

# Soil Temperature, Moisture, and Carbon and Nitrogen Mineralization at a Taiga-Tundra Ecotone, Noatak National Preserve, Northwestern Alaska

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## Abstract

Northwestern Alaska has been warming ( $0.3^{\circ}\text{C}/\text{yr}$ ) since the early 1990s. Ecotonal (treeline) Arctic ecosystems are expected to exhibit the effects of climate change earliest. High-latitude terrestrial ecosystems contain from 30 to 45 percent of the global organic-C pool. Soil warming may enhance release of  $\text{CO}_2$  and  $\text{CH}_4$ , soil N mineralization, and the production and export of dissolved organic C and N to the aquatic ecosystem. In 1990, we began our research on climate-change effects in the small (800-ha area) Asik watershed, Noatak National Preserve, northwestern Alaska. We report results here from an intensive study conducted during 1997–98 on the relation between soil temperature, moisture, and C and N mineralization rates across a treeline taiga-tundra ecotone within the watershed. Soil C and N contents and C/N ratio were greater ( $p<0.05$ ) beneath tundra. The depth of the soil active layer (annual thaw depth) increased ( $p<0.001$ ) more than 40 cm during the growing season. Thaw depths reached most of the deeper layers of surface organic matter. Despite this warming, most plots did not show a clear relation between soil temperature and soil respiration ( $\text{CO}_2$  efflux). Peak soil temperatures were below the threshold needed for a respiration response to temperature, and the thawing resulted in saturated deeper soils keeping temperatures low. Soil C respiration rates did increase through the summer. Soil inorganic-N pools were larger early in summer ( $p<0.001$ ) and beneath tundra ( $p<0.05$ ). Net N mineralization rates were higher ( $p<0.01$ ) in spruce but were positive only during early summer. Rates were negative for tundra and the taiga-tundra transition zone. In midsummer, soil microbial N consumption exceeded gross N mineralization rates except beneath tundra. Rates of gross ammonification ( $p<0.01$ ) and microbial N consumption ( $p=0.05$ ) increased with moisture content in the surface organic matter (Oa soil horizon). Soil-water organic and inorganic chemistry did not reflect the patterns in stream water, suggesting that the processes observed within these plots may not dominate at the watershed level. Stream-water  $\text{NO}_3^-$  concentrations at the mouth of

the watershed increased with discharge ( $p<0.01$ ,  $r^2=0.52$ ), and autumn inorganic-N flux from the watershed increased tenfold from summer lows.

## Introduction

Ecotonal Arctic and high-latitude boreal ecosystems are expected to exhibit the effects of climate change earliest and to a greater degree than other regions (Shaver and others, 1992). High-latitude taiga and tundra ecosystems have large, mostly unavailable organic reservoirs of carbon, nitrogen, and phosphorus. Typically, more than 95 percent of total ecosystem carbon, nitrogen, and phosphorus is contained in soil organic matter (SOM). The nutrient and C storage in SOM pools is a function of high soil moisture and low temperature, which slow decomposition. The percentage of an ecosystem's organic-matter pools stored in the soil increases with latitude, further limiting nutrient availability.

In the Alaska taiga-tundra ecotone at the northward extent of the boreal biome, much of this organic matter is deeper than the annual soil thaw zone (soil active layer) and unavailable to the C or nutrient cycles. In this extensive taiga-tundra region, any factor that increases the depth or temperature of the soil active layer could reduce soil moisture content but increase SOM decomposition, nutrient availability and cycling rates, and soil respiration rate (Chapin and others, 1995; Jonasson and others, 1999). Our studies in the southern boreal Wallace Lake watershed, Isle Royale National Park, Mich., show that slight gains in SOM decomposition will increase available nutrients as inorganic N in amounts greater than the sum of other nitrogen sources (precipitation, fixation) (Stottlemyer and Toczydlowski, 1999a, b). An increase in N availability will alter above- or below-ground C/N ratios, which, in turn, could accelerate above-ground production or below-ground heterotrophic respiration (Shaver and others, 1992). Which process occurs most rapidly could determine whether the ecosystem becomes a C source or sink. Change in such processes, especially in the taiga-tundra ecotone, may lead to altered patterns of treeline advance (Lloyd and Graumlich, 1997; Suarez and others, 1999).

The strong interaction of the C cycle with nutrients complicates prediction of the taiga-tundra and boreal ecosystem response to climate change (Shaver and others, 1992; Stottlemyer and others, 1995; McKane and others, 1997). The effect of climate change on the N cycle, in particular, will determine or constrain the effect of such change on the C cycle. Soil C provides energy for microbial transformations that, in turn, regulate ecosystem N availability, and N availability largely determines biomass-production rates in the taiga-tundra ecotone.

An additional dimension in assessing the effects of climate change on high-latitude ecosystems is the likely variation in export of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON). Changes in N availability due to climate change could increase forest-floor and soil DOC and DON production. However, there has been little study of how a change in N availability might alter DOC and DON production and export to the aquatic ecosystem, where these more labile organic C and N forms are important energy and nutrient sources. The export of DOC and DON to the aquatic ecosystem is primarily a function of seasonal flowpath (Rice and Bricker, 1995; McNamara and others, 1997; Kallbitz and others, 2000) and, probably, soil temperature, moisture, total C and N pool size and quality, and (inorganic) N availability

