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Nitrogen mineralization in high elevation forests of the Appalachians. I. Regional patterns in southern spruce-fir forests

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Abstract. Annual and seasonal rates of net nitrogen mineralization were determined for 19 sites in the spruce-fir forests of the Southern Appalachian Mountains. These sites included high and low elevation stands of red spruce (*Picea rubens* Sarg.) and Fraser fir (*Abies fraseri* (Pursh.) Poir.) on east and west exposures on Whitetop Mountain, Virginia; Mt. Mitchell, North Carolina; and Clingman's Dome in the Great Smoky Mountains National Park. Mineralization rates were determined using in situ soil incubations in PVC tubes with ion exchange resin bags placed in the bottom of the tubes to collect leachate. Throughfall was collected in resin bags placed in the top of the tubes. Average initial NH_4-N + NO_3-N ranged from 0.6 to 4.8 kg N/ha across all plots, and average mineralization rates ranged from 26 to 180 kg-N ha^{-1} yr^{-1}. Throughfall ranged from 18 to 32 kg-N ha^{-1} yr^{-1} with NH_4-N accounting for about two-thirds of the throughfall N across all sites. Throughfall and mineralization rates were not related to elevation or exposure. The high rates of N mineralization and relatively high nitrate concentrations indicate that leaching losses of nitrogen and associated cations could be substantial.

The high-elevation spruce-fir forests of the Southern Appalachian Mountains are the focus of many studies on the effects of atmospheric deposition on forest ecosystems. These forests are experiencing growth declines and mortality from uncertain causes. Several authors have associated this decline with atmospheric deposition of pollutants (Bruck 1985; Bartuska & Medlarz 1986), while others have suggested that the decreases in radial increments may simply reflect normal growth patterns (Zedaker et al. 1987), or may relate to climatic patterns (Johnson & McLaughlin 1986).

Inorganic nitrogen (N) is a major constituent of air pollution and several hypotheses about the effects of atmospheric deposition on forest health depend upon the dynamics of the N cycle. Nitrogen often limits productivity in forest ecosystems, and inputs of NO_3^- and NH_4^+ may improve forest productivity. Wood & Bormann (1977) reported that in a greenhouse study additions of nitric acid increased foliar N concentrations and stimulated growth of eastern white pine (*Pinus strobus* L.) seedlings. Abrahamsen (1980, cited in Cowling & Dochinger 1980) also concluded that atmospheric N deposition often increases forest productivity due to a fertilization effect. However, where N inputs exceed the nutritional requirement of the forest, the excess N could perhaps cause nutritional imbalance, excessive leaching of other nutrients, and soil acidification (Reuss & Johnson 1986; Binkley et al. 1988). These conditions could alter the physiological status of trees, perhaps leading to growth declines or decreased resistance to other stresses.

Foliar N concentrations, and stand dieback and mortality of Northeastern spruce-fir stands have been reported to increase with elevation (Johnson & Siccama 1983). Friedland et al. (1984) suggested nitrogen-induced winter damage was a possible cause of spruce-fir declines, although they later reported foliar N concentrations were not unusually high (Friedland et al. 1985, 1988). Conditions where excessive N may cause ecosystem instability include large N inputs, low rates of utilization by plants and precipitation greatly in excess of evapotranspiration. High-elevation forests in the Southern Appalachian Mountains exhibit all these conditions.

The objectives of our study were to determine seasonal and annual rates of N-mineralization in soils of the Southern Appalachian spruce-fir region, and to determine if mineralization rates differed by elevation and exposure.

Methods

Our study sites were located on Mt. Mitchell in Yancy County, North Carolina; on Clingman's Dome in the Great Smoky Mountains National Park; and on Whitetop Mountain in Grayson County, Virginia. These mountains exceed 1650 meters in elevation and red spruce (*Picea rubens* Sarg.) and Fraser fir (*Abies freaseri* (Pursh) Poir.) are the dominant tree species. Most red spruce in the South occurs between 1370 and 1870 meters elevation. Fraser fir usually occurs with red spruce between 1525 and 1830 m, and forming almost pure stands above 1830 m (Stupka 1964).

