IMPACT OF FIRE ON SOIL RESOURCE PATTERNS IN A NORTHERN CALIFORNIA MONTANE ECOSYSTEM

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ABSTRACT

The montane ecosystems of the Cascade Range have been subjected to repeated manipulation and active fire suppression for more than a century. This has resulted in changes in community structure that contribute to increased wildfire hazard and severity. Ongoing efforts to return these ecosystems to a state with intrinsic low fuel loads have received substantial attention in recent years; however, many ecological questions remain unanswered. This study addresses belowground impacts of restorative treatments. We report proximate effects of the application of prescribed fire (burn-only) and the combination of fire and mechanical thinning (thin + burn) on soil chemical and microbial parameters in treatment units of 10 ha each in the Klamath National Forest of northern California. Soil organic carbon (C) decreased and C:N (carbon:nitrogen) ratio increased as a result of fire in the burn-only treatment; however, no significant changes from pre-fire to post-fire were observed for thin + burn treatment plots. N mineralization rates did not change as a result of fire in either burn-only or thin + burn plots. Nitrification rates decreased as a result of fire in thin + burn units, but did not change significantly in the burn-only treatment. Total inorganic N increased from pre-fire to post-fire, with and without thinning. Activity of acid phosphatase, an indicator of overall microbial activity, was reduced by fire, both with and without thinning, whereas activity of chitinase was reduced by fire in thin + burn plots only. There were no significant changes in phenol oxidase activity as a result of fire, with or without thinning. This study demonstrates that fire has short-term effects on soil ecological properties, e.g., soil organic matter, N turnover and availability, and microbial function, and that the combination of mechanical thinning and fire may have different effects from fire alone.

keywords: California, thinning, mixed conifer, prescribed fire, soil enzyme activity, soil resources.

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INTRODUCTION

Fire has been an important process in determining vegetation structure and composition of ecosystems throughout North American history. In western North America pre–European settlement ponderosa pine (*Pinus ponderosa*) (nomenclature follows Hickman 1993) forests experienced fire return intervals as frequent as 2 to 15 y (Weaver 1951, Agee 1993). These fires resulted from both natural causes, such as lightning strikes or volcanic activity, and anthropogenic ignitions, such as seasonal burns set by Native American peoples (Weaver 1951, Agee 1993). The historic pattern of frequent, low-intensity fires limited understory growth and selected for resistant, thick-barked, shade-intolerant tree species such as ponderosa pine. Reports of presettlement forests describe open, park-like stands of trees (Laudenslayer and Darr 1990, Covington and Moore 1994), and detailed dendrochronological analysis of forests dominated by ponderosa pine and Jeffrey pine (*P. jeffreyi*) in the Cascade Range and Sierra Nevada of California and Oregon profile a pine-dominated forest that was originally moderately open, uneven-aged, large-tree dominated, and shaped by frequent, low-intensity fires (Agee 1993, Skinner and Chang 1996, Taylor 2000).

Today's mixed-conifer forests of the Southern Cascades differ substantially from historic conditions in several characteristics, including increased stand density, altered species composition, increased presence of disease, and nutrient cycling, among others (Agee 1993, Skinner and Chang 1996, Taylor 2000). Grazing, logging, and aggressive fire-suppression policies have contributed to these post–European settlement changes in stand composition and structure (Weaver 1951, Agee 1993). Forests that were historically dominated by a low density of large pines now include large numbers of white fir (*Abies concolor*) and other shade-tolerant species, and stem density in these stands has increased dramatically since European settlement. The

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combination of fire suppression and higher stem density has led to the accumulation of both surface and vertical fuels such that conditions are now conducive to the development of fires with intensity far greater than the historical condition. Large, catastrophic wildfires in California during the summers of 1977, 1987, 1990, 1992, 1999, 2001, and 2003 provide stark evidence of the potential of existing forest conditions for extensive and severe fires.

The problem of hazardous fuel conditions in forests has received substantial attention in recent years as land managers attempt to reduce the threat of catastrophic fires. Reduction of fuel loads, especially in areas of wildland–urban interface, has been conducted primarily via mechanical treatment (usually thinning from below); however, prescribed burning or combinations of thinning and burning are also used. Although such stand manipulations may be able to return forests to approximate historic structural conditions, many questions about the ecological consequences of these fire surrogate treatments remain unanswered (Sierra Nevada Ecosystem Project 1996). For example, the question of the effects of structural and functional manipulations on soil fertility, microbial ecology, and nutrient cycling has only recently begun to attract scientific attention (e.g., DeLuca and Zouhar 2000).

This study details one portion of the National Fire and Fire Surrogate Network study (www.fs.fed.us/ffs), which is designed to evaluate the efficacy of alternative management strategies for the mitigation of the current wildfire hazard and for the improvement of forest ecosystem sustainability and health on a national scale. Our study site in the southern Cascades Range of northern California is one of 13 in which a common experimental design is being employed to determine whether prescribed fire, mechanical treatment (usually thinning from below), or a combination of the two could best 1) minimize the hazard of catastrophic fire and 2) accelerate and sustain the development of a large-tree–dominated, late-successional pine forest similar to that originally created and sustained by the historical fire regime. Within that larger experimental context, we present here the results of a study designed to determine the belowground impacts of prescribed fire, both alone and in combination with thinning.

