



Wildfire effects on carbon and nitrogen in inland coniferous forests

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Abstract

A ponderosa pine/Douglas-fir forest (*Pinus ponderosa* Dougl., *Pseudotsuga menziesii* (Mirb.) Franco; PP/DF) and a lodgepole pine/Engelmann spruce forest (*Pinus contorta* Loud., *Picea engelmannii* Parry ex Engelm.; LP/ES) located on the eastern slopes of the Cascade Mountains in Washington state, USA, were examined following severe wildfire to compare total soil carbon and nitrogen capitals with unburned (control) forests. One year after fire, the average C content (60 cm depth) of PP/DF and LP/ES soil was 30% (25 Mg ha⁻¹) and 10% (7 Mg ha⁻¹) lower than control soil. Average N content on the burned PP/DF and LP/ES plots was 46% (3.0 Mg ha⁻¹) and 13% (0.4 Mg ha⁻¹) lower than control soil. The reduction in C and N in the PP/DF soil was largely the result of lower nutrient capitals in the burned Bw horizons (12–60 cm depth) relative to control plots. It is unlikely that the 1994 fire substantially affected nutrient capitals in the Bw horizons; however, natural variability or past fire history could be responsible for the varied nutrient capitals observed in the subsurface soils. Surface erosion (sheet plus rill) removed between 15 and 18 Mg ha⁻¹ of soil from the burned plots. Nutrient losses through surface erosion were 280 kg C ha⁻¹ and 14 kg N ha⁻¹ in the PP/DF, whereas LP/ES losses were 640 and 22 kg ha⁻¹ for C and N, respectively. In both forests, surface erosion of C and N was ~1% to 2% of the A-horizon capital of these elements in unburned soil. A bioassay (with lettuce as an indicator plant) was used to compare soils from low-, moderate- and high-severity burn areas relative to control soil. In both forests, low-severity fire increased lettuce yield by 70–100% of controls. With more severe fire, yield decreased in the LP/ES relative to the low-intensity burn soil; however, only in the high-severity treatment was yield reduced (14%) from the control. Moderate- and high-severity burn areas in the PP/DF were fertilized with ~56 kg ha⁻¹ of N four months prior to soil sampling. In these soils, yield was 70–80% greater than the control. These results suggest that short-term site productivity can be stimulated by low-severity fire, but unaffected or reduced by more severe fire in the types of forests studied. Post-fire fertilization with N could increase soil productivity where other environmental factors do not limit growth.

Introduction

Wildfire and control of wildfire have affected forest ecosystems in the United States during the past decades. Since 1980, over 200 thousand hectares of National Forest lands have been burned annually by wildfire (USDA Forest Service 1980 through 1995). In 1994, one of the most severe fire seasons in recent years, nearly 100 thousand hectares of national, state, and private forest lands were burned by wildfire

in Washington state alone (Washington DNR, 1995; USDA Forest Service, 1995). Wildfire could have impacts on forest recovery and long-term productivity by reducing nutrient reserves (Smith, 1970; Grier, 1975), altering rates of nutrient cycling (Kutiel and Naveh, 1987; Prieto-Fernandez et al., 1993), and increasing erodibility (Campbell, 1977; Leitch et al., 1983; Amaranthus and Trappe, 1993; Andreu et al., 1996).

During fire, nutrients held in vegetation, litter, and soil can be lost to the atmosphere in gaseous or particulate form (Evans and Allen, 1971; Radke et al.,

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1978) or returned to the soil in ash (Raison et al. 1985; Trabaud, 1994). The amount of nutrient loss is a function of biomass, elemental composition of the fuel, and the intensity and duration of fire (Woodmansee and Wallach, 1981). Carbon and nitrogen are vulnerable to loss due to their low volatilization temperatures. Following high severity wildfire in various forest ecosystems, large reductions in total soil C and N have been reported with some reductions in excess of 25% of the soil nutrient capital (Smith, 1970; Grier, 1975; Kutiel and Naveh, 1987). Conversely, Prieto-Fernandez (1993) reported a 6% increase in N capital in the 0–10 cm mineral horizon following severe wildfire in a Mediterranean chaparral. The increase in soil N was attributed to deposition of incompletely burned biomass. Small reductions in soil total C and N capital have been reported following less severe wildfire or prescribed fire where the ignition temperature of soil organic matter may not be reached (Nissley et al., 1980; Rashid, 1987; Binkley et al., 1992).

In the western interior United States, forest productivity is often limited by low N availability (Brockley et al., 1992). Following prescribed or natural fire, several studies have reported increased concentrations of soil inorganic N (Christensen, 1973; White, 1986; Rashid, 1987; Kutiel and Naveh, 1987; Covington and Sackett, 1992; Prieto-Fernandez et al., 1993). The increase in inorganic N may be due to heat-induced release of NH_4^+ from organo-clay complexes (Russell et al., 1974; Giovannini et al., 1990), deposition of mineral N in ash residues, N-fixation, or an increase in N mineralization. Greater availability of mineral N can increase the productivity of forest soil following fire (Vlams et al., 1955; Wangle and Kitchen, 1971; Kutiel and Naveh, 1987). However, N released during combustion or post-fire microbial decomposition may be vulnerable to leaching and erosion loss. For example, Leitch et al. (1983) estimated that 82 kg ha^{-1} of N was removed in overland flow from a single thunderstorm immediately following severe wildfire in a eucalypt forest.

