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Nitrogen loss from watersheds of interior Alaska underlain with discontinuous permafrost

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[1] We constructed annual nitrogen budgets for four years for three watersheds underlain with discontinuous permafrost in interior Alaska. During all years, nitrogen export in stream flow exceeded input from deposition, with loss rate greatest from the two watersheds with the lowest spatial extents of permafrost. Elevated nitrogen export appears to be common in regions with discontinuous permafrost, based on nitrogen concentration in streams spanning a latitudinal gradient in permafrost coverage. This pattern of nitrogen loss is counter to temperate regions, where watersheds retain nitrogen even with elevated atmospheric deposition, and unexpected, given that terrestrial primary production appears to be nitrogen limited. **Citation:** Jones, J. B., Jr., K. C. Petrone, J. C. Finlay, L. D. Hinzman, and W. R. Bolton (2005), Nitrogen loss from watersheds of interior Alaska underlain with discontinuous permafrost, *Geophys. Res. Lett.*, *32*, L02401, doi:10.1029/2004GL021734.

1. Introduction

[2] The boreal forest of interior Alaska is thought to be limited by nitrogen, yet stores vast amounts of organic nitrogen in cold or frozen soils [*Post et al.*, 1982]. Soil warming could stimulate mineralization of stored nitrogen, potentially altering terrestrial and aquatic ecosystem productivity, or lead to increased riverine nitrogen export [e.g., *Shaver et al.*, 1992]. Temperate ecosystems tend to retain nitrogen, with export in stream water less than or equal to atmospheric deposition [e.g., *Vitousek et al.*, 1982; *Howarth et al.*, 1996]. In contrast, in boreal forest watersheds of interior Alaska, fluvial export consistently exceeds atmospheric input [*Stottlemyer*, 1992, 1997, 2001; *Hinzman et al.*, 2005a]. We investigated nitrogen losses from boreal forest watersheds to determine if watersheds in interior Alaska are indeed losing nitrogen and if the pattern of nitrogen loss is related to the distribution of permafrost. First, we calculated annual budgets for three watersheds for four years. Second, we conducted a survey of stream chemistry along a latitudinal gradient that spanned from the zone of discontinuous to continuous permafrost in interior Alaska.

2. Methods

2.1. Study Sites

[3] We measured nitrogen fluxes in three sub-catchments of the Caribou Poker Creeks Research Watershed (CPCRW) located NE of Fairbanks, Alaska (65°N, 147°W). CPCRW is a pristine 104-km^2 watershed with no current human influence other than scientific research. The three sub-catchments studied (designated C2, C3 and C4) had watershed areas of 5.2, 5.7 and 10.0 km^2, and underlying permafrost extents of 4, 53 and 19%, respectively. The climate of CPCRW is continental, with warm summers (mean = 16.4°C in July), cold winters (mean = −24.9°C in January), and low precipitation (411 mm, of which 31% falls as snow). The watershed is located in the zone of discontinuous permafrost, where permafrost temperature is near 0°C and thus vulnerable to loss with small changes in climate or surface energy exchange [*Osterkamp*, 1983]. Discontinuous permafrost underlies most of interior Alaska and large areas of boreal Canada and Russia.

[4] Vegetation types in the study watersheds are typical of interior Alaska. Uplands are dominated by well-drained hardwood forests (*Betula paprifera*, *Populus tremuloides*) on south facing slopes, and black spruce (*Picea mariana*) with feathermoss (*Pleurozium schreberi*), moss (*Hylocomium*, others) and lichen understories on north facing slopes. Uplands also have patchy understory of alder (*Alnus crispa*). Soils in valley bottoms are typically saturated with extensive coverage of mosses (*Sphagnum* spp., *Hylocomium*) and dwarf shrubs (*B. nana*, *Salix* spp., *Vaccinium uliginosum*) and patchy coverage of alder (*A. tenuifolia*).

2.2. Field and Laboratory Measurements

[5] Nitrogen inputs via atmospheric deposition and outputs in stream flow were calculated for four years (1986, 2001, 2002 and 2003). Wet deposition was obtained from the Poker Creek National Atmospheric Deposition Program (NADP) station located 1.5–5.5 km from the study watersheds and at an elevation similar to the stream outflows (230 m). In the CPCRW watershed, total annual precipitation does not significantly vary with elevation based on seven years of data collected along an elevation gradient (230–826 m) (W. R. Bolton et al., unpublished data, 2004) and so orographic differences in precipitation are not likely. Mean annual nitrogen deposition was calculated as the sum of monthly mean rates averaged from 10 years of data obtained from the NADP website (nadp.sws.uiuc.edu). We used monthly means because most years had periods in which data collection was interrupted. To provide an estimate of dry deposition, data were obtained from the Clean

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Air Status and Trends Network station located at Denali National Park located ~200 km from CPCRW.

