Seasonal ice and hydrologic controls on dissolved organic carbon and nitrogen concentrations in a boreal-rich fen

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[1] Boreal wetland carbon cycling is vulnerable to climate change in part because hydrology and the extent of frozen ground have strong influences on plant and microbial functions. We examined the response of dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) across an experimental manipulation of water table position (both raised and lowered water table treatments) in a boreal-rich fen in interior Alaska. DOC and TDN responses to water table manipulation exhibited an interaction with seasonal ice dynamics. We observed consistently higher DOC and TDN concentrations in the lowered water table treatment (71.7 ± 6.5 and 3.0 ± 0.3 mg^{-L}) than in both the control (55.6 ± 5.1 and 2.3 ± 0.2 mg^{-L}) and raised (49.1 ± 4.3 and 1.9 ± 0.1 mg L^{-1}, respectively) water table treatments. Across all plots, pore water DOC concentrations at 20 cm increased as the depth to water table increased (R^2 = 0.43, $p < 0.001$). DOC concentrations also increased as the seasonal thaw depth increased, with solutes increasing most rapidly in the drained plot (R^2 = 0.62, $p < 0.001$). About half of the TDN pool was composed of dissolved organic N (DON). Inorganic N and DON were both highly correlated with changes in DOC, and their respective constraints to mineralization are discussed. These results demonstrate that a declining water table position and dryer conditions affect thaw depth and peat temperatures, and interactions among these ecosystem properties will likely increase DOC and TDN loading and potential for export in these systems.

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1. Introduction

[2] Arctic and boreal soils serve as an important reservoir for terrestrial carbon (C), likely containing about half (1672 Pg C) of the world's soil C [*Tarnocai et al.*, 2009]. The majority of soil C at high latitudes is found in wetlands, particularly peatlands, which accumulate deep organic soil layers due to anoxic conditions [*Gorham*, 1991; *Clymo et al.*, 1998; *Bridgham et al.*, 2006]. The formation and maintenance of boreal wetlands is influenced by relatively low rates of evaporation and the presence of perennially (i.e., permafrost) and seasonally frozen ground, which impedes drainage and also reduces organic matter decomposition [*Dingman and Koutz*, 1974; *Roulet and Woo*, 1986; *Ford and Bedford*, 1987]. Therefore, the fate of boreal wetland C stocks depends in part on the response of seasonal ice to changing climate regimes, and its interactive effect on water table position [*Turetsky et al.*, 2007; *Tarnocai*, 2009].

[3] Alaska's arctic and boreal regions are experiencing substantial changes in climate that have caused longer, drier growing seasons [*Keyser et al.*, 2000; *Serreze et al.*, 2000; *Goetz et al.*, 2005; *Euskirchen et al.*, 2006], and degradation of permafrost [*Osterkamp and Romanovsky*, 1999; *Hinzman et al.*, 2005]. While wetland ecosystems dominate the landscape of Alaska [*Ford and Bedford*, 1987], with peatlands spanning over 4.2 × 10^7 ha [*Bridgham et al.*, 2006], continued changes in climate are likely to alter the distribution and functioning of these systems. Recently, water bodies in some wetland regions in arctic Alaska are drying [*Yoshikawa and Hinzman*, 2003], while other regions are becoming wetter. For example, expansion of open water in the Tanana Flats region is occurring due to hydrologic upwelling with increased meltwater from the Alaska Range [*Osterkamp et al.*, 2000]. In other regions of Alaska, remote

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sensing analyses indicate a significant loss of open water over the past 50 years [*Riordan et al.*, 2006], sometimes accompanied by the encroachment of drier terrestrial systems.

[4] Changes in boreal wetland moisture status are likely to influence not only the accumulation of C in peat and soil, but also the production, transformation, and lateral transport of dissolved organic C (DOC), total dissolved nitrogen (TDN), and other solutes to aquatic ecosystems [*Kane et al.*, 1992; *Moore et al.*, 1998; *Strack et al.*, 2008]. Lower water table position and/or thicker active layers due to warmer and drier climatic conditions generally promote aerobic decomposition and increased DOC production in organic soils [*Qualls et al.*, 1991; *Oechel et al.*, 1993; *Christensen et al.*, 1998; *Turetsky et al.*, 2000; *Freeman et al.*, 2001; *Strack et al.*, 2008]. Warmer temperatures occurring with the thawing of frozen ground stimulates microbial activity, also potentially increasing DOC production [*Moore et al.*, 1998]. Though future global warming will influence thermal and moisture regimes in high-latitude wetlands, the net effect on DOC concentrations is not clear because the production and transport of DOC may be affected in opposing directions [e.g., *Ball et al.*, 2010]. For example, drying and increased peat aeration increase decomposition processes, but water and hydrologic connectivity are needed for DOC export [*Moore et al.*, 1998; *Pastor et al.*, 2003; *Worrall and Burt*, 2008]. Moreover, disentangling production/consumption relationships for DOC can be complicated because DOC is both produced by microbes [*McKnight et al.*, 1985; *Bourbonniere*, 1989; *Neff and Hooper*, 2002] but also serves as a highly labile substrate for microbial activity [*Qualls and Haines*, 1992; *Michaelson et al.*, 1998; *Wickland et al.*, 2007; *Balcarczyk et al.*, 2009].