We established 19 plots on these three mountains, as a part of a large research program sponsored by the Spruce-Fir Research Cooperative whose objectives are to determine the effects of pollutant deposition on spruce-fir forests, and to determine the causes of observed growth declines. Plot locations were chosen by elevation and aspect; we expected that atmospheric deposition would increase with elevation (Scherbatskoy & Bliss 1983; Lovett

Table 1. Elevation, aspect, and general stand characteristics of study sites.[1]

Location	Exposure	Plot No[2]	Elev (m)	Asp	Basal area spruce (m²/ha)	fir	Stand density (#/ha)	Age (yrs)
Clingman's Dome	Low-East	S17	1707	E	41.7	0.1	275	200–300
		S32	1677	E	45.9	0.0	875	NA
		801	1634	E				
Clingman's Dome	High-Ridge	S05	2006	E	15.5	16.9	425	50–260
		S06	1982	N	0.8	19.2	1450	40–150
		S16	1957	N	5.7	17.3	525	90–200
Mt. Mitchell	Low-East	B32	1680	SE	58.5	0.0	1075	53
		901	1686	SE				
		902	1671	S				
Mt. Mitchell	High-East	B34	1829	SE	28.8	1.2	2075	40–60
		B35	1854	SE	19.9	0.1	1975	55–65
		906	1951	NE				
Mt. Mitchell	High-West	903	1921	SW				
		904	1915	SW				
		905	1927	SW				
Whitetop Mountain	West	R13	1668	NW	24.8	0.0	2025	40–80
		R20	1579	N	30.4	0.0	1400	75–135
Whitetop Mountain	East	R17	1640	SE	48.4	0.0	7950	24–28
		R27	1674	E	53.2	0.0	4450	40–50

[1] Information on general stand characteristics provided by: S. Zedaker, N. Nicholas and C. Eggar. Site and stand characteristics of Southern Appalachian spruce/fir project funded by Spruce/Fir Cooperative of US Forest Service. (Unpublished data).
[2] Plots with number beginning with B, R, or S are adjacent to permanent plots of the Spruce/Fir Cooperative.

1984), and would be greater on windward (western and northern) exposures. Eleven plots were located adjacent to the permanent plots already established by other cooperators. One plot on Clingman's Dome was also located adjacent to a plot established by Oak Ridge National Laboratory as part of the Electric Power Research Institute's (EPRI's) Integrated Forest Study. The other seven plots were located in spruce or fir stands close to the permanent plots. On Mt. Mitchell we established three plots at each of three exposures: high-west, high-east, and low-east (Table 1). Comparable low-west exposures were not available. On Clingman's Dome, three plots were established on low-east and three on high-ridgeline exposures. On Whitetop Mountain, our most northern site, two plots were on high-west and two on high-east exposures.

Each plot was a 20 meter transect parallel to the contour. Along these

Table 2. Average soil properties of top 10 cm from two composite samples for each plot

Location	Exposure	Plot No	pH	Loss on Ignition (%)	Total C (%)	N (%)	C:N	Sampl. Pts (%)
Clingman's Dome	Low-East	S17	3.8	23	14	0.65	21	85
		S32	3.8	24	14	0.58	24	80
		801	4.0	14	8	0.38	22	85
Clingman's Dome	High-Ridge	S05	4.0	20	12	0.66	18	85
		S06	4.3	16	9	0.50	19	20
		S16	4.3	12	7	0.49	14	55
Mt. Mitchell	Low-East	B32	4.1	29	17	0.62	27	78
		901	4.2	24	14	0.60	23	18
		902	4.3	24	14	0.61	23	78
Mt. Mitchell	High-East	B34	4.1	49	28	1.05	27	52
		B35	4.1	38	22	0.96	23	22
		906	4.1	28	16	0.70	23	62
Mt. Mitchell	High-West	903	4.5	29	17	0.78	22	72
		904	4.2	39	23	0.99	23	88
		905	4.0	39	22	0.92	24	48
Whitetop Mountain	West	R13	3.9	49	28	1.18	24	18
		R20	4.2	21	12	0.58	21	75
Whitetop Mountain	East	R17	4.1	24	14	0.63	22	74
		R27	4.1	31	18	0.74	24	66

