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A BIOGEOCHEMICAL SURVEY OF AN ARCTIC COASTAL WETLAND

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Abstract

The "Betty Pingo" wetland study site in Prudhoe Bay, Alaska has been extensively studied for five years. The work discussed here examines the biogeochemistry of the tundra ponds and the drained lake basin marsh which constitute the major surface features of this area. Meteorological and hydrological data were gathered, and dissolved inorganic ions were sampled regularly during the summers of 1993 and 1994. Major plant nutrients such as NH_4^+, NO_3^- and PO_4^{3-} were present in oligotrophic concentrations, usually <50 μg l^{-1}. The major source of these inorganic nutrients is atmospheric - material arriving dissolved in precipitation or on the wind as dryfall.

Introduction

The primary objective of this project was to investigate the biogeochemical status of the wetlands of the Alaskan Arctic Coastal Plain and continue the hydrologic studies of the wetland complex that had been initiated in 1992 (Rovansek, 1994). In conjunction with this work, a detailed examination of the chemical limnology of the tundra ponds that characterize the landscape of these wetlands was begun in order to determine the range and magnitude of ionic concentrations exhibited throughout the year.

There is a growing amount of detailed knowledge concerning high latitude wetland form and function (Hobbie, 1980; Kling et al., 1992; Rovansek, 1994), although the depth of information pales in comparison to what is known about temperate and tropical ecosystems. The information presented in this study builds on the work that has been compiled by previous arctic wetlands researchers, and seeks to expand the boundaries of what is known about the biogeochemical processes within the tundra ponds of the Alaskan Arctic Coastal Plain

Site description

The Betty Pingo study site is located on the West Operating Area of the Prudhoe Bay oil field on the Alaskan Arctic Coastal Plain, specifically centered at 70°26'N and 148°53'W (Figure 1). The Betty site is located 16 km south of the Beaufort Sea and 2.5 km east of the Kuparuk River. The site is situated on the edge of the drained basin of a large, ancient thaw lake, and is divided into an upper watershed ("uplands") and a lower marsh (as defined by Committee on Characterization of Wetlands, 1995) area down in the basin. This marsh is bounded on the West, South and East sides by a "scarp" of raised peat, where the tundra slumped down during the lake basin formation from melting ice lenses long ago. The "uplands" are drained by small ephemeral streams that cut through the scarp and run into the marsh.

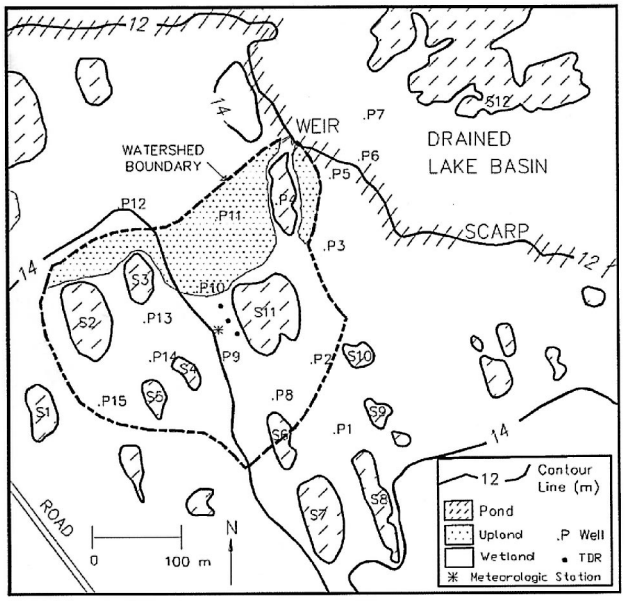

Figure 1. Detailed map of Betty Pingo study site with small 8.15 ha watershed delineated.

The total area of the study site, as delineated by Rovansek (1994), is ~22.4 ha, of which the portion above the S-12 marsh is ~12.4 ha. During the field season of 1994, this upper portion of the study site was further divided into an 8.15 hectare watershed (the area within the heavy dashed lines on Figure 1), which is the area of tundra that drains directly towards the weir during spring runoff. The remaining 4.25 ha of the upper portion of the study site was determined to primarily drain towards the marsh through a separate cut in the scarp south of the weir. The entire upper watershed area is dominated by a series of small to medium-sized thaw ponds (shown as S-2 through S-11 on Figure 1). These ponds can be from 1,000 to 5,000 m^2 in area, and range from 0.25 to 0.7 m in depth in early June. The sediment is largely unconsolidated peat particles, coated with a growth of benthic micro-algae and bacteria.

