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Temporal and Spatial Changes in Soil Carbon and Nitrogen After Clearcutting and Burning of an Old-Growth Douglas-Fir Forest

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Abstract

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We used 135 permanent plots (4 m^2) nested within 15 blocks (121 m^2) to quantify changes in concentration and spatial variation of carbon (C) and nitrogen (N) in the mineral soil (0- to 10-cm depth) after logging and broadcast burning of an old-growth, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest. Before harvest, surface soils averaged total C of 7.2 percent, total N of 0.19 percent, extractable NH_4^+-N of 5.2 μg/g, extractable NO_3^--N of 0.19 μg/g, and pH of 5.3. Samples collected 9 months after burning showed a 26-percent decline in concentration of total C, but a 5-percent increase in concentration of total N. Concentrations of extractable mineral N (NH_4^+-N + NO_3^--N) increased to five time initial levels but returned to preharvest levels 1 year later. The coefficient of variation in extractable mineral N more than doubled after burning. Two and 3 years after burning, extractable N showed a significant and increasingly strong negative relation with plant biomass suggesting that N concentration was measurably reduced by plant uptake. Most variation in soil C and N before harvest occurred at small spatial scales (within and among 2- by 2-m plots); logging and broadcast burning had little effect on this pattern.

Keywords: Broadcast burning, soil carbon, soil nitrogen, soil variability, coast Douglas-fir, clearcutting.

Summary

We assessed the immediate and longer term effects of clearcut logging and broadcast burning on the concentration and spatial variability of carbon (C) and nitrogen (N) in the mineral soil (0 to 10 cm) of a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest in western Oregon. The 4-ha study site, the Starrbright timber sale, is located in the Cascade Range about 25 km south of the H.J. Andrews Experimental Forest. Our specific objectives were to quantify and interpret (1) initial effects of logging and burning on the concentrations of total C, total N, and extractable mineral N (NH_4^+-N + NO_3^--N); (2) correlations between the magnitude of initial effects on extractable mineral N and predisturbance concentrations of N or burn severity; (3) longer term (3-year) changes in N and how these changes correlate with increases in plant biomass during succession; and (4) variability in C and N as a function of spatial scale, and whether this variability is affected by logging and broadcast burning.

The study site was clearcut logged in late May and early June 1991. Logs were removed with a tracked skidder that moved between experimental blocks; yarding was completed in mid-July. The site was broadcast burned on 11 September 1991 with a uniform, moderate-intensity fire. We used 135 permanent plots (4 m^2) within 15 blocks (121 m^2) installed before logging and burning to quantify changes in concentration and spatial variation of carbon and nitrogen.

Before harvest, surface soils averaged total C of 7.2 percent, total N of 0.19 percent, extractable NH_4^+-N of 5.2 μg/g, extractable NO_3^--N of 0.19 μg/g, and of pH of 5.3. Samples collected 9 months after burning showed a 26-percent decline in concentration of total C. As organic matter burns, C is volatilized, lost as particulates, or converted to inorganic carbon. However, addition of C to the surface soil also is possible if charcoal particles from burned duff or logging slash are leached into the soil. Because we used the dry-combustion analytical method that does not distinguish between organic and inorganic forms of C, the decline we observed is a minimum estimate of loss of organic C, which was likely greater, but partly offset by addition of charcoal.

Concentrations of total N changed little after logging and burning, but extractable mineral N increased to five times initial levels 9 months after burning then declined to preburn values in year 2. The coefficient of variation in extractable mineral N more than doubled after burning, which, together with the large increase in the mean, yielded extremely high variation in available N after fire. In contrast to extractable mineral N, soil pH remained elevated through final sampling in 1994. Changes in concentration of extractable mineral N were weakly, but significantly, correlated with preharvest concentrations, but were unrelated to burn severity. Increases were observed in nearly all plots, and relatively large increases of extractable N were found in plots that had low, as well as high, initial concentrations. Nine months after burning (1992), concentration of extractable mineral N showed no relation to total plant biomass, which was invariably low during the first postburn growing season. Two and 3 years after burning, however, extractable mineral N showed a significant and increasingly strong negative relation with plant biomass (which had increased substantially), suggesting that N availability was measurably reduced by plant uptake.

Most variation in soil C and N before harvest occurred at small spatial scales (within and among the 2- by 2-m plots); logging and broadcast burning had little effect on this pattern. The large, but transient increase, and the high spatial variation in available N after burning may contribute to the rapid changes in abundance and the patchy spatial distributions of early successional plants that benefit from catastrophic disturbance.

Introduction

Timber harvest and slash burning can cause substantial loss and redistribution of organic matter and nitrogen (Belillas and Feller 1998, Little and Ohmann 1988, Neary et al. 1999, Wan et al. 2001). Because these disturbances are frequent in many forest ecosystems, an understanding of the effects of logging and burning on the quantity, quality, and spatial distribution of soil nutrients is of critical importance in managing and maintaining the long-term productivity of forests and in understanding patterns of vegetation recovery following disturbance. Effects of timber removal and prescribed or natural fire can be highly variable (Wan et al. 2001) and thus difficult to predict. Although surficial organic matter and nutrients invariably decrease after fire, total amounts of carbon (C) and nitrogen (N) in the soil can decline (Dyrness and Norum 1983, Martin and Harr 1989), increase (Choromanska and DeLuca 2001, Johnson and Curtis 2001, Prieto-Fernandez et al. 1993, Raison 1979), or remain relatively constant (see review in Wan et al. 2001). Concentrations of extractable N usually increase after harvesting and burning (Choromanska and DeLuca 2001, Knoepp and Swank 1995, Pietikainen and Fritze 1995, Prieto-Fernandez et al. 1993, Vance and Henderson 1984), often in association with increases in soil pH (Attiwill and Adams 1993, Grier 1975, Lynham et al. 1998, Pietikainen and Fritze 1995). An understanding of the consequences of these disturbances requires an examination of both their short-term effects and the longer term changes that occur during vegetation succession.