transects we installed mineralization cores at approximately two-meter intervals; the precise location was adjusted to avoid rocks and large roots. The mineralization procedure was adapted from DiStefano & Gholz (1986). We collected the top 10 cm of surface material (forest floor and mineral soil) in sharpened PVC tubes 3.8 cm in diameter and 15 cm long. An ion exchange resin bag was placed in the top of each tube to collect throughfall, and another resin bag was placed in the bottom of the tube to trap ions leaching from the soil within the tube. We then reinserted these tubes into the soil creating in situ mineralization cores. It is possible that the bottom resin bag might adsorb ions diffusing from the surrounding soil and overestimate the mineralization in the core. However, earlier work with resin bags showed very little diffusion of ions into the bags; mass flow appeared to be the major vector (Binkley 1984).

Resin bags contained one tablespoon (14 mL) each of a cation resin (4.5 g dry weight) and an anion resin (4.0 g dry weight) in a nylon stocking. The cation resin (Dowex 50W-X8 strongly acidic) was obtained loaded with H^+, with a total exchange capacity of 6.3 $mmol_c/g$ (dry basis). The anion resin

(J.T. Baker strongly basic) was obtained loaded with OH^-, with a total exchange capacity of 3.2 $mmol_c$/g (dry basis). The resin bags were soaked in 100 mL of 2 *M* NaCl for 30 min and then spun dry. This pretreatment reduced the background (blank) levels of NH_4-N in a 100 mL extract of a resin bag from 1 mg/L to 0.22 mg/L, and reduced NO_3-N from 2 mg/L to 0.57 mg/L.

We measured nitrogen mineralization and throughfall over four sequential intervals: November 1985 through April 1986; May 1986 through June 1986; July 1986 through August 1986; and September 1986 through October 1986. Establishment of one high-east plot and three high-west plots on Mt. Mitchell was delayed until May 1986.

At the beginning of each incubation period we collected soil samples at four-meter intervals along the same transect. We used these samples to estimate pre-incubation levels of NH_4-N and NO_3-N. We also measured soil temperature at the beginning of most incubation periods.

Some of our incubation cores were disturbed by animals. The top resin bag was occasionally missing, and a few tubes were pulled from the ground. Overall we had about 20- to 30-percent loss of incubation cores. On one occasion in one plot, all the cores were pulled from the ground and scattered down the hillside (Mt. Mitchell, Plot 34, Period 4).

We estimated rockiness of the transect by inserting a screwdriver 10 cm into the soil at 0.5-meter intervals. If we could insert the screwdriver into the soil the full 10 cm, the point was counted as samplable. We used this estimate of rockiness (percent samplable points), to extrapolate mineralization rates to a hectare basis.

At the end of each incubation period we collected all resin bags and soil cores. We extracted four grams fresh weight of each soil sample with 40 mL of 2 *M* KCl by shaking the suspension for 30 min; we found that recovery of extractable ammonium was incomplete if we used a lower solution:soil ratio, or more dilute KCl. The suspensions were centrifuged to clarity and then aliquots were pipetted into 4 mL sample vials for NH_4-N and NO_3-N analysis. Initial soil samples were extracted in the same manner. Duplicate samples were extracted for approximately 25% of all soil samples, and concentrations between duplicated were within 10%.

Resin bags were extracted by shaking intact bags in 100 mL of 2*M* KCl for 1 h. The extract was filtered through lab tissues to remove suspended soil and debris, and stored at 4 C prior to colorimetric analysis for NH_4-N and NO_3-N (Scientific a and b). This extraction method did not remove all NH_4-N and NO_3-N from the resins. To determine percent recovery of NH_4-N and NO_3-N from the resin bags, we placed several resin bags in 100 mL of solutions of known concentration (usually 5 mg/L) and shook the bags for one hour. All ions were absorbed from the solutions. We then extracted these bags and measured the concentration in the extract. Recovery of NH_4-N and NO_3-N was approximately 85% and 75%, respectively. We used the percent recovery factor to adjust the sample concentration values upward to account for incomplete N recovery.

Soil moisture was determined by drying 10 g samples at 105 C.

In November 1986, we collected two composited soil samples from each transect for additional chemical analysis. The pH of each sample was determined in a 1:2 soil/water mixture; loss on ignition by ashing samples at 450 C for 12 h; and total nitrogen using standard Kjeldahl procedures. Percent carbon was estimated as loss on ignition times 0.58.