The tundra surrounding these ponds is marked by many typical coastal tundra landforms and surface features, such as long curving peat ridges up to 0.5 m in height called strangmoor ridges, ice wedge polygon ridges, ice wedge troughs, which can be as much as 1 m deep, as well as frost boils, marled, peaty mud-flat areas and some relatively unpatterned tundra.

Data collected in this study, and that of Haugen (1982), show that annual precipitation can be on average <50% snow during the long winter, with maximum snowfall during September and October, and ~50 - 65% as rain during the short summer months, with maximum rainfall during August. There is very limited active layer throughflow during the summer, due to extremely low hydraulic gradients and low hydraulic conductivity in the peat mat that comprises the tundra active layer at Prudhoe Bay (Rovansek, 1994). There was similarly no overland flow once the snowmelt runoff passed through the site in early to mid-June during the years of this study.

The average annual temperature at Prudhoe Bay is -11.4°C (NOAA 1986-1996), which has resulted in the formation of permafrost as much as 680 m thick (Osterkamp et al., 1985). The active layer has an average depth of between 30 and 100 cm, depending on aspect, wetness and soil type (Walker et al., 1980).

Winds during the summer are remarkably consistent from the North-East (Walker et al., 1980). This means that the air blowing across the site, with its inherent load of particulates, is arriving from across the width of the oil fields, and beyond that, the Sagavanirktok River delta and the Beaufort Sea. Consequently, much of the material deposited onto the site in rain, or as dryfall, consists of compounds from this area. Sea spray salts, minerals from the limestone areas along the Sagavanirktok River floodplain, road dust and oil production exhaust products all are introduced into these wetlands.

The vegetation of this site is typical of the Coastal Plain (Walker et al. 1980). Wetter areas are dominated by *Carex* and *Eriophorum* spp., with the deeper marsh areas being comprised primarily of *Arctophila* spp. Slightly greater relief provides for a drier tundra and the predominant ground cover of upland ridges are mosses and lichens, as well as sedges, prostrate willow shrubs and a limited variety of flowering herbaceous species. Plant species within the ponds themselves are primarily comprised of Chrysophytic and Cryptophytic nano-plankton (Alexander, 1980). There are also two species of the colonial macroalgae *Nostoc* present.

The tundra pond biotic communities are very limited in scope. Since all the ponds freeze solid each year, there can be no resident fish populations. Consequently, filter feeding zooplankton can grow large and dominate the water column, and large shoals of *Daphnia middendorffiana* are common. Other macrozooplankton include cyclopoid *Copepoda* spp. and the fairy shrimp *Polyartemiella* spp. and *Brachinecta* spp. There are numerous benthic dwellers including the larvae of various *Chironomidae* spp., *Lepidurus* tadpole shrimp, *Oligachaete* worms, snails of the *Physa* genus, *Plecoptera* stonefly larvae, *Trichoptera* caddisfly larvae, and lesser numbers of other classes of invertebrates.

Data collection and processing

Hydrological measurements began each May when extensive snow surveys were carried out on the site to determine the snowpack water equivalence. The ablation of the snowpack was measured through time as the melt proceeded. Measurements of the discharge from the wetland area were monitored throughout the thawing season. In addition, a weekly site survey was carried out during all years to measure changes in pond levels and groundwater levels through the season.

All ponds and one ice wedge trough were sampled for water temperature, electrical conductivity and pH, and four water samples were collected weekly through a 1μm filter from each sampling site. One sample was transported on ice to the University of Alaska Fairbanks (UAF) Toolik Lake research station within 15 h of collection to be analyzed for dissolved inorganic nutrients on an Alpkem auto-analyzer. One sample was acidified with Ultrex HNO_3 to pH 2, then shipped on ice to Fairbanks for metals analysis on a DCP atomic absorption spectrophotometer at the UAF Forest Soils laboratory. One sample was left untreated and sent on ice to Fairbanks for anion analysis on a Dionex ion chromatograph, also located at the Forest Soils laboratory. The final sample was hand titrated for alkalinity determination.