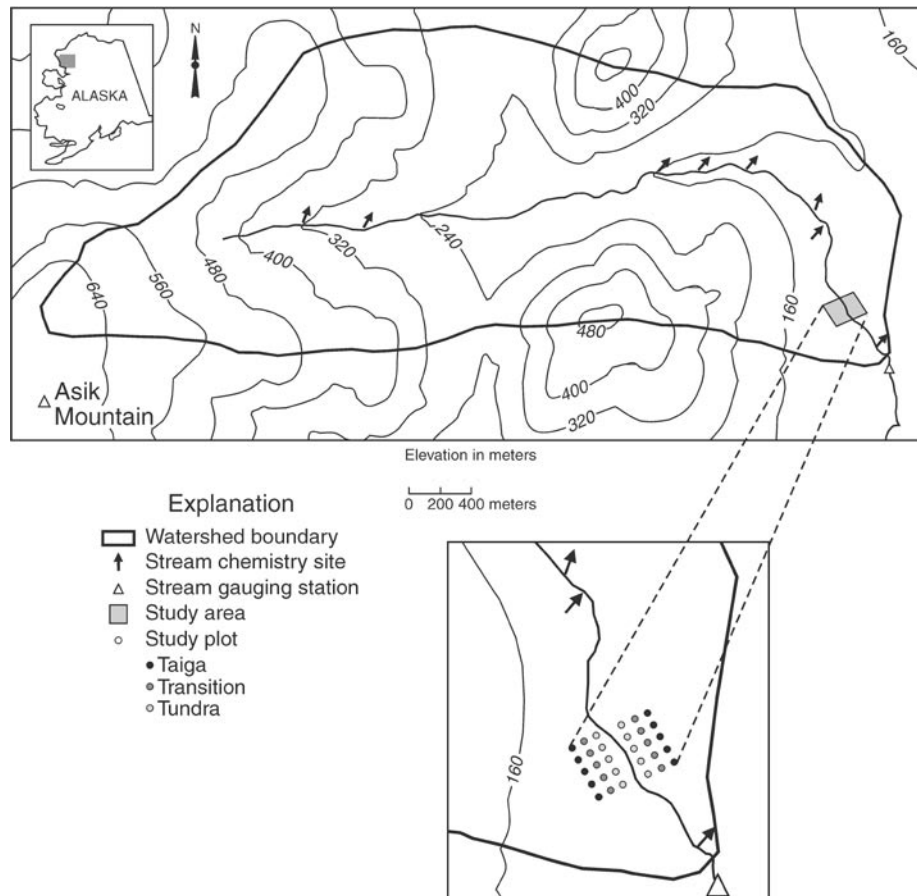
(Sommaruga and others, 1999; Kallbitz and others, 2000; Lipson and others, 2000).

Research was initiated in 1990 in the treeline Asik watershed (800-ha area), a U.S. Geological Survey Reference Ecosystem in Noatak National Preserve, northwestern Alaska (Binkley and others, 1994, 1995; Suarez and others, 1999; Rhoades and others, 2001; Stottlemyer, 2001). Much of this study has focused on quantifying the sensitivity of the terrestrial ecosystem to climate change, especially temperature and available nitrogen. This chapter updates results from studies on treeline sensitivity to climate change and presents (1) preliminary results from a recent intensive study of below-ground processes in taiga, tundra, and the taiga-tundra transition zone; and (2) a summary of current and planned site research.

## Methods

### Site Description

The 800-ha-area treeline Asik watershed (lat 67°58' N., long 162°15' W.) is in Noatak National Preserve, 95 km north-



**Figure 1.** Asik watershed (lat 67°58' N., long 162°15' W.), Agashashok River drainage, Noatak National Preserve, northwestern Alaska, showing location of study area.

east of Kotzebue, Alaska (fig. 1). Watershed elevation ranges from 100 to 725 m, and its first-order stream drains from the north and northwest into the Agashashok River. Temperatures in the Arctic region and locally have been warming (Illeris and Jonasson, 1999; Herrmann and others, 2000). National Oceanographic Atmospheric Administration (NOAA) temperature data from northwestern Alaska show a warming trend ( $0.3^{\circ}\text{C}/\text{yr}$ ) since the late 1980s, approaching the maximum recorded. However, no annual trend in precipitation has been observed. During the 1997–98 growing season in the Asik watershed, the mean daily air temperature was  $11.6^{\circ}\text{C}$ , about  $1^{\circ}\text{C}$  warmer than in previous and subsequent summers.

The soils of the Asik watershed are dominated by volcanic ash and loess. At the subgroup level, the soils are generally considered as Histic Pergelic Cryaquepts. Discontinuous permafrost exists in the watershed, especially where no forest is present. The bedrock is sedimentary and metamorphic rock, and 5 to 7 percent of the watershed area is covered by talus.

About 60 percent of the watershed area is forested. Better-drained parts of the lower third and most of the middle half of the watershed are dominated by white spruce (*Picea glauca* [Moench] Voss). Spruce basal area ranges from  $23\text{ m}^2/\text{ha}$  in bottom land to  $4\text{ m}^2/\text{ha}$  on southern aspects (Suarez and others, 1999). Forest understory consists primarily of *Hylocomium splendens* (Hedw.) B.S.G., *Equisetum arvense* L., and *Boykinia richardsonii* (Hook.) Gray, with shrubs of *Salix* and *Vaccinium uliginosum* L. The understory of the taiga-tundra transition zone and tundra is dominated by tussocks of *Eriophorum vaginatum* L., *Vaccinium uliginosum*, *Potentilla fruticosa* L., and *Betula nana* L. A more detailed site description of the watershed was presented by Stottlemeyer (2001).

This study was conducted in the lower third of the watershed above the stream-gauging station at the mouth (fig. 1). A total of 30  $25\text{-m}^2$ -area plots, at least 15 m apart, were established in a rough grid pattern; 15 plots were located on an eastern aspect (slope 10 percent), with transects of 5 plots each in wet sedge tundra at the toe of the slope, the transition between tundra and taiga, and in spruce. This layout was repeated across the stream, opposite the first array, in an area with a slope of 10 to 12 percent and a western aspect. In the study plots, surface mineral soils were typically covered by 20 to 30 cm of organic matter consisting of recent litterfall (Oi horizon) and partially decomposed debris (Oa horizon).

The center of each plot was flagged. Each plot was equipped with a tension lysimeter (at 30-cm depth in the Oi horizon) to sample the soil solution. A subset of six plots was equipped with Licor dataloggers that continuously monitored air temperature, as well as temperature at 5-, 10-, and 20-cm depth in the Oi horizon. All the data presented here were collected from these six plots.

The depth of the soil active layer (thaw depth) was measured by driving in a pointed stainless-steel rod at 10 additional plots located along a transect tangential to the stream and conterminous with the south boundary of the soil-process plot layout. At each plot and sampling date, four measurements were taken and averaged.

## Nitrogen and Carbon Mineralization and Pools

Measurements were made of net  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ , and total inorganic-N mineralization in each plot at intervals of 3 or 4 weeks, using the buried-polyethylene-bag method (Eno, 1960). With this method, net mineralization is the sum of mineralized  $\text{NH}_4^+$  plus  $\text{NO}_3^-$  from organic N, minus microbial immobilization of  $\text{NH}_4^+$  and  $\text{NO}_3^-$ . Net nitrification is the sum of  $\text{NO}_3^-$  from both organic N and  $\text{NH}_4^+$ , minus microbial immobilization of  $\text{NO}_3^-$ .

