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Nitrogen Mineralization in Aspen/Conifer Soils After a Natural Fire

Michael C. Amacher, Dale L. Bartos, Tracy Christopherson, Amber D. Johnson, and Debra E. Kutterer[1]

Abstract—We measured the effects of the 1996 Pole Creek fire, Fishlake National Forest, Utah, on available soil N and net N mineralization for three summers after the fire using an ion exchange membrane (IEM) soil core incubation method. Fire in mixed aspen/conifer increased the amount of available NH_4, and a subsequent net increase in soil nitrification was observed. Release of NH_4 from the ash and a net increase in soil nitrification were still observed 3 years after the fire. The fire-caused increase in available soil N provides a source of N for aspen regrowth.

Introduction

Aspen (*Populus tremuloides*) provide many ecological benefits to resource users, including protection of watersheds from erosion, some protection against rapid wildfire advance, increased biological diversity in the species-rich grass-forb understory, wood fiber, wildlife habitat, forage for domestic livestock and native ungulates, recreational sites, aesthetic considerations (e.g., fall leaf colors), and more water yield than conifers (Bartos and Campbell 1998a). Some authors have suggested that aspen are in decline throughout the Interior Western United States (Bartos and Campbell 1998a), although the extent of decline has been the subject of much debate. National Forest inventory and analysis data indicate that about 60% of aspen stands have disappeared since the mid-19th century (Bartos and Campbell 1998b). Decline of aspen stands is attributed to natural succession (e.g., invasion of conifers) (Harniss 1981), fire suppression (Jones and Debyle 1985), and overbrowsing by domestic livestock and native ungulates (Kay 1990).

Western aspen, which reproduce primarily by suckering from lateral roots, often need disturbances to stimulate the suckering response (Schier 1981). In the past, these disturbances included lightning-caused fires that killed mature aspen, and insects and diseases that weakened old decadent stands before toppling by wind. Suppression of human-caused and lightning-caused fires throughout the twentieth century has greatly reduced one of the main forces of aspen regeneration from the landscape. Even when a disturbance such as fire or wind does stimulate aspen regeneration, overbrowsing of new aspen suckers by domestic livestock and native ungulates quickly suppresses regeneration. Evidence indicates that overbrowsing and conifer invasion of declining aspen stands have led to the precarious state of aspen in the Interior Western United States, although this assessment is not universally accepted.

In addition to stimulating aspen suckering, fire can also exert a large influence on soil properties in burned stands, depending on the intensity of the burn. Increases in plant available nutrients usually occur following fire because of the transfer of nutrients from the ash to the soil (Schlesinger 1997). These

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increases are usually considered to be short lived because of nutrient uptake by new vegetative growth and losses from leaching (primarily NO_3) and erosion.

During June and July of 1996, an 8,000-acre natural fire (the Pole Creek fire) occurred in the area of Betenson and Grindstone Flats on the Beaver Ranger District of the Fishlake National Forest, Utah. This moderate-intensity fire burned in mixed stands of older aspen and invading conifers, primarily subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*). After the fire, some cutting of fire-killed aspen and conifers was done to thin the stands, and four exclosures were constructed by Utah Division of Wildlife Resources and Fishlake National Forest personnel to protect aspen suckers from browsing by domestic livestock and native ungulates. Two exclosures were built in the Grindstone Flat area and two in the nearby Betenson Flat area.

We present results of the effects of a natural fire on available soil N and net soil N mineralization during the first, second, and third summers after the fire year. In particular, we studied the effects of fire on the amounts of extractable soil NH_4 and NO_3, amounts and rates of leaching of NH_4 and NO_3 from plant litter or ash layers, and net changes in some reactions of the internal soil N cycle (e.g., nitrification, mineralization).

Methods

We measured net soil N mineralization/immobilization during the summer months in 1997, 1998, and 1999, following the 1996 Pole Creek fire using an ion exchange membrane (IEM) soil core incubation technique. The method was similar to that developed by DiStefano and Gholz (1986) except that we used ion exchange membranes (Ionics Inc., Watertown, MA) in place of ion exchange resin bags. The IEMs have identical ion exchange properties to the more familiar resin beads and have shown considerable promise for assessing soil nutrient availability (Cooperband and Logan 1994).

Ion Exchange Membrane Soil Core Method

The assembly of the soil cores with IEMs is shown in figure 1. The soil core is enclosed in a 2-inch diameter x 4-inch long plastic liner (Forestry Suppliers, Jackson, MS). End caps were used to hold the IEMs against each end of the soil core. Circular holes (1.5-inch diameter) were cut in the center of the 2-inch diameter end caps. Cation (CEM) and anion (AEM) exchange membranes were prepared by cutting 2-inch diameter circles from the original membrane sheets and drilling nine evenly spaced $\frac{1}{8}$-inch holes in each circle to allow movement of air and slow percolation of water through the soil cores. The CEMs and AEMs were soaked five times in 1 M HCl and 1 M $NaHCO_3$, respectively, rinsed with deionized water, and sealed in ziplock plastic bags for transport to the field. To protect the IEMs from abrasion and excessive desiccation and to direct infiltrating water to flow across the surfaces of the IEMs to increase the efficiency of ion exchange, porous screens were prepared by cutting 2-inch diameter circles from 114-um Spectra/Mesh polyethylene filter screens.

