Short- and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon[1]

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Abstract: The effects of prescribed underburning on soil total C pools, total and inorganic N pools, and in situ net N mineralization were examined during a 1-year study in ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) sites that had been experimentally burned 4 months, 5 years, or 12 years earlier. At the sites burned 4 months previously, total C concentration and inorganic N concentration increased significantly ($p < 0.1$) after prescribed burning, compared with unburned controls. However, inorganic N concentration declined during the 1-year duration of this study to reach the levels of the control plots at the end of the second growing season. At the site burned 5 years previously, total C and N concentrations, inorganic N concentration, and net N mineralization decreased significantly after prescribed burning. At the sites burned 12 years previously, N and C pools were not affected, but net N mineralization decreased significantly after burning. The decrease in net N mineralization is likely caused by a decrease in substrate quantity 5 years after burning, and by changes in substrate quality 12 years after burning. A long-term decrease in net N mineralization in the N-poor ponderosa pine stands of central Oregon may result in a decrease in long-term site productivity and may explain the observed pattern of long-term decrease in stand growth after prescribed burning.

Résumé : Les effets du brûlage dirigé sur les pools de C total, de N total et de N inorganique du sol ainsi que sur la minéralisation nette de N *in situ* ont été évalués dans une étude d’une durée d’un an réalisée dans des stations de pin à bois lourd (*Pinus ponderosa* Dougl. ex P. & C. Laws.) qui avaient été brûlées expérimentalement 4 mois, 5 ans et 12 ans auparavant. Dans les stations brûlées 4 mois auparavant, les concentrations de C total et de N inorganique ont augmenté significativement ($p < 0{,}1$) après brûlage, comparativement aux aires témoins non brûlées. Cependant, la concentration de N inorganique a diminué pendant l’année qu’a durée cette étude pour atteindre les niveaux des parcelles témoins à la fin de la deuxième saison de croissance. Dans la station brûlée 5 ans auparavant, les concentrations de C total, de N total et de N inorganique, de même que la minéralisation nette de N, ont décru significativement après le brûlage dirigé. Dans les stations brûlées 12 ans auparavant, les pools de N et de C n’ont pas été affectés mais la minéralisation nette de N a diminué significativement après brûlage. Cette diminution de la minéralisation nette de N est probablement attribuable à la baisse de la quantité du substrat 5 ans après brûlage et aux modifications de sa qualité 12 ans après brûlage. Une diminution prolongée de la minéralisation nette de N dans les stations de pin à bois lourd pauvres en azote de la région centrale de l’Orégon pourrait entraîner en une baisse de la productivité à long terme de la station et pourrait expliquer les patrons observés de diminution de la croissance des peuplements à long terme après brûlage dirigé.
[Traduit par la Rédaction]

Introduction

After decades of fire suppression, forest managers are increasingly using low-intensity, prescribed underburning in ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) forests to reduce fuel loads and fire hazards. These forests had a pre-European settlement regime of frequent, low-intensity surface fires. In central Oregon, fire-recurrence intervals varied from 6 to 20 years; since the early 1900s, however, fire has been virtually eliminated (Bork 1985). The suppression of fire has caused dramatic changes in ecosystem structure and function. These changes include increased tree density, decreased tree growth and vigor, higher susceptibility to diseases and pests, higher fuel loads, and changes in species composition (see Kilgore 1981).

The effects of fire or its suppression on long-term site productivity are unclear. Several authors have inferred that fire suppression results in stagnated nutrient cycles, and thus, decreased nutrient availability and tree growth (Biswell 1973; Covington and Sackett 1990). Cochran and Hopkins (1991) observed, however, that current growth of managed ponderosa pine stands was higher than the growth predicted from yield tables developed shortly after fire exclusion. They attributed the faster growth under fire suppression to an increase in soil productivity without fire.

First-entry prescribed fire in managed ponderosa pine stands in the Pacific Northwest has resulted in a decrease in tree

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growth that may last for 12 years or more (Grier 1989; Landsberg 1992). Ponderosa pine growth in central Oregon is severely N limited (Cochran 1979). The decrease in growth has been accompanied by a 14% to 33% reduction in foliar N content 4 years after burning, a much greater reduction than the initial losses caused by crown scorching (Landsberg et al. 1984). In these nutrient-poor sites, prescribed burning often causes heavy losses of N (Nissley et al. 1980; Landsberg 1992; Shea 1993), which may increase N stress and reduce productivity.

Although the short-term effect of prescribed fire in ponderosa pine ecosystems is an increase in available N (Covington and Sackett 1986, 1992; Kovacic et al. 1986; White 1986), that increase lasts only for several months. After the initial pulse, the amount of N available for plant uptake and growth is determined by its mineralization rates; the effects of fire on this process have not been studied. Prescribed burning can affect long-term mineralization rates by decreasing the total amount of N available, by changing the quality of the remaining organic matter (Klemmedson 1976; Vance and Henderson 1984), and by modifying the microclimate and biological activity of the soil (Raison et al. 1986). The objectives of this study were to determine both short- and long-term effects of a first-entry prescribed fire on N mineralization, N availability, and total N and C concentrations at experimental sites.

Materials and methods

Study sites

This study was carried out on five sites, Lava Butte, Annabelle, Swede Ridge, Sugar Cast, and Far East, in the Deschutes National Forest near Bend, Oregon (44°N, 121°W). The sites were established and are maintained by personnel of the USDA Forest Service Silviculture Laboratory in Bend as part of long-term research on the effects of prescribed underburning in ponderosa pine ecosystems.

The climate of the area is continental and dry, with hot, dry summers and cold winters. In Bend, mean annual precipitation is 29.3 cm, which falls mainly as snow between November and April. Mean monthly temperatures range from –0.7°C in January to 17.3°C in July (National Oceanic and Atmospheric Administration 1991, 1992); however, all of the study sites are cooler than Bend. Annual precipitation for the sites is estimated at 65 cm for Annabelle and from 43 to 50 cm for the remaining sites (D.M. Larsen, 1976, unpublished document on file at Deschutes National Forest). During the year of the study, the winter was exceptionally warm and dry. Winter precipitation was 35% of average, and mean monthly temperatures were about 2°C warmer than average (National Oceanic and Atmospheric Administration 1991, 1992).