After the surface organic matter (Oi soil horizon) was removed intact, the uppermost 10 cm of the Oa/Oe horizon was sampled with a 5-cm-diameter soil corer. Paired cores were retained from each plot. One core from each pair, representing a nonincubated sample, was placed in a Whirl Pac and brought to the field laboratory; the other core was placed in a 0.025-mm-thick polyethylene bag and returned to the same hole for incubation. The surface organic matter was then replaced. After about 20 to 25 days, the field-incubated sample was removed and returned to the field laboratory for processing.

Soil moisture was determined by oven drying ( $105^{\circ}\text{C}$  for 24–30 hours) a subsample, with the moisture content (in percent) equal to the weight of water lost per soil dry weight times 100. Bulk density was calculated from the ratio of total oven-dry weight to total soil volume. A large subsample was then sieved in a 2-mm sieve. The  $<2\text{-mm}$  fraction was weighed and divided into two samples; one subsample was extracted for  $\text{NO}_3^-$  and  $\text{NH}_4^+$  by using 2M KCl, and the other frozen for total C and N analyses on a Leco CHN analyzer at our laboratory in Fort Collins, Colo.

The  $^{15}\text{N}$  isotope-dilution method was used to estimate in-place gross N ammonification and nitrification rates. Field incubations were conducted in early July 1997. Gross mineralization is defined as the sum of  $\text{NH}_4^+$  from organic N, and gross nitrification as the sum of  $\text{NO}_3^-$  from  $\text{NH}_4^+$  and organic-N substrates. On the date of the analysis, net mineralization and nitrification were estimated by the methods described above. Initial inorganic-N pools in the soils were determined, and a net mineralization and nitrification incubation (20–25 days) started as described above. In addition, a separate set of intact soil cores was collected immediately adjacent to the net incubation samples and processed as follows. Using a spinal needle (18 gauge, 10 cm long) and syringe, one intact core received a 6-mL aliquot of  $\text{Na}^{15}\text{NO}_3$  solution, providing about  $2\text{ }\mu\text{g N/g}$  of soil (dry-weight equivalent). A separate intact core received 6 mL of  $(^{15}\text{NH}_4)_2\text{SO}_4$  solution, again providing about  $2\text{ }\mu\text{g N/g}$  of soil.

After a 24-hour in-place incubation period, the cores were retrieved, taken to the field laboratory, and mixed, and a subsample was extracted by using 2M KCl. After at least 1 hour of mixing, all KCl extractions were filtered through Whatman No. 1 filters prerinsed with 2M KCl. The samples were forwarded to our laboratory in Fort Collins, Colo., where  $\text{NH}_4^+$  and  $\text{NO}_3^-$  analyses were made on a Lachat flow-injection autoanalyzer. Nitrogen diffusion (Brooks and others, 1989)

was used to prepare the samples for  $^{15}\text{N}$  analyses by using glass-fiber filter traps. Gross  $\text{NH}_4^+$  immobilization and mineralization rates were calculated for the cores labeled with  $^{15}\text{NH}_4^+$  by the isotope-dilution method of Kirkham and Bartholomew (1954), and gross  $\text{NO}_3^-$  immobilization and mineralization rates were calculated for cores labeled with  $^{15}\text{NO}_3^-$  by using the same method but replacing  $\text{NO}_3^-$  for  $\text{NH}_4^+$ . The  $^{15}\text{N}$ -enriched samples were analyzed by mass spectroscopy at the University of California, Davis.

Soil respiration rates, as indicated by surface  $\text{CO}_2$  efflux, were determined by using the dynamic method on a PP Systems portable infrared gas analyzer.

## Stream and Lysimeter Samples

Stream samples were collected weekly just above the gauging station, using 500-mL amber polyethylene bottles. Soil solution was collected from tension porous-cup lysimeters. Tension was placed on the lysimeters 24 hours before sample collection. Stream- and soil-water samples were taken to the field laboratory, where pH, alkalinity, and specific conductance were measured and a subsample filtered (0.45  $\mu\text{m}$ ) for ion or dissolved-organic-matter analyses. Field analyses were generally completed within 8 to 12 hours after sample collection.

The filtered subsamples were then shipped to our laboratory in Fort Collins and analyzed for macroions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{NH}_4^+$ ,  $\text{PO}_4^{3-}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ) on a Waters ion chromatograph. DOC content was determined on filtered samples kept frozen until analyzed on a Shimadzu TOC-5000 Series analyzer.

## Data Analyses

We used ANOVA to test for differences by vegetation type, soil depth, and date. The homogeneity of variance was checked (Bartlett's test) for each variable analyzed. The plot layout was on gradually sloping areas with clearly defined taiga-tundra gradients on eastern and western aspects. Although slopes were slight, we checked for any differences by aspect; none were present. Statistical analyses were done by using Systat modules (Wilkinson, 1990).