STUDY AREA

This study took place in the Goosenest Adaptive Management Area (GAMA) of the Klamath National Forest in Siskiyou County, California (lat 41°35′N, long 121°53′W). The forests of GAMA were logged between 1900 and 1920. The gentle, dissected landscape of GAMA was the result of recent volcanic activity. Slopes were generally $<10\%$ but could locally be $>50\%$, with elevation ranging from 1,500 to 2,000 m. White fir and ponderosa pine were dominant in the forest canopy, with sugar pine (*P. lambertiana*), incense cedar (*Calocedrus decurrens*), Shasta red fir (*Abies magnifica* var. *shastensis*), and Sierra lodgepole pine (*P. contorta* var. *murrayana*) common. Shrubs included ceanothus (*Ceanothus* spp.), manzanita (*Arctostaphylos* spp.), antelope bitterbrush (*Purshia tridentata*), curl-leaf mountain mahogany (*Cercocarpus ledifolius*), rabbitbrush (*Chrysothamnus* spp.), and sagebrush (*Artemisia* spp.) (USFS 1996).

The soils of the experimental area were the Belzar–Wintoner complex of inceptisols mixed with lesser cover of alfisols (USFS 1982). The Belzar series consists of loamy-skeletal, mixed, frigid Andic Xerochrepts. The Wintoner series, pumice overburden phase, consists of fine-loamy, mixed, frigid Ultic Haploxeralfs. These sand and sandy loam soils drain rapidly and have relatively low water-holding capacity. The climate was Mediterranean-type, and the study site received most of the 25- to 100-cm annual precipitation as winter snowfall (USFS 1996).

METHODS

Study Design and Field Methods

The base Fire and Fire Surrogate (FFS) study design is a completely randomized design consisting of four treatments each replicated three times, with pretreatment sampling to be done in 2000 and treatments implemented in 2001. The intended location of the Southern Cascades FFS study site in the Klamath National Forest became unavailable in 2000, too late for us to restart and complete the permitting process for an entirely new location in time to meet the implementation schedule. In order not to lose the opportunity to include the Southern Cascades in the national FFS study, we decided to overlay the treatment units of this study on preexisting research plots of the Little Horse Peak Interdisciplinary Study (LHPIS). The LHPIS was established in 1998 to accelerate the development of late-successional characteristics of eastside pine forests (Zack et al. 1999, Ritchie 2005). Several of the LHPIS treatments paralleled the base FFS design closely. The combination of mechanical treatment (i.e., thinning from below) and prescribed fire (hereafter thin + burn) was replicated in five experimental units for the LHPIS study, three of which were randomly selected in 2000 for this FFS study. In contrast, the LHPIS did not include a treatment that paralleled the FFS burn-only treatment. Treatment units for FFS burn-only treatments (hereafter burn-only) were interspersed among the Little Horse Peak in 2001. Although vegetation and fuels data were taken in 1998, prior to treatment of the LHPIS units, no pretreatment soil sampling was done.

The thinning of the thin + burn units involved thinning from below combined with selection cutting that focused on removing shade-tolerant species such as white fir. An average of 34% of the basal area was removed as mean basal area was reduced from 36.5 m^2/ha to 24.1 m^2/ha. Processing followed standard harvesting procedure for forests in this region. Whole trees were transported to central processing landings where limbs and tops were removed from larger trees and logs cut to appropriate length for hauling to processing plants. Limbs, tops, and small trees were

Table 1. Fire weather and behavior characteristics for prescribed fires in the burn-only and thin + burn treatment areas of the Goosenest Adaptive Management Area, northern California. Means ± standard deviations are given. Data are from USDA Forest Service, Pacific Southwest Research Station, Redding, California.

Parameter	Treatment	
	Burn-only	Thin + burn
Air temperature (°C)	6 ± 5	12 ± 5
Relative humidity (%)	24 ± 13	32 ± 16
Wind speed (km h^{-1})	1.7 ± 1.3	2.6 ± 1.6
Flame length (cm)	24 ± 11	40 ± 18

chipped at the landings and removed; thus, all the slash generated by the thinning was removed from the units prior to burning. Removal of slash from landings is the usual practice in this region.

Thinning was done during the summers of 1998 and 1999, and was followed by a prescribed fire in the late fall of 2001. Our soil samples in the thin + burn treatment from the summer of 2001 therefore represent pre-fire but post-thinning, and our 2002 samples represent post–burning and thinning. The burn-only treatment consisted of a late-fall prescribed burn in 2002. Stand structure was not modified mechanically prior to burning in the burn-only units. We sampled the burn-only units in 2002 for pre-burn conditions and in 2003 for post-burn conditions. The lack of synchrony in our sampling was an artifact of our having to overlay the FFS study on the preexisting LHPIS design.

