvesting.

The results presented here suggest that modest thinning and low intensity prescribed fire may be applied to eastern oak forests as part of a management or restoration strategy without doing significant damage to the soil resource. Managers should apply the conclusions presented here with caution until longer term, replicated studies in the region confirm them.

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