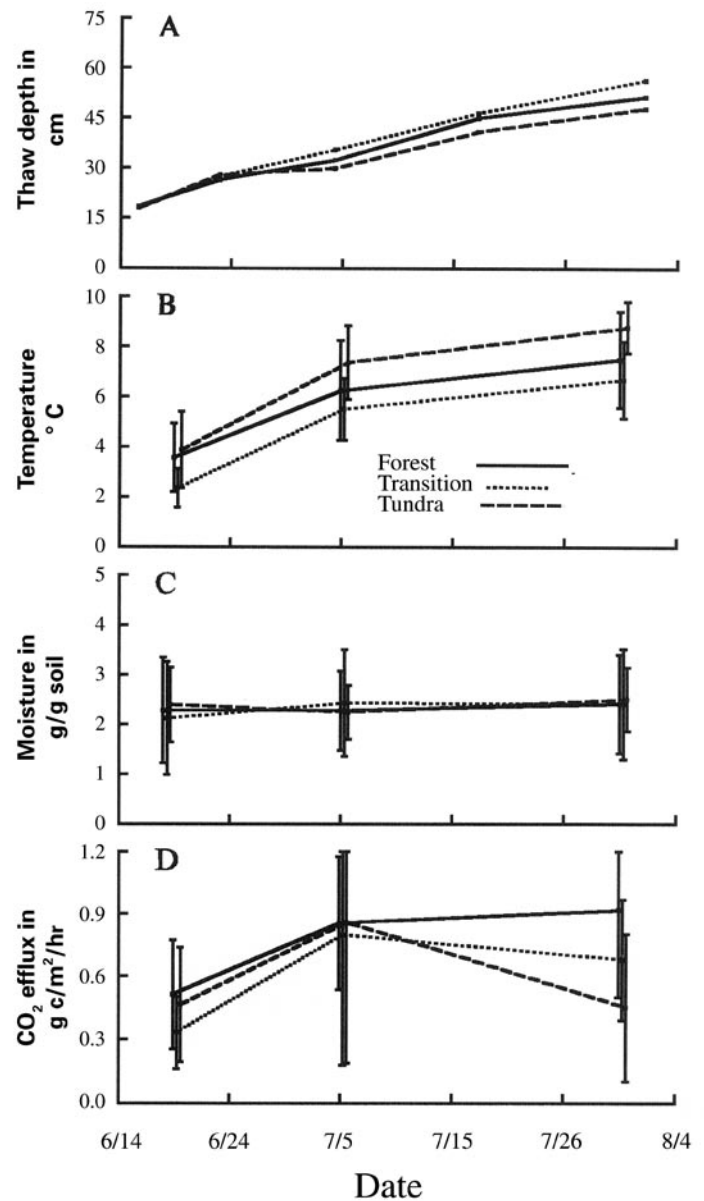
## Results

### Soil Thaw Depth, Temperature, and Moisture Content

The depth of the soil active layer (thaw depth) was similar beneath the three vegetation types but increased ( $p < 0.001$ ) to more than 40 cm during the growing season (fig. 2; table 1). Soil temperatures at 10-cm depth in the Oa horizon increased ( $p < 0.001$ ,  $r^2 = 0.5$ ) during the growing season and were correlated ( $p < 0.001$ ,  $r^2 = 0.58$ ) with thaw depth. The maximum

seasonal mean temperature in the Oa horizon occurred beneath tundra in early August. At the continuously monitored subset of plots, daily soil temperatures at 5-, 10-, and 20-cm depth in the Oa horizon also increased ( $p < 0.001$ ,  $r^2 > 0.2$ ; not plotted) during the growing season. Daily mean temperatures at 5-cm depth in the Oa horizon ranged from 2.6 to 10.5°C, at 10-cm depth from 1.4 to 8.7°C, and at 20-cm depth from 0.3 to 5.6°C.

Soil moisture content, expressed as a percentage of soil dry weight, was more than 200 percent throughout the growing season; it showed no seasonal trend (fig. 2).



**Figure 2.** Seasonal changes in the Asik watershed, Noatak National Preserve, northwestern Alaska, during June–August 1997. *A*, Depth of thaw (soil active layer) from surface of Oi. *B*, Soil temperature at 10-cm depth in Oa. *C*, Soil moisture at 1 to 10 cm depth in Oa. *D*, Soil  $\text{CO}_2$  efflux from Oa surface.

**Table 1.** Change in soil physical properties, N pools, and processes during the growing season from early to late summer 1997 in the Asik watershed, Noatak National Preserve, northwestern Alaska.

[All measurements except thaw depth and CO<sub>2</sub> efflux were taken in the top 10 cm of the Oa soil horizon. ns, not significant]

	Probability ( <i>p</i> )	Increase (+) or decrease (–)
Soil thaw depth-----	<0.001	+
Soil temperature-----	<.001	+
Soil moisture content-----	>.05	ns
Soil inorganic-N pool -----	<.001	–
Soil NO <sub>3</sub> pool-----	<.001	–
Soil CO <sub>2</sub> efflux -----	<.001	+
Net N mineralization -----	>.05	ns
Net nitrification -----	>.05	ns