Nitrogen mineralization was calculated for each core by subtracting the NH_4-N and NO_3-N concentrations in the initial soil samples from the concentrations in the incubated samples and multiplying by total soil dry weight for each core. The amount of NH_4-N and NO_3-N in the bottom resin bags was added to the soil value to give total net mineralization per core.

We used analysis of variance for unbalanced data (SAS Institute, 1985) to evaluate net mineralization, throughfall, percent nitrification, and percent of total mineralization N recovered in the bottom bags. The model tested for exposure effects by comparing plot averages of the cores using core replicates as an interaction variable. We completed this statistical analysis for each period and for the annual sum within each mountain.

Results and discussion

Soil pH of the top 10 cm of forest floor and mineral soil averaged about 4.0 for all sites (Table 2). Total N was less than 1% for most plots, but was marginally greater in one plot on Mt. Mitchell and one plot on Whitetop Mountain. Loss on ignition was variable with a range from 14 to 50%. The mean C:N was 22 with a range from 14 to 27. Soil moisture ranged from about 45% to 65% for all sampling periods in these high-precipitation sites even though some samples were collected immediately following rain and some after more than a week without rain. Soil moisture inside the cores was generally about 5–10% (on a soil weight basis) than in the surrounding soil at the end of the incubation periods. The maximum soil temperature at time of sampling was 17 C in August 1986, and the soils were frozen in winter. Soil temperatures were usually 1–2 C higher at the low elevation plots than at the high elevation plots in both mid-summer and late fall measurements. Soil temperatures at the most northern site, Whitetop Mountain, were also 1–2 C cooler than comparable elevations from the other mountains. The soil

Table 3. Average initial NO_3-N and NH_4-N in the top ten cm of forest floor and soil (means and standard errors)

Exposure	Plot	NO_3-N	NH_4-N	NO_3^+ NH_4-N	NO_3-N	NH_4-N	NO_3^+ NH_4-N	NO_3^+ NH_4-N Kg/ha
		mg/kg soil			mg/core			
Clingman's Dome								
Low-	S17	6.9(0.4)	7.5(1.2)	14.4(0.9)	0.21(0.03)	0.23(0.04)	0.44(0.06)	3.3
East	S32	11.2(3.2)	6.2(2.6)	17.4(4.9)	0.24(0.08)	0.13(0.04)	0.36(0.11)	2.5
	801	10.8(2.4)	9.5(2.1)	20.3(3.9)	0.34(0.07)	0.03(0.06)	0.64(0.11)	4.8
High-	S05	12.8(2.6)	4.5(0.9)	17.3(2.5)	0.44(0.06)	0.15(0.02)	0.59(0.06)	4.4
Ridge	S06	6.1(1.1)	3.6(0.8)	9.7(1.8)	0.22(0.03)	0.13(0.03)	0.35(0.06)	0.6
	S16	6.1(1.0)	2.7(0.7)	8.8(4.0)	0.28(0.03)	0.12(0.03)	0.40(0.01)	1.9
Mt. Mitchell								
Low-	B32	2.7(0.8)	4.3(1.0)	7.0(1.1)	0.10(0.03)	0.16(0.04)	0.25(0.04)	1.7
East	901	12.4(1.1)	12.9(5.6)	25.3(6.1)	0.45(0.05)	0.49(0.22)	0.94(0.24)	7.3
	902	9.0(0.9)	5.2(1.5)	14.2(0.9)	0.44(0.06)	0.24(0.07)	0.68(0.05)	4.7
High-	B34	7.8(1.9)	12.3(3.3)	20.2(3.9)	0.24(0.03)	0.33(0.10)	0.57(0.08)	2.6
East	B35	18.2(2.1)	3.9(0.9)	21.4(1.7)	0.46(0.04)	0.10(0.03)	0.56(0.05)	1.1
	906	10.7(3.3)	7.3(3.9)	18.0(7.1)	0.33(0.10)	0.22(0.12)	0.55(0.21)	3.0
High-	903	7.9(1.8)	8.7(2.8)	16.5(3.6)	0.23(0.05)	0.24(0.07)	0.47(0.07)	3.6
West	904	12.3(1.6)	6.2(2.7)	18.4(4.2)	0.34(0.06)	0.16(0.05)	0.49(0.09)	3.8
	905	7.2(0.6)	5.0(0.7)	12.2(1.2)	0.20(0.03)	0.14(0.03)	0.34(0.06)	1.4
Whitetop Mountain								
West	R13	18.6(4.2)	12.9(3.5)	31.1(1.8)	0.31(0.08)	0.19(0.02)	0.50(0.07)	0.8
	R20	11.3(3.2)	6.2(2.4)	17.5(5.6)	0.32(0.07)	0.17(0.05)	0.49(0.13)	3.2
East	R17	7.7(1.3)	9.8(0.8)	17.2(1.4)	0.18(0.05)	0.21(0.05)	0.39(0.09)	2.5
	R27	12.0(2.6)	12.1(3.6)	24.1(1.8)	0.18(0.04)	0.16(0.01)	0.34(0.04)	1.8