In addition to temporal variation, soil properties can be highly patchy in space (Beckett and Webster 1971; Homann et al. 2001; Robertson et al. 1988, 1993; Schlesinger et al. 1996), and this variation can occur over very small distances (Lechowicz and Bell 1991). Therefore, reliable assessments of the variability in soil C and N may be difficult without large numbers of samples. Within old-growth forests, spatial variation in soil properties could relate to differential effects of individual tree species, presence of canopy gaps, the patchy distribution of understory plants and coarse woody debris, and microtopography. Conversely, soil variation affects the distribution and growth of individual trees (van Breemen et al. 1997) and forest herbs (Bell et al. 1991). The effect on variability in soil properties is an important, but seldom-considered influence of disturbance. Logging and burning of old-growth forests can eliminate many sources of variation, and thus, could result in a more spatially homogeneous soil. Conversely, soil variability could increase in response to small-scale variation in the intensity of burning and in the ground-surface conditions produced by disturbance (e.g., Grogan et al. 2000).

Clearcut logging and broadcast burning are traditional silvicultural practices in Douglas-fir forests of the Pacific Northwest. Succession after timber harvest and burning is characterized by rapid recolonization by annual and perennial herbs and shrubs (Dyrness 1973; Gholz et al. 1985; Halpern 1988, 1989; Halpern and Franklin 1990; Morris 1970), a process important in maintaining nutrients and long-term site productivity (Bormann and Likens 1979, Miller et al. 1989). In 1990, we initiated a series of field experiments to examine how plant species' interactions shape early patterns of postharvest succession (Antos and Halpern 1997; Halpern et al. 1992, 1996, 1997) and how particular species may influence soil properties during community recovery. In this paper, we take advantage of these experiments to assess the immediate and longer term effects of clearcut logging and broadcast burning on the concentration and spatial variability of C and N in the surface mineral soil (0 to 10 cm). Our specific objectives are to quantify and interpret

(1) initial effects of logging and burning on the concentrations of total C, total N, and extractable mineral N (ammonium N [NH_4^+-N] + nitrate N [NO_3^--N]); (2) correlations between the magnitude of initial effects on extractable mineral N and predisturbance concentrations of N or burn severity; (3) longer term (3-year) changes in N and how these changes correlate with increases in plant biomass during succession; and (4) variability in C and N as functions of spatial scale, and whether such variability is affected by logging and broadcast burning.

Methods

Study Site

The 4-ha study site, the Starrbright timber sale, is located in the Cascade Range of western Oregon, about 25 km south of the H.J. Andrews Experimental Forest (HJA) (44°00' N, 122°11' W). Before harvest, the site supported an old-growth forest of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in the upper canopy, with western redcedar (*Thuja plicata* Donn), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Pacific yew (*Taxus brevifolia* Nutt.) in the lower and subcanopies. The understory was dominated by rhododendron (*Rhododendron macrophyllum* G. Don), salal (*Gaultheria shallon* Pursh), and Oregongrape (*Berberis nervosa* Pursh). The site lies at 730 m elevation on a gentle (0 to 10 percent) east-facing bench. Climate and soils are typical for this area of the western Cascade Range (Franklin and Dyrness 1973). At the central meteorological station at HJA, annual precipitation averages 2302 mm, with 6 percent falling between June and August (Bierlmaier and McKee 1989). Average minimum air temperatures range from -5.5 °C in January to 11.9 °C in August; average maximums range from 5.5 °C in January to 23.3 °C in July. The average frost-free period is 134 days. The soil at Starrbright is a deep (>1.5 m) loamy Andisol (frigid typic Hapludand) formed from weathering of andesite, breccia, and volcanic ash. The A horizon is deep (0 to 25 cm), homogeneous, and largely free of coarse fragments (gravel size and larger).

The study site was clearcut logged in late May and early June 1991. Logs were removed with a tracked skidder that moved between experimental blocks (see below); yarding was completed on 11 July. On 11 September 1991, the site was broadcast burned by the U.S. Forest Service, Blue River Ranger District, with a uniform, moderate-intensity fire (fig.1). After ignition with drip torches, fuels burned for about 2.5 hours, reaching flame heights of about 3 m. Relative humidity during the afternoon of the burn ranged from 28 to 36 percent.

Study Design

The current work was conducted within the context of a larger set of experiments that examine the role of plant species' interactions during early succession (Halpern et al. 1992, 1997). The overall experimental design consists of eight treatments removing early successional species that differed in growth form and life history (Halpern 1989), plus a control (i.e., no plant removals), replicated in each of 25 blocks (table 1, fig. 2). Within each block (11 by 11 m), the nine, 2.5- by 2.5-m treatment plots were located in a 3-by-3 array, with plots spaced about 1 m apart (fig. 2). Each plot contains a central 1- by 1-m quadrat for vegetation sampling surrounded by a 0.5-m-wide soil sampling area (fig. 2). Plots were established in June 1990, 1 year before harvest. Species-removal treatments were initiated in late June to early July 1992 (9 months after broadcast burning), synchronous with collection of the first postburning soil samples (see below), and were conducted monthly during the growing season thereafter. Soil sampling occurred in all the plots within 15 of the blocks, distributed evenly across the study site. Here we take advantage of this plot design to address the overall effects of logging and burning on soil nutrients; we do not examine treatment-specific responses, which will be addressed elsewhere.

Figure 1—One of the experimental blocks as it appeared on 26 June 1992, one growing season after broadcast burning. Steel reinforcing bars mark the corners of nine, 1- by 1-m vegetation sampling quadrats.

Table 1—The 8 species-removal treatments and control treatment randomly assigned to plots within each block (see fig. 2)

Treatment	Species removed	Response variable(s) in plant community studies
A	None (control)	All species
B	*Senecio sylvaticus*	All other species
C	*Epilobium angustifolium*	All other species
D	*Senecio sylvaticus* and *Epilobium angustifolium*	All other species
E	All species except *Epilobium angustifolium*	*Epilobium angustifolium*
F	All species except *Senecio sylvaticus*	*Senecio sylvaticus*
G	All species except *Senecio sylvaticus* and *Epilobium angustifolium*	*Senecio sylvaticus* and *Epilobium angustifolium*
H	*Rubus ursinus*	All other species
I	*Berberis nervosa* and *Gaultheria shallon*	All other species

Note: See Halpern et al. (1997) for details on plant community studies.

