Wildfire mitigation strategies affect soil enzyme activity and soil organic carbon in loblolly pine (*Pinus taeda*) forests

R.E.J. Boerner, T.A. Waldrop, and V.B. Shelburne

Abstract: We quantified the effects of three wildfire hazard reduction treatments (prescribed fire, thinning from below, and the combination of fire and thinning), and passive management (control) on mineral soil organic C, and enzyme activity in loblolly pine (*Pinus taeda* L.) forests on the Piedmont of South Carolina. Soil organic C was reduced by thinning, either alone or with prescribed fire, and this effect persisted through the fourth post-treatment year. Fire also resulted in reduced soil organic C, but not until several years after treatment. Soil C/N ratio initially increased after fire, either alone or with thinning, but this difference did not persist. The activities of three soil enzymes (acid phosphatase, chitinase, and phenol oxidase) in the upper mineral soil were quantified as measures of microbial activity. During the fourth post-treatment year we observed significant stimulation of all three enzyme systems as a result of thinning or thinning and burning. Although the patterns of variation in acid phosphatase and chitinase activity among treatments were similar during the first and fourth post-treatment years, the first-year treatment effects were not statistically significant. Given the management objective of utilizing these stands for timber production, the increased potential for rapid nutrient turnover offered by thinning gives this approach advantages over prescribed fire; however, management for maximum long-term storage of soil C may be better facilitated by prescribed fire.

Résumé : Nous avons quantifié les effets de trois traitements pour réduire les risques d'incendie de forêt (brûlage dirigé, éclaircie par le bas et combinaison du brûlage et de l'éclaircie), d'un aménagement passif (témoin) sur le C organique du sol minéral et l'activité enzymatique dans les forêts de pin à encens (*Pinus taeda* L.) dans le Piémont de la Caroline du Sud. Le C organique du sol a diminué à la suite de l'éclaircie, seule ou combinée au brûlage dirigé, et cet effet a persisté jusqu'à la 4^e année après le traitement. Le rapport C/N dans le sol a d'abord augmenté après le feu, seul ou combiné à l'éclaircie, mais cette différence n'a pas persisté. L'activité de trois enzymes présentes dans le sol (la phosphatase acide, la chitinase et la phénol-oxydase) a été quantifiée dans la partie supérieure du sol minéral pour évaluer l'activité microbienne. Durant la 4^e année après le traitement, nous avons observé une augmentation de l'activité des trois enzymes à la suite de l'éclaircie ou de l'éclaircie et du brûlage. Bien que les patrons de variation de l'activité de la phosphatase acide et de la chitinase dans les différents traitements aient été similaires durant la 1re année après les traitements à ceux qui ont été observés pendant la quatrième année, les effets observés pendant la 1re année n'étaient pas statistiquement significatifs. Étant donné l'objectif d'aménagement qui consiste à utiliser ces peuplements pour la production de matière ligneuse, la possibilité accrue d'un recyclage rapide des nutriments offert par l'éclaircie confère à cette approche des avantages supérieurs à ceux du brûlage dirigé. Cependant, le brûlage dirigé serait plus efficace dans le cas d'un aménagement visant le stockage maximum du C du sol à long terme.

[Traduit par la Rédaction]

Introduction

The forests of the Piedmont of the southeastern United States have been subjected to frequent fire for most of the last millennium (Stanturf et al. 2002). At the time of significant European contact in the 1600s, the species that occupied ecosystems of the southeastern Piedmont had been subject to selection by frequent fire to the point where most either required fire or were strongly tolerant of fire (Stanturf et al. 2002).

Colonists quickly learned that the soils of the Piedmont were easy to cultivate and in many areas had already been cleared by Native Americans using dormant season fire. Corn and cotton farming was common until the 1930s, and the cultivation of many of the rolling landforms of the Piedmont was facilitated by conversion to terraces (Van Lear et al. 1994). After that time, most of the farms were abandoned; and these intensively cultivated soils were degraded further by strong erosion (Trimble 1974).

