Treeline Biogeochemistry and Dynamics, Noatak National Preserve, Northwestern Alaska

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Abstract

The extensive boreal biome is little studied relative to its global importance. Its high soil moisture and low temperatures result in large below-ground reservoirs of carbon (C) and nitrogen (N). Presently, such high-latitude ecosystems are undergoing the largest temperature increases in global warming. Change in soil temperature or moisture in the large pools of soil organic matter could fundamentally change ecosystem C and N budgets. Since 1990, we have conducted treeline studies in a small (800 ha) watershed in Noatak National Preserve, northwestern Alaska. Our objectives were to (1) gain an understanding of treeline dynamics, structure, and function; and (2) examine the effects of global climate change, particularly soil temperature, moisture, and N availability, on ecosystem processes. Our intensive site studies show that the treeline has advanced into tundra during the past 150 years. Inplace and laboratory incubations indicate that soil organic-layer mineralization rates increase with a temperature change >5ºC. N availability was greatest in soils beneath alder and lowest beneath willow or cottongrass tussocks. Watershed output of inorganic N as NO_3^- was 70 percent greater than input. The high inorganic-N output likely reflects soil freeze-thaw cycles, shallow flowpaths to the stream, and low seasonal biological retention. Concentrations and flux of dissolved organic carbon (DOC) in streamwater increased during spring melt and in autumn, indicating a seasonal accumulation of soil and forest-floor DOC and a shallower flowpath for meltwater to the stream. In sum, our research suggests that treeline transition-zone processes are quite sensitive to climate change, especially those functions regulating the C and N cycles.

Introduction

The boreal biome covers an area of 15 million km^2, second in extent only to tropical forest. Boreal lakes and ponds cover approximately 10 percent of the biome. In the taiga-tundra treeline of northwestern Alaska, temperatures have increased since 1950, especially in spring (Herrmann and others, 2000). The rate of regional climate change may be more significant than its magnitude (Solomon and Bartlein, 1992). The level of research on boreal forests does not match the extent or importance of this ecosystem (Botkin and Simpson, 1990; Mooney and others, 1991).

In the boreal biome, warming temperatures and change in moisture could increase above-ground production or below-ground respiration (Shaver and others, 1992). A change in available soil N may alter above- or below-ground C/N ratios, possibly also accelerating above-ground production or below-ground respiration. Which process is greater in magnitude may determine whether the ecosystem becomes a C source or sink (Oechel and others, 1995; McKane and others, 1997). To assess the effect of climate shift on the boreal C cycle requires knowledge of how temperature and moisture change affect soil organic reservoirs and other element cycles, especially N.

The boreal biome contains large, but mostly unavailable, reservoirs of C, N, and P. High-latitude terrestrial ecosystems contain from 20 to 45 percent of the global pool of soil organic C. Typically, >95 percent of tundra ecosystem C, N, and P occurs in soil organic matter (SOM) (Shaver and others, 1992). In such ecosystems, the nutrient and C storage in SOM pools is a function of high soil moisture and low temperature, both of which slow decomposition.

In the taiga-tundra transition zone at the northernmost extent of the boreal biome, most SOM is below the annual thaw depth (soil active layer) and not readily available for biological uptake. Any factor that increases the depth of the soil active layer or the depth to permafrost could change soil moisture and temperature, SOM decomposition, nutrient availability, and respiration rates (Chapin and others, 1995; Jonasson and others, 1999). Research in Michigan shows that slight gains in soil temperature result in an increase of SOM decomposition and available nutrients as inorganic N in amounts greater than the sum of other N sources, such as precipitation and fixation (Stottlemyer and Toczydlowski, 1999).

The National Park Service (NPS) manages an area of 7 million ha in northwestern Alaska, or about 25 percent of

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the Nation's total land in national parks. The northwestern Alaska region stretches inland from the Chukchi Sea almost 600 km, mainly along the Brooks Range, encompassing much of Alaska's taiga-tundra treeline transition zone. Much of this NPS land is in Noatak National Preserve, which, along with the western part of Gates of the Arctic National Park, contains the entire 500-km-long Noatak River Basin (Kepner and Stottlemyer, 1990). Ecologic studies in the region are few and largely confined to wildlife. Except for the National Science Foundation studies at Toolik Lake and vicinity in east-central Alaska, few studies of ecosystem processes have been conducted within the region.

In 1989, studies were begun in Noatak National Preserve to assess surface water quality, treeline dynamics, ecosystem processes that may regulate terrestrial nutrient and energy cycles, and terrestrial and aquatic ecosystem linkages. In this chapter, we summarize results from several intensive studies in a small (800-ha area) watershed to (1) relate changes in upstream and downstream water chemistry to soil conditions and possible changes in hydrologic flowpath, (2) investigate the relations between soil temperature and moisture in regulating soil N supply in major ecosystems in and adjacent to the watershed, and (3) quantify the extent to which forest stands have invaded tundra along transects in and adjacent to the watershed.