The soils are xeric Vitricriands that developed in a layer of Mazama volcanic pumice and ash 0.4 to 1.0 m deep deposited 7000 years ago. Soil textures range from loamy sand to coarse loamy sand (Landsberg 1992; Shea 1993). Forest floor mass, including the duff layer, ranged from 78 to 85 $\mathrm{Mg \cdot ha^{-1}}$ (Shea 1993). The terrain is flat or has a moderate slope. Elevation ranges between 1210 m (Annabelle) and 1540 m (Swede Ridge and Far East). All sites belong to the ponderosa pine community type, except Annabelle, which belongs to the more mesic, mixed-conifer type (Volland 1988). The area is covered by even-aged, second-growth ponderosa pine that regenerated naturally after logging in the 1920s. The sites were thinned in the 1960s and the residues were left in place. At the beginning of this study, stand density ranged from 480 to 780 trees/ha and basal area ranged from 24 to 36 $\mathrm{m^2 \cdot ha^{-1}}$ (Cochran and Hopkins 1991; Landsberg 1992).

Lava Butte was burned in 1979, Annabelle in 1986, and Swede Ridge, Sugar Cast, and Far East in 1991. The sites burned in 1991 follow a gradient in productivity; site indices are 35, 31, and 25 m at 100 years, respectively, based on Barrett (1978). Site indices for Lava Butte and Anabelle are 31 and 27 m, respectively, at 100 years, based on Barrett (1978). Soil measurements at the sites began in September 1991, which was 12 years, 5 years, and 4 months, respectively, after the three burnings. Hereafter, Lava Butte will be referred to as year 12, Annabelle as year 5, and Swede Ridge, Sugar Cast, and Far East as year 0. Tree growth measured in both year-5 and year-12 sites had decreased significantly after prescribed burning (Landsberg 1992).

Treatments and experimental design

At each site, two treatments were applied: spring prescribed underburning and no-burn control. The fires were of low intensity (less than 300 $\mathrm{kW \cdot m^{-1}}$ fireline intensity) and consumed less than 60% (typically about 40%) of the forest floor (Landsberg 1992; Shea 1993). The experimental design at year-5 and year-12 sites was completely randomized, with 4 plots at each site, 2 burned and 2 unburned. At year-0 sites, the experimental design was a randomized block, where each site was a block with 2 plots, 1 burned and 1 unburned (6 plots total). Thus, each treatment was replicated 2 times at the year-12 site (Lava Butte), another 2 times at the year-5 site (Annabelle), and a total of 3 times at the year-0 sites (Swede Ridge, Sugar Cast, and Far East). Each plot was 25 × 25 m and was surrounded by a buffer strip at least 10 m wide.

Soil sampling and analysis

Sequential incubations in minimally disturbed soil cores (Raison et al. 1987) were used to measure N fluxes in situ during 1 year. Fluxes were measured during four periods that corresponded roughly to each season. Measurements started in September 1991; the plots were sampled again in November and in April (after complete snowmelt), June, and September 1992. The control plot at Swede Ridge could not be sampled in November; therefore, incubation in this plot lasted from September until April. At the beginning of every period, fivegroups of three PVC tubes (30 cm long, 5 cm diameter) were driven into the soil at randomly located points within each plot. At year 0, six groups of three tubes per plot were used.

In each group, one tube was immediately removed for initial analysis of the unconfined soil, as explained below. The other two cores were left in place for field incubation, one capped with a plastic cup to prevent leaching and the other left open. After field incubation, the tubes were removed and the soil cores were carefully extracted. The undecomposed litter was discarded and each core was divided into 0–5 and 5–15 cm depth layers and bulked to yield one sample per plot for each depth and type of core (unconfined, covered, and uncovered). At the same time, a new set of tubes was installed for the next incubation period. The soil samples were kept at 4°C and carried to the laboratory. The soil samples from September and November 1991 were frozen at –18°C until analysis, but the samples from the other dates were processed within 3 days of sampling.

In the laboratory, large roots and gravel were discarded, then a 10-g field-moist subsample was extracted with 50 mL of 2 M KCl by shaking for 1 h. The suspension was allowed to equilibrate for 12 h and was then filtered. Ammonium and nitrate were determined colorimetrically in an automatic autoanalyzer (Alpkem, RFA). A Carlo-Erba C-N-S analyzer was used to determine total soil C and N concentrations on one composite sample per plot and depth. This sample was obtained by bulking equal volumes of soil from the unconfined soil cores from each plot and depth obtained from all the sampling dates. The soil was sieved to pass a 2-mm mesh. Moisture content was determined gravimetrically, with oven-drying at 100°C. All C and N values were calculated with this same ovendry weight basis.

For each incubation period, N fluxes were determined for each soil depth as follows. Net N mineralization was determined by subtracting the concentration of inorganic N in the unconfined soil at the beginning of the period from the inorganic N concentration in the covered-core soil at the end of the period. Maximum loss of N through leaching was determined by subtracting the inorganic N concentration

Table 1. Carbon and nitrogen concentrations and C/N ratios in the 0–5 cm depth soil layer.

	Total C (%)		Total N (%)		C/N ratio	
Site	Control	Burned	Control	Burned	Control	Burned
Year 0	2.91	3.92	0.122	0.139	23.8	28.2
	(0.77)	(0.66)	(0.026)	(0.015)	(1.6)	(1.6)
Year 5	5.57	3.11	0.182	0.125	30.5	24.9
	(0.59)	(0.20)	(0.005)	(0.009)	(2.4)	(0.2)
Year 12	3.35	3.54	0.135	0.130	24.9	27.4
	(0.39)	(0.39)	(0.015)	(0.001)	(0.2)	(3.1)

Note: Standard error is in parentheses; $n = 3$ composite samples per treatment at year 0 and $n = 2$ composite samples per treatment at year 5 and year 12.