Firing techniques used in the prescribed burning were strip-head firing and tree-centered spot ignition (Weatherspoon et al. 1989). Weather conditions and flame lengths are given in Table 1.

Although the full FFS design includes mechanical thinning, prescribed fire, and their combination, in this paper we focus on the issue of how fire, as a single factor, affects belowground ecological components in relation to vegetation and fuel status, i.e., whether the site had been commercially thinned prior to fire or not. As such, it represents an attempt on our part to focus on a specific aspect of the larger FFS design that is of immediate interest to land managers. In addition, we did not include the untreated control units in this study, as the question on which we wished to focus was one of the effects of fire with and without thinning, not the effects of fire and/or thinning relative to an untreated site.

Soil Sampling and Laboratory Analysis

In each 10-ha FFS treatment unit ten 20 × 50-m (0.1-ha) random, permanent sampling plots were established on a 50-m grid and the corners marked with permanent posts. Four soil sampling points were located at each of the corners of the 0.1-ha plot, and one sampling point was located at the midpoint of each of the long sides of the 0.1-ha plot. In June–August of 2001–2003 soil samples to 10-cm depth were taken from those six points in each sample plot as follows: thin + burn pre-fire 2001 (after thinning was completed), thin + burn post-fire 2002, burn-only pre-fire 2002, and burn-only post-fire 2003. Soil samples on successive dates in each treatment unit were taken within 1.0 m of those from the previous year. All samples were returned to the laboratory under refrigeration. Each sample was passed through a 5-mm sieve to remove stones and root fragments. Sieved, air-dried soil samples were extracted with 0.5 M K_2SO_4 for NO_3^-, NH_4^+ (Olsen and Sommers 1982) and analyzed using the microtiter methods of Hamilton and Sims (1995).

Estimation of nitrogen (N) mineralization and nitrification for all study plots was done using aerobic, in situ incubations following the method of Raison et al. (1987). Groups of three 10-cm-deep polyvinyl chloride (PVC) soil cores were taken at each of the six sampling points around each permanent sampling plot (n = 720). One core was returned to the lab immediately, whereas the remaining two incubated in situ for 20–30 d. One of the in situ cores was covered with a PVC cap while the other remained open. As the results from capped and uncapped cores were not significantly different, they were pooled for later data analysis. All three cores from a given sampling point were extracted and analyzed for inorganic N as indicated above. Net N mineralization was calculated as the difference in total inorganic N (NO_3^- + NH_4^+) concentration between the initial samples and those that incubated for 20–30 d. Net nitrification was calculated as the difference in NO_3^- in the incubated and initial samples. Proportional nitrification was estimated by dividing the net NO_3^- accumulation due to nitrification by total amount NH_4^+ available to be nitrified (initial NH_4^+ + net N mineralization).

Two additional soil samples for analysis of acid phosphatase, chitinase, and phenol oxidase activity were taken at opposite corners of each permanent sample plot during each sampling year (n = 240). Enzyme activities were analyzed 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 mM 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 3.1.3.2) and chitinase (EC 3.2.1.14) activities 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 3,000 × 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 M NaOH was added to halt enzymatic activity and facilitate color development. Prior to spectrophotometric analysis at 410 nm, each sample of the supernatant was diluted with 8.0 mL of distilled, deionized water.

Phenol oxidase (EC 1.14.18.1, 1.10.3.2) activity was measured by oxidation of L-DOPA (L-3,4-dihydroxyphenylalanine) during 1-h incubations at 20–

22°C. Following incubation, samples were centrifuged as above and analyzed at 460 nm without dilution. Parallel oxidations using standard horseradish peroxidase (Sigma Chemical, St. Louis, MO) were used to calculate the L-DOPA extinction coefficient.

Organic carbon (C) and total N were determined by oxidation/fluorescence on a Carlo Erba CN analyzer (Carlo Erba, Milan, Italy) after grinding air-dried soil samples to pass through a 0.32-mm-mesh screen.

Data Analysis

All response variables were either normally distributed or could be transformed to normality with a square root transformation. As the prescribed fires applied to the burn-only and thin + burn treatments occurred in successive growing seasons, this experiment was not a 2 × 2 factorial design with years and fire as main effects. Instead, we treated it as two separate experiments, each with a completely randomized design, and evaluated the effect of fire on the burn-only and thin + burn units as independent one-way analyses of variance (SAS Institute 2004). Statistical significance is reported at $P = 0.05$.

RESULTS

Fire significantly reduced soil organic C in the burn-only treatment ($P < 0.001$) but not in the thin + burn treatment ($P < 0.188$) (Figure 1a). Fire reduced soil organic C in the burn-only treatment by an average of 29%. Similarly, fire significantly affected soil C:N ratio in the burn-only ($P < 0.001$) but not in the thin + burn treatment ($P < 0.266$) (Figure 1b). In the burn-only treatment, soil C:N ratio increased by 18%. Thus, fire significantly reduced both organic matter quantity and quality in units that had not been mechanically thinned, but not in units that had been thinned prior to burning.