Site Description

Noatak National Preserve

Noatak National Preserve is just north of the Arctic Circle. Its south boundary is the Baird Mountains, and its north boundary is the De Long Mountains near the west end of the Brooks Range (fig. 1), which represents the west end of the Rocky Mountain Physiographic Division of Alaska.

The geology of the preserve is dominated by Quaternary deposits at low elevations; Permian, Triassic, and Jurassic volcanic rocks in the western part; and Mississippian conglomerate, shale, limestone, and dolomitic rocks along its north border. Some Precambrian bedrock is present, and much of the rest of the preserve is underlain by Upper Devonian shale, sandstone, chert, and conglomerate (Plafker and Berg, 1994); however, loess and volcanic ash cover most of the Noatak Basin. Much of the region is characterized by continuous permafrost, but large areas of discontinuous permafrost are present, especially along forested southern aspects (Ferrians, 1965).

Air and soil temperatures in the region have warmed since 1950 (fig. 2). The mean annual temperatures at National Oceanographic and Atmospheric Administration (NOAA) stations in Bettles (lat 66º55′ N., long 151º31′ W.) and Kotzebue, Alaska, have increased (p<0.01) by about 0.04ºC/yr (Herrmann and others, 2000), with most of the increase occurring in April (p<0.01, r^2=0.16, b=0.16ºC/yr). The warming at high latitudes is consistent with other findings (Illeris and Jonasson, 1999).

The NOAA weather stations show considerable annual variation (fig. 2). Winter temperatures are extreme, and most of the annual precipitation (mean, 35 cm) occurs during the summer months. The snowpack rarely exceeds 1 m in depth in protected areas. Wind redistributes the snow in exposed areas, and the depth and duration of the snowpack are major factors regulating vegetation (Lavoie and Payette, 1994).

Bailey (1998) classified the region of the Noatak National Preserve as a westward extension of the subarctic-regime mountains. Tundra dominates in the northern part of the preserve, taiga-tundra treeline in the central and western parts, and taiga along the south boundary with Kobuk National Park. Forested areas are characterized by spodosols, with histosols in wetter sites (Rieger and others, 1979).

Asik Research Watershed

The 800-ha-area Asik watershed (lat 67º58′ N., long 162º15′ W.) is in the south-central part of Noatak National Preserve, 95 km northeast of Kotzebue (fig. 1). The watershed is at treeline, and its first-order stream drains from the north and west into the Agashashok River, which in turn feeds into the Noatak River. Since 1996, the daily mean air temperature in the watershed has ranged from −47 to 20ºC (fig. 2). Annual precipitation averages 30 cm, with about 10 cm falling during the growing season (June to mid August). The peak snowpack averages about 1 m in depth in the more sheltered lower and middle elevations of the watershed.

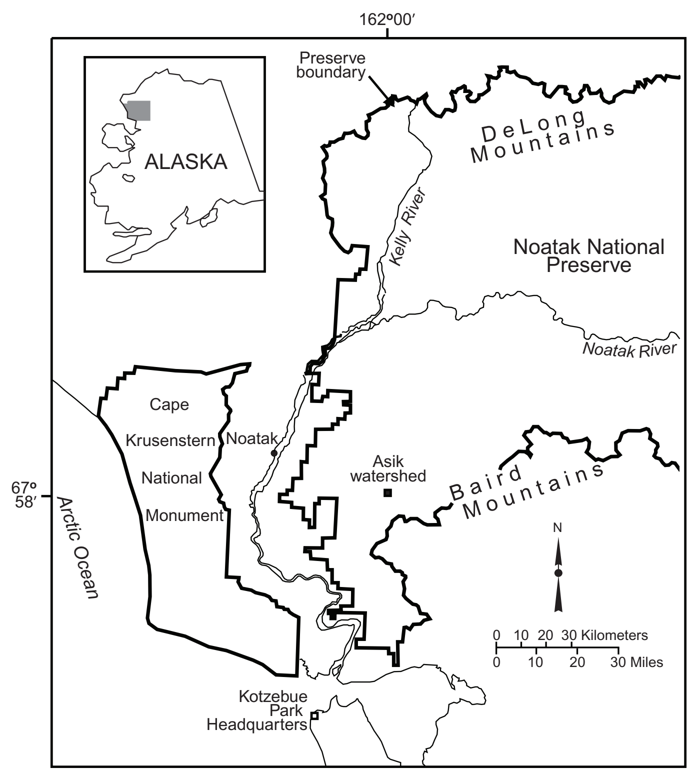

Figure 1. Northwestern Alaska, showing location of the Asik watershed, Agashashok River drainage, Noatak National Preserve.