In the early 1900s, government agencies began to reforest the region with pines, especially loblolly pine (*Pinus taeda* L.), and fire suppression was a major part of that ef-

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R.E.J. Boerner.[1] Department of Evolution, Ecology, and Organismal Biology, Ohio State University, Columbus, OH 43210, USA.
T.A. Waldrop. Southern Research Station, USDA Forest Service, Clemson, SC 29634, USA.
V.B. Shelburne. Department of Forestry and Natural Resources, Clemson University, Clemson, SC 29634, USA.

[1]Corresponding author (e-mail: boerner.1@osu.edu).

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fort until the 1950s (Healy 1985). Although prescribed burning to control fuel loads in these forests began in the 1960s, the large majority of the forest land in the southeastern Piedmont is owned by nonindustrial private landowners, and fuel reduction burning has not been commonly used on those lands (Stanturf et al. 2002). Thus, fuels have accumulated since the beginning of reforestation to the point where there is a significant potential for wildfires at intensities uncharacteristic of the historic condition.

This study describes one part of a larger, national-scale experimental assessment of management strategies designed to protect these forests from devastating crown fires by removing vertical fuels and reducing forest density (National Fire and Fire Surrogate Network 2006). At this site on the Piedmont of South Carolina, we sought specifically to evaluate the use of prescribed fire, mechanical treatment consisting primarily of thinning from below, and the combination of prescribed fire and mechanical thinning for facilitating economically feasible stand management, wildfire hazard reduction, and conversion of these dense, fuel-rich stands to more of a savannah-like community (Waldrop et al. 1992).

In addition to determining the degree to which these three management strategies would reduce fuel accumulations, a central focus of the Fire and Fire Surrogate Study (FFS) study is the determination of the longer term effects of these treatments on productivity and sustainability. To this end, we chose to focus on soil organic C and the activity of soil exoenzymes produced by the microbial assemblage as indicators of longer term ecosystem effects because (1) they reflect emergent properties that are the results of the diverse interactions among many ecosystem components, including trees, other vegetation, microclimate, soil physicochemical properties, and soil organisms, and (2) changes in characteristics of the organic C pool and the rate at which nutrients are cycled through that pool can be used to predict the potential longer term effects of management treatments. Within this context, the specific questions we sought to answer with this study were (1) How do thinning and burning, either alone or in combination, affect soil organic C and soil C/N ratio in these degraded soils? (2) How do wildfire hazard mitigation strategies affect the activity of soil enzymes produced by the microbial assemblage in these soils?

Materials and methods

Study site and treatments

This study was done in the Southeastern Piedmont FFS site, part of the Clemson Experimental Forest, an area of >6900 ha in Anderson, Oconee, and Pickens Counties, South Carolina (Sorrells 1983). The Clemson Experimental Forest is representative of approximately 12×10^6 ha of commercial forestland in the southeastern Piedmont of North America. These forests are typically a mixture of pine and oak with loblolly pine, shortleaf pine (*Pinus echinata* P. Mill.), white oak (*Quercus alba* L.), scarlet oak (*Quercus coccinea* Muenchh.), southern red oak (*Quercus falcata* Michx. var. *falcata*), and post oak (*Quercus stellata* Wangenh.) being the most common tree species (Sorrells 1983).

The Clemson Experimental Forest area varies in elevation from 200 to 300 m above sea level, and parts of its rolling topography were converted to terraces during the height of cotton farming in the late 1800s (Sorrells 1983). The parent materials are granites, phyllites, and schists, ranging in age from Precambrian to early Paleozoic, and the majority of the soils are moderately to severely eroded Ultisols (Byrd 1963, 1972; Herren 1979). The most common soils in the areas where our experimental plots were located were sandy loams of the Madison, Cecil, and Pacolet series (all Typic Hapludults), Hiwassee series (Typic Rhodudult), and Cataula series (Typic Fragidult) (Byrd 1963, 1972; Herren 1979).