Table 2. Carbon and nitrogen concentrations and C/N ratios in the 5–15 cm depth soil layer.

	Total C (%)		Total N (%)		C/N ratio	
Site	Control	Burned	Control	Burned	Control	Burned
Year 0	1.49	1.58	0.078	0.072	19.0	21.9
	(0.23)	(0.17)	(0.010)	(0.003)	(1.7)	(1.5)
Year 5	1.85	1.41	0.070	0.067	26.4	21.0
	(0.31)	(0.10)	(0.004)	(0.004)	(5.8)	(0.4)
Year 12	1.26	1.29	0.075	0.075	16.9	17.2
	(0.02)	(0.14)	(0.002)	(0.009)	(0.7)	(0.1)

Note: Standard error is in parentheses; $n = 3$ composite samples per treatment at year 0 and $n = 2$ composite samples per treatment at year 5 and year 12.

in the uncovered-core soil at the end of the period from the concentration in the covered-core soil at the end of the period. Plant N uptake was calculated by subtracting the inorganic N concentration in the unconfined soil at the end of the period and the N leaching from the concentration in the covered-core soil at the end of the period (Raison et al. 1987). The net N mineralization results are equivalent to those of the buried-bag incubation method (see Binkley and Hart 1989 for a review).

Statistical analyses

In this study, the prescribed burning was carried out at different sites each time. Therefore, the different times since burning cannot be considered as a sequence at a single site, but rather as separate studies, which had to be analyzed separately.

Analysis of variance (ANOVA) was used to test the effects of prescribed burning on total C and N concentrations. Inorganic N concentrations and N fluxes, which were measured for several dates or periods in each plot, were analyzed with repeated measures ANOVA (Winer 1971; SAS Institute Inc. 1989). This method provided an overall test for the effect of treatment across the dates or periods, although the effect may not be significant at a given date. The test for treatment effect was equivalent to an ANOVA on the sum or average of the dependent variable over all sampling dates. Therefore, when the dependent variable was inorganic N concentration at each sampling date, the results of the test were interpreted as the effects of fire on the average inorganic N concentration during the five sampling dates. When the dependent variable was the N flux during each incubation period, a cumulative measure, the results of the test were interpreted as the effects of fire in the cumulative yearly flux, the net annual mineralization. In addition, repeated measures ANOVA provided an overall test for the effects of the sampling date or measurement period and its interaction with the treatment. A significant result here indicated that the variable of interest showed a seasonal pattern. The statistical tests for effects that included the repeated measure were corrected with the Huynh and Feldt ε (SAS Institute Inc. 1989). Data were transformed when necessary. Results were considered significant when $p < 0.1$, but the actual p-values were reported. Steel and Torrie (1980) suggested using $\alpha = 0.1$ for field experiments having smaller numbers of replicates for each treatment, since detection of differences at other significance levels, such as $\alpha = 0.05$ or $\alpha = 0.01$ may be more difficult unless large real differences exist. All statistical analyses were carried out with the SAS statistical package (SAS Institute Inc. 1989).

Results

Total carbon and nitrogen concentrations

After burning in the surface layer (0–5 cm), total C concentration increased significantly ($p = 0.017$) at year 0, decreased ($p = 0.043$) at year 5, and had negligible changes at year 12 (Table 1) compared with the control plots. At year 5, C concentration in the control-plot surface layer was 1.8 times as much as that in the burned plots. Total N concentration in the soil surface layer followed a similar pattern, increasing in the burned plots at year 0, although not significantly, decreasing significantly ($p = 0.031$) at year 5, and showing no difference at year 12. The C/N ratio increased significantly ($p = 0.033$) after burning at year 0, but it was not significantly affected by fire at year 5 and year 12. In the 5–15 cm soil layer, neither concentration of C or N nor C/N ratios changed significantly after prescribed burning, regardless of the time since the fire (Table 2).

At year 0, the ANOVA showed significant differences among the three sites in total C ($p = 0.009$) and N ($p = 0.065$) concentrations in the surface layer, regardless of treatment. This pattern may be related to the productivity of the site: mean total C and N concentrations were 4.8% and 0.17%, respectively, at Swede Ridge, the most productive site; 2.9% and 0.11% at Sugar Cast, the intermediate site; and 2.5% and 0.10% at Far East, the least productive site. In the deeper, 5–15 cm layer, the same trend was present, although differences were not statistically significant (data not shown).

Inorganic N concentrations

At year 5 and year 12, the concentration of NO_3^- was below detection (detection limit was approximately 0.0025 mg NO_3^--N·kg soil^{-1}) in most of the samples. When NO_3^- was detected, the concentration was very low (less than 2%) compared with the concentration of NH_4^+-N. The concentrations of NO_3^--N and NH_4^+-N were summed, and only the results for total inorganic N concentration are presented herein. At year 0, NO_3^- concentrations were somewhat higher than at year 5 and year 12, although they were often below detection.

In the surface layer, inorganic N concentrations increased significantly ($p = 0.014$) after burning at year 0, but decreased significantly ($p = 0.026$) at year 5, and had no significant change at year 12 (Fig. 1). The effect of sampling date on concentration of inorganic N was highly significant at all sites ($p < 0.005$), which indicates that the concentrations changed seasonally, regardless of treatment. However, at year 0 and year 5, the seasonal trend of inorganic N was different for burned ($p = 0.1$) and control ($p = 0.002$) plots, indicating an interaction between burning and sampling date. At year 0, inorganic N concentration was highest in the burned plots during the first sampling dates a few months after the fire and decreased thereafter to the levels of the unburned plots. At year 5, inorganic

Fig. 1. Inorganic N concentration in the 0–5 cm depth soil layer in burned and control plots. Error bars denote standard errors; $n = 3$ composite samples per treatment at year 0 and $n = 2$ composite samples per treatment at year 5 and year 12.