[5] While mesocosm experiments in controlled conditions have suggested that warmer, drier conditions are likely to increase DOC generation in peatlands [*Judd and Kling*, 2002; *Blodau et al.*, 2004], direct measures of how such climate perturbations are likely to affect DOC and TDN in boreal peatlands are rare in situ [cf. *Knorr et al.*, 2009]. *Strack et al.* [2008] found increases in pore water [DOC] following 11 years of water table drawdown (induced by trenching) in a poor fen complex in eastern Canada. The increase in [DOC] was attributed to leachates associated with vegetation community changes, increased net primary production, and also increased variability in aerobic conditions. A similar increase in pore water [DOC] was observed after 20 years of water table drawdown in a German peatland, with the sustained increase attributed to increased decomposition rates in aerated histic soil [*Höll et al.*, 2009]. Warmer temperatures and the degradation of ice have been nominated as principle mechanisms for increased DOC export from Siberian peatlands, as measured by increased [DOC] in streams draining watersheds with more extensive peatland coverage [*Frey and Smith*, 2005]. DOC and TDN concentrations in the Yukon River basin, which drains ~8.5×10^7 ha dominated by mineral wetland and peatland complexes across the interior region of Alaska, are also principally derived from terrestrial sources [*Guo and Macdonald*, 2006; *Spencer et al.*, 2008]. Recent studies have documented changes in interior and arctic Alaskan river hydrology [*Hinzman et al.*, 2005; *McClelland et al.*, 2007] and C and N concentrations [*Striegl et al.*, 2005; *Dornblaser and Striegl*, 2007] in response to warmer temperatures and changes in seasonal ice dynamics. However, direct study of the biological and biogeochemical processes in peatlands that determine the solute loads available for export into these stream networks in interior Alaska has received relatively little attention [*Wickland et al.*, 2007; *Myers-Smith et al.*, 2008; *Wyatt et al.*, 2010].

[6] In this study, we created two experimental water table position treatments in a moderately rich fen by facilitating drainage with trenches (lowered treatment) and by active pumping of water (raised treatment) for four field seasons [*Turetsky et al.*, 2008]. We monitored changes in water table and seasonal ice depth, as well as DOC, TDN, and a suite of anions and cations, in peat pore water in the third and fourth years of this study. Previous studies at this site have demonstrated the efficacy of the water table treatments in altering peat biophysical properties. For example, the increase in methanogenesis observed at the raised water table treatment likely reflected a decline in dissolved oxygen in peat pore water, owing to saturated conditions [*Turetsky et al.*, 2008]. Moreover, plant C uptake declined while peat CO_2 efflux remained unchanged in the drained treatment, which likely reflected an increase in heterotrophic activity relative to the raised treatment [*Chivers et al.*, 2009]. In both studies, there were strong interactive effects of temperature and water table position on peat mineralization processes. Based on these previous findings, we hypothesized that there would be greater accumulation of the water-soluble products of decomposition in the lowered water table treatment than in the raised water table treatment. Since the depth to seasonal ice not only influences water table position but also the temperature of the overlying peat layers, we expected strong interactive effects between ice depth and water table position in mediating DOC production, with the highest DOC concentrations cooccurring with the greatest extent of aerobic peat and depth to seasonal ice. We hypothesized that dissolved inorganic N (DIN) concentrations would increase in step with DOC (being higher in the lowered experimental treatment), as aerobic N and C mineralization processes exhibit similar requirements. Alternatively, anaerobic conditions can retard the mineralization of DON but can also stimulate denitrification, thereby reducing NO_3^- concentrations. In this study, we explore how the interaction between seasonal ice and water table position explains variation in DOC, TDN, and DIN, and also discuss the likely consequences for C and N mineralization.