This experiment was designed as a randomized complete block, with three blocks and four treatments allocated to each block (Callaham et al. 2004). Blocks were established to represent the three common ranges of tree size distribution present in the Clemson Forest (pulpwood, sawtimber, and mixed). Each block included four treatment units of 6–10 ha each, and treatment units within each block were randomly allocated to four treatments: control, dormant season prescribed fire, mechanical thinning, and the combination of mechanical thinning followed by prescribed fire.

Each 6–10 ha treatment unit and 4 ha surrounding buffer zone was overlain with a 50 m × 50 m grid, and ten 0.1 ha permanent sampling plots were established within each treatment unit using randomly chosen grid points to locate the first corner of each permanent plot. The landscape context of each of the permanent plots was assessed using a Landscape Ecosystem Classification (LEC) based on a combination of terrain (slope position, aspect, elevation), soil type, and depth to a clay-rich layer (as an indicator of past erosion) (Jones 1991).

The mechanical thinning treatment was applied during the winter of 2000–2001 and involved thinning from below to approximately 18 m^2/ha basal area. This basal area target was based on local management recommendations designed to maximize diameter growth of loblolly pine. Prescribed fires were conducted in April and May 2001 in the burn-only treatment units and in April 2002 in the mechanical thin and burn treatment units (Callaham et al. 2004). The prescribed burning of the mechanical thin and burn treatment units was conducted 1 year after that of the burn-only units to allow the leaves to fall from the slash, reducing the intensity of the prescribed fire.

Burning alone reduced the Oe + Oi by an average of 74%, whereas the mechanical thinning followed by burning treatment resulted in an average reduction of 83% (Waldrop et al. 2004). A preliminary review of post-treatment basal area indicates that basal area was reduced by an average of 12% by prescribed fire, 22% by mechanical thinning alone, and 37% by thinning followed by burning (Phillips et al. 2004).

Soil sampling and laboratory analysis

In June and July of 2000, 2001, 2002 (thin + burn only), and 2004, soil samples were taken from two of the four corners of each sampling plot (N = 20 per treatment unit per sample year, N = 60 per treatment per sample year). Prior to sampling, the Oa, Oe, and Oi layers were removed over an area of 225 cm^2. Mineral soil samples representing the 0–10 cm depth of the mineral soil were then taken at the center of that area with a 10 cm diameter corer, and all samples were returned to the laboratory under refrigeration. Samples on successive dates were always taken within 1 m of those from the previous year.

For all treatments, samples taken in 2000 represent the pre-treatment sampling. The samples taken in 2001 (control, mechanical thin-only, and burn-only treatments) and 2002 (thin + burn only) represent the first growing season after treatment in the respective treatment units. The samples taken in 2004 represent the fourth post-treatment growing season for the control, mechanical thin-only, and burn-only treatments, and the third post-treatment year for the mechanical thin + burn treatment.

Samples were kept refrigerated until the enzymes assays were completed. Each sample was passed through a 2 mm sieve to remove stones and root fragments and then analyzed for the activity of phosphomonoesterase (acid phosphatase), chitinase, and phenol oxidase.

Acid phosphatase was chosen as an indicator of overall microbial activity because its activity is strongly correlated with microbial biomass (Kandeler and Edler 1993), microbial biomass N (Clarholm 1993), fungal hyphal length (Häussling and Marschner 1989), and N mineralization (Decker et al. 1999). Chitinase is a bacterial enzyme that catalyzes the breakdown of chitin, a byproduct of both fungi and arthropods, into carbohydrates and inorganic N. As chitin is intermediate in its resistance to microbial metabolism, the synthesis of chitinase is only induced when other, more labile C and N sources are absent (Hanzlikova and Jandera 1993). Phenol oxidase is produced primarily by white rot fungi and is specific for highly recalcitrant organic matter, such as lignin (Carlile and Watkinson 1994).