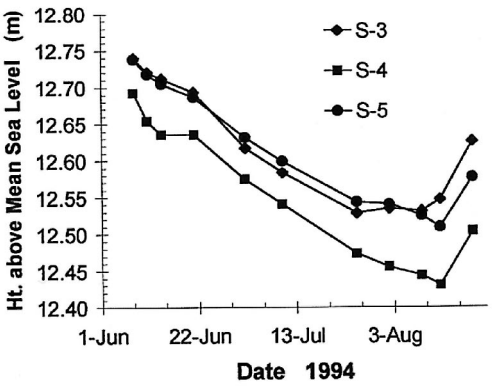

Figure 2. Typical pond water levels during the field season of 1994.

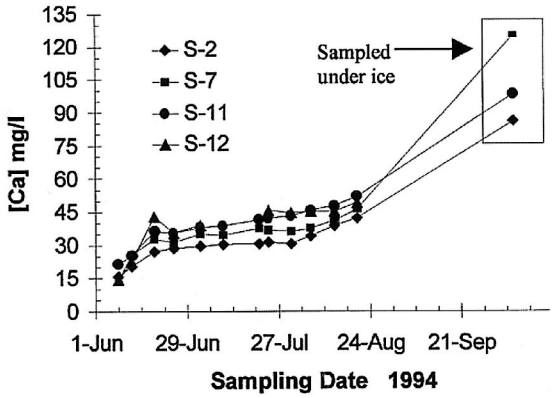

Figure 3. Calcium concentration in some larger wetland ponds during 1994.

Snow was sampled by means of snow pits that were cleaned by scraping with a plastic ruler, and then filling bottles from different depths within the snowpack. Rainfall was collected in a wetfall/dryfall collector, and then transferred to Nalgene bottles. All samples were treated in a manner similar to that described above.

Chemical limnology

Evaporative loss within the watershed was confirmed by the falling water levels of the ponds (Figure 2), and was also shown by the concentration of dissolved inorganic ions seen in water throughout the site as the summer season progresses (Figures 3 and 4). Samples that were collected in specific areas with a locally steeper hydraulic gradient, such as occurs near the ice wedge trough, show some ionic species increasing in concentration following rain events due to active layer transport of runoff from the surrounding tundra (note K^+ in Figure 4).

There was evidence for the translocation of dissolvable materials within the snowpack due to warming events during the early winter and in the spring. This process was especially pronounced during the initial days of snowmelt; the first runoff water from the melting snowpack in May was more concentrated in all ions

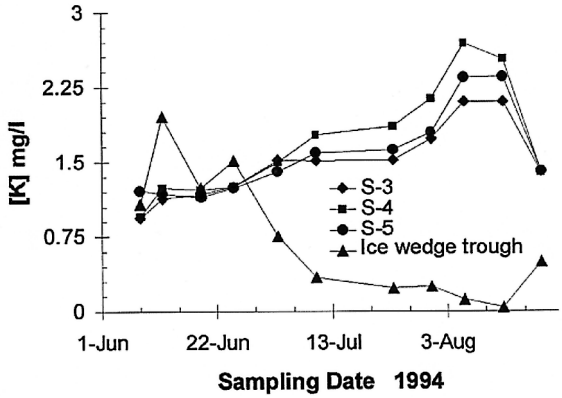

Figure 4. Potassium concentration in smaller ponds and ice wedge trough during 1994.

than the water that comes after the pack was largely ablated. The ion-rich initial flush of melt water refilled the ponds and increased their ionic concentration.

Within the pH range from 6.5 to 8.5 at this site, the predominant free species of carbon in the ponds was the bicarbonate ion (HCO_3^-), and this species was closely linked through the year with the concentration of calcium. The Ca^{2+} and HCO_3^- ions were the most abundant inorganic chemical species found in the ponds and their primary inorganic source was the Quaternary sediments of the Sagavanirktok formation (Walker et al., 1980). Much of this material had been disturbed and relocated in the period of industrial growth in Prudhoe Bay since the oil field development began in the 1970's, and the intense activity on the gravel roads and pads contributed substantially to increased ionic deposition.

The next level of abundance in the dissolved inorganic ions were those transported on the winds from salt spray off of the Beaufort Sea. These ions tended to be virtually unreactive biologically, and since they were easily dissolvable, the overall Na^+ / Cl^- ratio closely matches that of the sea throughout the year. Mg^{2+} was introduced in both wet and dryfall, and probably was also leached from the tundra in spring snowmelt flooding.