[6] Stream transport of nitrogen was calculated from discharge and the concentrations of nitrate, ammonium and dissolved organic nitrogen (DON). Such measurements present several challenges in boreal and arctic ecosystems. First, during winter, the active channel of headwater streams develops considerable aufeis (seasonal accumulation of ice), which commonly fills the active channel, and distributes flow across the valley floor in multiple channels. Thus, locating flowing water and measuring discharge is often difficult. During 1986 and 2001, winter discharge and water samples were collected every 1–2 months in all three watersheds. Second, the major hydrologic event each year is snowmelt, which typically lasts for 2–3 weeks. During snowmelt, flumes are typically encased in ice and discharge can only be estimated from manual measurements. Snowmelt discharge and water chemistry were sampled every 1–3 days during 2001 and 2003, but not in 1986 and 2002.

[7] During the ice-free months, stream stage height was measured continuously using flumes during all four years (approximately June–September). Flow was also quantified from velocity and stream cross-section measurements to develop rating curves to interpret flume depth measurements. Stream chemistry samples were collected weekly during 1986 (data from *Ray* [1988]). During the other three years, we collected samples daily using autosamplers, with several exceptions due to mechanical failures. In addition, we collected weekly grab samples from all three streams ($r^2 = 0.95$ for nitrate concentration measured in samples that remained in autosamplers for >1 week versus the respective daily grab samples; slope = 0.99). From each stream, 29–33 chemistry samples were collected in 1986, and 89–125 samples were collected in 2001, 2002 and 2003.

[8] To test if stream nitrogen concentrations were elevated in latitudes of discontinuous permafrost, we also collected one-time samples from 34 streams over summer 2002 to characterize stream water nitrogen concentrations across a gradient of discontinuous to continuous permafrost in Alaska (63°12′N to 68°5′N). For all water samples, we measured nitrate, ammonium, DON and chloride concentrations. Based on the assumption that chloride does not react biologically or chemically in watersheds, and that the major source of chloride is precipitation, we used total dissolved nitrogen to chloride (TDN:Cl) as an index of nitrogen retention. We fit both linear and Gaussian models with the prediction that the Gaussian model would better describe concentration versus latitude if concentrations were indeed elevated in the region of discontinuous permafrost. Improvement in model fit was evaluated with Akaike's Information Criterion (AIC) in which smaller AIC scores indicate the more likely model.

[9] Ammonium was not measured in 1986 or 2001 but was measured by ion chromatography in 2002 and 2003. Nitrate was measured colorimetrically following reduction to nitrite in cadmium-copper columns in 1986 and by ion chromatograph in 2001, 2002 and 2003. TDN was measured by persulfate digestion in 2001, and with a Shimadzu 5000 total organic carbon analyzer plumbed to an Antek 7050 nitric oxide chemoluminescent detector in 2002 and 2003 (TDN was not measured in 1986). DON was calculated as the difference between TDN and dissolved inorganic nitrogen (DIN; ammonium + nitrate).

2.3. Nitrogen Budget Calculations

[10] Annual loss rate of nitrogen in stream flow was calculated by summing daily flux estimates. Daily flux was calculated as the product of mean daily discharge and solute concentration. For days lacking discharge or solute measurements, values were linearly interpolated. For years lacking winter discharge and chemistry data, we attempted to be as conservative as possible with our interpolations as to not over estimate nitrogen loss from watersheds. We assumed winter flow and nitrogen concentrations were the minimums observed during the years with data, and that flow and concentrations declined to those levels immediately following the last sample date at the end of summer. Flow and nitrogen concentration were assumed to remain low until data collection resumed the following spring or May 1, which ever occurred first. Thus, for years lacking such data (i.e., 1986 and 2002), we did not include snowmelt in our flux calculations. Differences in nitrate export, DON export, and discharge among watersheds were assessed with one-way analysis of variance (ANOVA).

[11] To provide an estimate of the error associated with budget calculations we conducted uncertainty analyses of atmospheric wet deposition and stream export calculations. For deposition, we randomly varied each monthly measurement of precipitation and the concentrations of ammonium and nitrate ±25%, recalculated mean monthly deposition, and summed for an annual rate. For stream export, we randomly varied each daily estimate of discharge and each measurement of stream water TDN including interpolated values ±25% and calculated annual rate. The uncertainty of ±25% represents an approximate range in TDN concentration about the mean between the 10% and 90% quantiles for individual streams, and was intended as a conservative estimate of the error associated with missing or interpolated data. All uncertainty analyses were conduced 10,000 times.