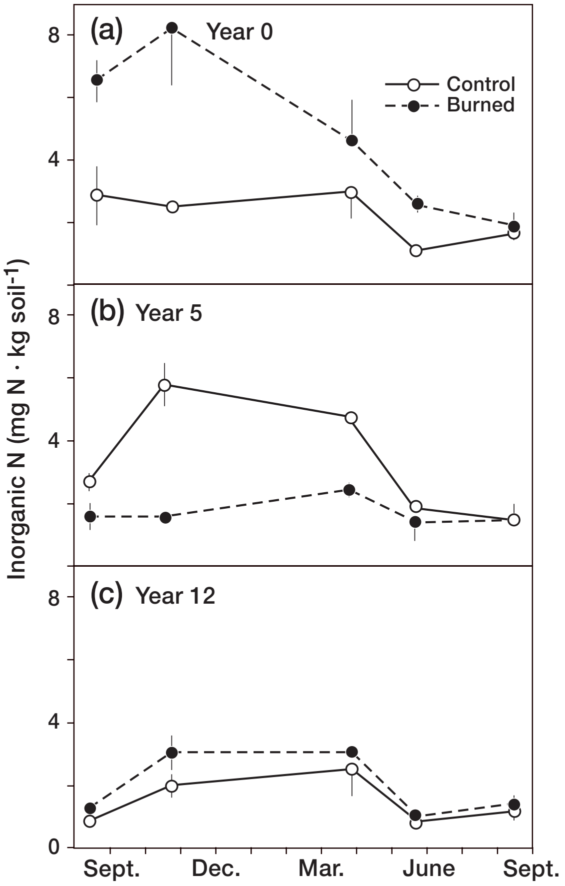
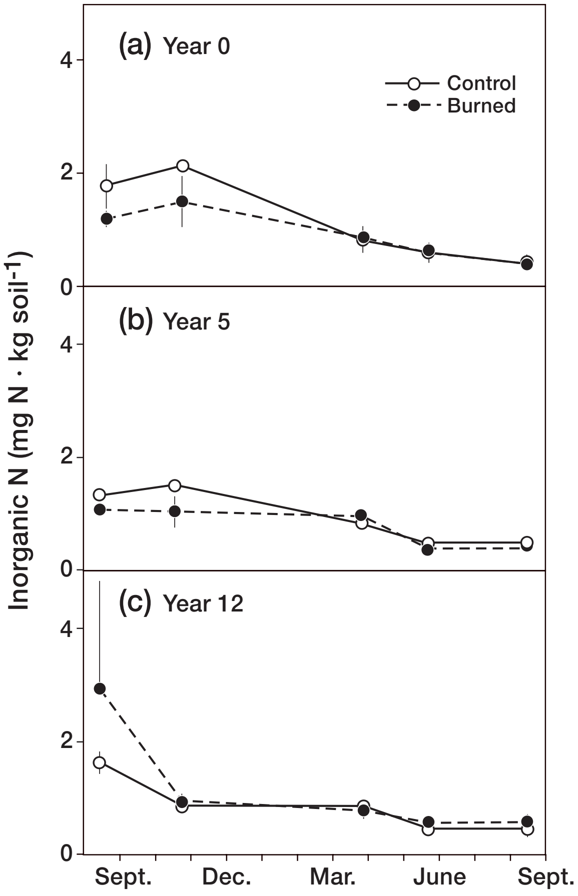


Fig. 2. Inorganic N concentration in the 5–15 cm depth soil layer in burned and control plots. Error bars denote standard errors; $n = 3$ composite samples per treatment at year 0 and $n = 2$ composite samples per treatment at year 5 and year 12.



N concentration in the unburned plots was highest during winter and decreased to the levels of the burned plots at the other seasons. At year 12, inorganic N concentration was highest in November and April in both the burned and unburned plots.

In the 5–15 cm soil layer, inorganic N concentration was lower than that in the surface layer, and did not change significantly after prescribed burning (Fig. 2), regardless of the time since the fire. Nitrate concentration at year 0 was low compared with NH_4^+, and although it was several times higher in the burned plots than in the control plots across all sampling dates, the difference was not statistically significant (Fig. 3).

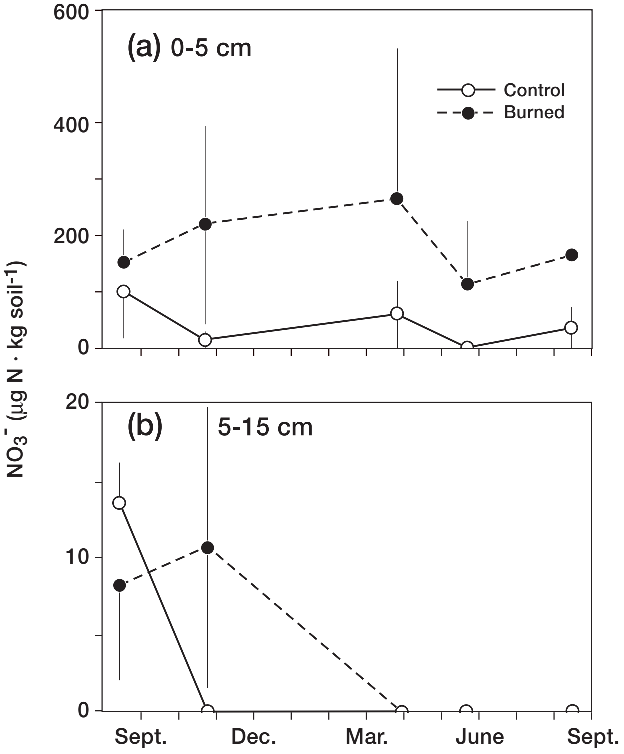
Net nitrogen mineralization and nitrogen fluxes

The net annual N mineralization rates at our sites ranged from 2.0 to 6.4 kg N·ha^{-1}, assuming a bulk density of 0.75 g·cm^{-3} in the surface soil layer of these ponderosa pine stands (Landsberg 1992). In the surface soil, net annual N mineralization rates decreased significantly after prescribed burning at year 5 (from 5.8 to 3.5 kg N·ha^{-1}; $p = 0.085$) and year 12 (from 6.4 to 2.0 kg N·ha^{-1}; $p = 0.086$), but not at year 0 (Fig. 4). At year 0, net N mineralization in the burned plots tended to be lower than that in the unburned plots, but very high values in Sugar Cast during winter, and especially in Far East during summer, obscured this pattern.