Table 4. Average seasonal and annual throughfall of NH_4-N and NO_3-N for each exposure (means and standard errors). Differences between exposures within locations do not differ significantly (at p = 0.10) for any period or for the annual totals

Exposure		Nov–April	May–June	July–Aug	Sept–Oct	Year mg/core	Year kg/ha
		μg/core					
Clingman's Dome							
Low-	NH_4-N	480 (50)	330((40)	670 (40)	540(100)	2.02	17.8
East	NO_3-N	1110(110)	90 (20)	300(110)	90 (10)	1.59	14.0
	Sum	1560(170)	420 (60)	970 (70)	630 (90)	3.61	31.8
High-	NH_4-N	420 (80)	350 (10)	680(100)	730 (40)	2.18	19.2
Ridge	NO_3-N	390(100)	50 (20)	90 (20)	30 (10)	0.56	4.9
	Sum	780(160)	410 (30)	760 (90)	760 (40)	2.71	24.1
M. Mitchell							
Low-	NH_4-N	250 (50)	260 (10)	670(100)	380 (30)	1.56	13.8
East	NO_3-N	810 (80)	120 (10)	220 (40)	160 (20)	1.31	11.6
	Sum	1060(120)	380 (10)	890(140)	540 (20)	2.84	25.4
High-	NH_4-N	190 (20)	340 (30)	480 (90)	390(100)	1.40	12.3
East	NO_3-N	340 (30)	90 (20)	120 (40)	140(100)	0.69	6.1
	Sum	530 (20)	430 (50)	600 (60)	530(100)	2.09	18.4
High-	NH_4-N	NA	330(130)	620(130)	380(220)	1.33[1]	11.7[1]
West	NO_3-N	NA	30 (20)	70 (20)	20 (10)	0.12[1]	1.1[1]
	Sum	NA	360(110)	690(150)	400(230)	1.44[1]	12.8[1]
Whitetop Mountain							
West	NH_4-N	340 (30)	370–	650(180)	510 (30)	1.87	16.5
	NO_3-N	650 (10)	210–	320(120)	210 (50)	1.39	12.3
	Sum	990 (20)	580–	970(300)	720 (30)	3.26	28.8
East	NH_4-N	270(120)	220 (20)	620 (60)	640 (20)	1.75	15.4
	NO_3-N	610(320)	80 (20)	260(120)	160(100)	1.11	9.8
	Sum	880(450)	300 (40)	880(180)	800 (80)	2.86	25.2

[1] Sum of only three periods.

temperature was above 0 C when we collected samples in late October, 1986, and had reached 8–10 C in early May, 1986.

The average annual initial levels of NH_4-N plus NO_3-N in the soil ranged from 0.25 mg/core to almost 1 mg/core for these sites (Table 3). On an area basis, the initial levels ranged from less than 1 kg/ha of mineral N to about 5 kg/ha of mineral N (Table 3). NO_3-N usually exceeded NH_4-N, often by 2-fold and occasionally by 3- to 4-fold.