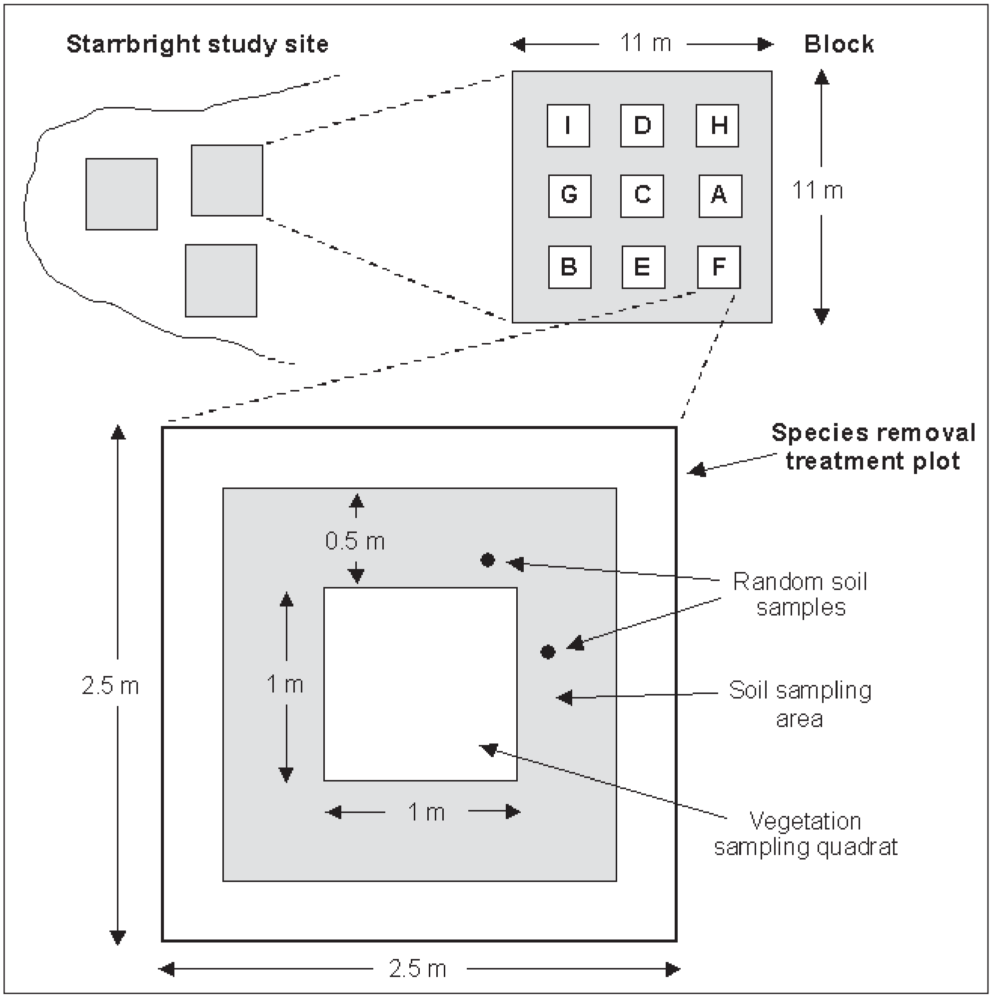

Figure 2—The spatial arrangement of blocks, plots with plant species-removal treatments, soil sampling areas, and vegetation sampling quadrats. Only three blocks are shown for simplicity. Letters refer to the randomly assigned species-removal treatments described in table 1. Although two soil subsamples are shown in this example, the number of subsamples per plot differed by year (see "Methods").

Assessment of Vegetation Damage, Duff Reduction, and Burn Severity

On 1 August we estimated the average depth (centimeters) and percentage of cover of logging slash in each plot. Two days after burning, each vegetation quadrat was assessed for vegetation damage, duff consumption, and burn severity. Vegetation damage was qualitatively rated as (1) nonburned, (2) scorched but not consumed by fire, and (3) largely to completely consumed by fire. To quantify duff consumption, a notched steel rod was inserted at the northwest corner of each vegetation quadrat prior to the burn, with the notch placed at the surface of the forest floor. Duff loss was calculated as the distance from the notch to the duff or ground surface after the burn. To quantify relative burn severity, pine stakes (about 30 cm long and 2 by 5 cm in cross section) were driven about 10 cm into the ground at the other three corners of each vegetation quadrat before burning. After burning, each stake was assigned to one of five burn classes ranging from nonburned (value of 1) to completely consumed by fire (value of 5); an average index of burn severity was then calculated for each quadrat (range of 1.0 to 5.0).

Soil Sampling

Predisturbance mineral soil samples were collected between 20 and 29 May 1991. Forest floor material including moss was removed before samples were extracted with a sliding-hammer bulk density sampler (about 9 cm deep by 7.5 cm diameter and about 400 cm^3 volume; Blake and Hartge 1986). Samples were taken from two random locations in the soil sampling area surrounding each vegetation quadrat (fig. 2).

In 1992, soil samples (collected 30 June and 1 July) were extracted with a bulb planter (about 10 cm deep by 5.9 cm in diameter and about 275 cm^3 volume). Two cores (subsamples) were taken from random locations in the soil sampling area (fig. 2) of each of the treatment plots sampled prior to harvest; subsamples were then composited. To reduce further disturbance to soil and vegetation caused by the larger coring devices, subsamples in 1993 (10 to 11 July) and 1994 (2 July) were extracted with a narrower Oakfield™[1] tube-type sampler (about 10 cm deep by 2.1 cm in diameter and about 35 cm^3 volume). Cores were taken from six random locations in the soil sampling area of each treatment plot and were composited. All soil samples were placed on ice and transported within 24 hours to an analytical laboratory at Oregon State University.

Laboratory Preparation and Analysis of Soils

Samples were air dried for at least 72 hours at room temperature (<25 °C), then sieved to obtain the <2-mm fraction used for analysis. For analyses of total C and N, a subsample was ground to 100 mesh, dried at 80 °C, and analyzed in a Carlo/Erba NA-1500 Series 2 CHN-analyzer (Nelson and Sommers 1996). This dry-combustion technique quantifies all organic C, including charcoal. Concentrations of extractable NH_4^+-N and NO_3^--N (expressed, for simplicity, as extractable NH_4^+ and NO_3^- or, in sum, as extractable mineral N) were obtained after 2 molar potassium chloride extraction and subsequent analyses with an Alpkem Rapid Flow Analyzer (Model 300) (Mulvaney 1996). Nutrient concentrations are expressed on an oven-dry (80 °C) weight basis and are presented either as percentage or μg/g. Soil pH was determined in a 2:1 water-to-soil suspension in deionized, distilled water. Samples from all collection periods were treated identically.