Potassium is an essential plant nutrient that is vital for root growth and function. The data showing only the ice wedge trough exhibiting a steep drop in K^+ concentrations (Figure 4) is understandable when one considers the surface area to volume comparisons between this ice wedge trough, and the true tundra ponds. It is much easier for the peripheral ring of plant growth around the trough to access the K^+ and deplete it, than it is in the much larger ponds, whose relatively spacious surface areas ensure they will not be totally depleted in K^+. However, this cation is always present in low concentrations wherever it is sampled.

Iron (Fe) was detectable, but present in dissolved form only and at micromolar concentrations in these tundra ponds. Manganese (Mn) was not consistently detectable, but when it was, it was always in concentrations at least an order of magnitude less than found for iron. Fe and Mn are, however, very important in the tundra wetland organophosphate buffering system (Prentki et al., 1980; Cornwell and Kipphut, 1992; Sugai and Kipphut, 1992).

The summation of major cations at the tundra trough sampling site on 20 August 1994 was equal to: 6.774 meq./l (Ca^{2+} = 5.05 meq./l, Na^{+} = 0.818 meq./l, and Mg^{2+} = 0.806 meq./l). The summation of major anions on that date was equal to: 6.458 meq./l (HCO_3^{-} = 5.168 meq./l, Cl^{-} = 1.279 meq./l, SO_4^{2-} = 0.011 meq/l). Other ions not measured account for the imbalance, but do not contribute enough to change this overall pattern.

Dissolved inorganic nutrients

Spring snowmelt is responsible for the movement of a large volume of water and the dissolved mass of readily mineralizable plant nutrients and other soluble ions (Hendershot et al., 1992). This represents the single biggest biogeochemical event of the year.

Of interest is the data indicating the amount of nutrient mass lost with the discharge flowing through the Betty weir and down into the S-12 marsh complex as runoff. The total estimated average nutrient mass in the snowpack on the 8.15 ha of the Betty watershed prior to the onset of spring melt in 1994 was: 39.27 moles (0.56 kg) of N as NO_3^{-} , 12.61 moles (0.18 kg) of N as NH_4^{+} , and 1.03 moles (0.03 kg) of P as PO_4^{3-} . This material was contained in ~ 5.95×10^6 l of snowpack water equivalence. Approximately 50% of this water (3×10^6 l) was lost from the upper basin through the weir following snowmelt, and it is estimated that between 40 - 50% of the mass of the dissolved inorganic nutrient species were likewise lost into the lower Betty basin. This means that the remainder of the average nutrient load in the 1994 snowpack water equivalence was distributed to the polygon troughs, ponds and tundra of the upper watershed as an essential replenishment of both nutrients and water as the growing season began.

It is very interesting to find that as the year advanced, the mean nutrient concentration in the ponds were relatively constant through a small range (Figures 5 and 6). This fact, when considered in the light of the decreasing pond levels through evaporative losses, indicates that

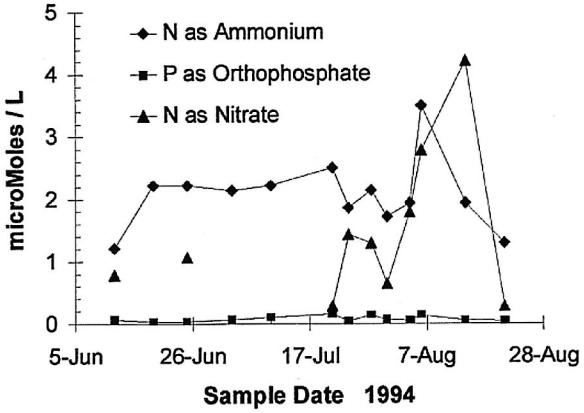

Figure 5. Dissolved inorganic nutrients in pond S-2 during 1994.

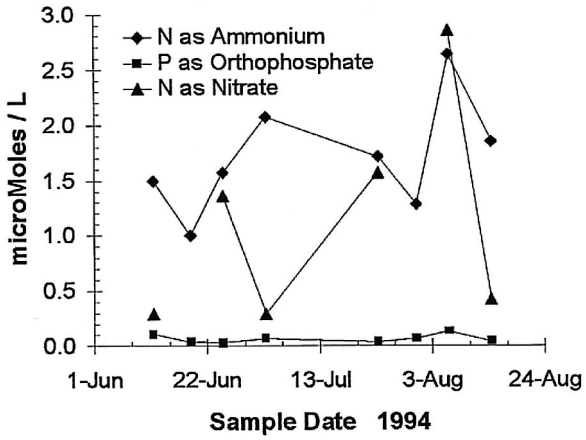

Figure 6. Dissolved inorganic nutrients in marsh S-12 during 1994.

the overall mass of nutrients within the ponds was being transformed from inorganic forms to organic complexes and biotic tissue. This transformative capacity of turning inorganic material into organic forms is one of the most important wetland functions (Mitsch and Gosselink, 1993).