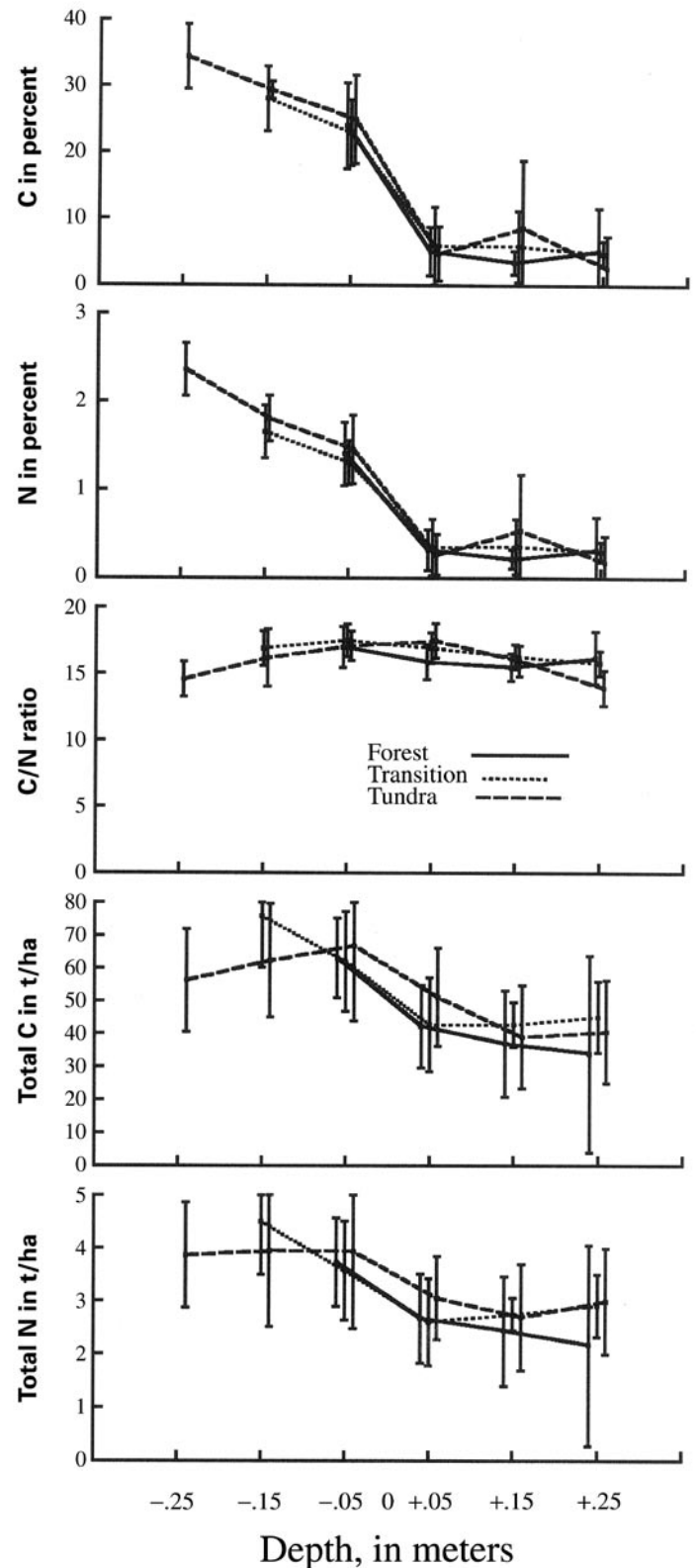
### Soil Carbon and Nitrogen Pools

In the surface organic matter (Oa and Oe soil horizons), C and N percentages were greater ( $p < 0.05$ ) beneath tundra than in either spruce or the transition zone, and the C/N ratio was greater beneath tundra than in spruce (fig. 3). The C content ( $p < 0.01$ ) and N content ( $p < 0.05$ ) were greater beneath tundra than in either spruce or the transition zone. The C and N contents in the Oa soil horizon were lower ( $p < 0.001$ ) than in the Oe soil horizon.

The inorganic-N pool size differed by vegetation type ( $p < 0.05$ ) and season ( $p < 0.001$ ) (fig. 4; table 1). Pools were greater beneath tundra (mean, 239 mg N/m<sup>2</sup>). The average N pool size was 169 mg N/m<sup>2</sup> in the transition zone and 189 mg N/m<sup>2</sup> in the forest. Seasonally among all vegetation types, the inorganic-N pool size decreased from 234 mg N/m<sup>2</sup> in early July to 52 mg N/m<sup>2</sup> in August. The variation in seasonal inorganic-N pool size was greatest beneath tundra (180–929 mg N/m<sup>2</sup>). The NO<sub>3</sub>-N pool did not differ by vegetation type but declined ( $p < 0.001$ ) during the growing season. The NO<sub>3</sub>-N pool made up 13 percent of the total inorganic N.

### Soil Respiration and Nitrogen Mineralization

Soil respiration rates, as estimated by CO<sub>2</sub> efflux (fig. 2) in the Oi horizon, did not differ by vegetation type. Pooling the results from all plots, CO<sub>2</sub>-efflux rates were lower ( $p < 0.001$ ) in June than in July or August. For all sample dates combined, CO<sub>2</sub> efflux was unrelated to the soil temperature measured at 10-cm depth in the Oi horizon. In June, however, there was a weak ( $p < 0.05$ ,  $r^2 = 0.16$ ) positive correlation of CO<sub>2</sub> efflux with temperature for all vegetation types. For the growing season, only spruce showed a positive, but weak,

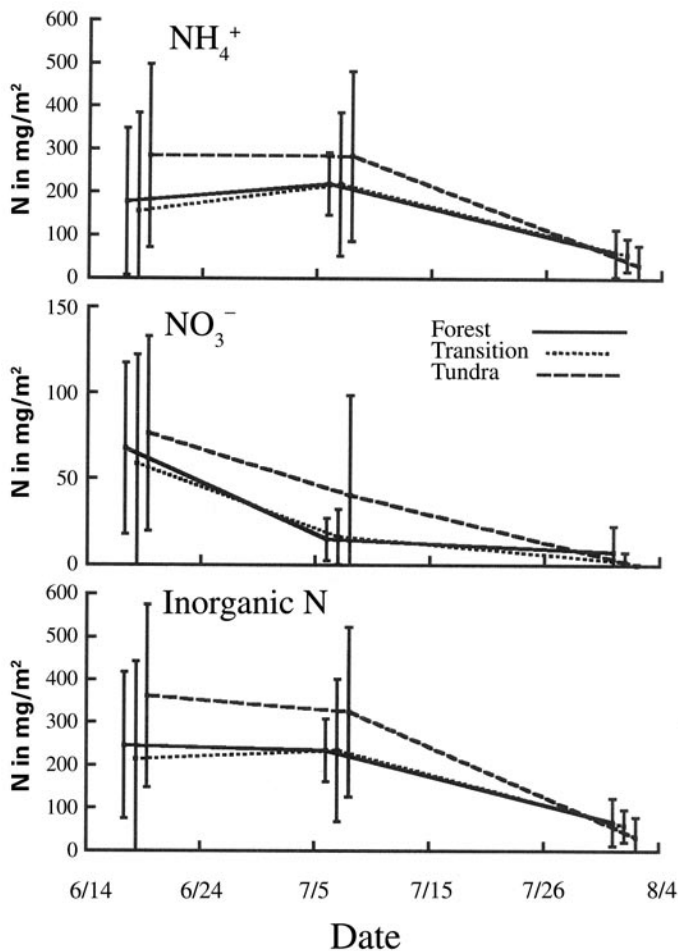


**Figure 3.** Total C and N contents in surface organic matter and mineral soils, C/N ratios, and organic-C and organic-N pool sizes, by vegetation type, at plots in the Asik watershed, Noatak National Preserve, northwestern Alaska. 0-m reference depth is interface between Oa and Oe soil horizons. Samples were collected July 31–August 1, 1997.

correlation ( $p < 0.05$ ,  $r^2 = 0.18$ ) between  $\text{CO}_2$  efflux and surface temperature. The averaged mean daily temperatures monitored by data loggers at three depths (5, 10, and 20 cm) in the Oi horizon in spruce showed an inverse relation ( $p < 0.01$ ,  $r^2 = 0.26$ ) between  $\text{CO}_2$  efflux and soil temperature in early August.

Net N mineralization rates from mid-June to early August were negative except in spruce (table 2). By vegetation type, net ammonification and nitrification rates were higher ( $p < 0.05$ ) in spruce, as were net N mineralization rates ( $p < 0.01$ ). Sampling frequency was insufficient to analyze for seasonal trends. The net ammonification, nitrification, and total N mineralization rates were negatively correlated ( $p < 0.001$ ) with inorganic-N pool size.

Gross N mineralization and microbial consumption rates, as determined by the enriched  $^{15}\text{N}$  dilution procedure, showed that total mean microbial N consumption exceeded ammonification and nitrification rates everywhere except beneath the sedge tundra (table 2). In spruce, the  $\text{NH}_4^+$ -N consumption rate exceeded ( $p < 0.05$ ) the gross ammonification rate. Pooling the results from all three vegetation types,  $\text{NO}_3^-$ -N consumption exceeded ( $p < 0.001$ ) gross nitrification rates. Differences were



**Figure 4.** Seasonal changes during June–August 1997 in soil inorganic-N pool size, by vegetation type, at plots in the Asik watershed, Noatak National Preserve, northwestern Alaska.

most evident in spruce ( $p < 0.001$ ) and beneath sedge tundra ( $p < 0.01$ ).