Statistical Analyses

Several samples were considered to be outliers based on two criteria and were not included in subsequent analyses. Nine samples with a C concentration >20 percent were dropped because they probably contained material from organic horizons (USDA SCS 1993: 141); seven of these were pretreatment samples. After eliminating these samples, several data points more than four standard deviations from the mean were dropped for specific variables because we suspected that these values were erroneous (1 to 3 of 270 subsamples in 1991 and 0 to 2 of 135 samples for 1992-94).

Initial effects of logging and slash burning on mineral soil properties (objective 1) were assessed with paired *t*-tests that compared preharvest (1991) and first-year, postburn (1992) samples (n = 131 to 134). Values for the two soil subsamples per plot in 1991 were averaged before statistical analysis. Thus the comparison is based on paired samples at the plot level, which makes the values directly comparable. Although the small (1 cm) difference in total depth of preharvest and postburning samples may affect our estimates of change in concentrations of soil C and N, this effect should be small compared to those from logging and burning. To examine factors likely to have influenced the magnitude of change in extractable mineral N (objective 2), we correlated change in extractable mineral N (1992 minus 1991 values) with predisturbance concentration and with burn severity in each plot.

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[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

To examine longer term changes in soil properties (1992-94), we compared annual means of total N, extractable mineral N, and pH for the 15 control plots in which no plant biomass was removed (i.e., those plots in which temporal trends were not confounded by removal treatments). To test the hypothesis that plants reduce available N in the soil (objective 3), we regressed the concentration of extractable mineral N on the total aboveground biomass of vascular plants, performing separate regressions for 1992, 1993, and 1994 with the full set of species-removal and control plots (i.e., plots representing a broad range of plant biomass; n = 131 to 133 after dropping outliers). Biomass was estimated from data on species cover, stem height, or diameter, collected in the central 1- by 1-m quadrat in each treatment plot (fig. 2) by using species-specific regression equations developed through destructive sampling of plants outside the experimental blocks (Halpern et al. 1996).

We used two approaches to quantify variability in soil C and N and to determine how this variability was affected by logging and broadcast burning (objective 4). First, we used the coefficient of variation (CV) to examine total variability among preharvest and postburning samples. Second, we used nested ANOVA (SAS Institute 1989) to examine the spatial scale of variation, based on the percentage of the total sum of squares at each of three spatial scales (within plots, among plots within blocks, and among blocks) as a measure of the relative contribution of each spatial scale to the deviation of sample points from the grand mean (Sokal and Rohlf 1995). We limited our analyses of variability to preharvest (1991) and immediate postburning (1992) samples because after 1992 most plots were affected by the plant removal treatments. All three spatial scales were considered before harvest, but after burning we could not assess within-plot variation because subsamples were composited before chemical analysis.

Results

Initial Effects of Logging and Broadcast Burning

Most aboveground portions of the understory vegetation were consumed in the burn. No live foliage remained in any of the 135 vegetation quadrats, and no woody stems remained in 76 of these quadrats. Depth of logging slash averaged 17.5 cm on 1 August, about 1 month before burning; virtually all of this slash was consumed by the fire. In nearly all plots, most of the original forest floor (duff) was consumed by the burn; reduction in duff depth averaged 5.6 cm (CV = 39 percent).

Of the soil properties considered, most changed significantly in response to logging and burning (table 2). Measured 9 months after burning, mean concentration of total C declined by 26 percent. In contrast, concentration of total N increased by 5 percent, although the change was not statistically significant. The C/N ratio declined considerably (from 37 to 26). Concentration of extractable mineral N (NH_4^+ plus NO_3^-) increased to fives times initial levels. Although concentration of NO_3^- increased to more than 10 times initial levels, 93 percent of extractable mineral N was in the form of NH_4^+. Relative to preharvest levels, soil pH increased about one-half unit (table 2).

Factors Correlated With the Magnitude of Change

Changes in concentration of extractable mineral N (i.e., 1992 minus 1991 values) were weakly, but significantly, correlated with preharvest concentrations (r^2 = 0.034; P = 0.036; fig. 3A), but were unrelated to burn severity (r^2 = 0.006; P = 0.400; fig. 3B). Increases were observed in nearly all plots, and relatively large increases were found in plots that had low, as well as high, initial concentrations (fig. 3A).

Table 2—Results of paired *t*-tests comparing properties of the mineral soil before (May 1991) and 9 months after (June-July 1992) clearcut logging and broadcast burning

		1991		1992				
Soil property	***n***	**Mean**	**CV (%)**	**Mean**	**CV (%)**	**Difference**	***t***	***P***
Total carbon (percent)	133	7.19	37	5.30	28	-1.89	7.07	<0.001
Total nitrogen (percent)	133	.194	28	.204	23	-.010	-1.77	.079
C/N ratio	132	36.9	17	26.1	18	-10.8	16.49	<.001
Extractable:								
NH_4^+-N (*µ*g/g)	132	5.17	33	24.21	74	19.04	-12.45	<.001
NO_3^--N (*µ*g/g)	132	.18	40	1.92	151	1.74	-6.90	<.001
NH_4^+-N + NO_3^--N (*µ*g/g)	131	5.32	31	26.08	73	20.76	-12.67	<.001
pH	134	5.32	5	5.86	5	.54	-17.65	<.001

n = number of paired samples after outliers were dropped (see “Methods”). CV = coefficient of variation (standard deviation expressed as a percentage of the mean).