In the 5–15 cm layer, annual net N mineralization did not change significantly after the fire, regardless of the time since burning (Fig. 5). At this depth, there were very low net mineralization rates and there often was net immobilization. Immobilization tended to occur during spring, and mineralization, during summer in the 5–15 cm layer at all sites (Fig. 6). The monthly mineralization rates were very low, however, and the differences between seasons were not statistically significant.

There was a significant difference ($p = 0.001$) in net N mineralization rates among incubation periods only at year 5 in the surface layer, where N mineralization was highest during winter (Fig. 4). Here, the interaction between treatment and incubation period was also significant ($p = 0.045$); separate ANOVAs for each period indicate that burning appeared to significantly decrease N mineralization only during winter ($p = 0.003$), the season with the highest mineralization rate. In this study, the length of the incubation periods varied greatly; thus, net N mineralization during a given period was the result of both the actual rates of mineralization and the length of the period. To better compare net N mineralization rates during the different seasons, the rates for each period were normalized to a monthly basis, and the statistical analyses repeated. Again, the 0–5 cm layer showed a seasonal difference ($p = 0.001$) only at year 5, with a higher monthly mineralization rate during the

Fig. 3. Nitrate (NO_3^-) concentration in the 0–5 and 5–15 cm depth soil layers in burned and control plots at year 0. Error bars denote standard errors; $n = 3$ composite samples per treatment.



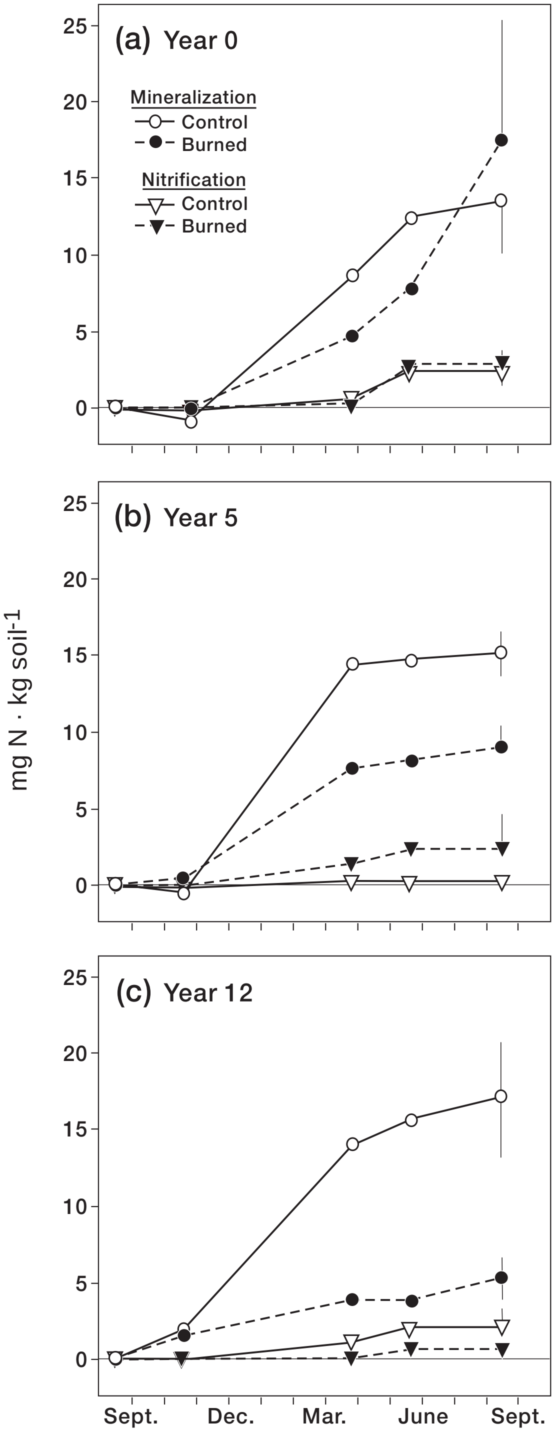
winter period (Fig. 6). Although not significant at the other sites, mineralization rates tended to be higher during winter and spring.

In the surface layer, annual net nitrification showed little change after prescribed burning, regardless of the time since fire (Fig. 4). Annual net nitrification was low, and the variability was very high compared with the absolute values. There were significant seasonal effects only at year 0 and year 12, where the rate of nitrification was highest during spring. In the 5–15 cm layer, prescribed burning appeared to have a significant effect on annual net nitrification at year 5 (Fig. 5). The actual values (0.0022 and 0.008 mg NO_3^-·kg soil^{-1}·year^{-1} in the control and burned plots, respectively) were negligible, however. Nitrification at this depth was very low in all the plots.

Discussion

The effects of prescribed fire were appreciable only in the surface (0–5 cm depth) soil layer, regardless of the time since burning. The following discussion will refer to this surface mineral soil, unless otherwise indicated. The effects of fire on this layer are most relevant because nutrient availability is concentrated in the first few centimeters of the young, pumice soil of central Oregon (Geist and Cochran 1991).