Although gross N ammonification rates increased with temperature at 10-cm depth in the Oa horizon, the relation was not significant ( $p = 0.2$ ). Gross N ammonification rates increased ( $p < 0.01$ ) with soil moisture content, as did microbial consumption ( $p = 0.05$ ) at 0- to 10-cm depth in the Oa horizon. Gross nitrification rates were correlated with the initial  $\text{NH}_4^+$  pool ( $p < 0.01$ ),  $\text{NO}_3^-$  pool, and total inorganic-N pool size ( $p < 0.001$ ). Gross  $\text{NO}_3^-$  consumption was also related ( $p < 0.05$ ) to the initial inorganic-N pool size.

## Soil and Stream Water

Soil water may not have been sampled frequently enough to provide a temporal comparison with stream water. Many of the lysimeters were frozen well into July.  $\text{Ca}^{2+}$  concentrations ( $1,753 \pm 450$   $\mu\text{equiv/L}$ , table 3) in soil water averaged 70 percent of those in stream water at the mouth of the watershed.  $\text{NO}_3^-$  concentrations in soil water were 16 percent, and  $\text{SO}_4^{2-}$  concentrations 25 percent, of those in stream water. In contrast, the DOC content of soil water was more than 6 times that of stream water.

During the year, stream-water  $\text{NO}_3^-$  concentrations at the mouth of the watershed increased with discharge ( $p < 0.01$ ,  $r^2 = 0.52$ , fig. 5), whereas stream-water base-cation (CB) concentrations, as indicated by  $\text{Ca}^{2+}$  concentration, did not show the usual inverse relation with discharge.

## Discussion

### Soil Thaw Depth, Temperature, and Moisture

The increase in thaw depth during the growing season reached all layers of surface organic matter and the shallow mineral soils (figs. 2, 3). Thaw depths could already reflect the recent warming-trend ecologic responses to change in thaw depth that can occur within a few years, and have been documented in central Alaska for the early 1990s (Jorgenson and others, 2001). With the increase in regional temperatures since the 1960s, particularly in late spring (Herrmann and others, 2000), the rate and depth of annual thaw will likely increase. Increases could be accentuated on steeper, better-drained slopes, especially on southern aspects at this latitude. At present, thaw depths include soils with the highest C and N contents (figs. 2, 3). Any change in temperature or moisture content at these depths could alter C and N mineralization rates, increase  $\text{CO}_2$  loss from organic-C decomposition, and increase  $\text{NH}_4^+$  and  $\text{NO}_3^-$  availability for microbial or above-ground plant uptake (Stottlemyer, 2001).

Several factors, however, complicate estimating the degree to which this ecosystem might become a C source. The interaction between surface-organic-matter thickness and

**Table 2.** Net N mineralization and nitrification rates during two incubation periods from June 15 to August 5, 1997, and gross N mineralization, nitrification, and consumption rates during July 4–5, 1997, in the Asik watershed, Noatak National Preserve, northwestern Alaska.

[All values in milligrams per square meter per day]

	N Mineralization		Total inorganic N	N Consumption	
	NH <sub>4</sub> <sup>+</sup> -N	NO <sub>3</sub> <sup>-</sup> -N		NH <sub>4</sub> <sup>+</sup> -N	NO <sub>3</sub> <sup>-</sup> -N
<b>Net rates (June 15–Aug. 5)</b>					
Spruce -----	1.0	-0.3	0.6	--	--
Transition -----	-1.2	-1.1	-2.3	--	--
Tundra -----	-4.8	-1.9	-6.8	--	--
<b>Gross rates (July 4–5)</b>					
Spruce -----	483	21	--	541	135
Transition -----	417	75	--	464	186
Tundra -----	354	124	--	339	242

soil temperature and moisture content determines much of the productivity from these taiga-tundra sites. The thick layers of surface organic matter in our plots have a low bulk density (<0.3), which helps insulate deeper soils against temperature change and partly explains why the soil-temperature increase at 20-cm depth was only half that at 5-cm depth during the growing season. Another factor is the high soil moisture content that occurs as a result of thaw. Saturated deeper soils could offset some of the effect of shallower soil warming on respiration and N mineralization rates. Seasonal change in the depth of subsurface flowpath would have a similar effect. In the present study, the July increase in discharge (fig. 5) was the result of rainfall on relatively wet soils. The Asik watershed generally has two annual peaks in stream discharge (Stottlemyer, 2001). The high discharge in spring and early summer results from snowmelt and icemelt, whereas the high discharge in autumn partly results from continued soil thawing, because soil temperatures peak in August, a month later than air temperatures. The increase in stream-water NO<sub>3</sub><sup>-</sup> concentration with discharge, especially in autumn, indicates increasing shallow subsurface lateral flow through the biologically active soils relative to the dormant season.

### Soil Carbon and Nitrogen Pools

The soil C pool size was midway in the range of values measured across a long gradient on the North Slope that

included sites ranging from a northern foothills ridgetop to the coastal-plain tundra near Barrow (Michaelson and others, 1996). The C and N pool sizes in the Oe soil horizon were more than 40 percent higher than in the surface organic matter (fig. 3). However, C/N ratios remained somewhat constant throughout the surface organic matter and matched those generally measured in Arctic soils (Shaver and others, 1992). Above-ground live-biomass C/N ratios range from 35 to 66, or 2 to 4 times the ratio below ground (Robert Stottlemyer, unpub. data, 1999–2001). Such a C/N-ratio gradient indicates that nitrogen is relatively more abundant for mineralization by the soil microbial community. Any factor that increases below-ground N mineralization rates increases N availability as NH<sub>4</sub><sup>+</sup> or NO<sub>3</sub><sup>-</sup>, which can then be taken up by roots, in turn affecting above-ground plant production. The degree to which soil organic-C and organic-N mineralization rates differ in response to such factors as soil temperature or moisture content will determine the rate at which inorganic N may be transferred above ground.