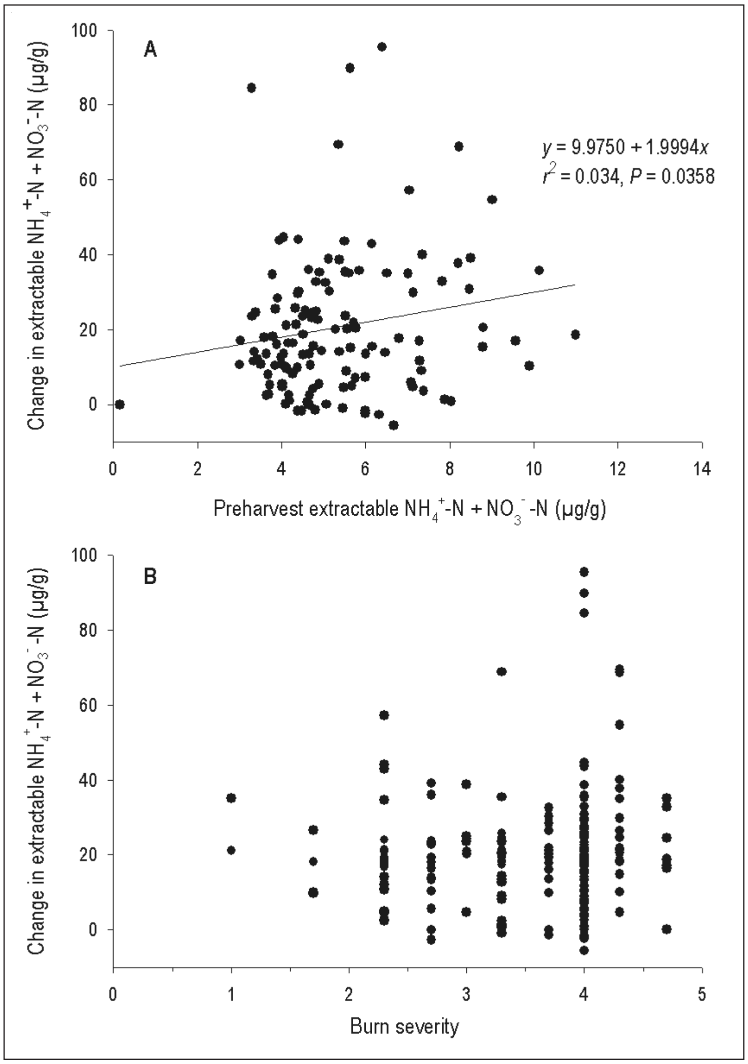

Figure 3—Initial changes in concentration of extractable mineral N within each plot (1992 minus 1991 values) in relation to (A) preharvest concentration of extractable mineral N, and (B) burn severity (*n* = 131).

Longer Term Changes in Soil Properties

Longer term trends in soil properties were examined by using the 15 control plots in which plant species were not removed. Here, concentrations of total N changed little after logging and burning (fig. 4A). In contrast, extractable mineral N increased to five times initial levels in year 1 (1992), then declined dramatically to preburn values in year 2 (1993) (fig. 4B). That the first-year increase in these 15 plots was very similar to that observed in the full set of 135 plots (table 2) indicates that the control plots were representative of the site and that the abrupt decline in year 2 was not an artifact of a smaller sample size. In contrast to extractable mineral N, soil pH remained elevated through final sampling in 1994 (fig. 4C).

Nine months after burning (1992), concentration of extractable mineral N showed no relationship to total plant biomass, which was invariably low during the first postburn growing season (fig. 5A). However, in subsequent years as plant biomass increased, this relationship was highly significant (figs. 5B, 5C). In 1993, 6 percent of the variation in concentration of extractable mineral N could be explained by total aboveground biomass; this increased to 39 percent in 1994.

Variability in Soil Properties as Influenced by Logging and Burning

Coefficients of variation for total C, total N, and pH changed little after logging and burning (table 2). In contrast, CVs for the concentration of NH_4^+-N more than doubled and for NO_3^--N, almost quadrupled (table 2).

Considerable variation in soil properties was observed at each of the spatial scales examined (fig. 6A). Before harvest, variation within and among plots accounted for much of the total variation (i.e., percentage of total sums of squares) in total C, total N, and extractable mineral N (fig. 6A). After burning, the proportion of total variability attributable to variation among plots (the smallest spatial scale that could be considered) changed little for total C and total N, but increased considerably for extractable mineral N (fig. 6B).

Discussion

Before harvest, properties of the upper mineral soil layer at Starrbright were typical of old-growth, Douglas-fir forests of the area, with concentrations of total C and N within the range of those reported for the nearby Andrews Experimental Forest (Binkley et al. 1982, McNabb et al. 1986, Sollins et al. 1980). Our estimate of duff consumption (5.6 cm) suggests that the fire was more intense or more uniform in its effect than most broadcast burns. By comparison, reductions in duff depth ranged from 0.8 to 5.2 cm for 15 logged and burned sites in western Oregon and Washington (Little et al. 1986). At Starrbright, the burn was fairly uniform across the site, consuming the ground-layer vegetation, finer logging residues, and the forest floor sufficiently to deposit extensive ash and to heat the surface mineral soil.

Disturbance Effects on C and N

We observed a large and significant decrease in carbon concentration in the surface mineral soil after burning (table 2), as has been reported previously (e.g., Dyrness and Youngberg 1957, Isaac and Hopkins 1937). As organic matter burns, C is volatilized, lost as particulates, or converted to inorganic carbon. However, addition of C to the surface soil also is possible if charcoal particles from burned duff or logging slash are leached into the soil (see review in Johnson and Curtis 2001). Because we used the dry-combustion analytical method that does not distinguish between organic and inorganic forms of C, the decline we observed is a minimum estimate of loss of organic C, which was likely greater but partly offset by addition of charcoal.