We installed the IEM soil cores in the following manner. Leaf litter (unburned areas) or ash layer (burned areas) was first removed from the soil surface and set aside. The soil coring head with a plastic liner was driven into the soil using a slide hammer attachment (Forestry Suppliers, Jackson, MS) until flush with the top of the soil. The intact soil core was removed from the coring
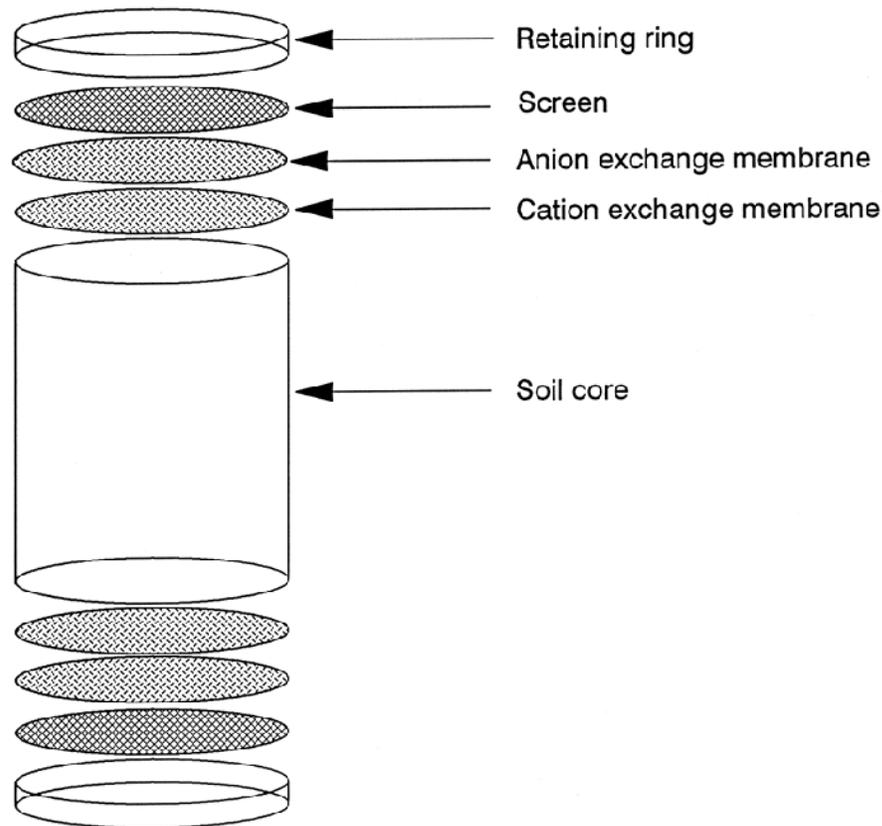
Figure 1–Ion exchange membrane soil core assembly.

head, the ends of the core were trimmed, and the excess soil was returned to the soil hole. The end caps, plastic screens, and IEMs were assembled as shown in figure 1, the IEM soil core was placed in the hole with the top end up, and the core was covered with leaf litter or ash. Core locations were marked with flagged rebar stakes. An additional soil core was taken adjacent to the installed IEM soil core to determine initial soil exchangeable NH_4 and NO_3 levels. The initial cores were removed from the coring tool and placed in labeled zip-lock plastic bags. The cores were transported to the laboratory in a cooler and stored at <4 °C until extraction (usually within 2 weeks of sampling).

The IEM soil cores were installed in burned and unburned areas on Grindstone and Betenson Flats: four cores were installed in each of the four exclosures in burned aspen/conifer stands, four cores were installed in each of three unburned aspen/conifer stands near the burned areas, and four cores were installed in each of two unburned aspen stands that regenerated as a result of a fire in 1958. Soil temperature in each area was monitored at a 4-inch depth using Optic StowAway temperature loggers (Onset Computer Corp., Bourne, MA).

Two incubation periods were used each summer: 6/25 to 7/22/97 (27 d), 7/22 to 9/23/97 (63 d), 6/23–24 to 7/21–22/98 (27–28 d), 7/21–22 to 9/19/98 (59–60 d), 7/1 to 7/29/99 (28 d), and 7/29 to 9/19/99 (52 d). At the end of each incubation period, the leaf litter or ash layer was removed from the tops of the cores and the cores were removed from the ground and placed in labeled zip-lock plastic bags. The cores were transported to the laboratory in a cooler and stored at <4 °C until extraction. New initial cores for the second incubation period were collected when the IEM soil cores from the first period were removed and the new IEM soil cores were installed.

The IEM soil cores were disassembled, and top and bottom CEM-AEM pairs were rinsed with deionized water to remove soil particles and placed in

separate labeled petri dishes. The soil cores were removed from the plastic liners, returned to the zip-lock bags, and mixed by kneading the bags. Each CEM-AEM pair was extracted with 100 mL of 2 M KCl in 250-mL wide-mouth plastic jars by shaking for 1 h on an orbital shaker at 150 rpm. The extracts were frozen until analysis.