In the burn-only units there was no significant effect of fire on either net N mineralization rate ($P < 0.987$) (Figure 2a) or net nitrification ($P < 0.874$) (Figure 2b). In contrast, in the treatment units that were mechanically thinned prior to burning, fire resulted in a trend toward a reduction in net N mineralization ($P < 0.097$) (Figure 2a) and a significant reduction in net nitrification ($P < 0.029$) (Figure 2b). The reduction in net nitrification rate due to burning in the thin + burn units averaged 31%. Total inorganic N (TIN) in the soil solution increased significantly as a result of fire in both the burn-only and the thin + burn treatments ($P < 0.001$ in both) (Figure 2c).

Acid phosphatase activity was significantly reduced by fire in both treatments ($P < 0.001$ burn-only; $P < 0.013$ thin + burn) (Figure 3a). Acid phosphatase activity was reduced by an average of 42% in the burn-only treatment but by an average of 17% in the thin + burn treatment. Chitinase activity was reduced significantly by fire in the thin + burn ($P < 0.028$) but not in the burn-only treatment ($P < 0.116$) (Figure 3b). Phenol oxidase activity was not significantly affected by fire in either treatment ($P < 0.103$ burn-only; $P < 0.137$ thin + burn) (Figure 3c).

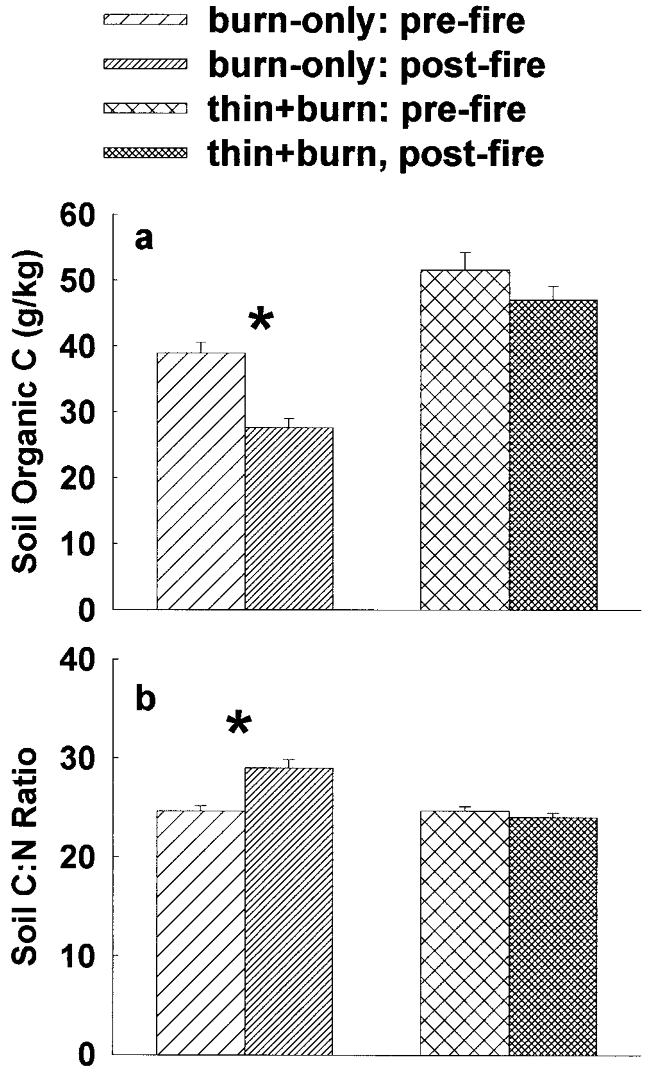

Fig. 1. Soil organic C (a) and C:N ratio (b) before and 1 y after fire (2001 and 2002 for thin + burn treatment; 2002 and 2003 for burn-only treatment) at the Goosenest Adaptive Management Area, northern California. Histogram bars denote means with standard errors of the means; significant differences at $P = 0.05$ are indicated by asterisks.

DISCUSSION

The primary objective of this study was to assess proximate belowground responses to prescribed fire, alone and in combination with pre–commercial mechanical thinning. Although the larger National Fire and Fire Surrogate Study, of which this study is a part, was designed to be a long-term analysis of the efficacy of these and other treatments for reducing wildfire hazard and improving ecosystem sustainability, we present here a more focused assessment of the proximate effects of fire in the Southern Cascades FFS study site. We do so both as a benchmark against which to evaluate longer-term ecosystem responses and for compar-