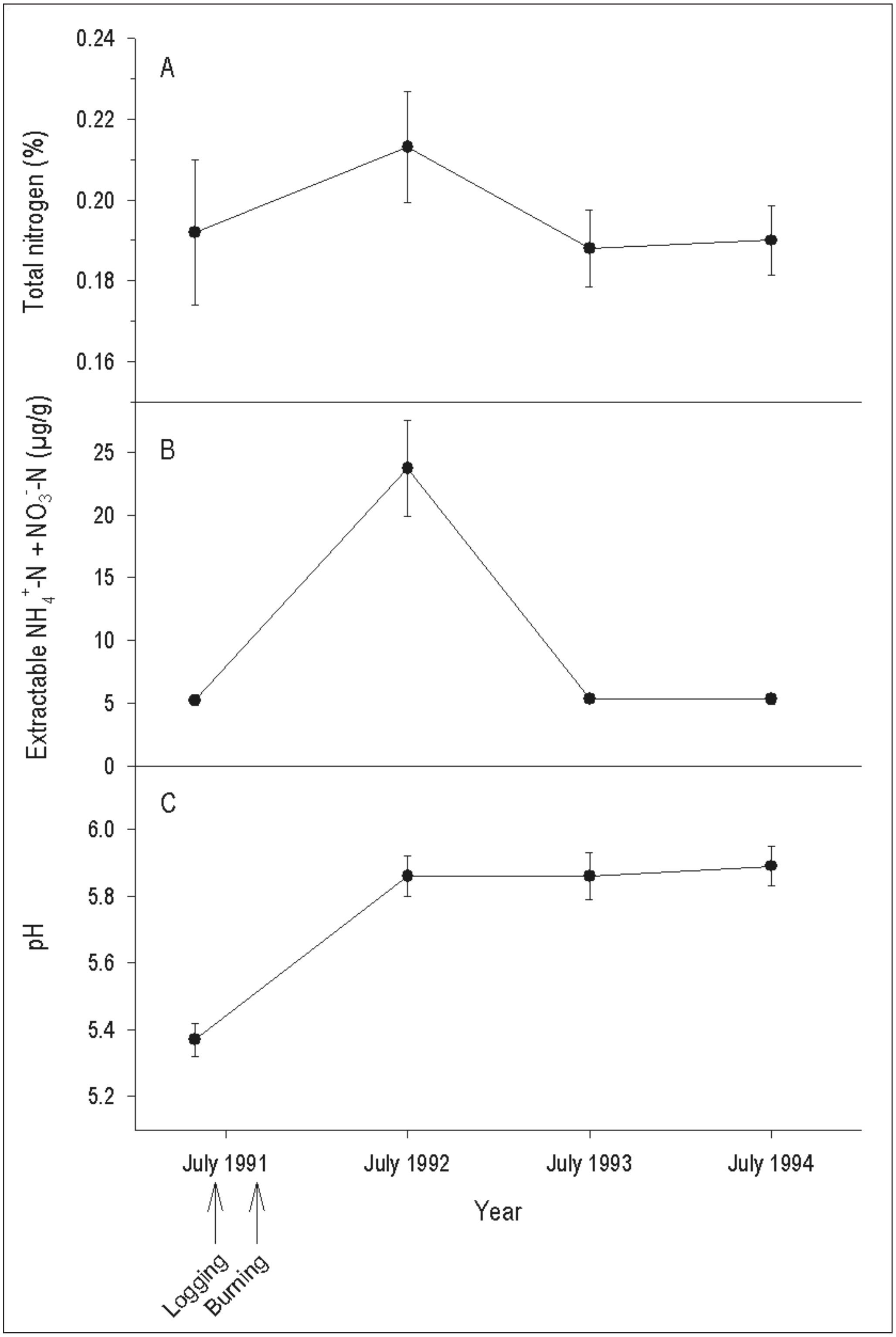

Figure 4—Changes in soil characteristics in the 15 control plots (in which no plant species were removed): (A) total N concentration, (B) concentration of extractable mineral N, and (C) pH. Vertical bars represent ± 1 standard error (SE) (SEs in the nonpeak years were <0.5 and are not visible).

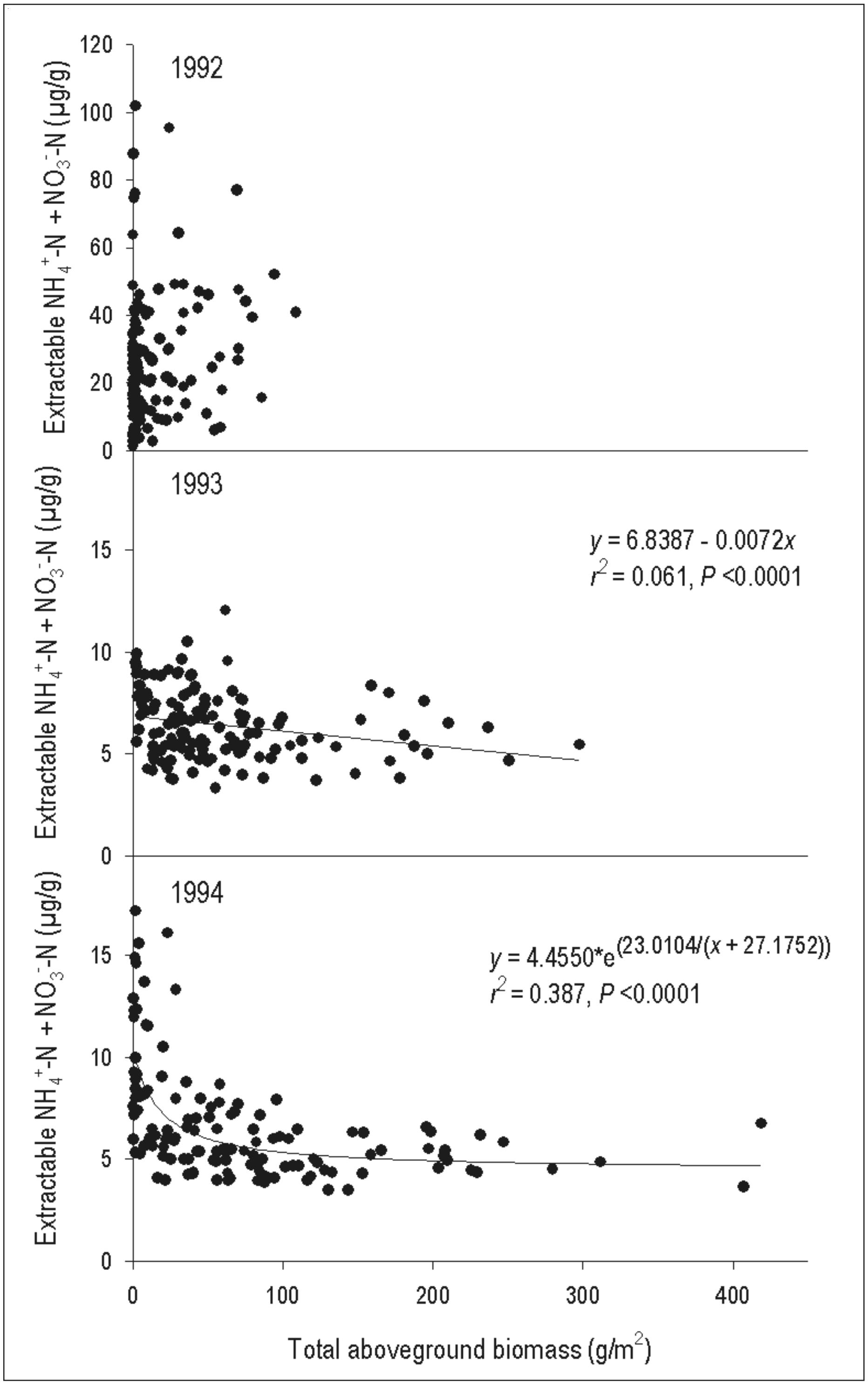

Figure 5—The relation between concentration of extractable mineral N and estimated total aboveground plant biomass during each postburning year. Sample sizes (*n*) were 131 for 1992 and 1993 and 133 for 1994. The regression is not significant for 1992 ($P = 0.652$) and thus is not plotted. Note the difference in scale of the Y axis for 1992.