What is most clear in these plots, is the extremely conservative nature of the orthophosphate concentrations in the troughs, ponds and marshes of the Betty site (Figures 5 and 6). At all sites sampled, the typical strength of PO_4^{3-} concentration was only variable through a small range of values during the growing season, between 0.05 to 0.8 μmol/l. The nature of this tight control on the Soluble Reactive Phosphorus (SRP) dynamics within these ponds is certainly very similar to the organo-complexing of any reactive PO_4^{3-} with Fe or Mn enriched sediments. This process has been described in detail for Toolik Lake (Cornwell, 1987; Cornwell and Kipphut, 1992; Sugai and Kipphut, 1992) and for the tundra thaw ponds at Barrow (Prentki et al., 1980).

Dissolved Inorganic Nitrogen (DIN) concentrations are generally more variable than the SRP levels

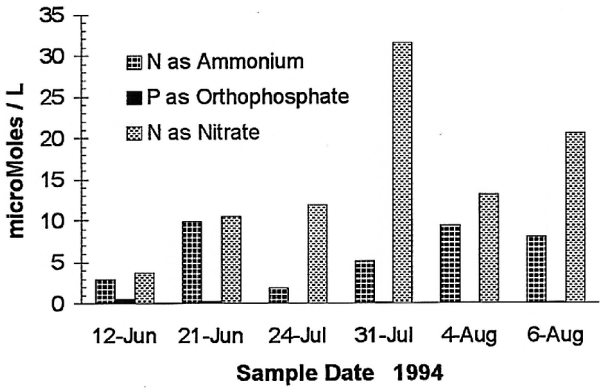

Figure 7. Dissolved inorganic nutrients in the Betty Pingo rainfall during 1994.

throughout the year, but still are limited between a tight oligotrophic range of values. The concentration of nitrogen as NH_4^+ can range from 0.4 to 3.5 (mol/l during the open water season, and appears to be a more consistent source of nitrogen for the bulk of the biotic community of these ponds, both pelagic and benthic. Nitrogen as NO_3^- on the other hand, can vary between not detectable (low limit averaging <0 .11 (mol/l), to 0.66 (mol/l, and appears to be more subject to rapid depletion from algal growth, as well as showing rapid elevations in conjunction with inputs from wetfall/dryfall (Figure 7).

Conclusions

The results presented here are descriptive of an oligotrophic system that is inextricably a part of the overall arctic coastal cycle of seasonal hydrology and energy balance. The hydrology of this area is characterized by low precipitation and a negative summer water balance. Much of the snow that falls during the winter months is destined to replenish the storage lost from the ponds and marshes of the area during the previous year's growing season. Surface drainage of runoff occurs for a short period of time following snowmelt, but after this initial flush has passed through the area, there is no surface movement, and only very minor subsurface flow of water at this site. The magnitude of evaporative losses can completely dry up some of the smaller, shallower ponds during the summer, and all ponds experience a stage drop of between 150 and 400 mm of water. August brings increasing rain which recharges the ponds to some degree, but during the course of this study they did not reach their spring bankfull levels by the onset of the winter freeze.

Inorganic ions are introduced in precipitation and on the wind as dryfall, and there is probably some release from the sediments as well, as the season progresses and the depth of thaw under the ponds increases. Biologically inactive ion species are concentrated in the ponds during the summer, and in general, pH and electrical conductivity rise as the season progresses.

Inorganic nutrient species are present in the ponds in oligotrophic concentrations, and in general, the mass of dissolved forms of NH_4^+ , NO_3^- , and PO_4^{3-} are being depleted throughout the year as these materials are incorporated into autotrophic tissue, and then passed up the food chain to higher level consumers. Orthophosphate concentrations are strongly buffered in the ponds, and the concentration of phosphorus as PO_4^{3-} is very consistent, albeit low throughout the growing season. The oligotrophic condition these ponds show with respect to phosphorus is the primary limitation, other than the short growing season, that the aquatic organisms of these wetland ponds must accommodate each year.

Acknowledgments

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