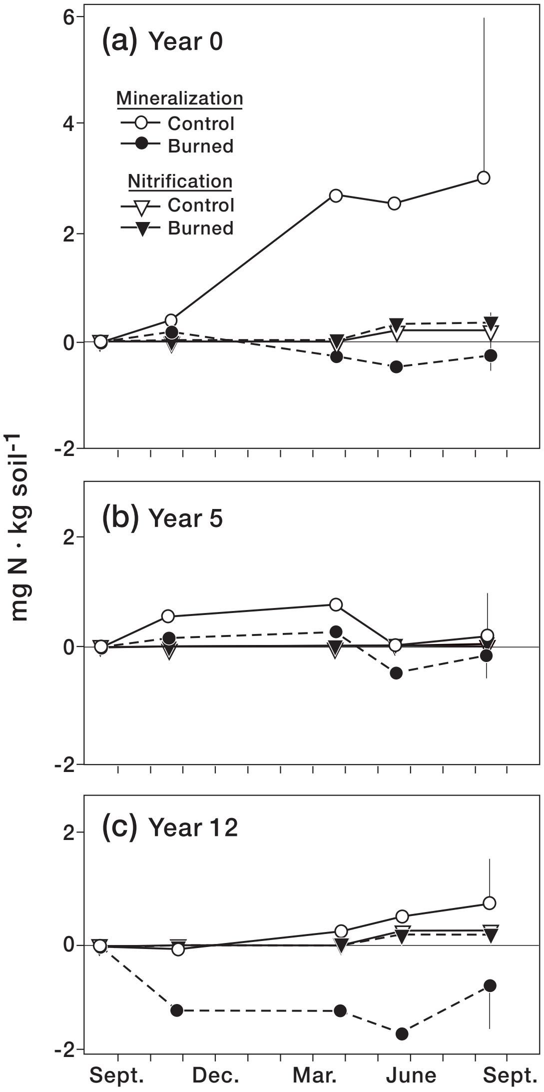
Fig. 4. Cumulative net N mineralization and nitrification in the 0–5 cm depth soil layer in burned and control plots. Error bars denote standard error of the annual cumulative values; $n = 3$ composite samples per treatment at year 0 and $n = 2$ composite samples per treatment at year 5 and year 12.



Short-term effects of prescribed burning

As expected, fire mineralized part of the organic matter on the forest floor and resulted in an increase in available N. Several months after burning, the mean inorganic N concentration in the year-0 burned plots was approximately 3 times higher than in the control plots, an increase within the range usually reported in the literature (Covington and Sackett 1986, 1992; Kovacic et al. 1986; White 1986). Covington and Sackett (1992), however, observed a 20-fold increase in inorganic N concentration in the soil of some of their stands immediately after

Fig. 5. Cumulative net N mineralization and nitrification in the 5–15 cm depth soil layer in burned and control plots. Error bars denote standard error of the annual cumulative values; $n = 3$ composite samples per treatment at year 0 and $n = 2$ composite samples per treatment at year 5 and year 12.



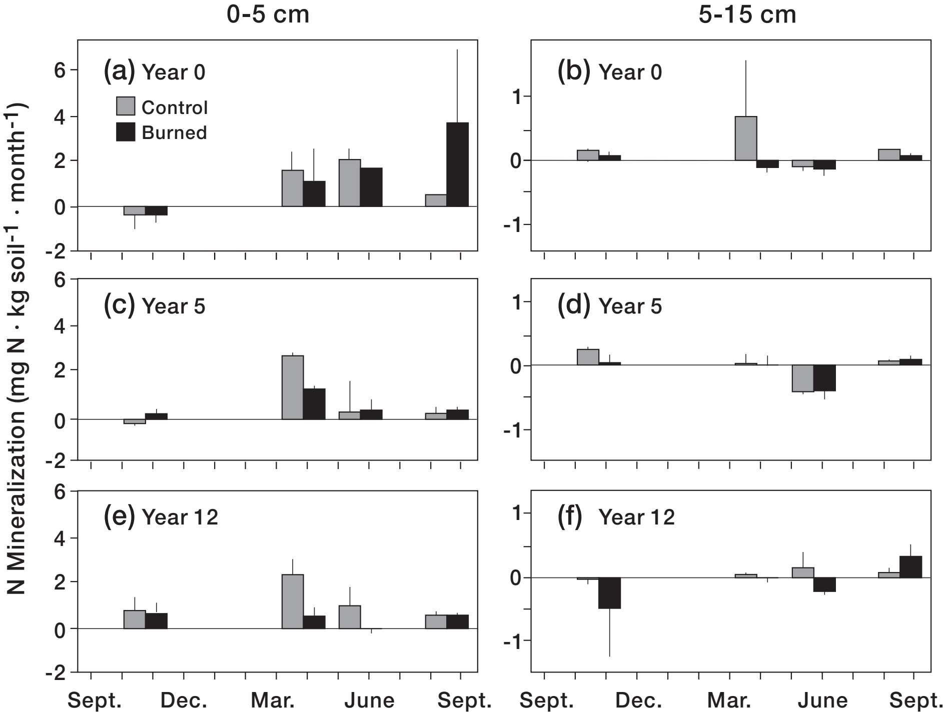
burning, which in some sites remained almost that high for the 1-year duration of their study. They attribute this very large increase to the high forest floor consumption (98.5 Mg·ha^{-1}) in these stands, even though they observed increases of the same magnitude after 7 months in other stands where only 19.2 Mg·ha^{-1} of the forest floor was consumed. In this study, average fuel consumption was 60 Mg·ha^{-1} (Shea 1993), yet both the magnitude of the increase and the actual inorganic N concentrations a few months after burning were several times lower than those reported by Covington and Sackett (1992).

Covington and Sackett (1992) suggested that the actual N volatilization losses after prescribed burning are often overestimated because they are not corrected by the increase in soil inorganic N concentration after the fire, which they believe may account for a significant portion of the losses. In our sites, inorganic N concentration in the burned plots increased only about 6 mg N·kg soil^{-1}, as measured 4 months after the fire. Surface soil bulk density in the area is typically 0.75 g·cm^{-3} (Landsberg 1992). Thus, the increase in inorganic N content in the first 5 cm of soil was about 2.25 kg N·ha^{-1}, a very small amount compared with the estimated mean losses of 414 kg N·ha^{-1} at our year-0 sites (Shea 1993). However, total N concentration in the burned plots increased by 170 mg N·kg soil^{-1}, which brings the total increment in soil N after the fire to 63.8 kg N·ha^{-1}, only 15.4% of the estimated volatilization losses. Prieto-Fernandez et al. (1993) also observed an increase in both organic and inorganic N in the upper 5 cm of mineral soil following a wildfire in a *Pinus pinaster* Sol. forest in Spain. The increase in total N concentration in the top 5 cm of mineral soil in their site was about 20%, whereas in our year-0 sites it was about 14%. In their work and in our study, however, most (98.0% and 96.5%, respectively) of the increased N was as organic N, that is, in forms not directly available to plants. Prieto-Fernandez et al. (1993) suggested that the increase in organic N in the surface mineral soils may have been partly due to permeation of N into the ashes from incompletely burned plant residues; other suggested mechanisms are the downward movement and later condensation of volatilized N compounds formed during combustion (DeBano et al. 1970; Mroz et al. 1980). The mean soil C/N ratio increased in the 0–5 cm layer at our year-0 sites, while decreasing at the *P. pinaster* wildfire site (Prieto-Fernandez et al. 1993), possibly because of the greater fire intensity at their site.

