The Impact of Sediments Derived from Thawing Permafrost on Tundra Lake Water Chemistry: An Experimental Approach

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Abstract

Retrogressive thaw slumping can transport ion-rich meltwater and thawing sediment from terrestrial to aquatic systems. Tundra lakes affected by shoreline slumping have elevated ionic concentrations, low dissolved organic matter concentrations, and colour compared to unaffected lakes. To investigate the potential photochemical implications, an in situ microcosm experiment was performed involving the incubation of water from an undisturbed lake with thawed slump sediment. Sediment treatments were 10, 25, and 50% of the total container volume, and containers were incubated in the lake for 52 days during the summer of 2007. Water colour decreased successively with sediment volume, and was highest in the control. Specific conductivity was more than 8 times higher in the 50% sediment treatment water than in the control. Sedimentation of organic matter may explain the low colour in the treatment water. The transportation of thawing permafrost sediment into tundra lakes may rapidly increase water clarity and alter carbon supply.

Keywords: climate change; coloured dissolved organic matter; Mackenzie Delta region; microcosm experiment; retrogressive thaw slumping; tundra lakes.

Introduction

In the uplands east of the Mackenzie Delta, NWT, Canada, thousands of small lakes and ponds are surrounded by terrain underlain by ice-rich permafrost (Mackay 1992, Kokelj et al. 2005). In this region, thawing of the near-surface permafrost commonly leads to the formation of large retrogressive slumps on slopes adjacent to lake shores (Lantz & Kokelj 2008). Solute concentrations in permafrost may be enriched with respect to the overlying active layer (Kokelj & Burn 2003, 2005). The geochemical contrast between the active layer and permafrost is attributed to progressive leaching of soluble materials from seasonally thawed soils and preservation of solutes in underlying frozen sediments, and due to thermally induced migration of water and soluble materials from the base of the active layer into the top of permafrost (Kokelj & Burn 2005). Thaw slumping may release these solutes in the permafrost, with implications for sediment and runoff chemistry (Kokelj & Lewkowicz 1999).

A survey of 298 lakes on five 49 km^2 study plots between Inuvik and the Beaufort Sea indicated that 6 to 17% of the lakes were affected by shoreline slumping (Kokelj et al. 2005). Thaw slumps can be relatively large compared to the size of adjacent lakes. In a sample of 11 first-order upland lakes affected by slumping in the Delta region, the median disturbance area: lake area ratio was 0.48 (Kokelj et al. 2005). The median disturbance size was 1.9 ha, and the median lake size was 4.0 ha. In many cases, disturbance area was almost equivalent to lake area.

Lake chemistry interactions

The water chemistry of small tundra lakes is strongly influenced by lake catchment characteristics, including surficial geology, sediment development, peatland extent, and terrestrial vegetation (Pienitz et al. 1997, Duff et al. 1999, Frey & Smith 2005, Gregory-Eaves et al. 2000, Rühland et al. 2003). In the Mackenzie Delta region, a survey of 22 lakes indicated that those adjacent to retrogressive thaw slumps had elevated ionic concentrations, lower concentrations of dissolved organic carbon (DOC), and were less coloured compared to lake waters in undisturbed areas (Kokelj et al. 2005). Organic carbon supply and related changes in visible and UV light penetration influence the productivity of pelagic algal and bacterial communities (Jones 1992, Teichreb 1999).

Base cations can increase the adsorption and flocculation of coloured dissolved organic matter (CDOM), or humic matter, from the water column (reviewed in Jones 1992, Thomas 1997). Mineral soils, especially clays, that may enter lakes can adsorb humic matter leading to sedimentation (reviewed in Jones 1992, Thomas 1997). This raises the possibility

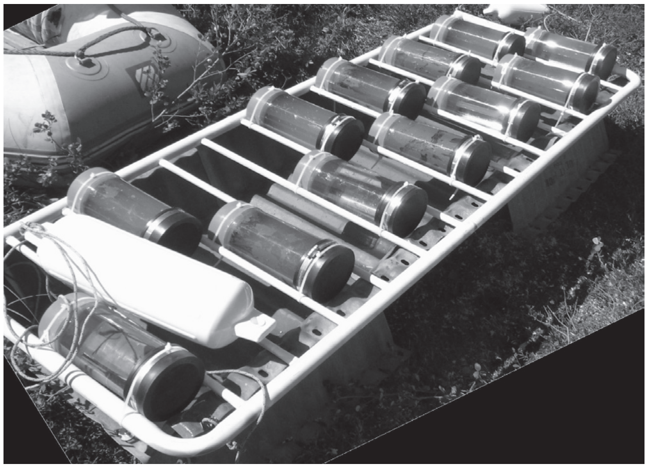

Figure 1. Experimental incubation containers positioned on rack prior to deployment in the lake.