The enzyme activities were determined on field-moist soil using methods developed by Tabatabai (1982), as modified by Sinsabaugh (Sinsabaugh et al. 1993; Sinsabaugh and Findlay 1995). Subsamples of approximately 10 g of fresh soil were suspended in 120 mL of 50 mmol/L NaOAc buffer (pH 5.0) and homogenized by rapid mechanical stirring for 90 s. To minimize sand sedimentation, stirring was continued while aliquots were withdrawn for analysis.

Acid phosphatase (EC 3.1.3.1) and chitinase (EC 3.2.1.14) activities in soil suspensions were determined using *p*-nitrophenol (*p*NP) linked substrates: *p*NP-phosphate for acid phosphatase and *p*NP-glucosaminide for chitinase. Samples were incubated for 1 h (acid phosphatase) or 2 h (chitinase) at 20–22 °C with constant mixing. Following incubation, samples were centrifuged at 3000*g* for 3 min to precipitate particulates. An aliquot of 2.0 mL of the supernatant was transferred to a clean, sterile tube, and 0.1 mL of 1.0 mol/L NaOH was added to halt enzymatic activity and facilitate color development. Each sample of the supernatant was diluted with 8.0 mL of distilled, deionized water prior to spectrophotometric analysis at 410 nm.

Phenol oxidase (EC 1.14.18.1, 1.10.3.2) activity in soil suspensions was measured by oxidation of L-3,4-dihydroxyphenylalanine (L-DOPA) during 1 h incubations at 20–22 °C. Following incubation, samples were centrifuged as above and analyzed at 460 nm without dilution. Parallel oxidations of L-DOPA using standard horseradish peroxidase (Sigma-Aldrich Corporation, St. Louis, Missouri) were used to calculate the L-DOPA extinction coefficient.

Soil organic C and total soil N were analyzed by micro-Dumas combustion on a Perkin-Elmer 2400 Series II CHNS/O Analyzer. Prior to the determination of soil organic C and total soil N, soil samples were dried at 70 °C for 48 h and then ground in order to pass through an 80 mesh screen.

Data analysis

Responses were either normally distributed (e.g., enzyme activity) or could be normalized by transformation (e.g., soil C). Differences in response parameters among treatments in 2001, 2002, and 2004 were analyzed by one-way analysis of covariance for a completely randomized block design, using the Landscape Ecological Classification metric (LEC) and pre-treatment enzyme activity, soil organic C content, or soil C/N ratio as covariates (SAS Institute Inc. 1995). Mean separations were calculated by least squares estimation, using the Bonferroni adjustment for multiple comparisons at $p < 0.05$ (SAS Institute Inc. 1995).

Results

In 2001 and 2002, the first post-treatment growing season, soil organic C concentration was significantly greater in soils from the control and burn-only units than from the thin-only and thin + burn units (Fig. 1, Table 1). On average, soil organic C concentration was 32.5% greater in control and burn-only units than in thin-only and thin + burn units. In contrast, in 2004 soil organic C concentration was significantly greater in control soils than in soils from the other three treatments (Fig. 1, Table 1). The mean differences in 2004 soil organic C concentration between the control and manipulative treatments ranged from 13.8% for the burn-only treatment to 39.1% for the thin-only treatment.

Soil C/N ratio, an estimator of organic matter quality, varied among treatments in both sampling years (Fig. 1, Table 1). During the first post-treatment year, the C/N ratio in soils from the thin + burn treatment was significantly greater than it was in soils from the thin-only treatment and control, with the C/N ratio of the burn-only units intermediate (Fig. 1). In contrast, soils collected in 2004 from the control and burn-only treatment had significantly higher C/N ratio than did soils from the thin-only and thin + burn units (Fig. 1).

Acid phosphatase activity did not vary significantly among treatments during the first post-treatment year (Fig. 2, Table 1). During the fourth post-treatment year, however, there were significant treatment effects. The soils of the thin-only treatment had greater acid phosphatase than did the soils of the control and burn-only treatments (Fig. 2, Table 1).