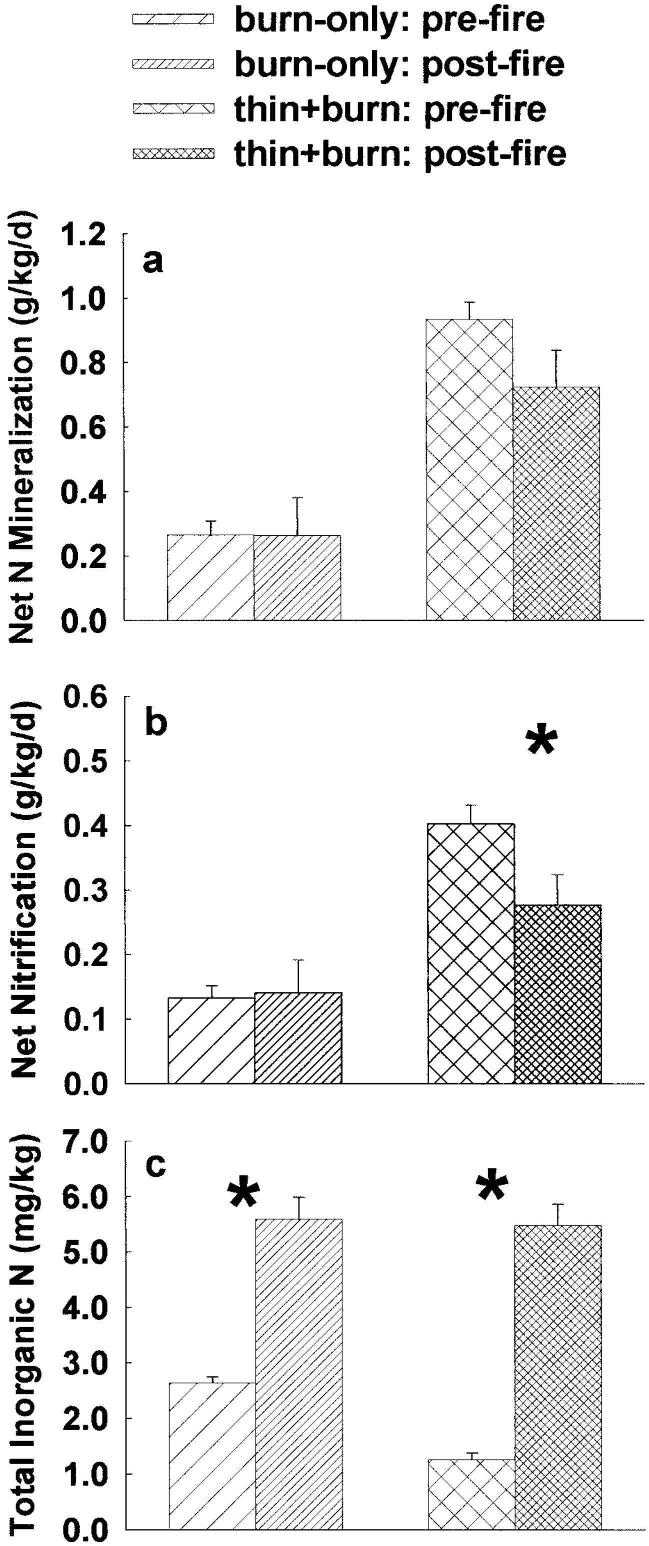

Fig. 2. Net N mineralization rate (a), net nitrification rate (b), and total inorganic N (c) before and 1 y after fire (2001 and 2002 for thin + burn treatment; 2002 and 2003 for burn-only treatment) at the Goosenest Adaptive Management Area, northern California. Histogram bars denote means with standard errors of the means; significant differences at $P = 0.05$ are indicated by asterisks.