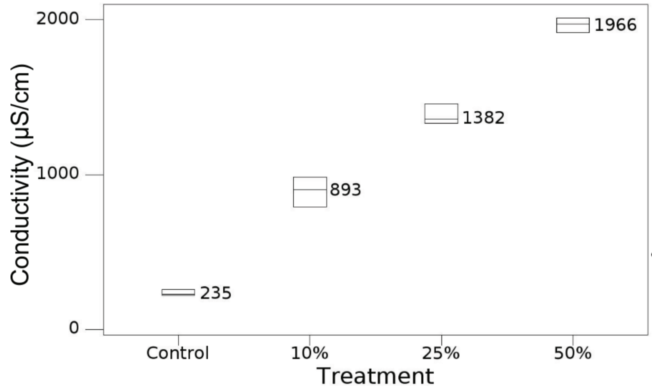

Figure 2. Mean specific conductivity of the incubated lake water in each of the permafrost sediment treatment and control containers (with 95% confidence intervals, mean value provided).

that sediment and soluble ions delivered from terrestrial to aquatic systems by the process of thaw slumping may affect CDOM concentrations and optical properties of water in small tundra lakes.

Here we examine the effects of ion and sediment additions on the colour of lake water by undertaking an incubation experiment. The goal was to test whether exposure of humic lake water to thawed permafrost sediment and associated runoff could produce similar water chemistry conditions characteristic of a "disturbed" lake affected by lake shore thaw slumping.

Methods

Incubation experiment

Recently-thawed sediments and pooled surface runoff were collected on 24 June 2007 from a thaw slump scar located on the shore of a small lake 60 km north of Inuvik. The sediments, comprised of silty clay, were homogenized by mixing with surface water collected from the slump (specific conductivity 2345 µS/cm) to form a saturated slurry. The gravimetric water content of the runoff-sediment mixture was 33% by weight.

The sediment mixture was added to containers constructed from sections of clear acrylic pipe (approximately 10 cm diameter) with a total volume of 2 L. The pipe sections were sealed on one end with a silicone-sealed cap and on the other with a removable rubber "test cap". A spectral scan of the acrylic pipe material indicated that it blocked most UV-B (absorbance at 320 nm = 1.027) and much of the UV-A (absorbance at 380 nm = 0.096) wavelength range. This desirable property of the pipe materials minimized the breakdown of coloured humic substances in lake water by incoming UV radiation (photolysis). The proportion of saturated sediment in each of three replicated container sets was 50, 25 and 10% of the container volume (1.0, 0.5, and 0.2 L respectively).

The incubation containers were installed in a shallow (estimated Z_{max}: 2 m), humic lake within 15 minutes road access of Inuvik, which is unaffected by thaw slumping. Before installation, surface lake water from the same incubation lake site was collected and added to each of these containers, along with a set of replicate control containers, to a total volume of 2 L. The sediment slurry in each container was purposefully not mixed homogeneously with the lake water, since slump materials often enter the lakes as intact blocks. The containers were sealed immediately after the lake water addition, and were attached to a rack apparatus which kept the containers horizontally aligned, approximately 0.75 m below the water surface and elevated approximately 0.75 m above the lake benthos (Fig 1). The containers were installed on 6 July 2007 and were retrieved on 28 August 2007 for a total incubation period of 52 days.

An additional container was filled with distilled and deionized water in order to test the water-tightness of the container seals. Initial specific conductivity of the distilled water was 2 µS/cm; —after incubation it was 20 µS/cm. Specific conductivity in the lake was 219 µS/cm just prior to deployment of the incubation containers.

Analysis

Following retrieval, the containers were removed from the support rack, immediately transported and refrigerated at the Aurora Research Institute lab. Within 3 hours of arrival at the lab, the incubated water was removed from the containers without disturbing the sediment settled at the bottom of each container. Specific conductivity, pH, dissolved oxygen (DO) and oxidation-reduction potential (ORP) of the water was measured using a YSI 556 multiprobe meter (Yellow Springs Instruments, Idaho, USA).