The soil association is gravelly, hilly to steep pergelic cryaquepts/pergelic cryorthents (Rieger and others, 1979). The association consists of poorly drained to well-drained soils, most with permafrost. Soils are poorly drained along long gradual slopes, valley bottoms, and on steeper northern aspects. Well-drained soils occur along ridges and on steeper southern-aspect slopes. Frost features are common. In the Agashashok River flood plain, soils are loamy. Along steeper slopes of the Asik watershed, soils are shallow and rocky, with a clay-loam texture. In the Asik watershed, the bulk density of the decomposed surface organic layer (O2 horizon) averages from 0.3 where the silt content is low to about 0.7 where the silt content is high. The O2-horizon pH ranges from 4.6 in tussock tundra to 6.0 beneath spruce, total C content from 15 weight percent beneath alder to 40 weight percent in tussock tundra, and total N from 0.8 weight percent beneath alder to 1.7 weight percent below tussock tundra. Discontinuous permafrost exists in the watershed, especially where there is no forest. The soil surface (uppermost 5 cm) is frozen from late September to May, except for upper reaches with southern aspects. The bedrock is Silurian and Devonian limestone, dolomite, marble, and shale (Plafker and Berg, 1994). About 5 to 7 percent of the watershed area consists of talus slopes. The Noatak River drainage was unglaciated during the last ice age.

The lower two-thirds of the watershed area is dominated by white spruce (*Picea glauca* [Moench] Voss). Spruce basal area ranges from 4 m^2/ha on south aspects to 23 m^2/ha in bottom land (Suarez and others, 1999). The spruce forest understory consists primarily of *Hylocomium splendens*