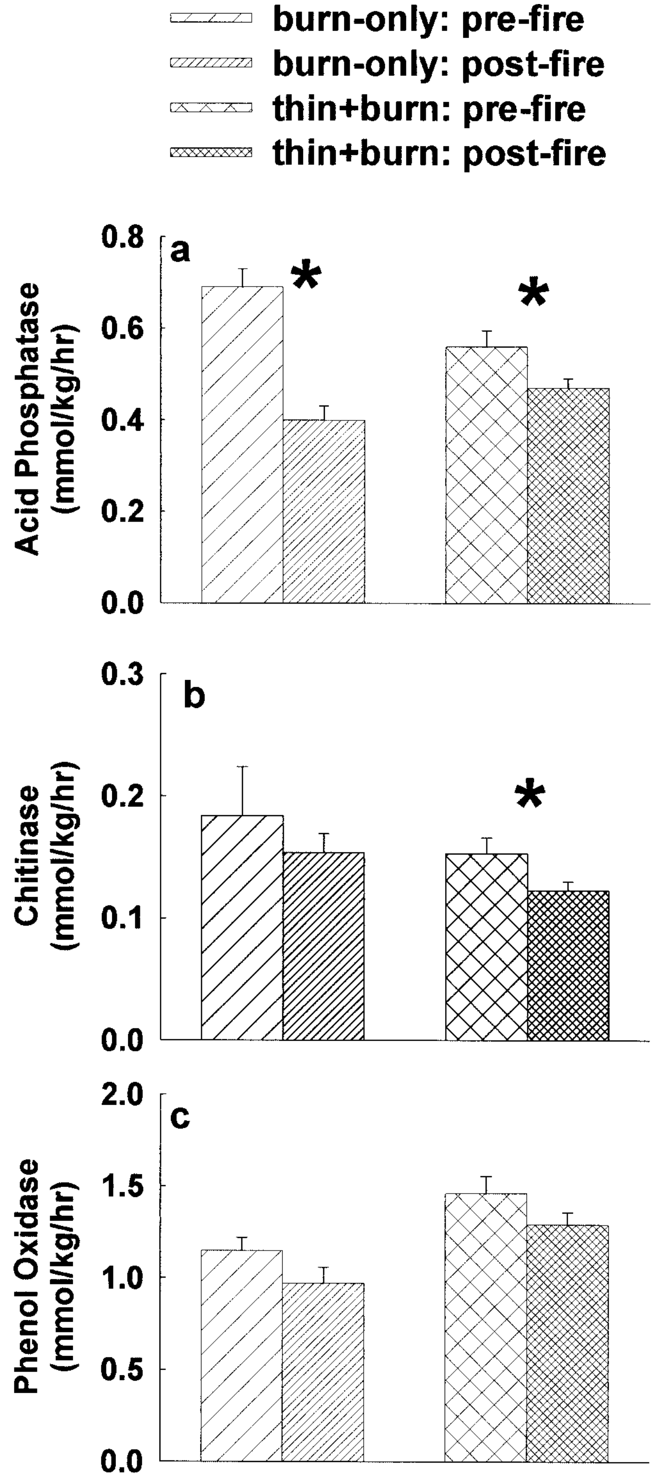

Fig. 3. Activity of acid phosphatase (a), chitinase (b), and phenol oxidase (c) before and 1 y after fire (2001 and 2002 for thin + burn treatment; 2002 and 2003 for burn-only treatment) at the Goosenest Adaptive Management Area, northern California. Histogram bars denote means with standard errors of the means; significant differences at $P = 0.05$ are indicated by asterisks.

ison with the existing fire-effects literature, most of which focuses on first-year effects.

When compared with pre-burn conditions, fire reduced soil organic matter quantity in the burn-only treatment, but not in the treatment units that had been mechanically thinned prior to burning. High pre-burn soil C content coupled with low fire severity may explain the lack of significant change in organic matter quantity in units that received thinning prior to prescribed fire. Other studies of mechanically thinned coniferous forests have also noted high soil C after logging, although post-harvest increases in soil C did not occur in the majority of studies reviewed by Johnson (1992). However, in two examples from mixed-conifer forests, increases in mineral soil C of 18% and 23% after whole-tree harvesting and 6 y after a clear-cut harvest, respectively, were reported; these increases may be attributed to the addition of slash to the forest floor, mixing of organic matter into mineral soil layers, and increased decomposition rates following harvesting (Johnson 1992).

The loss of soil organic matter is largely dependent upon the temperature and intensity of a fire (Ahlgren and Ahlgren 1960); prescribed burning generally results in increased soil C near the soil surface, but higher-severity fires have been shown to decrease soil C (Johnson 1992). Carbon can be added to the soil when charcoal from burned forest floor material is incorporated into the soil (Johnson 1992), and this can result in overly conservative estimates of the loss of soil organic C during a fire (Johnson and Curtis 2000). The significant loss of organic matter in the burn-only treatment could have been due either to loss via combustion during the fire or to increased microbial mineralization of organic matter after the fire (Johnson and Curtis 2000). As the results from our acid phosphatase activity assays do not support the latter, the more likely explanation appears to be greater consumption of organic matter by fire in the burn-only treatment than in the thin + burn treatment. Although fire weather and flame lengths were similar during the fires in the burn-only and thin + burn treatments, flame length (fire intensity) is not directly correlated with fire severity (loss of forest floor organic matter). For example, a slow-moving fire with low flame lengths may sustain greater soil heating and organic matter combustion than a relatively faster-moving fire with greater flame lengths (Busse et al. 2004).

More important to the difference in organic matter loss may have been the spatial continuity of the fuel bed. Our visual observations indicate that the activities associated with the thinning resulted in some mixing of litter, duff, and mineral soil in areas of particularly heavy vehicular and human traffic. This, in turn, could have resulted in a reduction of the exposure of some of that organic matter to direct combustion, thus preventing the prescribed fire from having as great an effect in the thin + burn treatment as it did in the burn-only treatment. Furthermore, although total pre-burn fine and coarse woody debris loads in the thin + burn treatment were equal to those of the burn-only treatment (both averaged 7.4 Mg ha^{-1}), fuels were not as continuous in the thin + burn as in the burn-only treatment (Schmidt 2005).

We observed an increase in C:N ratio as a result of fire in the burn-only treatment but no corresponding change due to fire in the thin + burn treatment. In the burn-only treatment, the C:N ratio of the soil organic matter was likely decreased by the combination of an addition of partially combusted woody material and charcoal, both of which have high C:N ratio, and a loss of relatively low C:N ratio organic matter to direct combustion. The lack of a similar effect on C:N ratio in the thin + burn treatment could have resulted from lower fire severity (as discussed previously) or a greater proportion of relatively low C:N ratio organic matter in the fuels (the result of green needles being deposited on the surface as a result of thinning operations), or both.