Water content of a representative subsample of each soil core was determined gravimetrically at 105 °C. A representative field-moist subsample of each soil core equivalent to 10 g of oven-dry soil was extracted with 100 mL of 2 M KCl in a 250-mL wide-mouth plastic jar by shaking for 1 h on an orbital shaker at 150 rpm. The extracts were filtered through Whatman 40 filter paper and frozen until analysis. The 2 M KCl extracts of IEMs and soil cores were analyzed for NH_4–N and NO_3–N by the automated phenate and Cd reduction methods, respectively, using a LACHAT flow injection analysis system (Zellweger Analytics, Milwaukee, WI).

The remaining soil from each soil core was air dried at room temperature and weighed. The total weight of each soil core was calculated by summing the oven-dry weight of the subsample used for determining water content, the oven-dry weight of the subsample used for determining extractable NH_4 and NO_3, and the air-dry weight of the remaining soil in each core.

Amounts of NH_4–N and NO_3–N accumulated by the IEMs (ug/cm^2) were calculated by multiplying the NH_4 and NO_3 concentrations in the KCl extracts by the extract volume and dividing by the surface area of the IEM ($20.27 \ cm^2$). Rates of NH_4 or NO_3 accumulation by the cores ($ug/cm^2/mo$) were calculated by dividing the accumulated amounts by the incubation time in days and multiplying by 30 days per month. The IEMs at the top of the soil core remove NH_4 and NO_3 in precipitation or leachate passing through the leaf litter or ash layers. The IEMs at the bottom of the soil core remove NH_4 and NO_3 leached from the soil core. Concentrations of NH_4 and NO_3 in the top and bottom IEMs on a soil weight basis for the entire soil core (mg/kg) were calculated by multiplying the amounts on the IEMs by the IEM surface area and dividing by the dry weight of the soil core.

Total NH_4 and NO_3 concentrations in the IEM soil cores were obtained by summing the concentrations of NH_4 or NO_3 in the soil core plus the amounts extracted from the bottom IEMs. Following terminology and definitions given by Stevenson (1986) and DiStefano and Gholz (1986), net ammonification is equal to total NH_4 in the IEM soil core minus NH_4 in the initial soil core. Net nitrification is equal to total NO_3 in the IEM soil core minus NO_3 in the initial soil core. Net mineralization (or immobilization) is equal to net ammonification plus net nitrification. Net ammonification, nitrification, and mineralization rates were calculated by dividing the net amounts by the incubation time. An example of these calculations for one of the soil cores from the burn area is shown in table 1.

Data Analysis

Because the data were nonnormally distributed, a Kruskal-Wallis (K-W) analysis of variance on ranks was run on each measured or derived N variable for each incubation period in each year with stand type as the factor and unburned aspen, unburned mixed aspen/conifer, and burned mixed aspen/conifer as levels within stand type (SigmaStat, ver. 2.0, SPSS Science, Chicago, IL). If a statistically significant difference among stand types was found ($p < 0.05$), a pairwise multiple comparisons test was conducted using Dunn's method to isolate which stand type was different from the others ($p < 0.05$). Also,

Table 1—Net ammonification, nitrification, and mineralization/immobilization for an IEM soil core from the Betenson 1 exclosure (7/22–9/23/97).

Initial soil core NH_4–N, mg/kg	39.0
Final IEM soil core NH_4–N, mg/kg	107.7
Bottom CEM NH_4–N, mg/kg	0.3
Final total (bottom CEM + IEM soil core) NH_4–N, mg/kg	108.0
Net (final total – initial) NH_4–N, mg/kg	69.1
Net ammonification rate (net NH_4–N / incubation time), mg/kg/mo	32.9
Initial soil core NO_3–N, mg/kg	11.6
Final IEM soil core NO_3–N, mg/kg	2.0
Bottom AEM NO_3–N, mg/kg	10.0
Final total (bottom AEM + IEM soil core) NO_3–N, mg/kg	12.0
Net (final total – initial) NO_3–N, mg/kg	0.4
Net nitrification rate (net NO_3–N / incubation time), mg/kg/mo	0.2
Net mineralization/immobilization rate (net ammonification + net nitrification), mg/kg/mo	33.1

Kolmogorod-Smirnov (K-S) tests were run to determine if the distribution of each variable for each incubation in each year differed by stand type (SYSTAT ver. 8.0, SPSS Science, Chicago, IL).

Results

The Pole Creek fire affected the post-fire rates of accumulation of NH_4 and NO_3 by the top and bottom IEMs in the incubated soil cores (table 2, figures 2 and 3). Rates of NH_4 accumulation by top and bottom CEMs in burned area soil cores were significantly greater than those in unburned areas during the first 1997 incubation, but were not significantly different during the second.

Higher rates of NH_4 accumulation by the top CEMs in unburned areas were observed in 1998 than in 1997. This resulted in no significant differences

Table 2—Median rates of NH_4 and NO_3 accumulation by IEMs at the top and bottom of IEM soil cores for two incubations in each of 3 years in unburned aspen, unburned aspen/conifer, and burned aspen/conifer. Different letters indicate that the median values for each stand type are significantly different within each incubation and year.