In preparation for measurement of water colour as spectral absorbance, a 125 ml volume of the incubated water was filtered through a 0.45 µm Supor membrane syringe filter (Pall Corporation, NY, USA). Samples were placed in glass containers and kept in a dark refrigerated area until absorbance could be measured. Absorbance was measured across the range 190–900 nm using an Ultrospec 3100 pro spectrophotometer equipped with a 1 cm cuvette (Biochrom, Cambridge, UK). Absorbance measurements at 320 nm (UV-B), 380 nm (UV-A) and 440 nm (PAR, photosynthetically active radiation) were corrected for

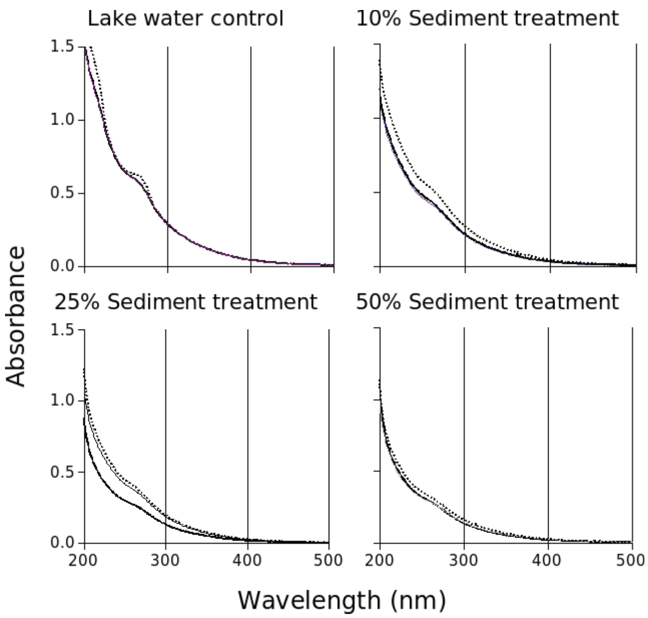

Figure 3. Replicate spectral scans of incubated lake water from the control and each sediment treatment container. For each treatment graph, $n = 3$.

Table 1. Relative decrease in mean spectral absorbance at representative wavelengths of lake water after incubation with thaw slump sediment. Change is relative to the untreated control mean. *PAR* is photosynthetically active radiation. *aX* is absorbance at wavelength X.

Sediment treatment	UV-B (a320)	UV-A (a380)	PAR (a440)
50%	49%	43%	27%
25%	43%	44%	44%
10%	20%	22%	13%

turbidity-related light scattering by subtracting absorbance values at 740 nm. These corrected values were used in statistical analyses.

A one-way analysis of variance (ANOVA) was used to assess the response of the lake water specific conductivity to the sediment treatments. The effect of the sediment treatments on the spectral absorbance of the incubated lake water was tested using a repeated measures ANOVA, including absorbance values at wavelengths in the UV-B (320 nm), UV-A (380 nm) and photosynthetically active radiation (PAR, 440 nm) ranges. Post hoc Tukey tests were used to distinguish between significantly different treatment level. Finally, conductivity and all absorbance measurements were tested for significant Pearson correlations across treatments, with Bonferroni adjusted significance levels. All analyses were completed using SPSS 13.0 (SPSS Inc., Illinois, USA).

Results

Specific conductivity

The measured specific conductivity of the incubated lake water in each of the treatment and control containers are shown in Figure 2. The water at each sediment treatment level and in the control had significantly different mean specific conductivity, with relatively little variation within treatments (one-way ANOVA, $F = 396.23$, $df = 3$, $p < 0.000$). The control and treatment mean specific conductivities were all significantly different from each other (Tukey HSD test).

Water colour

The spectral scan absorbance values for each treatment replicate are shown in Figure 3. Absorbance is generally higher in the control than in all sediment treatments. The greatest difference in the absorbance values between the control and all sediment treatments is apparent in the UV-B and UV-A range (280–320 nm and 320–400 nm, respectively). Differences between the control and treatments in the photosynthetically active radiation range (PAR, 400–700 nm) were lower than observed for the UV range. Relative change in absorbance between the control and treatments for representative wavelengths are provided in Table 1. The change in absorbance across wavelengths in the 25% sediment treatment is somewhat obscured by one low-absorbance replicate (Fig. 3).

There was a highly significant effect of sediment treatment on corrected absorbance at all three representative wavelengths (UV-B, UV-A, PAR) (repeated measures ANOVA, $F = 15.156$, $df = 3$, $p = 0.001$). Error variance between treatments for the 320 nm measurements was not homogeneous and could not be remedied via transformation however, and this must be considered when interpreting the ANOVA results. Post hoc tests found no significant difference ($p > 0.05$) between the control, the 10% and 25% sediment treatment, but did indicate a significant difference between the control and 50% treatment (Tukey's HSD test).