Throughfall ranged from 18 and 32 kg NH_4-N + NO_3-N $ha^{-1} yr^{-1}$, (Table 4), which brackets the rate of atmospheric deposition estimated for

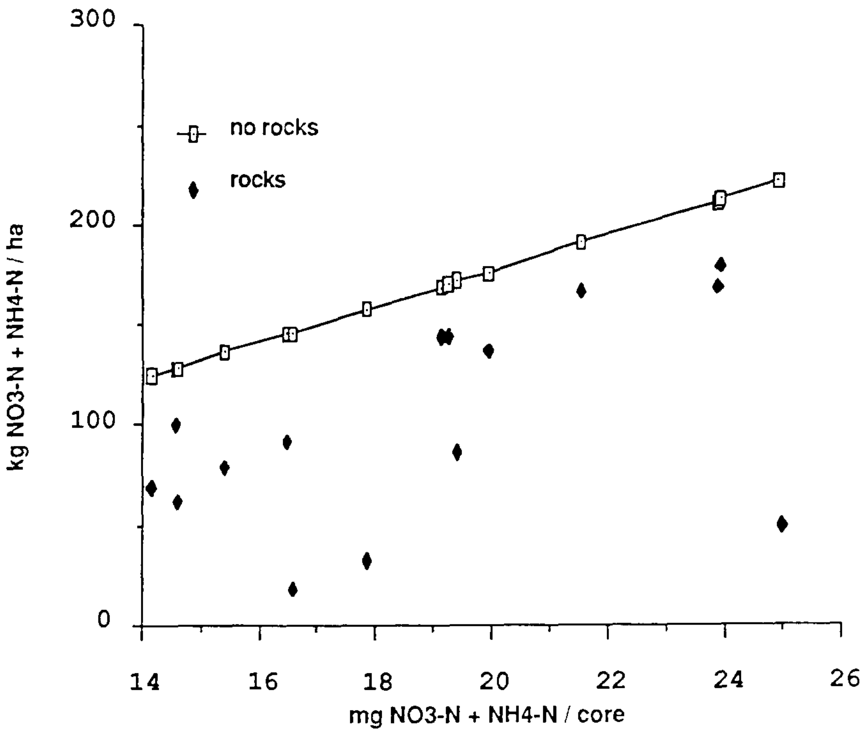

Fig. 1. The effect of rock estimate on the relationship between average mineralization per core and an average mineralization per hectare. The "no rocks" line indicates a 1:1 relationship. "Rocks" points indicate estimates of mineralization reduced by the percent non-samplable points.

the EPRI-IFS site adjacent to one of our plots (G. Lovett, D. Johnson, pers. comm.). Ammonium accounted for over 50% of the total throughfall-N in all plots. In the high-west plot on Mt. Mitchell, NH_4-N accounted for over 90% of the total throughfall. Lovett et al. (1982) estimated atmospheric inputs of various ions in a subalpine balsam fir forest at 1220 meters on Mount Moosilauke, New Hampshire. They estimated input rates of 16 kg NH_4 -N $ha^{-1} yr^{-1}$ and 28 kg NO_3-N $ha^{-1} yr^{-1}$ for combined cloud deposition and bulk precipitation. Their estimate of ammonium deposition matches our estimate of throughfall ammonium, but their nitrate value exceeds ours. Cloud deposition accounted for approximately 80% of the total input for both sources of N in their study.

Throughfall is a composite of cloud deposition and bulk precipitation minus the stem flow and evaporation from canopy surfaces, plus the net change due to absorption or leaching within the canopy. Lindberg et al. (1986) reported that canopy uptake decreased the flux of atmospheric NO_3^- and NH_4^+ by 50 to 70% during the growing season in an eastern deciduous

Table 5. Average seasonal and annual mineralization, average annual percent of mineralization as NO_3-N, and average percent of mineralized N leached to resin bags (means and standard errors). Within mountains, averages followed by the same letter do not differ significantly (at $p = 0.10$).