	Incubation number and year					
	1997		1998		1999	
Stand	1	2	1	2	1	2
	- $ug/cm^2/mo$ -					
Top CEM NH_4–N						
Unburned aspen	1.5 a	3.2 a	4.5 a	3.6 ab	1.0 a	1.2 a
Unburned aspen/conifer	1.6 a	3.1 a	7.6 a	5.6 a	3.0 ab	1.7 a
Burned aspen/conifer	10.3 b	1.0 a	6.4 a	0.2 b	9.8 b	1.6 a
Bottom CEM NH_4–N						
Unburned aspen	1.5 a	0.8 a	1.3 a	0.8 a	0.6 a	0.5 ab
Unburned aspen/conifer	1.7 a	0.4 a	1.3 ab	1.1 a	1.2 a	0.2 a
Burned aspen/conifer	4.5 b	0.8 a	2.6 b	1.0 a	1.2 a	0.8 b
Top AEM NO_3–N						
Unburned aspen	0.8 a	0.2 a	0.9 a	0.4 a	1.0 a	0.4 a
Unburned aspen/conifer	0.6 a	0.4 a	0.8 a	1.0 a	1.4 a	0.2 a
Burned aspen/conifer	0.6 a	44.4 b	78.6 b	91.0 b	29.1 b	26.6 b
Bottom AEM NO_3–N						
Unburned aspen	0.5 a	0.2 a	0.8 a	0.5 a	0.8 a	0.0 a
Unburned aspen/conifer	0.6 a	0.3 a	0.9 a	0.3 a	0.8 a	0.1 a
Burned aspen/conifer	4.8 b	94.6 b	26.6 b	85.6 b	4.6 b	7.2 b

Figure 2—Box plots of rates of NH_4 accumulation by cation exchange membranes (CEM) at the top and bottom of IEM soil cores for two incubation periods in each of 3 years in unburned aspen, unburned aspen/conifer, and burned aspen/conifer. The 25th and 75th percentiles are shown as a box centered about the median (50th percentile), the 10th and 90th percentiles are shown as error bars, and the 5th and 95th percentiles and outliers are shown as points.
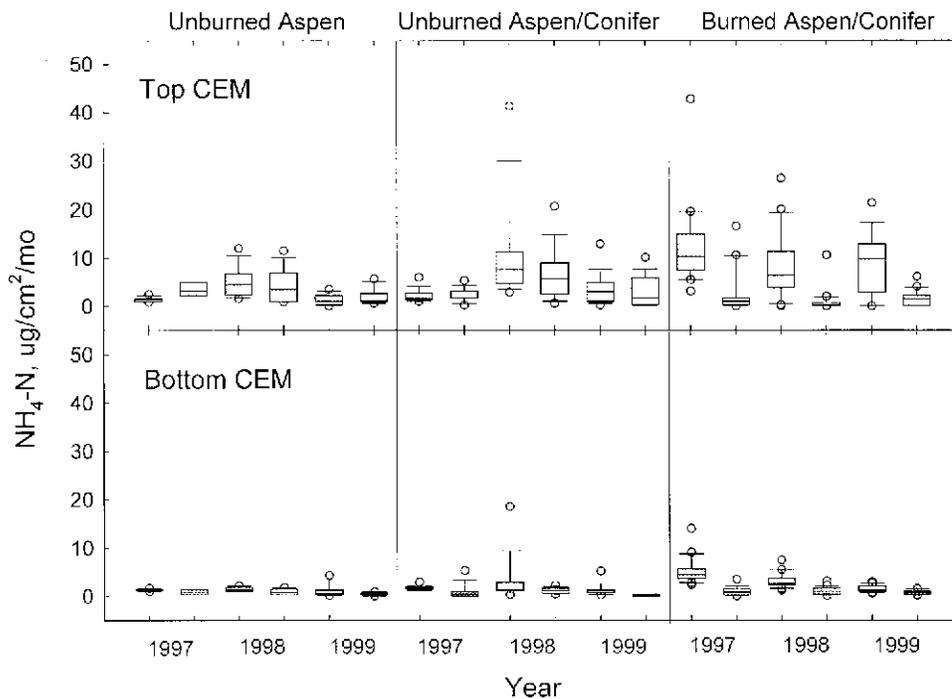
Figure 3—Box plots of rates of NO_3 accumulation by anion exchange membranes (AEM) at the top and bottom of IEM soil cores for two incubation periods in each of 3 years in unburned aspen, unburned aspen/conifer, and burned aspen/conifer. The 25th and 75th percentiles are shown as a box centered about the median (50th percentile), the 10th and 90th percentiles are shown as error bars, and the 5th and 95th percentiles and outliers are shown as points.
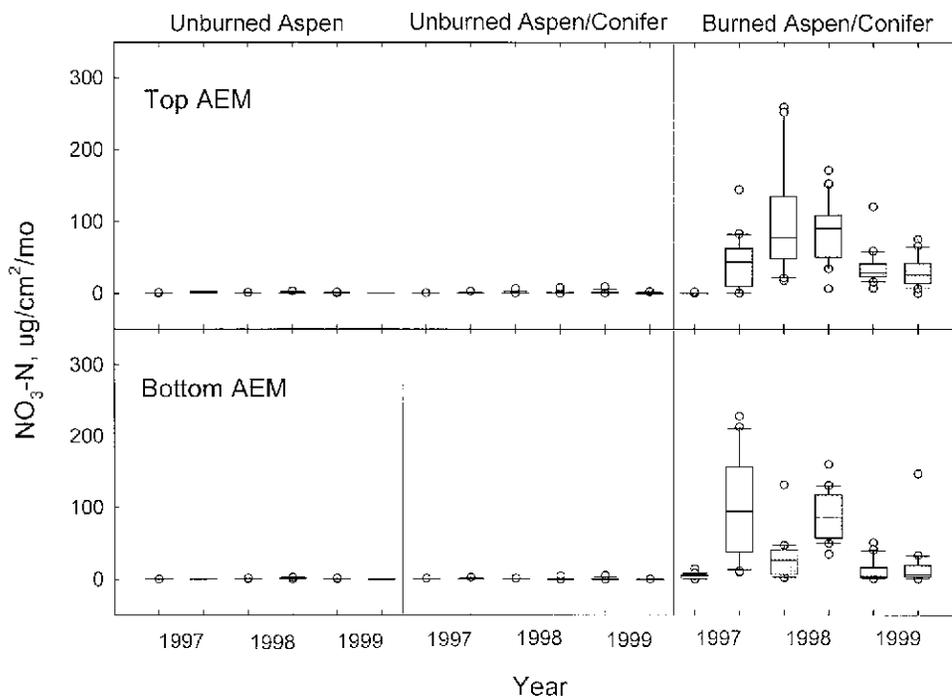
between burned and unburned areas for rates of NH_4 accumulation by the top CEMs during the first 1998 incubation. During the second 1998 incubation, higher rates of NH_4 accumulation by the top CEMs were found in unburned than burned areas. In contrast, higher rates of NH_4 accumulation by the bottom CEMs were found in burned areas than unburned areas during the first 1998 incubation. No significant differences between burned and unburned areas were found in NH_4 accumulation rates by the bottom CEMs during the second 1998 incubation.