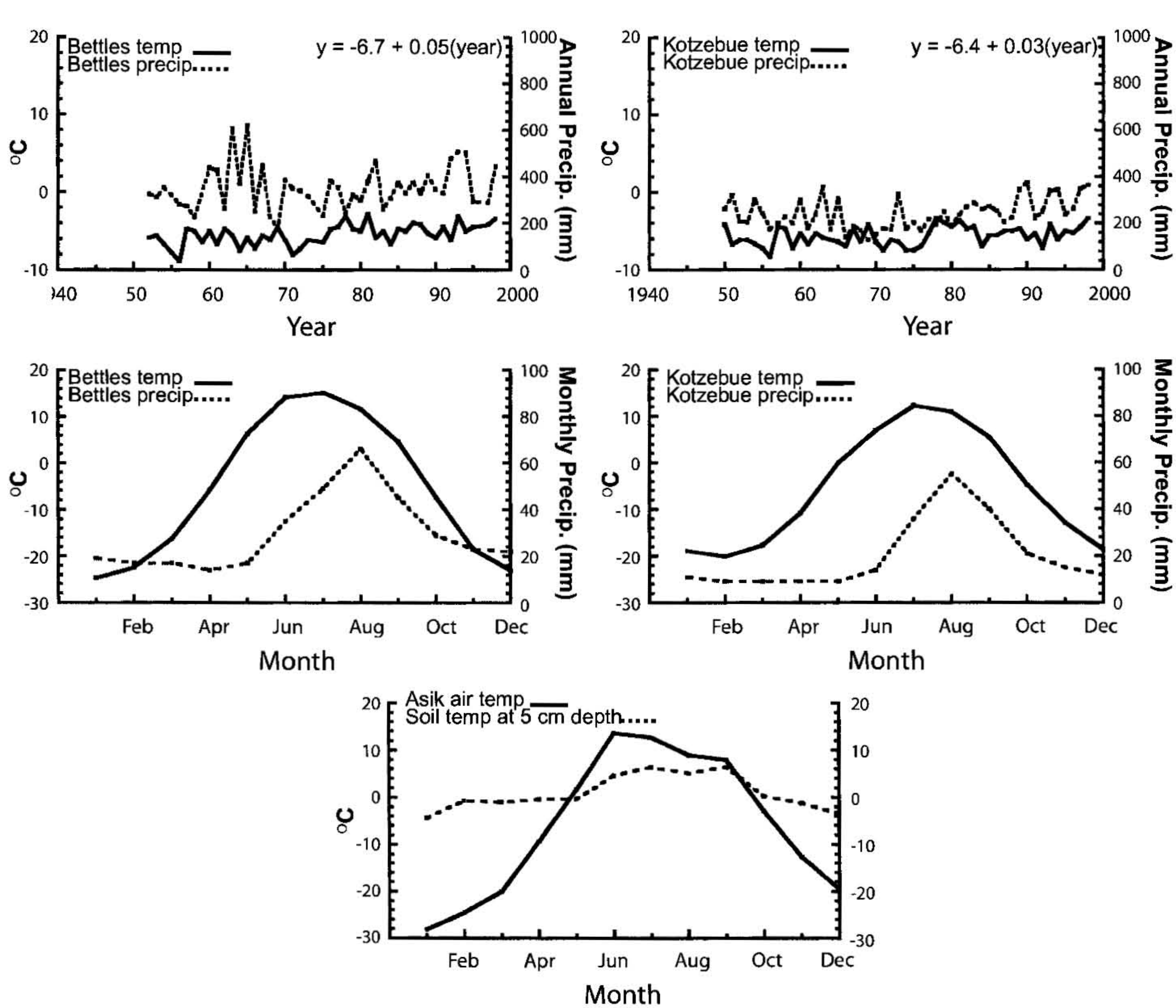

Figure 2. Mean annual (1951–98) and monthly temperature and precipitation for National Oceanographic Atmospheric Administration (NOAA) stations, Bettles and Kotzebue, Alaska; and (bottom) seasonal change (average, 1996–99) in air and soil temperature, Asik watershed, Noatak National Preserve, Alaska. Equations are given where time trend was significant.

(Hedw.) B.S.G., *Equisetum arvense* L., and *Boykinia richardsonii* (Hook.) Gray, with shrubs of *Salix* spp. 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. The upper 20 percent of the watershed area is dominated by such shrubs as *Betula nana*, scattered *Alnus crispa* (Ait.) Pursh on more northern aspects, and mesic nontussock tundra. The stream alluvial area is dominated by *Salix* spp.

Methods

Hydrology and Streamwater Chemistry

Because of the important role of hydrology in biogeochemical cycles and the need to study the ecosystem as an integrated unit, we chose the watershed-ecosystem design for most of our intensive studies of terrestrial processes and their linkages to the aquatic ecosystem (Likens and Bormann, 1995). In 1991, we began intensive study of the first-order, 800-ha-area treeline Asik watershed, which was selected for its central location in the taiga-tundra treeline, its small size, and its proximity to a river bar for relative ease of access by bushplane.

A 10-m-high meteorologic tower with data logger and solar panel was located in the lower third of the watershed. Air and soil temperature (at 5- and 10-cm depth), relative humidity, radiation, windspeed, and wind direction were monitored year round. In the alpine tundra, a data logger monitored air (1 m) and soil temperature (at 5- and 10-cm depth). Precipitation was sampled by using bulk collectors. During winter, the sampler was a 20-cm-diameter, 1.5-m-long tube lined with custom-fitted heavy plastic liners. During the growing season, a 10-cm-diameter plastic tube with funnel was used with a prerinsed qualitative filter in place to minimize dust and particulates entering the sample. Precipitation samples were collected weekly during the growing season and early fall.

Stream discharge was measured at a natural weir. Since 1996, stage height was monitored by standing stake and pressure transducer. Each year a discharge curve was developed by measuring cross sections and velocity (pygmy meter) at varying stage heights. Daily water temperature was monitored year round and recorded by data logger. Streamwater was sampled weekly at the mouth and five upstream stations from late May to mid-September. Sampling was daily or more frequent at the mouth during periods of rapid hydrograph change. The stream was frozen, with little or no flow from mid-October to late April or early May.

For analyses of precipitation and streamwater samples, pH, specific conductance, and alkalinity (titration with 0.02N H_2SO_4 to pH 4.5, streamwater samples only) were measured in the field laboratory. Separate filtered (prerinsed, 0.45 μm) subsamples were shipped in coolers to our laboratory in Fort Collins, Colo., for ion-chromatographic analysis, and an additional filtered sample was sent to the Michigan Technological University, Houghton, for dissolved-organic-carbon (DOC) analysis.

Nitrogen Mineralization Response to Temperature and Moisture

In 1990–91, we located three subplots beneath each of five vegetation types in or adjacent to the Asik watershed (Binkley and others, 1994). Willow and *Dryas* spp. subplots were located on the Agashashok River terraces across from the watershed. The alder subplots were on a north-facing slope upstream of the willow subplots, and the spruce subplots were along the north side of the watershed, with the tundra plots above the spruce.

To examine the effects of soil-temperature and moisture change on N transformations, principally mineralization (microbial breakdown of organic N to inorganic NO_3^- and NH_4^+) and immobilization (microbial uptake), we conducted a series of laboratory incubations. First, a composite sample from the soil surface organic layer, or O2 horizon, was collected from each subplot, placed in a cooler, and shipped to our laboratory in Fort Collins, Colo., where the samples were sieved. A 10-g subsample was extracted with 50 mL of 2M KCl to determine the initial inorganic-N (NO_3^- and NH_4^+) concentrations. Additional 10-g subsamples were incubated in the laboratory for a month at 5 and 12°C at four frequencies of wetting and drying (one to four times during laboratory incubation). At the end of a month, all samples were extracted with 2M KCl to determine the net change in mineralized N. Net N mineralization is the sum of mineralized NH_4^+ plus NO_3^- from organic N, minus immobilization of NH_4^+ and NO_3^- during the incubation period; net nitrification is the sum of NO_3^- from both organic N and NH_4^+ minus immobilization of NO_3^-.