Exposure	Plot	Nov-April	May-June	July-Aug	Sept-Oct	Year	Year[1] Kg/ha	Proportion as NO_3-N	Proportion Leached into bags
		ug/core							
Clingman's Dome									
Low-East	S17	2.1(0.4)	5.1(0.8)	6.3(0.7)	5.9(0.7)	19.3	145	0.42	0.78
	S32	5.3(0.8)	9.0(1.0)	5.9(0.7)	3.8(0.8)	24.0	169	0.60	0.82
	801	2.8(0.3)	5.6(0.6)	5.8(1.0)	5.0(0.9)	19.2	144	0.59	0.84
	Average	3.4(0.6)	6.5(0.8)	6.0(0.8)	4.9(0.6)	20.8a	152	0.52a	0.81a
High-Ridge	S05	2.9(0.5)	7.3(1.4)	5.6(0.4)	8.1(0.8)	24.0	180	0.49	0.82
	S06	2.1(0.5)	4.3(0.5)	5.1(0.5)	6.3(0.5)	17.8	31	0.45	0.77
	S16	2.0(0.5)	4.8(0.4)	3.8(0.3)	3.5(0.3)	14.2	69	0.48	0.77
	Average	2.3(0.3)	5.5(0.9)	4.9(0.5)	6.0(1.3)	18.7a	87	0.47a	0.79a
Mt. Mitchell									
Low-East	B32	2.8(0.4)	5.6(0.3)	4.6(1.1)	7.0(0.6)	20.0	138	0.25	0.63
	901	3.2(0.7)	4.7(0.7)	6.7(0.8)	7.0(1.0)	21.6	34	0.29	0.78
	902	1.9(0.3)	3.0(0.5)	4.3(0.7)	5.4(0.9)	14.6	100	0.30	0.75
	Average	2.6(0.4)	4.5(0.8)	5.2(0.7)	6.5(0.6)	18.8a	134	0.27a	0.72a
High-East	B34	1.4(0.5)	5.5(0.6)	5.7(0.6)	NA	12.6[2]	58[2]	0.35	0.74
	B35	2.6(0.7)	6.3(0.5)	8.2(0.7)	8.0(1.0)	25.0	48	0.35	0.73
	906	NA	4.8(0.5)	7.8(1.0)	3.9(0.5)	16.5[2]	90[2]	0.20	0.72
	Average	2.0(0.6)	5.5(0.4)	7.2(0.8)	5.9(0.8)	20.6a	82[2]	0.29a	0.73a

High-	903	NA	3.3(0.5)	6.0(0.5)	4.0(0.8)	13.4^{2}	85^{2}	0.12	0.69
West	904	NA	4.4(0.4)	7.5(0.7)	6.9(0.0)	18.8^{2}	146^{2}	0.01	0.59
	905	NA	5.3(0.6)	6.2(0.8)	4.5(0.3)	16.0^{2}	68^{2}	0.10	0.50
	Average	NA	4.3(0.6)	6.6(0.5)	5.2(0.9)	16.1a	98^{2}	0.08b	0.60a
Whitetop Mountain									
West	R13	1.8(0.3)	4.1(0.4)	6.0(0.6)	4.7(0.3)	16.6	26	0.39	0.85
	R20	2.1(0.3)	5.1(0.6)	5.4(0.4)	6.8(0.4)	19.4	128	0.62	0.84
	Average	1.9(0.2)	4.6(0.5)	5.7(0.3)	5.7(1.0)	18.0a	73	0.51a	0.85a
East	R17	1.3(0.3)	3.1(0.2)	5.3(0.5)	5.7(0.7)	15.4	100	0.34	0.75
	R27	0.8(0.1)	3.0(0.4)	5.7(0.4)	5.1(0.4)	14.6	85	0.43	0.86
	Average	1.0(0.2)	3.0(0.3)	5.5(0.2)	5.4(0.3)	15.0a	93	0.39a	0.81a

[1] Adjusted for estimate of rocks (% samplable points)
[2] Sum of only three periods

forest in Tennessee. Therefore deposition estimates cannot be directly compared to throughfall estimates but they may indicate the relative importance of NO_3^- and NH_4^+ inputs to these high-elevation forest ecosystems.

Sasser & Binkley (1988) reported average throughfall of 6.5 kg/ha for NH_4-N + NO_3-N in a Fraser fir regeneration wave on Mt. LeConte in the Great Smoky Mountains National Park from May 1986 to July 1986. They used the same resin core method we used in this study. Our estimate for the same three month period was 7.0 kg/ha (Period 2 + 1/2 Period 3).

Nitrogen mineralization rates averaged between 14 and 25 mg/core on an annual basis (Table 5) for these 19 plots. Only the two exposures on Whitetop Mountain differed significantly ($p \leqslant 0.10$), and then only for the winter incubation period. Our analysis of variance model did indicate plot differences (at $p \leqslant 0.10$) during some periods, but these plot differences often occurred within the same exposure. The range of values within each exposure was often as large or larger than the range between exposures.