As was the case for acid phosphatase, soil chitinase activity did not vary significantly among the four treatments during the first post-treatment year (Fig. 3, Table 1). However, post hoc pairwise comparisons suggested that soils from the thin-only treatment may have had greater chitinase activity than did those of the burn-only treatment ($t = 2.29$, $p < 0.025$). In samples collected in 2004, chitinase activity was significantly lower in soils from the burn-only treatment than in soils from the other three treatments. In addition, chitinase activity in thin-only treatment soils was greater than that in control soils (Fig. 3).

Phenol oxidase activity, a measure of the activity of wood decay fungi, was significantly greater in thin-only treatment soils than in soils from the control or burn-only treatments in

Fig. 1. Effects of four wildfire hazard management treatments on soil organic carbon quantity (g·kg^{-1}) and soil organic matter quality (C/N ratio). Each histogram bar represents the mean of $N = 60$. Error bars indicate the standard error of the mean. Histogram bars labeled with the same lowercase letter were not significantly different at $p \leq 0.05$.

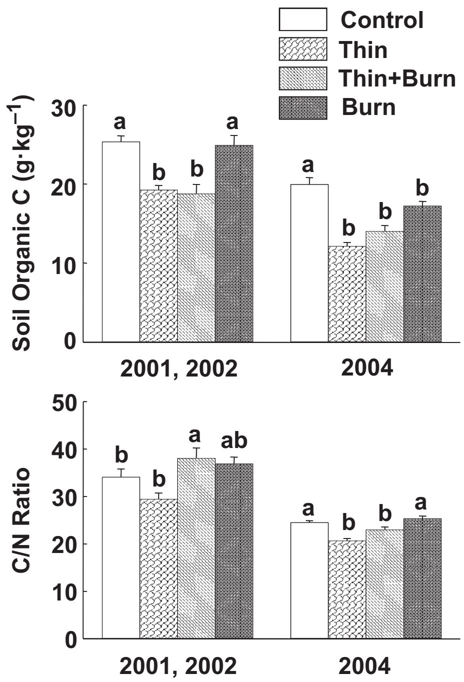


Table 1. Analysis of covariance for the randomized complete block design of the effects of the application of alternative wildfire management treatments to Clemson Forest areas, using pretreatment conditions as the covariate.

	Treatment effect	
Response variable	*F*	*p*
Soil organic C (g·kg soil^{-1})		
2001, 2002	13.27	<0.001
2004	3.99	<0.009
Soil C/N ratio		
2001, 2002	2.83	<0.040
2004	10.15	<0.001
Acid phosphatase (mmol·kg organic C^{-1}·h^{-1})		
2001, 2002	1.48	<0.221
2004	4.71	<0.004
Chitinase (mmol·kg organic C^{-1}·h^{-1})		
2001, 2002	1.93	<0.127
2004	4.99	<0.003
Phenol oxidase (mmol·kg organic C^{-1}·h^{-1})		
2001, 2002	4.84	<0.003
2004	2.72	<0.046

Note: *F* statistics and associated *p* levels are given for treatment effects. Mean separations were calculated by least square comparisons, using the Bonferroni adjustment for multiple comparisons.

both post-treatment years (2001, 2002, and 2004). Phenol oxidase activity in the thin + burn units was between those of the thin-only treatment and the remaining two treatments in both post-treatment years as well (Fig. 4, Table 1).

Fig. 2. Effects of four wildfire hazard management treatments on soil acid phosphatase activity (mmol·kg organic C^{-1}·h^{-1}). Format follows Fig. 1.