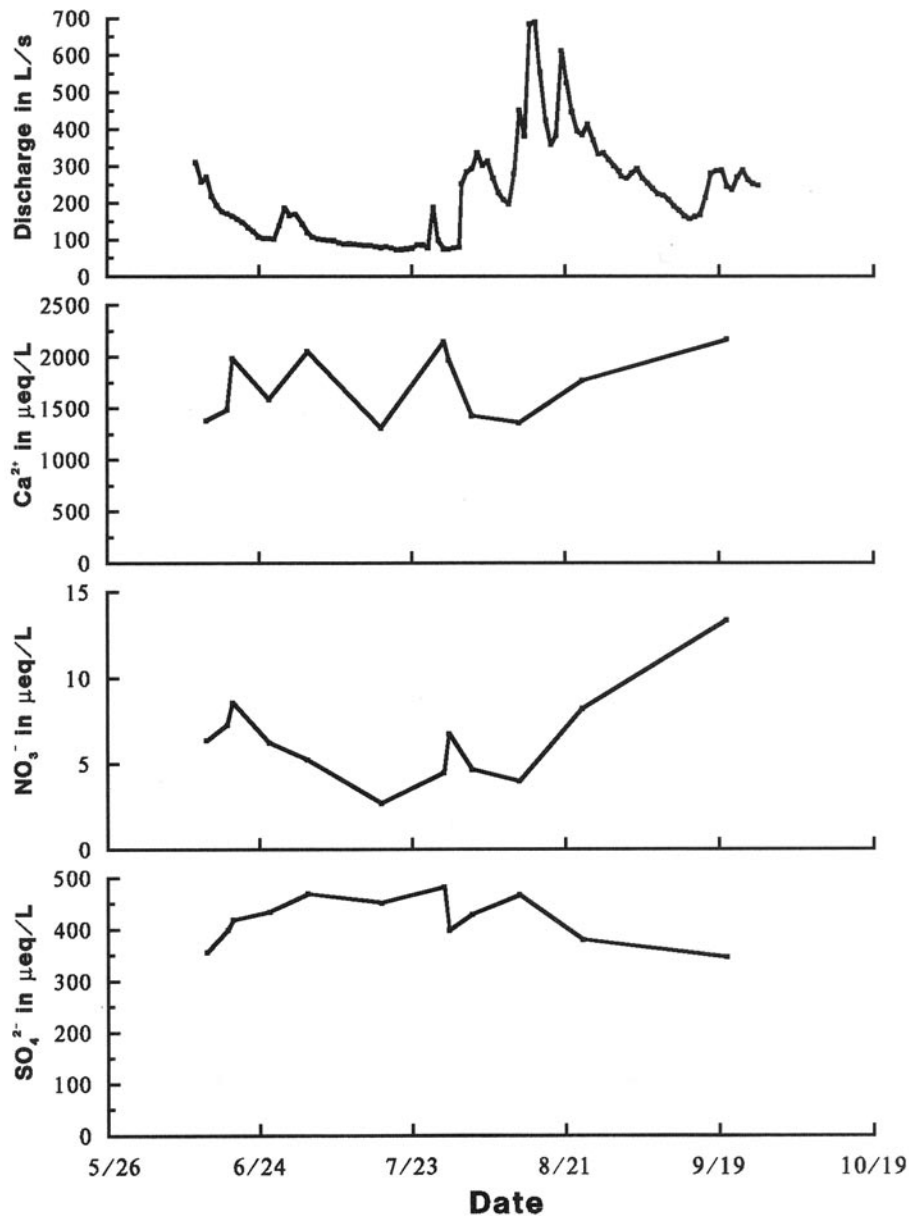
The seasonal change in soil inorganic-N pool size in the present study (fig. 4) was similar to that in a later study of 50 plots in the watershed (Stottlemyer, 2001). However, in the present study, the amounts were less than half the watershed levels found in the later study. We attribute this difference primarily to the consistently high soil moisture content and low temperature in the present study.

## Soil Respiration and Nitrogen Mineralization

The relation between soil CO<sub>2</sub> efflux and temperature varied by vegetation type and soil depth. Soil respiration rates were unrelated to thaw depth during the growing season, probably as a result of increasing soil moisture with depth. Only spruce showed a positive correlation between soil CO<sub>2</sub> efflux and temperature at 10-cm depth. In the later study in five vegetation types throughout the watershed, soil CO<sub>2</sub> efflux generally increased with temperature (Stottlemeyer, 2001). In the present study, the inverse relation between mean temperature, recorded continuously at three depths, and soil CO<sub>2</sub> efflux in spruce in August is attributable to the high soil moisture at

depth offsetting the effect on respiration of a slight temperature increase. Nadelhoffer and others (1991) found Arctic soil C mineralization rates in laboratory incubations insensitive to temperatures below 9°C. In the present study, mean daily shallow-soil temperatures peaked at 8°C (fig. 2). Our field results appear to confirm the laboratory results of Nadelhoffer and others (1991).

Because of the warming trend throughout northern Alaska, the region appears to be shifting from a C sink to a C source (Oechel and others, 1993). On a site-by-site basis, this relation varies as a result of changes in soil temperature and moisture (Oechel and others, 1995). In tundra along the North Slope, cooler and moister habitats continue to be C sinks,



**Figure 5.** Seasonal changes during June–September 1997 in stream-water discharge and ion concentrations at mouth of the Asik watershed, Noatak National Preserve, northwestern Alaska.



whereas warmer and drier sites are C sources. However, long-term comparative data from Arctic tundra ecosystems also suggests that continued warming and drying could diminish, if not reverse, the trend toward a C source (Oechel and others, 2000).

The inverse correlation between inorganic-N pool size and net ammonification, nitrification, and total N mineralization rates suggests that the response of soil processes mineralizing N and N uptake by the soil microbial community differ (Hart and others, 1994). The results of the present study are consistent with later work (Stottlemeyer, 2001) and suggest that during the growing season, mineralized N is sequestered in the surface organic matter, a result consistent with observations on stream-water inorganic-N export. The C and N cycles are closely linked, and the seasonal N retention suggests also that this ecosystem is currently a C sink.

The results from the in-place study of gross N mineralization and immobilization rates lend support to the observations of net N mineralization. The gross rates, which estimate total N cycling, indicate that the cycling of inorganic N is orders of magnitude greater than suggested by net N mineralization rates. Gross ammonification rates in the Asik watershed were equal to, and nitrification rates greater than, those recorded at the southward extent of the boreal biome (Stottlemeyer and Toczydlowski, 1999b). However, in most research plots at Asik, microbial N consumption exceeded mineralization rates, at least during the growing season, a result consistent with the negative net N mineralization rates and again suggesting that, except for early summer, this part of the watershed is losing little inorganic N during the growing season.