Few studies have examined wildfire effects on forest soil productivity. Although the effects of prescribed fire on forest soil have received much attention in recent years (Binkley et al., 1992; Covington and Sackett, 1992; Lopushinsky et al., 1992; Chorover et al., 1994), fires from controlled burning are generally not typical of wildfire conditions. The objective of the present study was to assess wildfire effects on site C and N capitals by examining nutrient pools in both soils and remaining above-ground debris in a ponder-

osa pine/Douglas-fir forest (*Pinus ponderosa* Dougl., *Pseudotsuga menziesii* (Mirb.) Franco.) and a lodgepole pine/Engelmann spruce forest (*Pinus contorta* Loud., *Picea engelmannii* Parry ex Engelm.) that were burned by wildfire in 1994.

Materials and methods

Site description

The ponderosa pine/Douglas-fir (PP/DF; $47^\circ 45' 50''$ N, $120^\circ 22' 30''$ W) and lodgepole pine/Engelmann spruce (LP/ES; $48^\circ 48' 30''$ N, $119^\circ 57' 30''$ W) study areas were located on the eastern slopes of the Cascade Mountains of Washington state, USA. Average annual precipitation is ~ 900 mm, falling mainly as winter snow and spring rain. Average annual air temperature is $\sim 8^\circ$ C. Soils in the study area are a mix of Inceptisols and Andisols with parent material consisting of dioritic and granodioritic bedrock overlain with pumice and volcanic tephra deposits. The soils are predominantly shallow, well-drained sandy loams on steep to moderately steep slopes (Beieler, 1975; Okanogan National Forest, 1996). Some characteristics of the study area soils are given in Table 1.

The PP/DF area was a mature, low elevation forest (400–1950 m) dominated by ponderosa pine on dry, southern aspects and Douglas-fir on northern aspects. Stand density averaged from 400 to 700 stems ha^{-1} . The predominant vegetation type was the *Pinus ponderosa*/*Calamagrotis rubescens* association described by Lillybridge et al. (1995). The PP/DF study area covered ~ 4000 ha, including two burned (2800 ha) and one unburned (1200 ha) catchments. Fire effects varied across the PP/DF landscape as a result of the 1994 fire, ranging from light surface burns to severe crown fire. In most areas all ground vegetation and O horizons were consumed by fire. In high-severity burn areas tree mortality was extensive: whole crowns were combusted and coarse roots were incinerated, resulting in a thick layer of white ash that covered the soil. Emergency rehabilitation measures were undertaken in the spring of 1995 (approximately 9 months after fire) in the moderate- and high-severity burn areas of the PP/DF in order to promote rapid ground cover. The rehabilitation included aerial seeding with sterile grasses (67 kg ha^{-1}) and N fertilization with $\leq 56 \text{ kg ha}^{-1}$ of N as ammonium nitrate and ammonium sulfate in a 3:1 ratio (Wenatchee National

Table 1. Average physical and chemical properties of soils in burned and unburned (control) forests following wildfire

| Forest type* | Post-fire interval | Treatment | n | Horizon | Depth (cm) | Mass (kg m ⁻²) | Bulk density (g cm ⁻³) | ≥2mm [†] (%) | pH | C/N |
|--------------|--------------------|-----------|----|---------|------------|----------------------------|------------------------------------|-----------------------|-----|-----|
| PP/DF | - | Control | 20 | O | - | 1.6 | - | - | - | 44 |
| | | | 20 | A | 0-10 | 100 | 1.1 | 24 | 6.7 | 18 |
| | | | 20 | Bw | 10-60 | 660 | 1.3 | 25 | 6.6 | 11 |
| | 3 mo | Burned | 33 | A | 0-12 | 110 | 1.1 | 23 | 6.7 | 19 |
| | | | 33 | Bw | 12-60 | 610 | 1.3 | 25 | 6.7 | 14 |
| | | | 33 | O | - | 0.16 | - | - | - | 48 |
| | 1 yr | Burned | 33 | A | 0-12 | 110 | 1.1 | 23 | 6.8 | 21 |
| | | | 33 | Bw | 12-60 | 610 | 1.3 | 25 | 6.4 | 15 |
| | | | | | | | | | | |
| LP/ES | - | Control | 15 | O | - | 2.0 | - | - | - | 42 |
| | | | 15 | A | 0-7 | 67 | 1.0 | 30 | 5.8 | 31 |
| | | | 15 | Bw | 7-56 | 700 | 1.3 | 34 | 5.9 | 17 |
| | 1 yr | Burned | 35 | O | - | 0.09 | - | - | - | 58 |
| | | | 35 | A | 0-7 | 65 | 1.0 | 32 | 6.2 | 30 |
| | | | 35 | Bw | 7-56 | 710 | 1.3 | 43 | 6.8 | 20 |

*PP/DF (ponderosa pine/Douglas-fir), LP/ES (lodgepole pine/Engelmann spruce);

[†]≥2 mm (Particle size).

Forest, 1995). Soils from the PP/DF were sampled three months and one year after fire.