The initial surge of inorganic N concentration in the burned plots after the fire decreased during the following months, as reported by others (Covington and Sackett 1986, 1992), and reached control-plot levels by the end of the next growing season. The greater quantity of ammonium after the fire can be used by plants and microbes; increases in the N content of grasses following prescribed burning have been reported (Harris and Covington 1983). Tree uptake will depend upon the degree of fire damage, especially to the root system. Grier (1989) observed that a spring fire decreased fine root production, which he attributed to heat injury. If the spring flush of fine root growth is reduced, N uptake during the growing season after the fire may be impaired, and the increase in available N not utilized.

Neither net N mineralization nor nitrification rates appeared to be significantly affected by prescribed burning. In various ecosystems, net N mineralization usually increases for a period of months or years after fire (Adams and Attiwill 1986; Schoch and Binkley 1986; White 1986; Knoepp and Swank 1995), although decreases have also been reported (Ellis and Graley 1983). In our study, net N mineralization was usually lower in the year-0 burned plots, but two outliers obscured this pattern and resulted in a slightly higher annual mineralization rate in the burned plots. In ponderosa pine, there is usually an increase in NO_3^- concentration several months after prescribed fire (Covington and Sackett 1986, 1992), which suggests increased nitrification in the postfire environment. White (1986) reported greatly increased nitrification rates in laboratory incubations, but those increases did not seem to be accompanied by corresponding NO_3^- increases in the field. Our results showed similar low nitrification rates at all sites not affected by burning. In addition, the observed increase in inorganic N concentration after burning was due primarily to an increase in NH_4^+ concentration; concentrations of NO_3^- were low in both burned and control plots for the duration of this study.

Fig. 6. Monthly rates of net N mineralization in burned and control plots. The bars are located at the end of each sequential incubation period. Error bars denote standard errors; *n* = 3 composite samples per treatment at year 0 and *n* = 2 composite samples per treatment at year 5 and year 12.



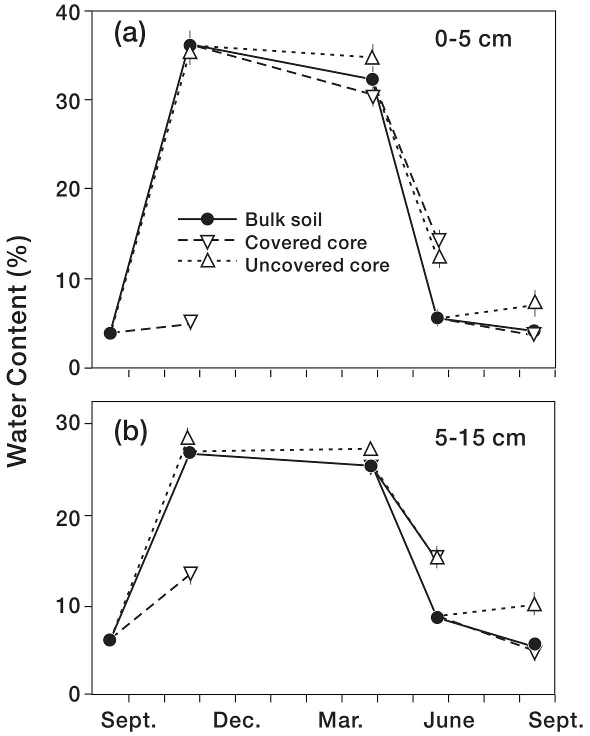
Long-term effects of prescribed burning

This study examined the effects of a first-entry prescribed fire on N mineralization and on the pools of total C, total N, and inorganic N in two different sites, one that had been burned 5 years earlier and another that had been burned 12 years earlier. Because of the different locations, changes in the patterns of fire effects between years 5 and 12 cannot be interpreted as a temporal sequence at a single site. Each site should be considered as a separate study.

Net N mineralization on the burned plots was significantly lower than that on the control plots at both sites. Thus, several years after the fire, the ability of the sites to supply N for plant uptake had decreased. Mean net annual N mineralization rates at our sites were quite low (2.0 to 6.4 kg N$\cdot$ha$^{-1}\cdot$year^{-1}, assuming a bulk density of 0.75 g$\cdot$cm^{-3} in the surface soil layer (Landsberg 1992)), but similar in magnitude to rates reported for other harsh, infertile conifer sites (Binkley and Hart 1989; Raison et al. 1992). Potential N availability at our sites, estimated on the basis of anaerobic laboratory incubations of eastern Oregon volcanic ash soils with a similar range of N concentrations (Geist 1977), would be 7 to 10 kg N$\cdot$ha^{-1} for the 0–5 cm mineral soil layer. Both the in situ incubation method used in this study and the laboratory incubation method used by Geist (1977) point to possible severe N limitations for plant growth in central Oregon, as do the fertilization response studies for ponderosa pine stands (Cochran 1979). After prescribed burning, net annual mineralization rates declined even further; mean rates at the burned plots were 31% and 60% of those at the control plots at Lava Butte and Annabelle, respectively. This reduction should affect tree growth and ecosystem productivity, and may explain the observed pattern of long-term decrease in stand growth after prescribed burning (Grier 1989; Cochran and Hopkins 1991; Landsberg 1992).