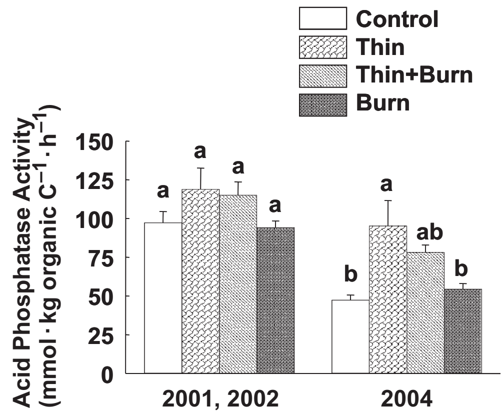
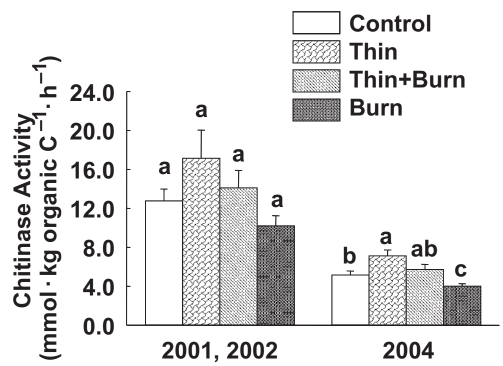


Fig. 3. Effects of four wildfire hazard management treatments on soil acid chitinase activity (mmol·kg organic C^{-1}·h^{-1}). Format follows Fig. 1.

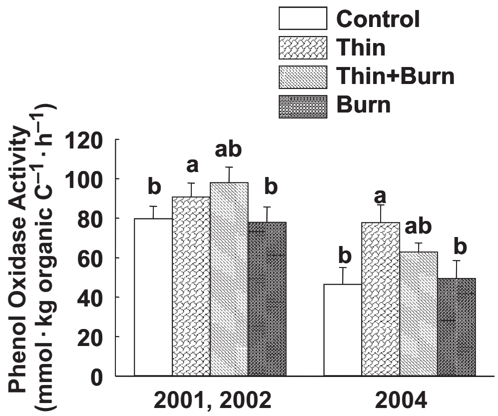


Discussion

Mechanical thinning and the combination of thinning and burning in these *P. taeda* forests resulted in a significant decrease in soil organic C concentration after treatment, and this effect persisted through the fourth post-treatment year. In contrast, there was no significant immediate effect of prescribed burning alone on soil organic C, though some reduction was noted by the fourth post-treatment growing season.

Results of previous studies of the effects of prescribed fire on soil organic C in southern pine plantations vary as much in magnitude and direction as they do in geography, soil types, fire severity, and pine species. Most of the available studies indicate that repeated prescribed fire has little impact on soil organic C (e.g., Moehring et al. 1966; McKee 1982; Richter et al. 1982), and in a recent study in a longleaf pine (*Pinus palustris* P. Mill.) ecosystem, Wilson et al. (2002) found that soil organic C varied more strongly as a function of landscape position than with fire. Some studies have demonstrated significant decreases in soil organic C as the result of repeated prescribed burns (e.g., Hunt and Simpson 1985; Mabuhay et al. 2003), while other studies show an increase in soil organic C after prescribed fire (e.g., Wells 1971). Fire severity is also a factor in determining the effect of fire on soil organic C; Groeschl et al. (1990) found that areas of a

Fig. 4. Effects of four wildfire hazard management treatments on soil acid phenol oxidase activity (mmol·kg organic $C^{-1}·h^{-1}$). Format follows Fig. 1.



Virginia *Pinus pungens* Lamb. forest that had experienced low-severity fires had 11% more soil organic C than unburned reference stands, whereas areas that had experienced high-severity fires had 19% less soil organic C than the unburned reference stands. The difference was attributed to the low-severity stands having had some combusted forest floor left to contribute charcoal and fine organic matter to the soil, whereas the high-severity burn stands had lost the entire forest floor and had experienced significant postfire erosion.

Harvesting can also have significant effects on the amount of organic C present in the soil, though most of the available literature considers more intensive harvesting than is represented by our thinning treatment. For example, Carter et al. (2002) reported significant short-term losses of soil organic C after the clear-cutting of loblolly pine plantations in Texas and Louisiana.