A subsample from the incubated samples was retained for a ^{15}N pool-dilution experiment to estimate gross, or total, N mineralization and immobilization during a 24-hour period. The gross results provide an estimate of the total NH_4^+ and NO_3^- cycled within a given time period. For details on the procedures used, see Kirkham and Bartholomew (1954) and Brooks and others (1989).

Expansion of Forest into Tundra

After a 1995 aerial survey of the Asik watershed, five stands of spruce that showed an apparent expansion pattern into tundra were selected for intensive study (Suarez and others, 1999). The normal vegetation transition was from pure spruce to forest mixed with tundra plants, then to tundra with numerous trees, then to treeless tundra. The spruce understory and tundra vegetation composition was similar to that described above. In each stand, three transects perpendicular to the direction of spruce expansion were located. The stand age of each plot was determined by sampling the five trees larger than 20 mm in diameter nearest each plot center. The diameter, height, and age of each sample tree were determined. In the transect with the oldest vegetation in each plot, cores were collected from 35 trees to determine annual growth increments. From each five-tree plot, seedlings by size class were recorded and aged, and dead trees and seedlings were tallied. For further details on data analysis, see Suarez and others (1999).

Results and Discussion

Streamwater Solute Concentrations and Budgets

Runoff in the Asik watershed averaged 45 percent of precipitation. Concentrations of streamwater base cations (C_B) (the sum of Ca^{2+}, Mg^{2+}, Na^+, and K^+), and HCO_3^- were higher than observed in most watersheds in North America (fig. 3; Kaufmann and others, 1991). Measured concentrations were similar to those in Rock Creek, Denali National Park, Alaska (Stottlemyer, 1992).

Streamwater C_B concentrations can provide indications of seasonal change in water source and age (Rice and Bricker, 1995). In early June and mid-June, low Ca^{2+} concentrations suggest that discharge from the watershed was dominated by "new water" from melting of snow and ice (McNamara and others, 1997). Later, in summer, the increase in streamwater Ca^{2+} concentrations suggests greater contributions from "old" water deeper in the soil and longer flowpaths to the stream.

Asik alpine-streamwater Ca^{2+} concentrations suggest that a combination of factors—short flowpath, less reactive soil and more talus, and domination by new water—contribute to low solute concentrations. In alpine streamwater, the absence of much seasonal change in Ca^{2+} concentration suggests rapid penetration of precipitation and meltwater through porous soil and talus before it enters the stream, with little contribution from substrate exchange or weathering (Stottlemyer and others, 1997).

Asik streamwater NO_3^- concentrations were also higher than observed in most surface waters, even in regions where atmospheric NO_3^- inputs are elevated (Kaufmann and others, 1991). However, undisturbed Alaskan streams commonly have high NO_3^- concentrations year round, with outputs exceeding inputs (Stednick, 1981; Stottlemyer and Rutkowski, 1987; Stottlemyer, 1992). Asik streamwater NO_3^- concentrations likely reflect a shallow soil active layer or discontinuous permafrost channeling runoff through near-surface soil source areas where pools of dissolved inorganic N (NH_4^++NO_3^-) are greater (Stottlemyer and Toczydlowski, 1990; Creed and Band, 1998; Stottlemyer and Troendle, 1999), with seasonal low biological uptake (especially in the alpine), and soil freeze/thaw cycles releasing biologically usable C and N from the microbial biomass (Mitchell and others, 1996).

Streamwater NO_3^- concentrations at the mouth of the Asik watershed varied little during the growing season and declined only slightly during late summer and early fall, when streamwater discharge increased. Alpine-streamwater NO_3^- concentrations especially suggest low biological uptake during the growing season, because precipitation inputs were small. In alpine headwaters where talus dominates, a small amount of soil and vegetation can still dominate inorganic-N concentra-