Although net N mineralization per unit weight of soil decreased after burning, net N mineralization per unit of total soil N was not affected in the site burned 5 years earlier (8.4 and 7.5 mg N$\cdot$g total N$^{-1}\cdot$year^{-1} on the control and burned plots, respectively, $p > 0.1$); however, on the site burned 12 years earlier, it decreased (12.6 and 4.2 mg N$\cdot$g total N$^{-1}\cdot$year^{-1} at the control and burned plots, respectively, $p = 0.04$). Differences in net N mineralization expressed as a proportion of total soil N indicate differences in the quality of organic matter, if soil temperature and moisture remain similar (Nadelhoffer et al. 1983; Powers 1990). The degree of similarity of soil environments between burned and control plots at our sites is not known, but we can speculate that they were reasonably similar. Soil moisture was approximately the same in burned and control plots (data not shown). We did not measure soil temperatures, but they were probably slightly warmer on the burned plots during the growing season because prescribed fire reduced the forest floor, even though tree cover was not affected (Landsberg 1992; Shea 1993). Mineral soil temperatures at 6 cm were measured during late summer of 1987; they averaged 2.3 and 2.7°C higher in the burned plots at Lava Butte and Annabelle, respectively, than in the unburned plots (J.D. Landsberg, unpublished data, 1987, on file at the U.S. Forestry Sciences Laboratory, Wenatchee, Wash.). Temperature differences should be less at the beginning of this study than 4 years after, because forest floor depth had increased. Therefore, assuming an overall similarity of soil environments of both burned and unburned plots, the lower net N mineralization rate in the burned plots was probably caused by a decrease in the quantity

Fig. 7. Water content in the bulked soil and in the covered and uncovered soil cores at the end of the field incubation. Error bars denote standard errors; $n = 14$ composite samples.



of the available substrate at the year-5 site and by changes in the quality of the substrate at the year-12 site. Similar reductions in substrate quality were observed after repeated prescribed burning in an oak savanna (Vance and Henderson 1984) and a loblolly pine (*Pinus taeda* L.) plantation (Bell and Binkley 1989).

Total N and C concentration decreased at the year-5 plots, but there were no differences between the control and burned plots at the year-12 site. The effects of prescribed burning on mineral soil total N appear to vary greatly; it has been reported to cause increases, decreases, and no changes (see Raison 1979; Wells et al. 1979 for a review). The different patterns of fire effects between years 5 and 12 could be the result of different site or burning conditions, or the length of time since fire. If the latter were the main reason, the large difference in total N concentration between the burned and control plots at the year-5 site (570 mg N·kg soil^{-1}, or 214 kg N·ha^{-1}) would decrease over time. Possible ways by which the N content in the burned plots can increase are reduced mineralization (this study), increased inputs through litter decomposition (Monleon and Cromack 1996), increased inputs through the recovery of the shrub cover (Busse et al. 1996), and N fixation by *Ceanothus velutinus* Dougl. ex Hook. or *Purshia tridentata* (Pursh) D.C. However, the likely rates of N accretion in soil through these processes indicate that the time necessary to reach the differences in total N values found in the burned and unburned plots at the year-5 sites may be much longer than 12 years.

Estimated N losses and uptake were inconsistent and difficult to interpret. Nitrogen concentrations in the uncovered soil cores were extremely variable and usually higher than those in the covered soil cores. Consequently, estimated N leaching usually had negative values and estimated N uptake was higher than mineralization; both were aberrant results with no biological meaning. Similar results have been reported by others (Becquer et al. 1990; Whynot and Weetman 1991), which suggests that this method may need further examination. The high, variable levels of inorganic N in the uncovered soil cores may have been caused by a higher soil moisture in the uncovered cores than in both the covered cores and the bulk soil (Fig. 7), which may have increased mineralization. Also, we observed that insects frequently used the uncovered PVC tubes for shelter, which may have influenced the nitrogen content of the soil.

Knoepp and Swank (1995) have shown that both field and laboratory incubation methods can be used successfully to compare the effects of prescribed fire on N mineralization, and that field incubations with paired, covered–uncovered cores (Raison et al. 1987, 1992; Whynot and Weetman 1991) or covered cores only (Knoepp and Swank 1995) can be used successfully to compare the effects of silvicultural manipulations such as prescribed fire or fertilization on N mineralization. As Whynot and Weetman (1991) note, however, the current emphasis on N mineralization studies does not account for other sources, such as organic N, that are available to plants. Recent work by Bending and Read (1995) and Turnbull et al. (1995) indicates that mycorrhizal fungi may access organic N directly through mechanisms such as increased competition with saprophytic fungi (Bending and Read 1995) or increased production of proteolytic enzymes in soil microbial communities dominated by ectomycorrhizal fungal mats (Griffiths and Caldwell 1992). Thus, N mineralization with laboratory incubations, such as those by Geist (1977), should consider incorporating some measure of labile organic N released during soil incubation (Brookes et al. 1985; Strickland et al. 1992). This approach could strengthen inferences from field core incubations concerning availability of N for plant uptake (Raison et al. 1992; Knoepp and Swank 1995).

Conclusions

A single-entry prescribed burn in the nutrient-poor ponderosa pine stands of central Oregon had lasting effects on N availability and N pools. Prescribed fire resulted in a long-term decrease in available N, despite a temporary postfire increase during the first several months. The decreased availability in the years that followed may explain the long-term decrease in tree growth observed after prescribed fire and support the theory that fire suppression may have increased site fertility (Cochran and Hopkins 1991). Although prescribed fire can be effectively used in ponderosa pine forests to reduce fire hazard, increase forage and landscape values, and restore stand structure to pre-European settlement conditions, its possible effects on site fertility should be considered. The intensity of prescribed fires, particularly in the 0–5 cm soil layer, should be examined as well. Future consideration should also be given to the role of N-fixing understory plants in long-term site maintenance of soil organic matter and N capital (Busse et al. 1996) and to the use of N fertilization after fire as management options for ponderosa pine.

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