2. Methods

2.1. Study Region and Experimental Design

[7] The APEX (Alaska Peatland Experiment) is located just outside the Bonanza Creek Experimental Forest, approximately 35 km southeast of Fairbanks, in the interior region of Alaska, USA (www.lter.uaf.edu). Central Alaska has a continental climate characterized by low levels of precipitation (~285 mm yr^{-1}), low humidity, and large annual temperature ranges (mean daily temperature of −24°C in January and 17°C in July) [*Slaughter and Viereck*, 1986]. The rich fen study site is located within a narrow alluvial plain <2 km north of the Tanana River, in the Middle Tanana Valley region. The Tanana River is adjoined

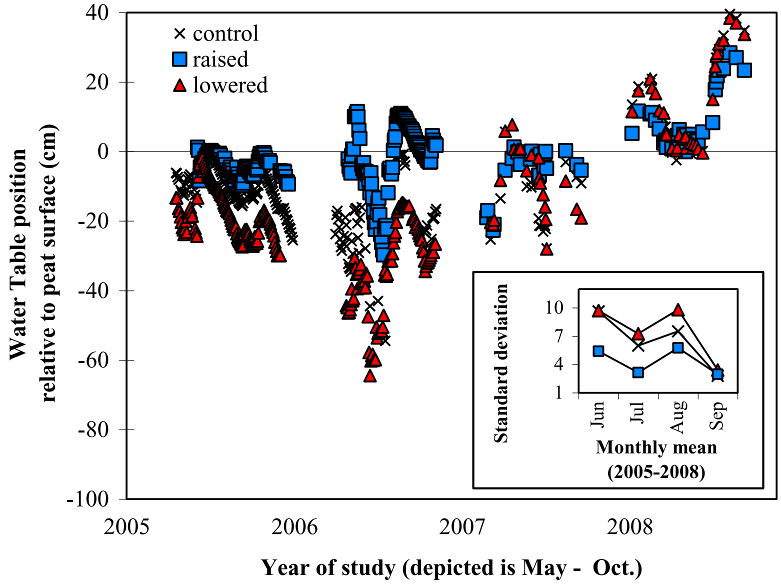

Figure 1. Seasonal trends in water table heights across the three manipulation treatments in interior Alaska (negative values indicate water table position below the surface of the peat). Inset shows standard deviation in mean monthly water table position across the 4 years of study (total of 1895 individual water table measurements).

by a low plain 8–40 km wide that is marked by many oxbow wetlands [e.g., *Hopkins et al.*, 1955]. This site lacks trees and is dominated by brown moss, *Sphagnum*, and emergent vascular genera (*Equisetum, Carex*, and *Potentilla*). There is little microtopography at the rich fen, which has accumulated peat to a depth of approximately 1–1.5 m across all plots. Based on cores obtained from the site in winter, the loess and mixed alluvial mineral soil underlying the peat remains unfrozen all year, and therefore the extent of seasonally frozen ground is limited to the top 1 m of peat.

[8] During early spring of 2005, we established three plots (approximately 20 × 20 m) and assigned each to one of three water table treatments (raised, lowered, and a control reference plot, each approximately 25 m apart), as previously described [*Turetsky et al.*, 2008; *Chivers et al.*, 2009]. While soils were still frozen, an excavator and chainsaws were used to dig channels facilitating water drainage from the lowered water table plot to a small holding trench downslope from the plot. Throughout the growing seasons of 2005–2008, solar powered bilge pumps were installed to move water into the raised water table treatment from a surface well located about 20 m downslope of the treatment. Water was added to the raised water table treatment at a rate of approximately 10 cm d^{-1}. The chemistry of water additions was similar to ambient pore water in the control water table treatment, with no significant differences in pH, electrical conductivity, DOC, TDN, or aromaticity [*Turetsky et al.*, 2008]. Lateral groundwater flow between the plots in this study was negligible, owing to the near zero hydraulic gradient across the study sites and the slow hydraulic conductivity of deeper peat (Ksat of ~10^{-6} cm s^{-1}) [*Macheel*, 2010]. The goal of the experiment was to maintain lowered (drained) and raised water table positions relative to the control without minimizing the considerable seasonal variability in water table position at this site. A Campbell Scientific data logger communication system (Logan, Utah) facilitated the maintenance of natural fluctuations in water table levels in the experimental treatments, relative to the control plot conditions (Figure 1).