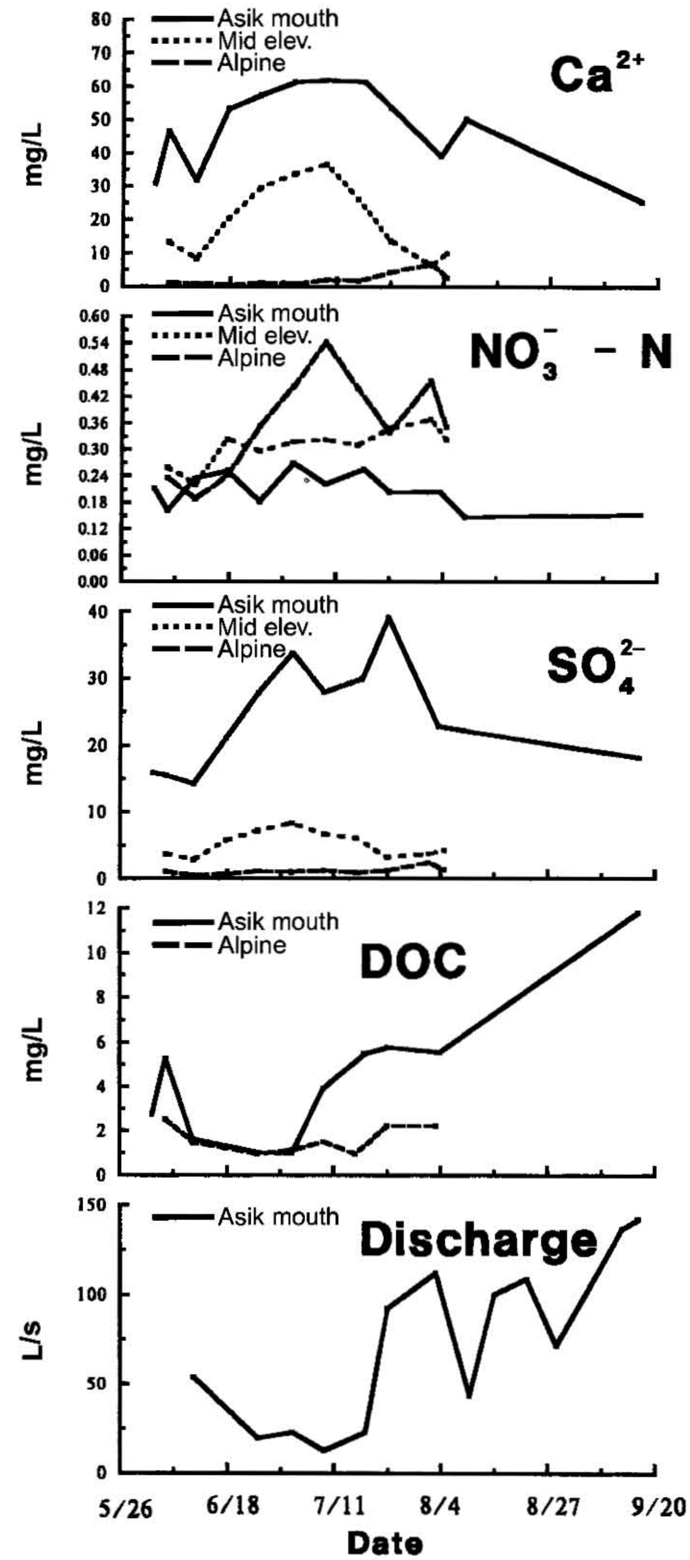

Figure 3. Mean weekly streamwater ion and DOC concentrations at different elevations and discharge from the Asik watershed, Noatak National Preserve, Alaska, in 1999.

tions in soil and streamwater (Campbell and others, 1995). The Asik watershed inorganic-N output, primarily NO_3^-, exceeded input by 70 percent.

The increase in streamwater DOC concentrations during spring melt suggests that large soil and forest-floor DOC reservoirs accumulated during the previous fall and winter. The increases in late summer streamwater DOC concentration and flux at the watershed mouth indicate considerable growing-season soil C mineralization, coupled with greater subsurface flow to the stream. Streamwater DOC output averaged 0.015 mg/m^2 per day, and dissolved-inorganic-carbon (DIC) output 0.3 mg/m^2 per day. The amount of C exported in streamwater was small relative to terrestrial CO_2 losses to the atmosphere in the Asik watershed and other study areas in northern Alaska (Oechel and others, 1995; McKane and others, 1997).

DOC concentrations in soil water below the rooting zone and in streamwater are hypothesized to be low where inorganic N is relatively high, because large amounts of biologically usable C are needed to fuel the N-immobilization processes in SOM (Aber, 1992). A synthesis of the European NITREX data, however, did not support this hypothesis (Gundersen and others, 1998), nor do the Asik watershed data. We suspect that the high Asik DOC export is a function of the large SOM pool, soil warming, and a larger proportion of the subsurface flow moving through shallower flowpaths to the stream.

Climate and Soil-N-Mineralization Rates

In our study of soils beneath five vegetation types in and adjacent to the Asik watershed, inorganic-N availability was highest beneath alder and lowest in plots dominated by willow or tussock-tundra (Binkley and others, 1994). However, all soils from the five vegetation types sampled responded strongly to an increase in the frequency of wetting and drying cycles, which raised the net N-mineralization rates 150 to 300 percent in laboratory incubations (fig. 4). An increase in the frequency of wetting and drying cycles is one potential effect predicted with global warming.

Net N-mineralization rates also responded strongly to temperature changes. Rates at 12ºC were 5 to 10 times the rate at 5ºC. The response of net N mineralization to both temperature and moisture treatments was consistent in soils from all the five vegetation types; however, the response to a change in soil-moisture content was much less than the response to an increase in temperature.