Higher rates of NH_4 accumulation were again found in the top CEMs in burned areas compared to unburned areas during the first 1999 incubation, but not during the second. Stand type had no effect on NH_4 accumulation rates by the bottom CEMs during the first incubation in 1999, and although significant differences due to stand type were observed during the second 1999 incubation, these differences were minor because accumulation rates were low during this period.

During the first 1997 incubation, NO_3 accumulation rates by the top AEMs in burned areas were not significantly different from those in unburned areas. However, NO_3 accumulation rates by bottom AEMs were significantly greater in burned areas than unburned areas during the first 1997 incubation. During the second 1997 incubation, NO_3 accumulation rates by both top and bottom AEMs were significantly greater in burned areas than in unburned areas. The higher rates of NO_3 accumulation by top and bottom AEMs in burned areas compared to unburned areas continued in 1998 and 1999.

Higher rates of NH_4 accumulation by the CEMs were found during the first incubation than during the second, whereas higher rates of NO_3 accumulation by the AEMs were found during the second incubation than during the first. The longer second incubation allowed more time for greater quantities of NH_4 and NO_3 to accumulate on the IEMs, but the quantities accumulated on the IEMs are divided by incubation time to obtain rates of accumulation to adjust for the time difference between the first and second incubation. This shift in the rates of accumulation by the IEMs and relative distribution of inorganic N species from the first to the second incubation period indicates an increase in net soil nitrification rates in burned areas as summer progressed. This pattern continued for NH_4 in top and bottom CEMs and NO_3 in bottom AEMs in 1998 and 1999, but not for NO_3 in top AEMs. Rates of NO_3 accumulation by top AEMs during the first incubation were similar to those during the second incubation in 1998 and 1999.

The distribution of NH_4 and NO_3 among the top and bottom IEMs tended to follow the relative mobility of the ions. Nitrate is more mobile than NH_4, so similar rates of NO_3 accumulation were found in top and bottom AEMs in burned areas. In contrast, higher rates of NH_4 accumulation were found in top than bottom CEMs.

During the first 1997 incubation, significantly more NH_4 and NO_3 were extracted from IEM soil cores (including bottom IEMs) in burned areas than from those in unburned areas (table 3, figure 4). Extractable NH_4 in IEM soil

Table 3—Median soil + bottom CEM NH_4 and soil + bottom AEM NO_3 in IEM soil cores for two incubation periods in each of 3 years in unburned aspen, unburned aspen/conifer, and burned aspen/conifer. Different letters indicate that the median values for each stand type are significantly different within each incubation and year.

| | Incubation number and year | | | | | |
| | 1997 | | 1998 | | 1999 | |
Stand	1	2	1	2	1	2
	- *mg/kg* -					
Soil + CEM NH_4–N						
Unburned aspen	3.8 a	2.0 a	2.2 a	3.2 a	1.8 ab	1.4 ab
Unburned aspen/conifer	5.1 a	5.2 a	10.8 a	13.0 a	3.5 a	4.0 a
Burned aspen/conifer	22.3 b	7.2 a	1.0 b	1.0 b	1.0 b	0.6 b
Soil + AEM NO_3–N						
Unburned aspen	0.6 a	0.6 a	1.5 a	4.6 a	0.1 a	2.1 a
Unburned aspen/conifer	0.5 a	0.8 a	1.4 a	1.7 a	0.2 a	2.0 a
Burned aspen/conifer	10.2 b	35.4 b	13.9 b	32.7 b	3.8 b	8.8 b