The LP/ES area was a mid-elevation forest (1750–2100 m) dominated by 70–90 year-old lodgepole pine. Stand density ranged from 700 to 1000 stems ha⁻¹. The principal vegetation type was the *Abies lasiocarpa/vaccinium* spp. association (Williams and Lillybridge, 1983). The LP/ES study area (450 ha) included two burned (400 ha) and one unburned (50 ha) catchments. Most of the LP/ES was burned by severe crown fire, resulting in nearly 100% tree mortality and complete consumption of surface vegetation, litter and organic soil. In the most severely burned areas, whole logs and coarse roots were incinerated by fire and there was evidence of heat-induced alteration of mineral soil. A thick layer of predominantly black ash, 1–5 cm deep, covered much of the study area. At the time of soil sampling, one year after fire, little regeneration of surface vegetation had occurred.

Field sampling and measurements

Circular plots of 29 m² were established in each forest type using a stratified-random sampling technique from which the number and approximate location of plots were determined on topographic maps prior to field sampling to ensure evenly distributed coverage of catchments. Twenty and fifteen plots were established in the PP/DF and LP/ES unburned (control)

catchments, respectively. Total plots in the burn catchments were 33 in the PP/DF and 35 in the LP/ES. Plots in burn areas were assigned a fire severity rating according to the degree of overstory crown burn:

1. High: greater than 75%,
2. Moderate: between 75 and 25%, and
3. Low: less than 25%.

In the PP/DF, 10 plots were established in low-severity areas, 19 plots in moderate-severity areas, and 4 plots in high-severity areas. In the LP/ES, 3, 5 and 27 plots were located in low-, moderate- and high-severity burn areas, respectively. The number of plots per burn severity was proportional to the natural burn intensity.

At each plot a soil pit was excavated to a depth of 60 cm and soil samples were collected from genetic horizons for chemical and physical analyses three months and one year following fire. Field measurements and sample collections were made during the months of August and September. O-horizon samples were not collected from the PP/DF burn area at the three month sampling period as fire had completely ashed O-horizon material at the study sites. Ash residues from the fire were incorporated in the surface, mineral horizon samples since it was not possible to separate the two materials at the time of soil sampling. O-horizon samples, consisting of post-fire litterfall, were collected from a 0.25 m² area on each plot one year after fire in both forests. Bulk density core samples were collected from mineral horizons, except

in gravelly or rocky soil where bulk density estimates were based on the soil mass and water volume of a small, plastic-lined hole excavated to a depth of ~15 cm (Helvey et al., 1985).

Soil samples were air-dried prior to chemical analyses. pH was measured on mineral soils using a 1:5 soil to water ratio. Concentrations of total C and N were determined on unsieved, ground soil samples using a Perkin-Elmer 2400 CHN analyzer (Perkin-Elmer Corp., Norwalk, CT). Soil C and N capital were corrected for moisture content and are presented on an oven-dry basis. Total C and N data within a forest type were compared by ANOVA with unequal numbers of observations in the burned and control treatments. A 95% confidence level was used for all tests of significance ($P < 0.05$).

Surface erosion (sheet plus rill) was measured in both forests one year after fire from a 1 m² area on each plot (Leitch et al., 1983). Sheet erosion, considered as erosion of less than 0.5 cm in depth, was estimated visually as the proportion of the 1 m² area affected. Soil volume was calculated by multiplying the area affected by a depth of 0.16 cm, which was the median depth of sheet erosion observed on the plots. Soil volume was multiplied by the A-horizon bulk density and concentration of total C or N to estimate soil and nutrient removal. Elemental concentrations of A horizons sampled one year after fire were used for the estimates. Rill erosion was determined from volumetric measurements of rill channels (≥ 0.5 cm depth) on the same 1 m² area. Rill erosion never exceeded 10 cm on the plots. Soil and nutrient removal through rill erosion were calculated in a similar manner as sheet erosion. Sheet plus rill erosion were summed for each plot and averaged for the two forest types.

To estimate nutrient storage in bole-wood of standing live and dead (snag) trees, a 100% tally of diameter at breast height (DBH) was made on 50% of the plots in both forest types. The DBH measurements were converted to biomass using linear regression equations for Pacific northwest ponderosa pine (PP/DF plots) and lodgepole pine (LP/ES plots) (Gholz et al., 1979). Nutrient storage was calculated by multiplying bole-wood mass by concentrations of C and N reported for ponderosa pine (Klemmedson, 1975) or lodgepole pine (Fahey et al., 1985), assuming any difference in elemental concentration between snag and live-tree wood is minor. Concentrations of C and N used for the bole-wood calculations are given in Table 4.

Coarse woody debris (CWD) volume was calculated on the same plots from length and diameter

measurements of forest floor woody material ≥ 3 cm in diameter. Specific gravity was determined on a subset of 12 burned and unburned CWD samples from each forest type using the method described by Forbes and Meyer (1955). The average specific gravity for a treatment was multiplied by plot CWD volume and a C or N concentration to estimate nutrient storage. Concentrations of C and N reported for unburned CWD in a ponderosa pine forest (Klemmedson, 1975) or lodgepole pine forest (Busse, 1994) were used for the control plot estimates. For the burned plots, a CWD sample from 4 plots in each forest type was oven dried (70 °C), ground, and analyzed for total C and N. The average elemental concentration for each forest type was used for the nutrient estimate. Live tree, snag and CWD measurements were taken on plots one year after fire.