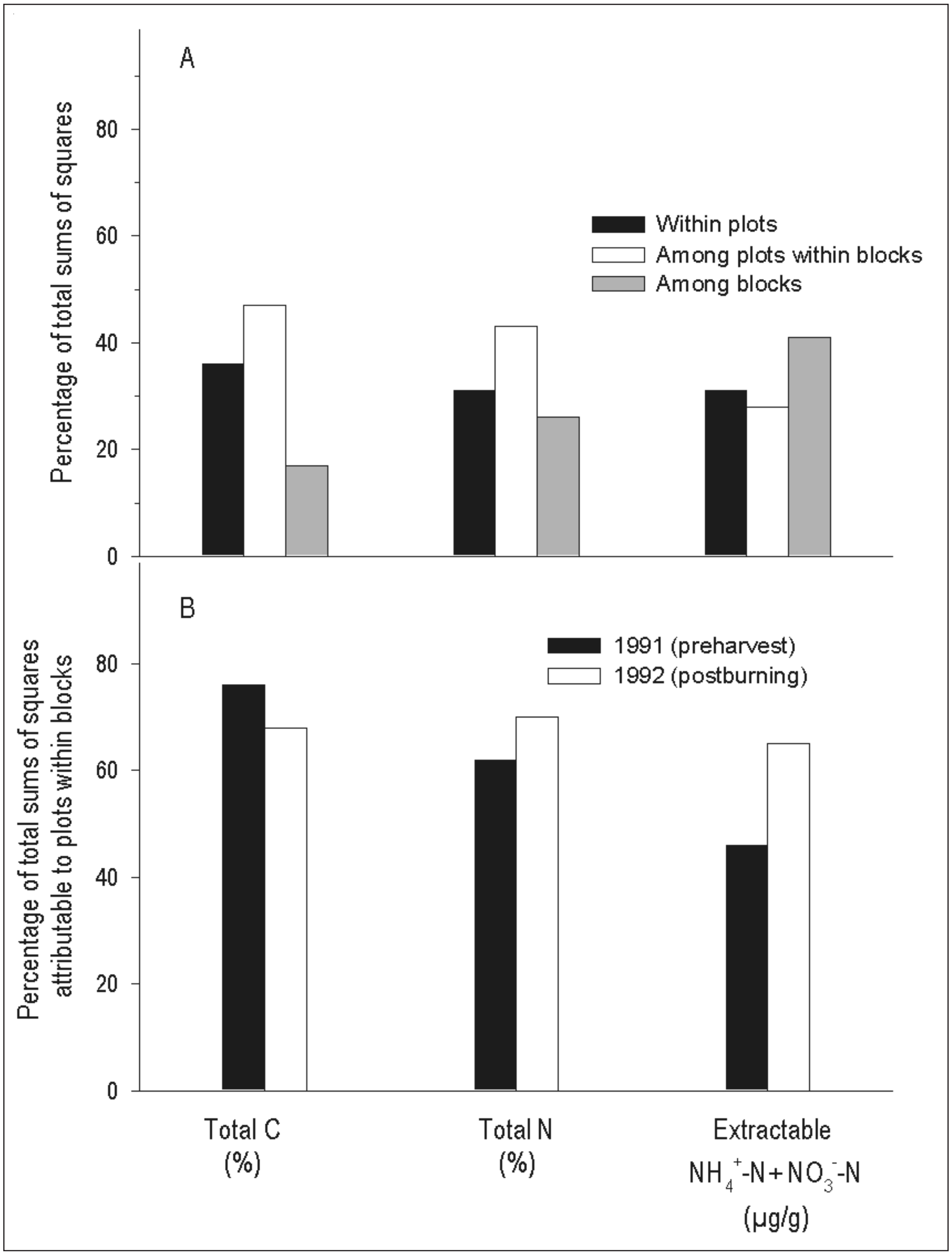

Figure 6—Proportion of total variation (percentage of total sums of squares) in concentration of total C, total N, and extractable mineral N for (A) each of three spatial scales prior to harvest (1991), and (B) the spatial scale of plots within blocks before harvest (1991) and 9 months after burning (1992). For the comparison in (B), values of preharvest subsamples within plots were first averaged.

Total N in mineral soil can increase, decrease, or remain unchanged by fire (Choromanska and DeLuca 2001, Johnson and Curtis 2001, Prieto-Fernandez et al. 1993, Raison 1979, Wan et al. 2001). We observed little change in total N. If surface heating of mineral soil is neither severe nor prolonged, more C than N can be lost. For example, Diaz-Ravina et al. (1992) found that 48 percent of soil C, but only 7 percent of total N were lost after 4 hours of heating of a forest soil (humic Cambisol) in a muffle furnace at 350 °C. After a forest wildfire in Spain on a humic Cambisol with a high organic matter content, Prieto-Fernandez et al. (1993) found decreased C concentrations down to 10 cm deep in the A horizon, increased concentrations of both organic and inorganic soil N at the 0- to 5-cm depth, and increased inorganic N at the 5- to 10-cm depth. This suggests a narrowing of the C/N ratio, as we observed at Starrbright (table 2).

Our interpretations of changes in total C and N must be tempered by consideration of the size fraction and soil layer examined. Although not often considered, the 2- to 6-mm fraction can contain a considerable proportion of soil N (Cromack et al. 1999). Moreover, the effects of disturbance can be manifested at greater depth than we measured (e.g., Little and Klock 1985, Wan et al. 2001). Our intensive sampling at 0- to 10-cm depth provides a detailed view of temporal and spatial changes in the soil layer that most affect short-term responses of the plant community. A more complete understanding of soil nutrient dynamics will require examination of coarser fractions and deeper soil layers (Corti et al. 1998).