3. Results

[12] Wet nitrogen deposition in CPCRW is low relative to many regions of the world, averaging 0.22 kgN ha^{-1} y^{-1}, of which nitrate and ammonium account for 60 and 40%, respectively (Figure 1). Dry deposition measured at Denali National Park is similarly low (0.09 kgN ha^{-1} y^{-1}) and assuming a similar rate for CPCRW then total deposition is ~0.3 kgN ha^{-1} y^{-1}. Based on the uncertainty analysis, the estimated range in annual wet deposition is 0.20 to 0.24 kgN ha^{-1} y^{-1}.

[13] TDN export in stream flow was nearly seven-fold greater than deposition, with DIN accounting for 66% of the total flux (range = 48–85%; Figure 1). Across years, nitrogen export varied two-fold in all watersheds and was greatest in 2003, a year with a large summer flood and sustained period of high flow. For 2001 and 2003, the years with snowmelt data, spring thaw accounted for an average of 10% (range = 7–19%) of the annual export (snowmelt defined as April 15–May 31), and for all four years of data, winter accounted from an average of 22% (range = 6–36%) of the annual export. Across watersheds, nitrogen export

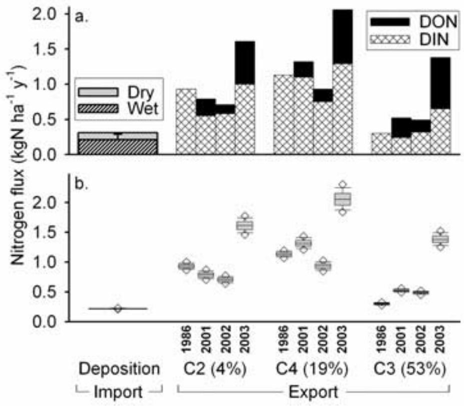

Figure 1. Annual nitrogen deposition and export in stream flow from subcatchments of the Caribou Poker Creeks Research Watersheds in interior Alaska for four years. Panel a shows the relative contributions of wet and dry fluxes for total deposition, and dissolved inorganic (DIN) and dissolved organic (DON) nitrogen in stream outflow. Panel b shows the range in estimates of total dissolved nitrogen (DIN+ DON) fluxes based on the uncertainty analysis. The center line, box extent, error bars, and diamonds denote the median, 25th and 75th, 10th and 90th, and 5th and 95th percentiles of estimates from the 10,000 model runs. See text for a description of the uncertainty analysis.

was lowest from the catchment with the greatest extent of permafrost (53%); nitrogen export in most years was not substantially different than deposition (Figure 1). In contrast, in the two low permafrost watersheds, nitrogen export was always greater than deposition. Of the nitrogen in transport, nitrate export significantly varied among watersheds and was lowest from the high permafrost watershed ($p = 0.006$) and was greatest from the medium permafrost catchment. The high nitrate export from the medium permafrost watershed is likely a consequence of larger area (double) and greater specific discharge (1982 m^3 ha^{-1} y^{-1}, compared with 1254 and 1441 m^3 ha^{-1} y^{-1} in the high and low permafrost catchments, respectively). In contrast to the pattern in nitrate, DON export did not significantly vary among watersheds averaging 0.37 kgN ha^{-1} y^{-1} ($p = 0.94$). From the uncertainty analysis, the coefficients of variation for TDN export estimates averaged 5.3% (range = 3.5–6.9%; Figure 1).

[14] At a broader spatial scale, watersheds in the zone of discontinuous permafrost appear to be losing nitrogen based on elevated nitrate and DON concentrations, and using TDN:Cl as an index of nitrogen retention, whereas more northerly catchments appear to be retaining or closer to steady state (Figure 2). The relationship between latitude and both nitrate and DON was better explained by Gaussian than linear models. Linear models explained 20% and 4% of the variance in nitrate and DON, respectively, whereas Gaussian models explained 65% and 41% of the variance (nitrate AIC = 315 for linear and 291 for Gaussian models; DON AIC = 304 for linear and 293 for Gaussian models). Moreover, streams draining watersheds in the southern boreal forest that lack permafrost [*Ford and Naiman*, 1989; *Bayley et al.*, 1992; *Cooke and Prepas*, 1998] and those in Arctic Alaska with continuous permafrost [*Peterson et al.*, 1992], have nitrate concentrations <50 μgN/L.