Figure 4—Box plots of soil + CEM NH_4 and soil + AEM NO_3 in IEM soil cores for two incubation periods in each of 3 years in unburned aspen, unburned aspen/conifer, and burned aspen/conifer. The 25th and 75th percentiles are shown as a box centered about the median (50th percentile), the 10th and 90th percentiles are shown as error bars, and the 5th and 95th percentiles and outliers are shown as points.
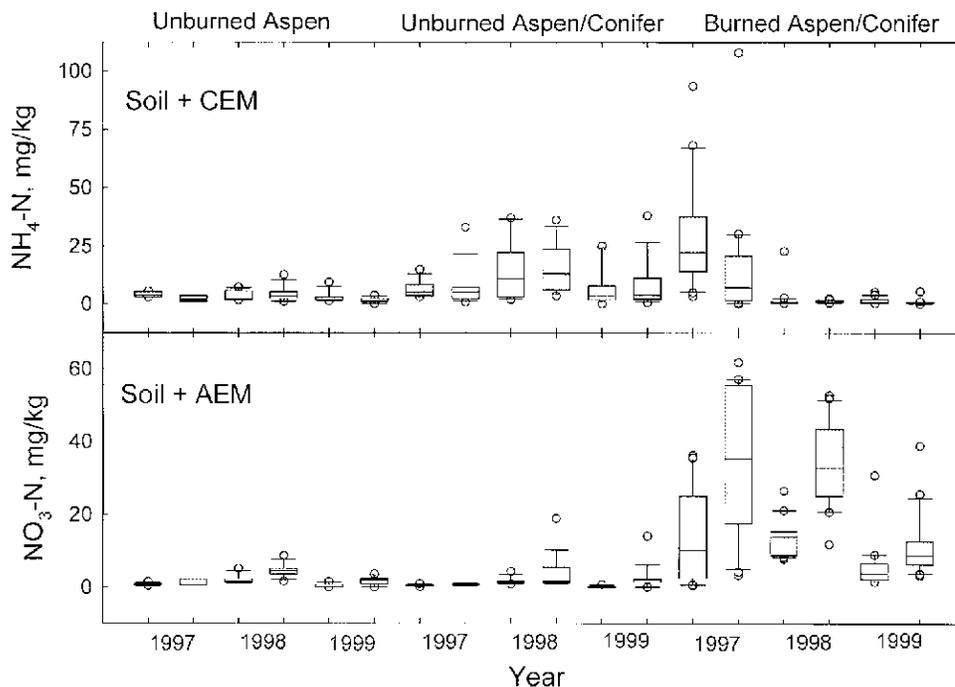
cores was not significantly different between burned and unburned areas during the second 1997 incubation. Significantly more NO_3 was extracted from IEM soil cores in burned areas than those from unburned areas during both 1997 incubations (table 3, figure 4). No significant differences were found between unburned aspen and unburned aspen/conifer for IEM soil core NH_4 or NO_3 during the first or second 1997 incubations.

In contrast with the 1997 results, more NH_4 tended to be extracted from IEM soil cores in unburned areas than in burned areas in 1998. Soil core NO_3 levels in burned areas in 1998 were similar to those observed in the same areas in 1997. Soil core NO_3 levels in unburned areas in 1998 tended to be higher than those observed in 1997, but were still significantly less than those in burned areas. The pattern of higher soil core NH_4 levels in unburned areas than burned areas and higher soil core NO_3 levels in burned than unburned areas continued in 1999.

To obtain an estimate of the total supply of inorganic N available for plant uptake or microbial activity during the summer months, the total amounts of NH_4 and NO_3 accumulated by the top and bottom IEMs from the first and second incubations were added to the total amounts of these ions remaining in the soil cores at the end of the second incubation period (table 4, figure 5).

Table 4–Median total IEM (top and bottom CEMs and AEMs from first and second incubations) + soil (IEM soil core from second incubation) NH_4 + NO_3–N in unburned aspen, unburned aspen/conifer, and burned aspen/conifer in 1997, 1998, and 1999. Different letters indicate that the median values for each stand type are significantly different within each year.

	Year		
Stand	**1997**	**1998**	**1999**
	- - - - - - - - - - - - - *mg/kg* - - - - - - - - - - - - -		
Unburned aspen	4.6 a	10.1 a	4.4 a
Unburned aspen/conifer	9.0 a	21.1 a	8.2 ab
Burned aspen/conifer	69.4 b	67.8 b	20.2 b
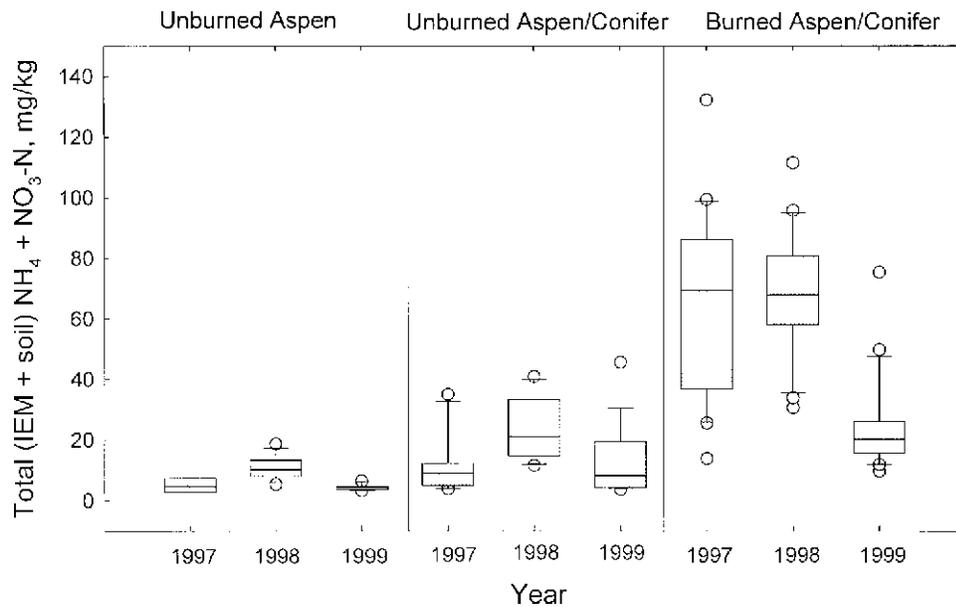
Figure 5–Box plots of total IEM (top and bottom CEMs and AEMs from first and second incubations) + soil (IEM soil core from second incubation) $NH_4 + NO_3$–N in unburned aspen, unburned aspen/conifer, and burned aspen/conifer in 1997, 1998, and 1999. The 25th and 75th percentiles are shown as a box centered about the median (50th percentile), the 10th and 90th percentiles are shown as error bars, and the 5th and 95th percentiles and outliers are shown as points.