Net N-mineralization rates reflected the strong effect of temperature and moisture treatments on both gross (total) soil-microbial N release (mineralization) and uptake (immobilization) (fig. 5). However, the response to temperature and moisture by mineralization processes differed in magnitude from the response by immobilization processes. For example, if the N-immobilization rate responds more strongly to temperature increases than does the total N-mineralization rate, net N-mineralization rates would decline with increasing temperature, as may also be reflected in the seasonal pool size of soil inorganic N. Thus, the effect of climate change and, especially, temperature on the available soil inorganic N in these ecosystems will depend on the relative magnitude of response in these opposing processes of microbial mineralization and immobilization. We also suspect that the balance of these opposing processes varies seasonally and with available, or labile, C.

Expansion of Forest into Tundra

Warming during the past 150 years appears to have increased spruce growth rates in the Asik watershed and resulted in forest expansion into the conterminous tundra ecosystem. The forest/tundra transition zone has moved about 80 to 100 m into the tundra. Our primary evidence is the progressive decline in maximum tree age from the spruce forest into the tundra and the frequency distribution of trees in spruce forest, forest-tundra, and areas where tundra is more prevalent than forest (fig. 6). The increase over time in spruce frequency where tundra was dominant is also associated with a broad

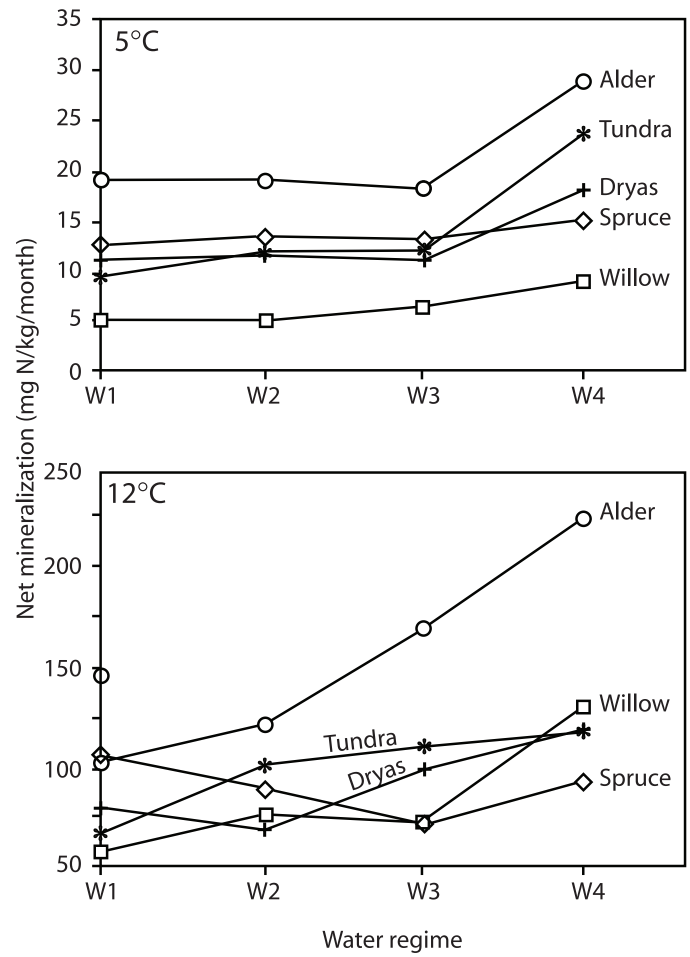

Figure 4. Laboratory net N mineralization in response to changes in temperature (5 and 12°C) and moisture. Responses to moisture and temperature were significant (p<0.05). Water treatments: W1, one moisture addition at beginning of 30-day incubation; W2, two moisture additions or two wet/dry periods; W3, three wet/dry treatments; W4, four wet/dry treatments. From Binkley and others (1994).

trend of increasing tree growth. The climate conditions that led to increasing tree growth appear to have promoted tree establishment in the tundra. The recent expansion of spruce forest occurred across topographic boundaries and in areas of both well-drained soils on slopes and poorly drained, flat tundra areas. However, future advance of spruce may be limited by increased topographic exposure to wind and snow (Sturm and others, 2001) and by the higher soil moistures characteristic of most tundra.

During the past several centuries, changes in Alaska treeline have been small (Brubaker and others, 1983). At the Asik watershed, however, the encroachment of spruce forest into tundra was characterized initially by a few trees and later by increased density. This process of infilling has also been observed along the north side of the Noatak River (Rowland, 1996) and elsewhere. Changes in spruce density in response to climate may have been missed in the past during the more synoptic surveys of treeline advance, which focused more on only the presence or absence of spruce trees.