Bioassay

To examine the relative N-availability of soils from the study area, a bioassay was undertaken using lettuce (*Lactuca sativa*) as an indicator plant. The bioassay included 8 treatments (2 forest types \times 4 burn severities (high, moderate, low and unburned)) with 4–6 replicates per treatment. Pots were randomly arranged in a growth chamber at 16 h lighting with weekly rotation and regular irrigation. Pots were filled with 200 g of air-dried soil that was collected from the study plots one year after fire. The PP/DF pots contained 150 g of A-horizon and 50 g of Bw-horizon soil, and LP/ES pots contained 100 g of both A- and Bw-horizon soil, representing the relative proportion of each horizon to a depth of 15 cm. Each pot was seeded with lettuce and thinned to 3 plants per pot at two weeks. All three lettuce plants per pot were harvested to the soil surface at 8 weeks after sowing. The tops were oven-dried (70 °C) for 48 hours prior to physical and chemical analyses. Total C and N were determined on ground samples using a CHN analyzer.

Results and discussion

Soil total C and N

One year after fire, average O-horizon mass was less than 10% of control levels on the burned PP/DF (0.16 vs 1.6 kg m⁻²) and LP/ES (0.09 vs 2.0 kg m⁻²) plots (Table 1). The O-horizon total C concentration was significantly higher in both burned forests than control soil (Figure 1). The increase in C was likely the result

Table 2. Soil total carbon and nitrogen (mean±SE) to a 60 cm depth in burned and unburned (control) forests after wildfire. Profile totals for C or N within a forest type with the same letter do not differ at $P < 0.05$

| Forest type* | Post-fire Interval | Treatment | Horizon | C N (Mg ha ⁻¹) | | | |
|--------------|--------------------|-----------|---------|-------------------------------|-----------|---------|----------|
| | | | | C | N | | |
| PP/DF | - | Control | O | 6.7±6 | 0.16±0.2 | | |
| | | | A | 23±20 | 1.3±1 | | |
| | | | Bw | 54±30 | 5.0±2 | | |
| | | | Total | 84±40a | 6.5±2a | | |
| | 3 mo | Burned | O | - | - | | |
| | | | A | 16±10 | 0.83±0.4 | | |
| | | | Bw | 37±20 | 2.7±1 | | |
| | 1 yr | Burned | O | 0.7±0.7 | 0.01±0.01 | | |
| | | | A | 21±10 | 1.0±1 | | |
| Bw | | | 37±20 | 2.5±1 | | | |
| Total | | | 59±20b | 3.5±1b | | | |
| | | LP/ES | - | Control | O | 8.6±0.6 | 0.21±0.2 |
| | | | | | A | 28±10 | 1.0±0.4 |
| Bw | 36±20 | | | | 2.0±1 | | |
| Total | 73±10z | | | | 3.2±1z | | |
| 1 yr | Burned | O | 0.5±0.9 | 0.01±0.02 | | | |
| | | A | 24±10 | 0.83±0.4 | | | |
| | | Bw | 40±20 | 1.9±1 | | | |
| Total | | | 66±30z | 2.8±1z | | | |

*PP/DF (ponderosa pine/Douglas-fir), LP/ES (lodgepole pine/Engelmann spruce).

of fresh litter inputs. Binkley et al. (1992) reported a similar increase in O-horizon C concentration one year after prescribed fire in a loblolly and longleaf pine forest (*P. taeda* L., *P. palustris* Mill.). The O-horizon concentration of total N was not affected by fire in the PP/DF but was significantly lower in burned LP/ES soil (Figure 2). In the LP/ES, the post-fire litterfall was composed of a high proportion of charred biomass which undoubtedly contributed to the decrease in N concentration. With the decrease in N and increase in C, the O-horizon C/N ratio rose sharply on the burned LP/ES plots (Table 1).

Fire reduced the O-horizon capital of total C by ~90% of control soil for both forest types (Table 2). The average loss of O-horizon C was 6.0 and 8.1 Mg ha⁻¹ in the PP/DF and LP/ES, respectively. Total N was reduced by ~95% compared to control levels with losses of 0.15 and 0.20 Mg (N) ha⁻¹ in the PP/DF and LP/ES soil. In the LP/ES, the average litterfall input

of N was 0.01 Mg ha⁻¹ during the first year after fire. This value is one-sixth the annual litterfall rate of N (0.06 Mg ha⁻¹ y⁻¹) reported for an unburned lodgepole pine forest of similar age and stand density in Wyoming (Fahey et al., 1985). Because fire consumed most of the LP/ES overstory canopy and regeneration of surface vegetation has been slow, reduced N input to the LP/ES O-horizon is expected in the short term.

A-horizon concentrations of total C and N were lower in burned compared to control soil from both forests (Figures 1 & 2). In the PP/DF, the difference between burned and control soil was significant for both elements and at both sampling dates. In the LP/ES, ANOVA results did not indicate a significant difference in C or N, probably owing to the greater degree of variability in elemental concentrations in the burned LP/ES soil.