Negative correlations (Pearson's r) between incubated lake water specific conductivity and absorbance values in the UV and PAR range were statistically significant with the exception of the correlation with PAR (corrected $p > 0.05$). The highest correlation occurred with UV-B absorbance ($r = -0.91$), followed by UV-A ($r = -0.85$) and PAR ($r = -0.64$). Absorbance was strongly positively correlated between the three wavelengths ($r > 0.85$).

Discussion

In the Mackenzie Delta uplands, lakes affected by shoreline thaw slumping contain elevated concentrations of major ions in contrast with lower concentrations in undisturbed lakes (Kokelj et al. 2005). The soluble materials that enrich the lakes are derived from the thawing ion-rich permafrost (Kokelj & Burn 2005). The effect of sediment slurry treatments had a similar effect on lake water specific conductivity in this experiment, as soluble ions were released into solution from the solute-rich slump sediment mixture.

In the natural setting, lakes affected by slumping have clear water in comparison with more coloured water in undisturbed lakes. The experimental response of lake water colour to the sediment treatments suggests that sediment slurry treatments caused the removal of coloured organic materials from the lake water. This is indicated by the lower spectral absorbance in sediment-incubated lake water compared to the lake water control. High-molecular weight CDOM absorbs UV radiation very effectively (Scully & Lean 1994, Laurion et al. 1997), and the relatively high change in absorbance in the 50% and 10% sediment treatments at the UV-B and UV-A wavelengths compared to the PAR wavelength suggests that it is this type of DOM which has been removed from solution in the incubated water.

The within-treatment variability between replicates was relatively large in the 25% and the 10% sediment treatments. This contributed to the heteroscedasticity in the 320 nm absorbance range and the nonsignificant Tukey test between these treatments. Presence of a slight biofilm on a few of the containers walls, variation in sediment-water interface surface area, and variations in possible photolysis rates may contribute to observed within-treatment differences.

Allochtonous (origin outside the lake, terrestrial) DOM content in lake water is linked to catchment conditions, especially the supply (related to catchment vegetation) and the delivery (related to catchment morphology) of carbon (Rasmussen et al. 1989, Pienitz et al. 1997). Subarctic lakes with catchments underlain by permafrost are typically high in DOM because waters are derived from surface runoff through a thin, often organic-rich active layer (Pienitz et al. 1997). Allochtonous DOM usually has a higher molecular weight and is more highly coloured than autochtonous (origin inside the lake) DOM (Lean 1998, Perdue 1998). Catchment-derived carbon is also generally more reactive with metals and base cations due to its more aromatic structure (Perdue 1998). Adsorption of this humic material to fine-grained clay particles readily occurs. Each of these processes can lead to dissolution and sedimentation of the allochtonous DOM. Field observations in conjunction with our experimental results indicate that degradation of permafrost within the catchment can influence the biological and geochemical availability of DOM within lakes (Kokelj et al. 2005).

Organic matter delivered from the lake catchment may be an important source of energy within the lake. For example, bacteria are known to utilize allochtonous sources of carbon as an energy supply (Jones 1992). DOM may also contain phosphorous, often a limiting nutrient for algal and bacterial production (Jones et al. 1988, Klug 2005). Indeed, uptake of DOM by algae and/or bacteria in the experimental containers used here may have contributed to the observed decrease in absorbance, especially if the slump sediment enhanced biological production by providing limiting nutrients (Hobbie et al. 1999). However, the habitat conditions within the incubation containers were likely not representative of *in situ* conditions, so that conclusions concerning biological activity cannot be made here. In addition to the role of DOM as an energy and nutrient source, allochtonous humic material is generally coloured, and capable of attenuating radiation within the water column. This can limit phytoplankton photosynthesis (Jones 1992, Klug 2002), but can also limit the penetration of damaging UV radiation through the water column (Laurion et al. 1997, Lean 1998).

Humic materials in lakes, therefore, can be involved in many interactions between planktonic biota through their effects on nutrient and light quality and supply. The fact that several of these interactions may be competitive or mutually beneficial, makes the ecological outcome of changes in tundra lake conductivity and DOM concentration difficult to predict. However, such shifts have been linked to the overall heterotrophic or autotrophic nature of lakes in northern/cold regions (Jansson et al. 2000). Certainly a reduction in humic matter content due to addition of ion-rich runoff and sediments derived from slumping permafrost appears to be capable of changing the physical and chemical conditions in the pelagic habitat of tundra lakes.

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