Extrapolations to a hectare scale gave mineralization rates up to 180 kg N/ha. The range in rockiness between plots had a larger effect on this estimate than did the range in rates per core. For example, Plot 35 on Mt. Mitchell had a high rate per core (23 mg/core), but high rock content (78% by our measure) gave a low rate per hectare (46 kg/ha annually). Figure 1 illustrates the effect of our estimate of rockiness on the estimate of N mineralization.

Of the total mineralized N, NO_3-N accounted for approximately 50% on the Clingman's Dome site and 40 to 50% on the Whitetop Mountain site (Table 5). Nitrification was approximately 30% on two east exposures on Mt. Mitchell and the high-west exposure had less than 10% N as NO_3^-. These differences between exposures were significant ($p \leqslant 0.01$).

Most (75–85%) of the nitrogen mineralized within the cores leached to the bottom resin bag for all plots except the high-west site on Mt. Mitchell (Table 5). This might reduce the amount of mineralized N that is immobilized by microbes, and might provide a higher mineralization estimate than would be obtained from incubations in buried bags (see discussion in Binkley & Hart 1988). However, such leaching is probably more realistic than high accumulation of ammonium and nitrate that would occur in buried bags, so we feel our mineralization estimates should be realistic.

Correlations between soil variables (total N, % carbon, and C:N) and net mineralization and nitrification were poor; the highest r2 was 0.23.

All measurements of net mineralization suffer from a variety of limitations (see Binkley & Hart 1988 for a review). Biases in this resin core method include the effects of freshly killed fine roots, and marginally greater water content in the cores. Freshly killed fine roots could induce immobilization if the C:N ratio were high (Popovic 1980), or could stimulate mineralization by providing a readily mineralizable substrate.

We are not aware of other N mineralization estimates for the spruce-fir ecosystems of the Southern Appalachians, but Thorne et al. (1987) have estimated N mineralization in several spruce-fir stands of various ages in the Adirondacks of New York. Using buried bag incubations, they found rates ranged from 18 to 54 kg-N/ha annually, with nitrate accounting for about 1 kg-N/ha annually in all sites. Rates for low-elevation forests in the mid-West and Eastern US have ranged from about 25 to 150 kg-N/ha annually (Nadelhofer et al. 1983; Pastor et al. 1984; Vitousek & Matson 1986; Mladenoff 1987). Our estimates are greater than or equal to the range reported for these other temperate forest ecosystems.

The growth rates of spruce and fir stands in the Southern Appalachians forests are low compared to many other temperate forests, and these probably have relatively low rates of N uptake and accumulation. For example, Sprugel (1984) reported annual uptake of N of about 40–70 kg-N/ha annually for the above-ground portion of stands of balsam fir (*Abies balsamea* (L.) Mill.) in New York, with above-ground accumulation rates of 5–30 kg-N/ha annually. Information on belowground N dynamics are not available for eastern spruce-fir stands, but Vogt et al. (1986) report the rate of N turnover in fine roots averaged about 60 kg-N/ha annually in cold, temperate conifer forests. Combining these budgets would give a rough estimate of annual N uptake in our stands of about 100–130 kg-N/ha annually. This is similar to our estimates of net N mineralization, indicating that these forests may be capable of retaining most or all of the mineralized N. However, modest decreases in uptake or increases in mineralization (as might occur in a declining stand) could result in mineralization exceeding uptake, leading to leaching losses of N.

Conclusions

The N content of throughfall was high in these spruce-fir forests, indicating substantial deposition from the atmosphere. The rates of net N mineralization were also high relative to lower-elevation forests in North America, but were probably similar to the rate of N uptake by the vegetation. Our results cannot show whether nitrogen cycling rates contribute to growth decline and mortality in the spruce-fir regions of the southern Appalachians. However, if the rate of N uptake by the vegetation decreased because of declining growth or increasing mortality, the high mineralization rates might lead to substantial leaching losses of N. The balance between N mineralization, uptake, and leaching needs to be quantified for this type of forest, for both healthy and declining stands.

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