One year after fire, total C capital in the A horizon was reduced from control levels by 2 Mg ha⁻¹

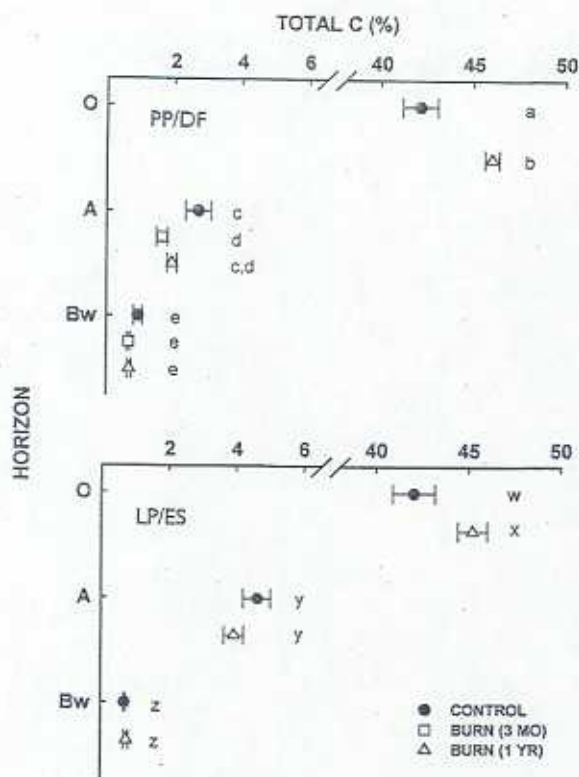


Figure 1. Soil total C concentration (mean \pm SE) by horizon from ponderosa pine/Douglas-fir forest (PP/DF) and lodgepole pine/Engelmann spruce forest (LP/ES) at 3 months and 1 yr following wildfire and from unburned forests (control). Values within a horizon of a forest type with the same lower case letter do not differ at $P < 0.05$.

in the PP/DF and 4 Mg ha⁻¹ in the LP/ES (Table 2). Total N was decreased by 0.3 and 0.2 Mg ha⁻¹ in the PP/DF and LP/ES, reductions equivalent to 23% and 20% of control plot levels. Comparable reductions in soil total N have been observed in other forest ecosystems following severe wildfire. Grier (1975) reported a 33% loss in total N (0.54 Mg ha⁻¹) from the 0 to 6 cm layer following wildfire in a ponderosa pine forest located near the PP/DF study area. Kutiel and Naveh (1987) reported a 25% loss of total N from the 0 to 2 cm layer following wildfire in an Aleppo pine (*P. halapensis* Mill.) forest in Israel.

From the three-month to one-year sampling period there was a slight but not significant increase in the A-horizon concentration of total C on the burned PP/DF plots. The increase may have been the result of grass seeding on moderate- and high-severity burn areas or organic matter incorporation from the O horizon. Although the PP/DF moderate- and high-severity burn areas were fertilized with N approximately 9 months after fire, a significant increase in A-horizon total N

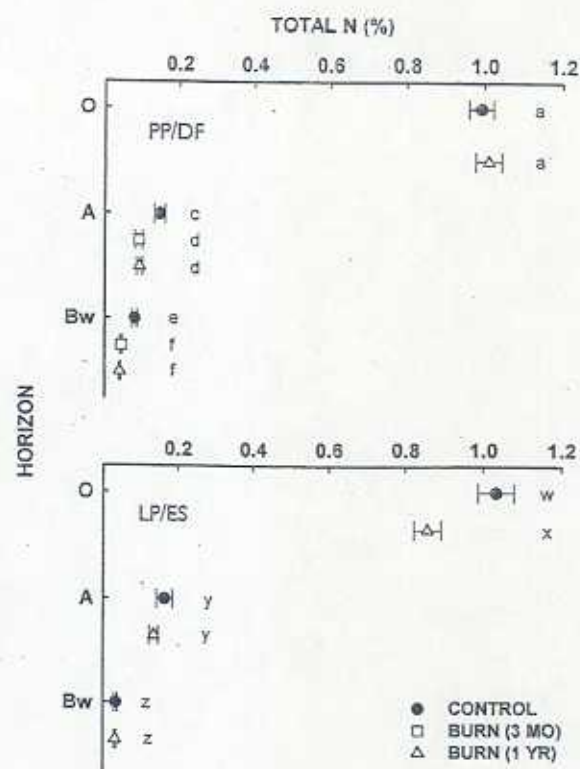


Figure 2. Soil total N concentration (mean \pm SE) by horizon from ponderosa pine/Douglas-fir forest (PP/DF) and lodgepole pine/Engelmann spruce forest (LP/ES) at 3 months and 1 yr following wildfire and from unburned forests (control). Values within a horizon of a forest type with the same lower case letter do not differ at $P < 0.05$.

was not detected. Undoubtedly, some of the fertilizer N was converted to plant biomass given the dense cover of ground vegetation observed on many PP/DF plots one year after fire. Additionally, some fertilizer N could have been lost by nitrate leaching.