We observed pronounced increases in NH_4^+ and NO_3^- after burning, and these are consistent with findings of previous studies (Choromanska and DeLuca 2001, Fisher and Binkley 2000, Grogan et al. 2000, Knoepp and Swank 1995, Prieto-Fernandez et al. 1993, Ryan and Covington 1986, Wan et al. 2001). These increases are due, in part, to formation of NH_4^+ and NO_3^- during combustion of organic matter above and at the surface of the mineral soil. Subsequent increases are due to increased microbial N mineralization after fire (DeBano et al. 1979, Dunn et al. 1979, Mroz et al. 1980, Pietikainen and Fritze 1995, Prieto-Fernandez et al. 1993, Vitousek et al. 1989). Prieto-Fernandez et al. (1993) suggest that permeation of organic and inorganic N into residual ash and partially burned organic fragments could be an additional mechanism of N retention by surface soils. Increased chemical reactivity of soil charcoal after fire also might explain part of the abrupt increase in NH_4^+ and NO_3^-. Although charcoal C may not be biologically decomposable, it can be chemically active after its initial formation and reactivated by steam heating in subsequent fires (Murphy and Rousseau 1975). Charcoal and fire-induced pyromorphic humus compounds also affect microbial colonization and N mineralization (Almendros et al. 1990, Fritze et al. 1994, Pietikainen and Fritze 1995). To tease apart the contributions and changes in these various forms of soil C after burning, two methods could be used in combination: the high-temperature, dry-combustion method and the traditional Walkley-Black wet-oxidation method (which does not oxidize charcoal C) (Nelson and Sommers 1996).

Factors Correlated With the Magnitude of Change

The correlation between disturbance-induced changes in extractable mineral N and preharvest concentrations was positive and statistically significant (fig. 3A) but explained little of the total variation in extractable N. This is not surprising given that fire greatly increased amounts of NH_4^+ and NO_3^- and that the processes responsible for such changes are likely to be very different from those affecting initial variation in the soil. Although we anticipated a relation with burn severity, we found no such correlation (fig. 3B). It is possible that burn severity had little or no effect on the magnitude of change in NH_4^+ and NO_3^-. A more probable explanation, however, is that effects of fire were manifested at very small spatial scales (i.e., centimeters) and that our coarser, plot-level assessments of burn severity (three wooden stakes at 1-m spacing) obscured these relationships.

Longer Term Changes in Soil Nutrients and pH

The abrupt decline in NH_4^+ and NO_3^- within 2 years after burning indicates that the initial pulse of extractable mineral N is extremely transient. In fact, the peak in concentration of extractable mineral N at Starrbright was probably higher and occurred earlier than the increase observed 9 months after burning. Neal et al. (1965) found increased concentrations of NH_4^+ in surface mineral soil samples after 2 days and the greatest concentrations (four to six times initial levels) 3 months after broadcast burning at a coastal Oregon site. At 6 months, however, concentrations were similar to those found in adjacent, nonburned sites. Burning-induced increases are fairly short-lived in other forest ecosystems as well (Adams and Attiwill 1986, Fisher and Binkley 2000, Monleon et al. 1997, Wan et al. 2001). Possible explanations for the rapid decline include leaching, microbial immobilization, and uptake by plants. Although we cannot assess the relative importance of each of these processes, we observed a significant negative association between available N and total plant biomass. That this relationship became stronger with time (fig. 5) suggests that plant uptake may become an increasingly important control on concentrations of mineral N in these forests. Conversely, the rapid decline in available N may be responsible for the decline or loss of many weedy species that characterize the early stages of postfire succession in these systems (Dyrness 1973; Gholz et al. 1985; Halpern 1988, 1989; Schoonmaker and McKee 1988).

In contrast to the pattern of extractable mineral N, the initial increase in pH at Starrbright was sustained for at least 3 years, which is consistent with other reports of postburning changes in the Douglas-fir region (Neal et al. 1965, Tarrant 1954). Increases in soil pH often observed after fire are due to increased availability of cations and consumption of organic acids during oxidation of litter and soil organic matter (Fisher and Binkley 2000). Although pH may remain elevated for years, it should slowly return to predisturbance levels as conifers regain dominance of the site.

Spatial Variation in Soil Properties

We observed considerable variation in soil C and N at the scale of individual plots in the original forest (i.e., the 2- by 2-m areas used for soil sampling). Our estimates of variation (CVs of 37 and 28 percent for total C and N, respectively; table 2) are typical of nonagricultural soils (Beckett and Webster 1971) but are somewhat higher than those reported for an old-growth forest about 25 km from our site (McNabb et al. 1986). The small scale of variation also is consistent with patterns observed in agricultural soils; Beckett and Webster (1971) concluded that although variability increases with area sampled, up to half of the variance within an agricultural field may be present within any square meter.

The limited change in variation in total C and N after logging and burning (table 2), and in the distribution of this variation among the spatial scales considered (fig. 6), suggests that either (1) patchiness of disturbance did not lead to greater variability, or (2) if it did, it was offset by homogenization of factors that had induced variability in the original forest. In contrast, the marked increase in variability in extractable mineral N suggests that spatial variation in fire effects was greater than any homogenizing influence. Because both the CV and mean concentrations of mineral N increased greatly after fire, the absolute variation in amounts of these critical plant nutrients was extremely high following burning. Thus, disturbance can lead to pronounced variation in soil nutrients at fine spatial scales and over short periods. This variation, in combination with the differences in growth form and root system morphology of the species present (Antos and Halpern 1997), may contribute both to the patchy nature of plant species' distributions and to the rapid changes in abundance that characterize the early stages of succession in these forests. Additional research is needed to refine our understanding of the spatial and temporal scales over which plants respond to, and in turn mediate, soil resource availability after large-scale disturbance.

Conclusions

1. Mineral soil samples collected 9 months after broadcast burning showed a 26-percent decline in concentration of total C and a 5-percent increase in concentration of total N.

2. During the same period, concentrations of extractable mineral N (NH_4^+-N + NO_3^--N) increased to five times initial levels, but returned to preharvest levels 1 year later. The coefficient of variation in extractable mineral N more than doubled after burning, which, together with the large increase in the mean, yielded extremely high variation in available N after fire.

3. Two and 3 years after burning, extractable mineral N showed a significant and increasingly strong negative relation with plant biomass, suggesting that N availability was reduced by plant uptake.

4. Most variation in soil C and N before harvest occurred at small spatial scales (within 2- by 2-m plots and among these plots within blocks); logging and broadcast burning had little effect on this pattern.

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English Equivalents

When you know	Multiply by:	To find:
Centimeters (cm)	0.394	Inches
Square centimeters (cm^2)	.155	Square inches
Meters (m)	3.28	Feet
Square meters (m^2)	10.76	Square feet
Kilometers (km)	.6125	Miles
Micrograms per gram (μg/g)	1.0	Parts per million
Hectares (ha)	2.47	Acres

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