Prior studies of the effect of the combination of mechanical treatment and prescribed fire on soil organic C also focus primarily on more intense harvesting practices. For example, Knoepp et al. (2004) attempted the restoration of degraded pitch pine (*Pinus rigida* P. Mill.) – mixed-oak (*Quercus* spp.) stands in western North Carolina by cutting all woody material and burning in late summer when intensity would be maximum. They observed no effect of this treatment on soil organic C. In contrast, Gholz and Fisher (1982) observed a short-term doubling of soil organic C after clear-cutting, burning, and site preparation in a Florida slash pine plantation. As the added organic C was highly labile, it was rapidly degraded and pre-harvest soil organic C levels were restored within 5 years (Gholz and Fisher 1982).

We also observed a significant first-year effect of the treatments on soil C/N ratio. Prescribed fire, either alone or in combination with thinning, resulted in significantly increased C/N during the first post-treatment growing season, and this effect persisted into the fourth post-treatment growing season in the burn-only treatment units. Although some studies of soil C/N ratio in pine-dominated ecosystems have also demonstrated significant increases after fire (e.g., Wells 1971; Groeschl et al. 1990), decreases or insignificant effects of harvesting (Carter et al. 2002) and no effect of harvesting followed by fire (Knoepp et al. 2004) have also been reported. Once again, the prior studies involved considerably more intensive harvesting practices than did this study, thus weakening their usefulness as comparators.

We observed no significant first-year effect of the three manipulative treatments on acid phosphatase; however, by the fourth year, acid phosphatase activity was significantly greater in soils from the mechanical thinning and thin + burn treatments than in the control or burn-only treatments. To the degree to which acid phosphatase activity can be extrapolated to represent overall microbial activity or biomass (e.g., Clarholm 1993; Kandeler and Edler 1993; Decker et al. 1999), this suggests that mechanical thinning has a stimulatory effect on microbial activity in this study site that is only apparent after a lag period of at least one growing season.

We also observed a modest, statistically significant stimulation of first-year phenol oxidase activity by the mechanical thinning treatment, and that effect increased in magnitude by the fourth post-treatment growing season. Callaham et al. (2004) found that the soils of the burn-only treatment in the same study sites had significantly lower rates of total soil respiration than did the soils from the mechanical thinning and thin + burn treatments. Shelburne et al. (2004) reported significant net NO_3^- immobilization in the soils from the burn-only treatment but positive net nitrification in soils from the other treatments.

No studies of soil enzyme activity in pine plantations or forests with which to compare our results could be located. However, in mixed-oak forests in southern Ohio, two to four prescribed fires over a 6 year period resulted in decreases in acid phosphatase activity, increases in phenol oxidase activity, and no change in chitinase activity (Boerner et al. 2000; Boerner and Brinkman 2003). This suggests that responses to fire in hardwood forests may be qualitatively different from those in southern pine ecosystems.

Conclusions and management implications

Low-intensity prescribed fire applied alone had little effect on soil organic C or enzyme activity. Given the long history of frequent low-intensity fire in this region, the lack of a strong effect of dormant season prescribed fire should not be a surprising result. Mechanical thinning, with or without prescribed fire, had a greater effect on the soil organic C, on the C/N ratio, and on the activity of both acid phosphatase and phenol oxidase than did low-intensity prescribed fire. Our results, when combined with previous studies of soil respiration and N transformations in these sites, suggest that mechanical treatment results in relative increases in overall microbial activity, and in the rate at which woody residues are consumed. In infertile soils such as those present in our study sites, treatments that increase the rate at which Ca and K are recycled from woody residues is likely to have a positive effect on tree yield, at least over the short term. At the same time, this may result in reduced sequestration of atmospheric C in soil organic matter; thus short-term and longer-term management objectives may be in some conflict here.

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