In the Bw horizon, concentrations of total C and N were not affected by fire in the LP/ES. However, in the PP/DF, C and N concentrations were significantly lower in burned compared to control soil at both sampling dates. Three months after fire, C and N capital in the burned Bw soil was 31% (17 Mg (C) ha⁻¹) and 46% (2.6 Mg (N) ha⁻¹) lower than control soil. Intense soil heating occurred during fire in the PP/DF as indicated by coarse-root incineration observed on severely burned plots. However, due to variability in burn severity throughout the PP/DF study area and the depth of the Bw horizon in the soil profile (12–60 cm), only minor changes in elemental content were expected in the Bw horizon. Other studies have not reported comparable reductions in nutrient capital from the subsurface soil following fire. In fact, Smith (1970)

Table 3. Average plot slope, estimated surface erosion (sheet plus rill) and carbon and nitrogen loss through surface erosion one year after fire

| Forest type* | Slope (%) | Soil (Mg ha ⁻¹) | C (kg ha ⁻¹) | N (kg ha ⁻¹) |
|--------------|-----------|-----------------------------|--------------------------|--------------------------|
| PP/DF | 40 | 15 | 280 | 14 |
| LP/ES | 33 | 18 | 640 | 22 |

*PP/DF (ponderosa pine/Douglas-fir), LP/ES (lodgepole pine/Engelmann spruce).

and Rashid (1987) found that the subsurface capital of organic C was increased after wildfire due to colloidal leaching. In the LP/ES, the Bw-horizon capitals of C and N were not substantially altered from control levels, even though the majority of plots were located in high severity burn areas. Thus, it is possible that nutrient capitals in the burned and control Bw horizons may not have been similar in the PP/DF prior to fire. These differences in pre-fire nutrient capitals between burned and control plots could be due to natural variability or past fire history.

Following fire, soil C and N capital to a 60 cm depth was lower on the burned plots of both forests relative to control soil. Results from ANOVA indicated that the difference in nutrient capital was significant only in the PP/DF, for both elements and at both sampling dates (Table 2). One year after fire, C capital in the burned PP/DF and LP/ES soil was 30% (25 Mg ha⁻¹) and 10% (7 Mg ha⁻¹) lower than control soil while N capital was 46% (3.0 Mg ha⁻¹) and 13% (0.4 Mg ha⁻¹) lower. The greater reduction in soil nutrient capital from the burned PP/DF plots was the result of an apparent C and N loss from the Bw horizon. Assuming that lower nutrient capitals in the burned Bw horizons do not represent true effects from the 1994 fires, C and N reductions from the soil profile in the PP/DF were 10% (8.0 Mg ha⁻¹) and 7% (0.45 Mg ha⁻¹), respectively [(Control O+A horizon capital - Burned O+A horizon capital) ÷ (Control total)] (Table 2). In the LP/ES, C capital was higher in the burned Bw horizons. Thus, the reduction in C from the O+A horizon was 17% (12 Mg ha⁻¹) of the profile total while the N reduction was 12% (0.37 Mg ha⁻¹).

Erosion

Surface erosion was not observed on control plots from either forest. However, on the majority (~90%) of burned plots in both forests either sheet, rill or both forms of erosion were evident. There was little dif-

ference in the quantity of soil eroded from the PP/DF (15 Mg ha⁻¹) and LP/ES (18 Mg ha⁻¹) (Table 3), which may reflect the similarities in topographic and soil factors between the forests (e.g. slope, surface soil bulk density and texture). Cover and soil stabilization provided by seeded grass on the moderate- and high-severity burn areas in the PP/DF may have contributed to the somewhat lower volume of soil eroded from this forest. Using the A-horizon bulk density, it was estimated that surface erosion removed an average of 1.8 and 1.7 mm of topsoil plus ash from the PP/DF and LP/ES plots, respectively. In both forests, gully erosion was evident but not quantified.

Several studies have reported accelerated surface erosion following wildfire (Leitch et al., 1983; Helvey et al., 1985; Scott and Van Wyk, 1990; Scott and Schulze, 1992; Andreu et al., 1996). The magnitude of soil and nutrient loss through surface erosion varies considerably in the literature since the production of sediment in runoff is influenced by climatic, topographic and edaphic characteristics of the site, as well as by the degree of fire severity (Tiedemann et al., 1979). For example, Campbell et al. (1977) estimated surface runoff at 1.3 Mg (soil) ha⁻¹ yr⁻¹ following wildfire in an Arizona ponderosa pine forest while Amaranthus and Trappe (1993) reported surface erosion at 85.3 Mg (soil) ha⁻¹ during the first 5 months after wildfire in an Oregon Douglas-fir forest. In the Amaranthus and Trappe (1993) study, it was estimated that surface erosion removed between 20 and 40 mm of topsoil, a considerably greater removal than observed in the PP/DF and LP/ES.

Site nutrient loss through surface erosion was greater in the LP/ES than the PP/DF (Table 3). This difference reflects the greater volume of soil eroded from the LP/ES plots as well as the higher A-horizon concentrations of C and N used for the erosion calculations (Figures 1 & 2). In both forests, site loss of C and N through surface erosion was ~1% of the A-horizon capital of these elements in control soil. The C and N values reported in Table 3 are considered conservative estimates of surface erosion because nutrient leaching from the ash layer most likely occurred before sample collections were taken and the estimates did not include removal of forest floor material.