Similar levels of $NH_4 + NO_3$–N were available for plant uptake or microbial activity in burned areas in 1997 and 1998, and these levels were significantly greater than those in unburned areas. In unburned areas, more $NH_4 + NO_3$–N was observed in 1998 than in 1997. In 1999, $NH_4 + NO_3$–N in unburned areas had declined to levels observed in 1997. Amounts of $NH_4 + NO_3$–N in burned areas also decreased in 1999, but were still significantly higher than those in unburned aspen but not in unburned aspen/conifer.

In 1997, net ammonification, nitrification, and mineralization/immobilization rates were not significantly different between burned and unburned areas or between unburned aspen and unburned aspen/conifer stands (table 5, figure 6). Even though median rates were not significantly different, there tended to be a greater net loss of NH_4 in burned areas during the early part of summer (first incubation) than later in the summer (second incubation). Net gains in soil NO_3 in burned areas tended to be greater during the latter part

Table 5—Median net ammonification, nitrification, and mineralization/immobilization rates in IEM soil cores for two incubation periods in each of 3 years in unburned aspen, unburned aspen/conifer, and burned aspen/conifer. Different letters indicate that the median values for each stand type are significantly different within each incubation and year.

| | Incubation number and year | | | | | |
| | 1997 | | 1998 | | 1999 | |
Stand	1	2	1	2	1	2
	---------------------- mg/kg ----------------------					
Net ammonification rate						
Unburned aspen	0.7 a	−0.2 a	0.9 ab	1.2 ab	1.5 a	0.6 ab
Unburned aspen/conifer	1.8 a	1.4 a	4.2 a	5.4 a	0.8 a	1.6 a
Burned aspen/conifer	−6.3 a	−7.3 a	−0.2 b	0.1 b	−0.5 a	−0.1 b
Net nitrification rate						
Unburned aspen	−0.2 a	0.2 a	0.5 a	1.8 ab	−0.3 a	0.5 a
Unburned aspen/conifer	−0.3 a	0.2 a	0.2 a	0.2 a	−0.9 a	0.8 a
Burned aspen/conifer	4.2 a	12.2 a	2.6 a	7.5 b	−0.6 a	2.7 b
Net N mineralization rate						
Unburned aspen	0.5 a	0.5 a	1.8 a	3.0 a	1.6 a	1.4 a
Unburned aspen/conifer	1.6 a	1.8 a	4.2 a	6.9 a	0.2 a	3.4 a
Burned aspen/conifer	8.4 a	3.9 a	2.4 a	7.4 a	−0.5 a	2.5 a