The N mineralization rate was essentially unaffected by prescribed fire, whereas nitrification rate was reduced significantly in the thin + burn treatment but not in the burn-only treatment. The processes of N mineralization are accomplished by a wide variety of soil organisms, including bacteria, fungi, and nematodes, whereas nitrification is accomplished primarily by a specialist guild of bacteria. Thus, modification of the chemical and biochemical conditions in the soil is more likely to have affected the latter more than the former (Raison 1979).

It was initially unclear to us why there was a lack of change in N mineralization in the burn-only units, as many studies have demonstrated increases in N mineralization after single fires (reviews by Raison 1979, Boerner 1982, Wan et al. 2001). Such increases are often attributed to the alteration of organic matter by fire in such a manner as to render it more susceptible to microbial attack, to increases in microbial activity, and to changes in microclimate. To the degree to which our enzyme activity assays reflect components of microbial activity, our results are not consistent with an increase in microbial activity. Similarly, if one assumes that C:N ratio and other properties associated with organic matter quality (e.g., phenolic content, sclerophyll index) vary in parallel, the increase we observed in C:N ratio would suggest that susceptibility to microbial attack would have been reduced rather than enhanced by fire in this site. Given the paucity of growing-season precipitation in this region (monthly averages for the June–August sampling period were 0.76 cm/mo for 2002 and 0.25 cm/mo for 2003 [USFS 2006]), changes in microclimate during the parts of the year that are otherwise suitable for mineralization may not have been sufficient to overcome the lack of rainfall. Thus, the lack of stimulation of N mineralization by fire in this study may have reflected a lack of the types of changes in microbial activity, organic matter quality, and microclimate that have occurred in sites where increases in N mineralization has been demonstrated.

Total inorganic N in the soil solution increased as a result of fire in both treatments, although thin + burn plots exhibited a 4-fold increase in TIN from pre-fire to post-fire years while levels in burn-only plots merely doubled. The difference in the magnitude of the increase in TIN is consistent with studies that report that thinning and the creation of canopy gaps as small as 0.07 ha in forests create areas of greater N availability (Prescott et al. 1992, Parsons et al. 1994, Bauhus and Barthel 1995).

This increase in mineral N was expected, as Wan et al. (2001) concluded from their meta-analysis of fire effects on N that TIN generally increases in coniferous forests during the initial post-fire growing season. The difference in magnitude of increase observed for TIN may be explained by difference in fire severity as lower-intensity fires transfer larger amounts of NH_4^+ to the soil than more severe fires, during which a greater amount of soil N is volatized (DeBano 1991). Mineral soil N may increase after fire due to transport of N from the forest floor (Wells et al. 1979), as well as from the release of NH_4^+ from soil minerals and clay-organic complexes during combustion, and both may be followed by conversion of NH_4^+ to NO_3^- due to nitrification (Russell et al. 1974, Raison 1979). However, such increases in available N are typically transitory and are likely to dissipate by the end of the second post-fire growing season (Wan et al. 2001).

We chose acid phosphatase as an indicator of overall microbial activity as the activity of this enzyme is often strongly correlated with microbial biomass (Kandeler and Eder 1993), microbial biomass N (Clarholm 1993), fungal hyphal length (Häussling and Marschner 1989), and N mineralization (Decker et al. 1999). Acid phosphatase activity was reduced significantly by both treatments. Similarly, Saa et al. (1993) reported 80–90% decreases in acid phosphatase levels after fire in gorse (*Ulex europaeus*) shrublands and pine plantations in Spain, and Boerner et al. (2000) reported decreases of similar magnitude to those we report here in their study of fire in mixed-oak (*Quercus* spp.) forests in eastern North America. Acid phosphatase activity may remain low for as long as 4 y after burning, at least in the jack pine (*Pinus banksiana*) forests of Ontario studied by Staddon et al. (1998).

In our study, acid phosphatase activity was reduced considerably more by the burn-only treatment (42%) than by the thin + burn treatment (16%). In a long-term (40+ y) study of microbial activity and soil organic matter in a Missouri oak flatwoods, Eivazi and Bayan (1996) demonstrated that more frequent burning causes greater reductions in acid phosphatase activity, β-glucosidase activity, and microbial biomass than did less frequent burning, and Staddon et al. (1998) demonstrated a direct correlation between fire severity and reduction in acid phosphatase activity in a jack pine forest. Thus, the greater reduction in acid phosphatase activity in our burn-only than the thin + burn treatment may again reflect greater effective fire severity in the former than the latter.