Live trees, snags and coarse woody debris

Tree mortality was extensive in the LP/ES one year after fire. As a result of mortality, average live-tree mass was reduced by 96% (68 Mg ha⁻¹) of the control

Table 4. Average total carbon and nitrogen stored in woody components of burned and unburned (control) forests following wildfire. CWD=coarse woody debris

| Forest type ^a | Component | Control | | | Burned | | |
|--------------------------|------------------|-----------------------------|--------------------------|--------------------------|-----------------------------|--------------------------|--------------------------|
| | | Mass (Mg ha ⁻¹) | C (Mg ha ⁻¹) | N (kg ha ⁻¹) | Mass (Mg ha ⁻¹) | C (Mg ha ⁻¹) | N (kg ha ⁻¹) |
| PP/DF | Live bole* | 60 | 31 | 82 | 42 | 21 | 55 |
| | Snag bole* | 0.6 | 0.3 | 0.8 | 9 | 5 | 12 |
| | CWD [†] | 6 | 3 | 23 | 4 | 2 | 5 |
| | Total | 87 | 34 | 106 | 55 | 28 | 72 |
| LP/ES | Live bole** | 71 | 35 | 28 | 3 | 1 | 1 |
| | Snag bole** | 0.1 | 0.1 | 0.1 | 51 | 25 | 21 |
| | CWD [‡] | 22 | 11 | 13 | 34 | 18 | 14 |
| | Total | 93 | 46 | 41 | 88 | 44 | 36 |

^aPP/DF (ponderosa pine/Douglas-fir), LP/ES (lodgepole pine/Engelmann spruce). * [C] = 49%, [N]=0.13% (Klemmedson, 1975). [†]Control CWD [C]=49%, [N]=0.37% (Klemmedson, 1975); burned CWD [C]=52%, [N]=0.13% (this study). ** [C]=49%, [N]=0.04% (Fahey et al., 1985). [‡]Control CWD [C]=49%, [N]=0.06% (Busse, 1994); burned CWD [C]=53%, [N]=0.04% (this study).

plot level (Table 4). High-severity, stand-replacement fire is not uncommon in mid-elevation coniferous forests such as the LP/ES because of the build up of heavy fuel loads and the relative intolerance to fire of most tree species in these forests (Agee, 1993). In the PP/DF, where fire severity was more variable, live-tree mass was reduced by 30% (18 Mg ha⁻¹).

From the difference in coarse woody debris (CWD) mass on control and burned plots, an estimated 33% reduction in CWD occurred in the PP/DF. Because of the addition of new CWD between the time of fire and plot sampling, the reduction in CWD from the PP/DF is a very conservative estimate of fire consumption. For example, in a before and after study by Covington and Sackett (1992), a 63% reduction in CWD was reported following prescribed burning in a ponderosa pine forest. In a similar study, broadcast burning consumed 80% of the logging residues from clearcut harvesting in a high elevation subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and lodgepole pine forest (Lopushinsky et al., 1992). The N concentration of burned CWD in the PP/DF was 0.13%±0.03 (mean±SD). This value is much lower than Klemmedson's (1975) reported value for intact CWD in a ponderosa pine forest (0.37%) but similar to the N concentration of burned CWD (0.143%) in the 2.55–7.62 cm diameter class reported by Covington and Sackett (1992). As a result of the reduced mass and N concentration of CWD on the burned PP/DF plots, it was estimated that N storage in CWD was reduced by 78% (18 kg ha⁻¹). Covington and Sackett (1992)

reported an 80% reduction in N storage. In the LP/ES, due to the high fall rate of fire-killed trees, CWD mass was higher on the burned than control plots.

Total wood mass (live tree+snag+CWD) was reduced on burned plots by 37% (32 Mg ha⁻¹) and 5% (5 Mg ha⁻¹) of control levels in the PP/DF and LP/ES forests. Carbon storage in wood was decreased by 18% (6 Mg ha⁻¹) and 4% (2 Mg ha⁻¹) while nitrogen storage in wood was reduced 32% (34 kg ha⁻¹) and 12% (5 kg ha⁻¹) in the PP/DF and LP/ES, respectively. Due to a high degree of variability in total wood mass on the LP/ES plots, the estimates for this forest are undoubtedly low.

Bioassay

Lettuce yield was substantially greater in PP/DF compared to LP/ES soil at all burn-severity levels (Figure 3). Foliar N showed a similar trend with greater N accumulation at all burn severities in the PP/DF, although the difference in foliar N was slight in the control- and low-severity burn treatments. Soil from the PP/DF had lower C/N ratios than the LP/ES except in the low-severity burn treatment (Figure 4). The lower C/N ratios may have resulted in higher N-mineralization and greater N availability in the PP/DF soil. The relatively low productivity of LP/ES soil is consistent with the poor regeneration of surface vegetation observed one year after fire. Radek (1997) also reported poor regeneration in burn areas near the LP/ES.