Figure 6—Box plots of net ammonification, nitrification, and mineralization/immobilization rates in IEM soil cores for two incubation periods in each of 3 years in unburned aspen, unburned aspen/conifer, and burned aspen/conifer. The 25th and 75th percentiles are shown as a box centered about the median (50th percentile), the 10th and 90th percentiles are shown as error bars, and the 5th and 95th percentiles and outliers are shown as points.
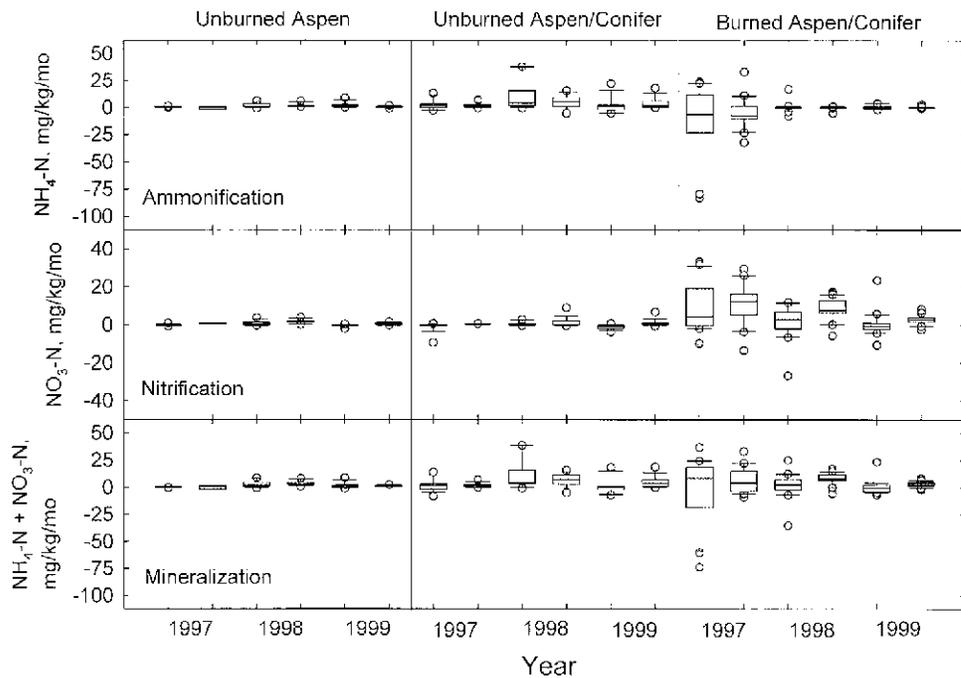
of summer than in the early part. The loss in NH_4 was largely balanced by the gain in NO_3 (nitrification), although some loss of NH_4 may have been from direct microbial utilization of this form of N. In 1998 and 1999, net ammonification rates tended to be higher in unburned areas than burned areas, whereas, the opposite was observed for net nitrification rates. Because of the relative balance of net ammonification and net nitrification rates, net mineralization/immobilization rates in burned and unburned areas tended to be similar in 1998 and 1999.

For cases where the K-W tests revealed that median values of the various N variables for the different stand types differed significantly, K-S tests showed that the data distributions also differed as the Box plots indicate (figures 2, 3, 4, 5, and 6). The range of values tended to be much greater in burned than in unburned areas.

Discussion

In undisturbed (unburned) aspen and mixed aspen/conifer soils, the various microbial mineralization and immobilization reactions of the internal soil N cycle tend to be balanced. There is usually little free NH_4 and NO_3 in the mineral soil (bottom of figures 2 and 3, figures 4 and 5) because it is quickly utilized by microorganisms or taken up by plant roots. Thus, net mineralization/immobilization rates tend to be low (figure 6). Low or unchanged levels of NH_4 and NO_3 and low or unchanged rates of net mineralization do not mean that active mineralization is not taking place or that the internal soil N cycle is not operating (Stevenson 1986). Gross rates of the microbially mediated reactions may be high, but since the reactions tend to be balanced, net rates are low (Stevenson 1986).

Depending on its intensity, fire alters many soil properties including exerting a strong influence on soil microbial mineralization/immobilization

processes (Schlesinger 1997). Losses of gaseous and particulate N occur during combustion of leaf litter and soil organic matter. Microbial populations and enzyme activity may decrease, but available nutrients are also returned to the soil by the residual ash (Schlesinger 1997). Even though total soil N may be lower because of combustion, residual N in the ash is subjected to rapid mineralization and nitrification provided the fire is not too intense and microbial and enzyme populations can recover (Schlesinger 1997).

The source of the high amounts of NH_4 accumulated by the CEMs and in the soil cores in the burn area the first summer after the fire may include NH_4 as a combustion product in the ash layer, release from mineral sources of NH_4, and rapid mineralization of combustion products. Much of this available NH_4 was probably carried over in the soil from the summer in which the fire occurred (6 to 7/96). Nitrification (microbial oxidation of NH_4 to NO_3) occurred mostly during the first summer after the fire (6 to 9/97) because of the observed decrease in NH_4 and increase in NO_3 accumulated by the IEMs and soil cores from the first to the second incubation period. The IEM soil core incubation method provides a snapshot of soil N mineralization/immobilization for the incubation periods studied, but since we did not have soil cores in place immediately after the fire, we could not quantify soil N transformations in late summer and fall of the fire year (7 to 9/96).

Nitrification is influenced by many factors, including temperature, moisture, and the substrates NH_4, O_2, and CO_2 (Stevenson 1986). The high amounts of available NH_4 found in burn area soils provide a ready substrate for surviving or post-fire invading populations of nitrifying microorganisms. Summertime soil temperature ranges and means in the burn area were higher than in unburned areas because the relatively open canopy and dark colored ash served to trap heat (data not shown), thus helping to accelerate nitrification. Adequate soil moisture was available in burned areas (mean soil core water content of 24.1% in 1997) for nitrification to occur throughout the summer.

Although denitrification and leaching can potentially remove much of the NO_3 produced by post-fire nitrification, the large amounts of available soil NH_4 and NO_3 present during the growing season provide a ready source of mineral N for uptake by aspen suckers. A strong aspen suckering response was observed on Betenson and Grindstone Flats and in other burned areas on the Fishlake National Forest during the first summer after the fires (Amacher and Bartos 1998). Leaching of NH_4 from the ash layer and subsequent nitrification of the leached NH_4 continued through the second and third summers after the fire. A longer residence time of post-fire soil NO_3 provides more opportunity for regenerating aspen clones to exploit this source of N. Thus, available N from ash may be an important source of N to young aspen until N mineralization in leaf litter and soil organic matter can resupply the nutritional needs of aspen.

Acknowledgments

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