4. Discussion

[15] The disparity between nitrogen inputs via atmospheric deposition and export in stream flow is not unique to CPCRW, with similar findings reported for other watersheds in central and western Alaska [*Stottlemyer*, 1992, 1997, 2001]. In addition to an apparent loss of nitrogen, DON only accounted for 27–51% of TDN, in contrast to pristine temperate and arctic ecosystems where DON is the dominant form of nitrogen in stream flow [*Peterson et al.*, 1992; *Hedin et al.*, 1995]. A number of key features of regions with discontinuous permafrost could account for deviations from current conceptual models of watershed nitrogen cycling. Much of boreal Alaska has remained unglaciated for 0.1 to 1 my, and stores vast amounts of nitrogen in cold, organic soils [*Post et al.*, 1982, 1985]. The climate of high latitudes, including interior Alaska, is warming rapidly [*Serreze et al.*, 2000], and decreasing the extent of permafrost [*Osterkamp and Romanovsky*, 1999]. In CPCRW, over a third of the permafrost has become unstable, at least 2% of the permafrost was lost during 20th century, and the depth of seasonal soil thaw has increased [*Hinzman et al.*, 2005b]. This loss of permafrost may release stored nitrogen that is inaccessible to terrestrial plant uptake, resulting in high nitrification and leaching loss rates.

[16] High rates of nitrogen fixation, and poor retention of fixed nitrogen, could also contribute to the imbalances in watershed nitrogen budgets. Many moss species harbor epiphytic cyanobacteria [*DeLuca et al.*, 2002] and alder are common in the boreal forest of interior Alaska and appear to be expanding north in response to climatic warming [*Sturm et al.*, 2001]. Data are lacking to estimate fixation rate by alder in CPCRW but two points of evidence suggests that input from alder is not a major source of nitrogen. First, alder are sparsely distributed in CPCRW

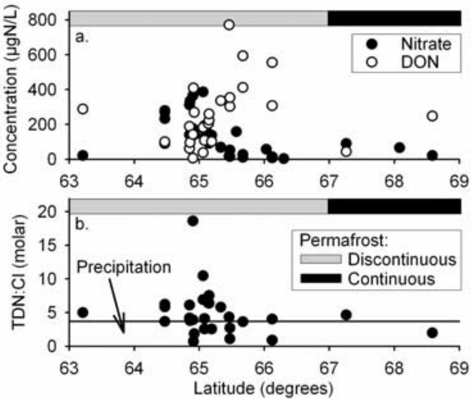

Figure 2. Stream water nitrate and dissolved organic nitrogen (DON) concentrations (panel a), and total dissolved nitrogen (TDN) to chloride ratios (panel b) along a latitudinal gradient spanning the distribution of discontinuous permafrost in interior Alaska. Bars along the top of each graph illustrate the approximate distribution of permafrost. TDN:Cl of precipitation (panel b) is from NADP data from Poker Creek station.

[*Jorgenson et al.*, 1986]. Second, alder are distributed throughout the boreal forest, yet streams at lower latitudes have low nitrogen concentration in stream water.

[17] Winter also likely plays an important role due to long periods of plant dormancy, evidence for significant microbial activity at low temperatures [*Fahnestock et al.*, 1998], and the importance of soil freezing to nitrogen dynamics [e.g., *Groffman et al.*, 2001]. Soluble nitrogen produced in uplands over winter may be lost in snowmelt, before it can be taken up by plants. Denitrifying bacteria and plant roots may also be more susceptible to freeze damage than nitrifying bacteria [*Groffman et al.*, 2001], and ammonium produced over winter may be more readily nitrified and lost to leaching. Interestingly, the concentration of nitrate in Arctic streams of Alaska is low [*Peterson et al.*, 1992], suggesting that winter dynamics are a minor source of nitrogen to streams at least in tundra ecosystems.

[18] Regardless of the source, a net export of nitrogen suggests an imbalance in nitrogen sources and sinks and that nitrogen storage in watersheds with discontinuous permafrost may be actively shifting. Terrestrial net primary production is nitrogen limited, so warming of boreal forests could stimulate plant growth and sequestration of nitrogen [*Shaver et al.*, 1992]. Alternatively, if mineralized nitrogen is not retained on land, substantial loading to aquatic ecosystems could occur. Because the boreal forest accounts for 80% of the landmass draining to the Arctic Ocean, such increases could significantly alter the productivity of marine ecosystems. These results may provide a useful model to facilitate prediction of evolution of boreal ecosystems in regions of discontinuous permafrost with a warming climate.

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