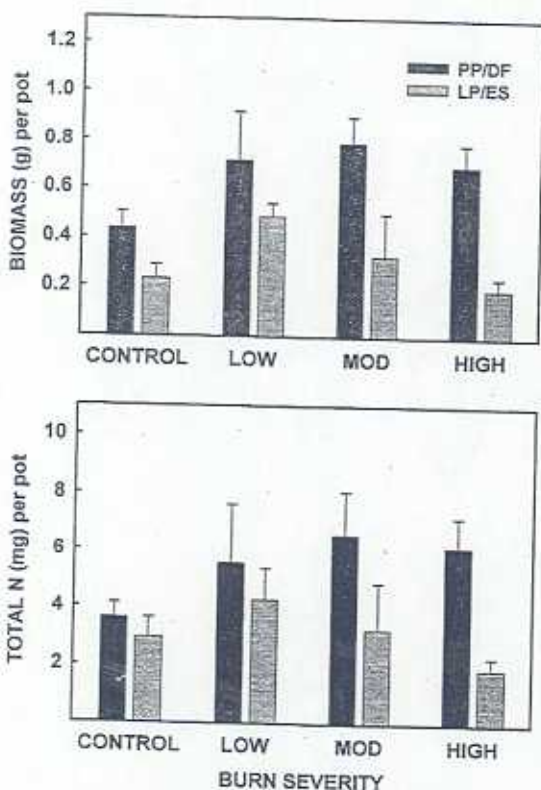


Figure 3. Average and SE of aboveground biomass and total N accumulation in bioassay lettuce plants ($n=4-6$). Soils were collected from control, low-, moderate- and high-severity burn areas 1 year after wildfire in a ponderosa pine/Douglas-fir forest (PP/DF) and a lodgepole pine/Engelmann spruce forest (LP/ES).

In both forests, soils from the low-severity plots yielded greater lettuce mass and foliar N than control soil. Lettuce response to more severe fire differed between forests. In the LP/ES, lettuce yield decreased with increased fire severity. However, only in the high-severity treatment was average plant yield and N accumulation reduced from the control level. In PP/DF soil, moderate- and high-severity fire resulted in increased plant productivity compared to the control. This may be the result of residual fertilizer N that remained available for uptake. The PP/DF moderate- and high-severity treatments had similar soil C/N ratios as the control (Figure 4) yet greater foliar N accumulation (Figure 3), suggesting a positive effect from N fertilization. The relative contribution of fertilization and fire to higher productivity in the PP/DF moderate- and high-severity treatments is unclear. Increased plant productivity following prescribed or natural fire has been reported by others (Vlaminis et al., 1955; Wangle and Kitchen, 1971; Kutiel and Naveh, 1987). These authors have suggested that plant growth

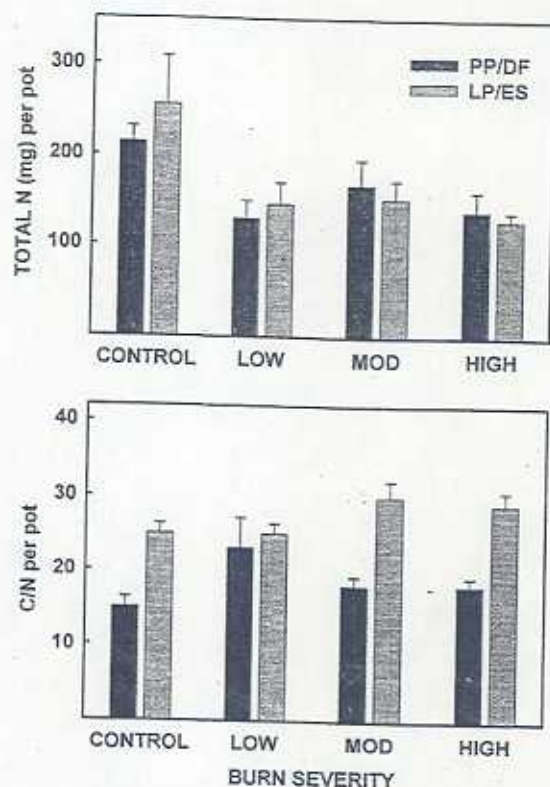


Figure 4. Average and SE of total N and C/N ratio in bioassay soils ($n=4-6$). Soils were collected from control, low-, moderate- and high-severity burn areas 1 year after wildfire in a ponderosa pine/Douglas-fir forest (PP/DF) and a lodgepole pine/Engelmann spruce forest (LP/ES).

could be enhanced in post-fire soils by higher N mineralization, greater availability of cations or a reduction in allelopathic growth inhibitors. Results from the present study suggest that short-term site productivity can be stimulated by low-severity fire but unaffected or reduced by more severe fire. On severely burned sites, post-fire N fertilization may enhance soil productivity.

Conclusions

Following wildfire in the PP/DF and LP/ES study areas, total soil C and N were reduced from control levels. In both forests, O horizons were almost completely consumed by fire, resulting in reductions of C and N capital of >90% from control soil. Fire reduced the A-horizon capitals of total C and N by ~10% and 20%, respectively in both forests. The estimated reductions in nutrient capitals from the Bw horizon following fire in the PP/DF were probably the result of dissimilar nutrient capital between burned and control plots prior to fire rather than a direct fire effect.

Mineral soil C/N ratios were not substantially changed by fire in either forest. Surface erosion redistributed between 15 and 18 Mg (soil) ha⁻¹ in the burn areas, including ~1% to 2% of the A-horizon capitals of C and N. It was estimated that fire reduced C and N stored in woody components (live tree+snag+CWD) by 18% and 32% in the PP/DF and by 4% and 12% in the LP/ES. Total site nutrient loss, including soil (O and A horizons only) and woody components was 14 Mg (C) ha⁻¹ and 0.5 Mg (N) ha⁻¹ in the PP/DF. In the LP/ES, the losses of total C and N were 14 and 0.4 Mg ha⁻¹, respectively. Results from the bioassay showed that site productivity was increased by low severity fire but unaffected or reduced by more severe fire. On severely burned sites, post-fire N fertilization may increase productivity.

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