Chitinase activity reflects the use of chitin (the detrital remains of arthropods and fungi) as a source of both C and N by bacteria and, in some ecosystems, actinomycetes. As chitin is intermediate in its resistance to microbial metabolism, its synthesis is only induced when other, more labile C and N sources are absent (Handzlikova and Jandera 1993). As chitinase is produced only by bacteria, changes in chitinase activity relative to that of other enzymes give an indication both of changes in the relative contribution of bacteria to microbial activity as well as changes in organic matter along the gradient from labile to recalcitrant (Handzlikova and Jandera 1993).

In our study, chitinase activity decreased as a result of the thin + burn treatment, but not as a result of fire alone. Such a decrease in chitinase activity should indicate a reduction in the importance of chitin as a source of C and N for bacterial production. As our results indicate that organic matter content and quality both decreased following the burn-only treatment but not the thin + burn treatment, one would anticipate that chitinase activity would increase in the burn-only treatment and remain unchanged in the thin + burn treatment. This is the opposite of what we actually observed. We currently have no mechanistic explanation for this apparent contradiction.

It should be noted, however, that the degree of variability present in chitinase activity in our pre-burn data for the burn-only treatment was 3- to 4-fold greater than was the case in any other enzyme–treatment–year combination. This variability was the reason that the difference between pre-burn and post-burn years was not statistically significant in the burn-only treatment, despite similar absolute (0.03 mmol g^{-1} h^{-1} for both) and relative (16% and 20%) decreases in chitinase activity in the burn-only and thin + burn treatments. Whether this greater variability was a reflection of a difference in spatial heterogeneity between treatment units or an aberration in sampling and/or analysis is unclear.

The index of fungal activity we used was phenol oxidase, an enzyme produced primarily by white rot fungi, which is specific for highly recalcitrant organic matter such as lignin (Carlile and Watkinson 1994). Although phenol oxidase activity should not be considered a proxy for the abundance or activity of all fungi, it is a useful indicator of the activity of fungi that specialize on the breakdown of wood, bark, and other lignin-rich substrates (Carlile and Watkinson 1994). Based on this parameter, fungal activity was not affected by burning, alone or in combination with mechanical thinning. Given the preponderance of relatively recalcitrant materials in the forest floor and soils of this (and most other) coniferous forests and the relatively low severity of the fires, the lack of response by organisms that specialize on low-quality organic matter is not surprising. Taken together, our enzyme activity results suggest that the impact of fire may differ among types of soil organisms associated with decomposition, and those effects may be influenced by treatment type.

MANAGEMENT IMPLICATIONS AND CONCLUSIONS

This study demonstrates that fire has short-term effects on soil ecological properties, such as soil organic matter, N availability, and microbial enzyme activity, and that the combination of mechanical thinning and fire may have different effects from fire alone. Fire alone resulted in reduced soil organic matter content and increased C:N ratio, whereas the combination of a mechanical thinning treatment and burning did not affect soil organic matter. Activities associated with thinning may mix litter, duff, and mineral soil materials in such a manner as to make some of the organic matter less susceptible to combustion. Thus, the more continuous ground fuels and lower relative humidity in the burn-only treatment and the less continuous fuel bed in the more open thinned stand may have contributed to greater fire severity in the burn-only treatment than in the thin + burn treatment.

Soil organic matter is important to a productive forest ecosystem because of its role in stabilizing soil, maintaining soil conditions suitable for seedling establishment and growth, and supplying both nutrient storage and water-holding capacity. Thus, managers should be aware not only of the effect that management activities may have on soil organic matter, but also of the strong interactions that exist among stand density, fuel loading, fire behavior, and post-fire soil organic matter.

Our results also show that burning influences nitrification and available N in the soil, and that those effects differed between burn-only and thin + burn treatments. Based on prior studies in coniferous forests, the increases we observed in available N are likely to be transitory, and further study is required to determine if there will be longer-term effects of these treatments on the supply of N to trees.

The results of our assays of the activity of three enzymes that microbes secrete into the soil to digest soil organic matter are consistent with what one would expect if overall microbial activity was somewhat reduced by fire in these sites. The significant reduction in acid phosphatase and chitinase activities we observed suggest that there may have been a decrease in the activity of microbes that rely on more easily digested (labile) organic matter, and the lack of change in phenol oxidase activity suggests that the activity of organisms that specialize on recalcitrant organic compounds (such as wood-rotting fungi) did not likely change to any appreciable degree. We assume that whatever effect these fires had on microbial community structure is likely to dissipate as new litterfall restores the pre-fire nutritional characteristics of the forest floor and soil organic matter, though longer-term studies are required to verify this.

Prescribed fire following thinning resulted in a greater impact on nitrification and soil enzyme activities than did prescribed fire alone, whereas changes in soil organic matter content and C:N ratio were greater as a result of fire alone. Thus, for our mixed-conifer site in northern California, the application of prescribed fire to mechanically thinned stands has a greater impact on soil biological processes 1 y after burning, whereas soil C and organic matter quality are impacted more by fire in stands that were not mechanically thinned prior to burning. This study provides information useful for predicting the short-term, ecosystem-level effects of different forest restoration and wildfire hazard–reduction techniques in the widespread ponderosa pine ecosystem type.

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