Acknowledgments

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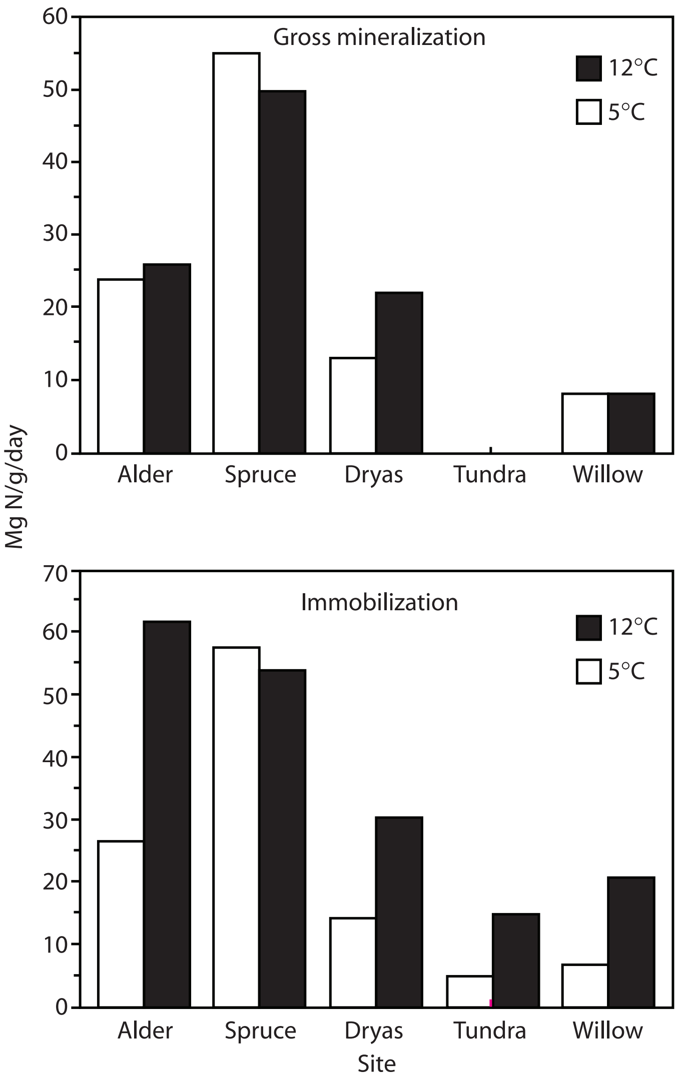

Figure 5. Laboratory 24-hour gross N-mineralization and -immobilization rates in response to a change in temperature (5 and 12°C). From Binkley and others (1994).

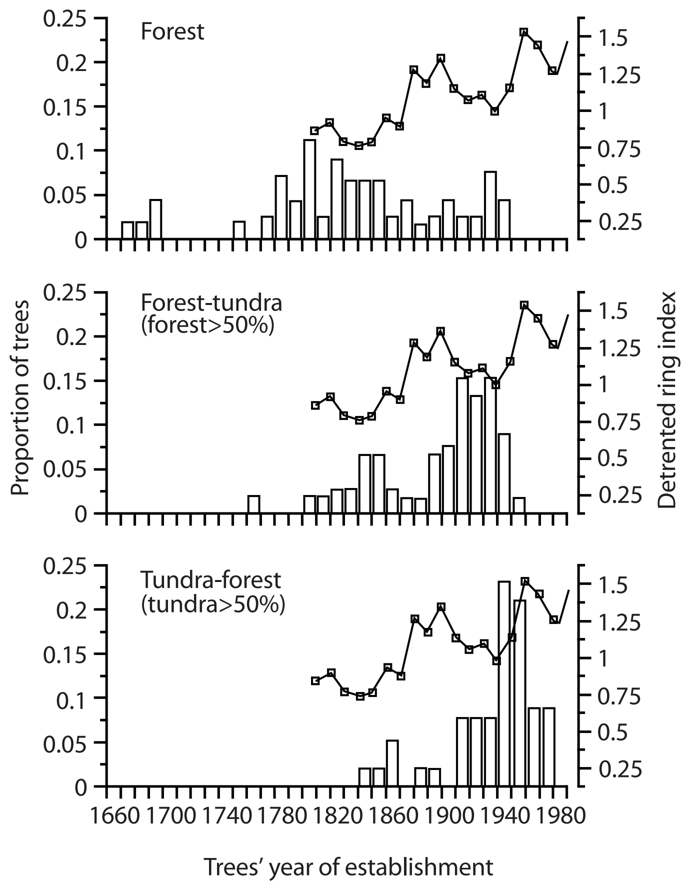

Figure 6. Relative-frequency histograms (10-year age classes) for spruce across five expanding stands, with detrended tree-ring-growth index. From Suarez and others (1999).

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