In comparing net and gross N mineralization rates, the results depend on the method used. Regardless of method, such potentially confounding factors as change in soil N leaching, moisture content, and root uptake are absent in these studies. The study of net N mineralization was conducted during much of the growing season, when microbial processes must integrate the effects of trends in soil temperature, availability of labile C, and other changing conditions. The factors regulating N mineralization and consumption rates generally do not affect both processes equally. Soil microbial functional composition also changes rather rapidly over time and would be reflected more in the net mineralization results than in the study of short-term gross N mineralization and consumption. Because of the short growing season, no attempt was made to examine the likely seasonal change in gross N mineralization rates, as reported in other studies (Stottlemeyer and Toczydlowski, 1999b).

## Soil and Stream Water

The differences in soil solution and stream-water DOC concentrations suggest poor linkage between the research plots and the stream during the growing season, as was true for such ions as  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$ , and for biologically derived  $\text{NO}_3^-$ . More intensive sampling of the soil-water lysimeters might have

**Table 3.** Mean concentrations of selected ions and DOC in soil solution during the 1997 growing season in the Asik watershed, Noatak National Preserve, northwestern Alaska.

[DOC, dissolved organic carbon. Standard deviations in parentheses]

	$\text{Ca}^{2+}$ ( $\mu\text{equiv}$ /L)	$\text{NO}_3^-$ ( $\mu\text{equiv}$ /L)	$\text{SO}_4^{2-}$ ( $\mu\text{equiv}$ /L)	DOC (mg/L)
Spruce -----	2,452 (713)	1.0 (2)	84 (63)	9.5 (6)
Transition -----	2,533 (1,027)	.5 (1.0)	149 (281)	12 (5)
Tundra -----	2,533 (1,072)	.02 (0.1)	59 (195)	12 (4)

shown a better correlation between plot soil-water chemistry and stream-water chemistry. However, the wide variation in rate of soil processes (fig. 4) and the lagtime in soil water reaching the stream could also account for the absence of correlation. The plots in the present study were located to examine soil processes across a taiga-tundra ecotone. Although this zone occurs throughout the watershed, it is not the dominant vegetation condition; most of the watershed is forest or tundra. Other studies in the Asik watershed show the large influence on stream-water solute concentrations and flux exerted by the alpine system (Stottlemeyer, 2001). The study plots reported here are but a small part of the total vegetated area in the watershed (fig. 1).

Although the stream is gauged year round, only seasonal flow can be measured in the Asik watershed. From late September to May, the stream is frozen from the bottom up, and little, if any, flow occurs. On the basis of seasonal flow measurements, discharge in 1997–98 did not greatly differ from that in other years (Robert Stottlemeyer, unpub. data, 1995–2001). The inverse relation between stream discharge and  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{SO}_4^{2-}$  concentrations previously observed in the Asik watershed was not apparent in 1997–98 (Stottlemeyer, 2001). At the watershed level, this absence of correlation suggests that waters were well mixed from various depths before reaching the stream. The correlation between stream discharge and  $\text{NO}_3^-$  concentration was also unusual. The stream-water  $\text{NO}_3^-$  flux was 10 times greater in September than in midsummer, indicating that much of the autumn increase in runoff—the product of reduced evapotranspiration, maximum soil thawing, and some increase in precipitation—was moving laterally through shallow soils and removing the mobile  $\text{NO}_3^-$ .

In the Asik watershed, inorganic-N outputs, almost all as  $\text{NO}_3^-$ , exceed inputs by an average of 70 percent. Results from the present study suggest that most of this excess inorganic N is lost, partly during the spring runoff but especially in autumn. Obviously, if this ecosystem is N limited, outputs can-

not exceed inputs over a long period. At the watershed level, another study shows soil inorganic-N pools and early summer net N mineralization rates to be positively related to temperature (Stottlemeyer, 2001). Warming regional temperatures could be accounting for the present net N loss from the watershed. However, year-to-year hydrologic variation can be a major source of change in watershed N output, and the short-term present study will not detect such change. Finally, N fixation occurs in this watershed at various places, especially in alder (Rhoades and others, 2001), and some of the N output could be the result of this process.

## Conclusion

In this high-latitude ecosystem, changes in the C and N budgets appear to be closely linked. The potential effects of seasonal changes in above-ground temperature and moisture content may be partly offset by significant increases in below-ground moisture content from thawing. The absence of correlation between soil respiration rates, thaw depth, and temperature suggests that high soil moisture content limited the response of soil processes to temperature increases. Such offsetting conditions make it difficult to link year-to-year climatic variation to any change in soil processes in the short term. The plots selected for this study were deliberately placed in or conterminous with a taiga-tundra transition zone. Considerable local variation occurs in soil temperature and moisture content and in the depth of surface organic matter across such a gradient. Soils were commonly saturated below 10-cm depth, and surface overland flow occurred in the sedge tundra. As observed in the more extensive 50-plot study of a subset of the processes examined in the present study, the taiga-tundra transition zone commonly showed relations between processes and soil characteristics not observed within the conterminous tundra or taiga (Stottlemeyer, 2001). Much of this variation appeared to result from changes in soil moisture content and subsurface flowpath. Except for the high early-summer  $\text{NO}_3^-$  flux in stream water concurrent with a high soil  $\text{NO}_3^-$  pool, no evidence was observed of a direct linkage between soil processes at the plot level and stream-water chemistry during the growing season.

## Ongoing Related Research in Fiscal Year 2002

Routine monitoring of weather, soil temperature, hydrology, and stream-water and precipitation chemistry in the Asik watershed is ongoing. During fiscal year 2002, intensive comparative study of N-fertilized and nonfertilized plots in all major vegetation types of the watershed will continue. An intensive study will be conducted of the watershed source areas for alpine and subalpine stream-water DOC and DON

contents, using  $^{15}\text{N}/^{14}\text{N}$  and  $^{13}\text{C}/^{12}\text{C}$  natural-isotope-abundance analyses. This study will also look at trends in isotopic ratios with depth of organic matter in soils to assess seasonal contributions from varying soil horizons. Finally, the study of "tree islands" in tundra will be continued to better define what soil conditions or processes account for island expansion or contraction.

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