[9] Our water table treatment was not replicated and thus location is confounded with water table plot. However, our baseline data suggested no differences in water table position, vegetation structure, or gas fluxes among water table plots prior to the manipulations [*Chivers et al.*, 2009]. Thus, although some caution is warranted due to the lack of true replicates, we believe that differences in our data are most parsimoniously interpreted as differences in experimental water table treatment.

[10] While our goal was to alter mean growing season water table position across the experimental treatments, the considerable seasonal variation in water table height that is typical for this ecosystem continued to occur across all plots (Figure 1). Our study period also captured large interannual variation. In particular, the end of the summer in 2008 was one of the wettest on record, with over 275 mm of precipitation falling throughout interior Alaska between the months of May and October (National Atmospheric Deposition Program, station AK01). As a consequence of this, the region around the experimental plots became flooded in August–September, which was evident in the Tanana River gage height increasing to 8.0 m, which is approximately 3 m above its winter base flow (U.S. Geological Survey, gage 15485500). Since the flooding event made it impossible to experimentally manipulate water table position across the treatment plots, we considered data collected during this period separately. The flooding event afforded a unique opportunity to quantify the effects of an extreme change in water table height on peat pore water chemistry.

2.2. Water Table and Seasonal Ice Measurements

[11] Within each treatment plot (control, lowered, raised) eight wells were inserted to measure the water table posi-

Table 1. Changes in TDN, DOC, and Aromaticity in Samples Repeatedly Obtained From Three Different Piezometer Depths, Across All Three Treatments[a]

Plot	Depth (cm)	Months	TDN ($mg\ L^{-1}$)		DOC ($mg\ L^{-1}$)		$SUVA_{254}$[b] ($L\ mg\ C^{-1}\ m^{-1}$)	
Control	20	May–Jun	1.86	(0.28)	31.91	(6.91)	5.56	(0.40)
	20	Jul–Aug	3.09	(0.63)	61.61	(6.02)	4.27	(0.22)
	20	Sep	2.58	(0.53)	64.96	(12.97)	4.17	(0.98)
	40	May–Jun	3.23	(0.03)	72.78	(3.43)		
	40	Jul–Aug	4.62	(0.75)	89.03	(8.05)	4.62	(0.24)
	40	Sep	3.19	(0.03)	78.29	(6.24)	6.03	
	80	Jul–Aug	2.47	(0.15)	70.59	(7.68)	4.26	(0.34)
	80	Sep	3.12	(0.13)	60.88	(3.30)	5.29	(0.34)
Lowered	20	May–Jun	2.95	(0.98)	46.93	(16.58)	4.72	(0.01)
	20	Jul–Aug	3.93	(0.67)	79.70	(6.87)	4.62	(0.33)
	20	Sep	3.01	(0.73)	72.60	(17.59)	3.29	
	40	May–Jun	3.35	(0.45)	68.19	(4.19)		
	40	Jul–Aug	3.76	(0.76)	63.96	(7.11)	4.65	(0.49)
	40	Sep	2.25	(0.04)	63.17	(6.06)		
	80	Jul–Aug	2.62	(0.07)	56.31	(6.14)	4.40	(0.29)
	80	Sep	3.06	(0.19)	56.02	(5.97)	5.12	(0.42)
Raised	20	May–Jun	1.56	(0.19)	32.29	(6.58)	5.62	
	20	Jul–Aug	2.85	(0.62)	54.01	(5.40)	4.26	(0.26)
	20	Sep	2.01	(0.25)	51.48	(8.92)	4.43	(0.56)
	40	May–Jun	1.99	(0.05)	42.35	(1.18)		
	40	Jul–Aug	3.82	(0.86)	68.26	(7.06)	4.29	(0.36)
	40	Sep	2.76	(0.09)	77.79	(4.42)	5.71	(0.09)
	80	Jul–Aug	2.71	(0.13)	62.71	(7.67)	4.01	(0.35)
	80	Sep	3.56	(0.39)	69.10	(4.24)	5.10	(0.52)

[a]Standard errors of the mean values are in parentheses. Total sample n = 136 (TDN), 214 (DOC), and 95 (SUVA).
[b]Specific ultraviolet absorbance at 254 nm, relative to the DOC concentration.

tion. Three of these wells were installed along the north and south sides of each plot, approximately 3 m apart and 1 m within the plot boundary, and one well was installed in the center of the east and west sides of each plot. Wells were constructed of 2.5 cm diameter polyvinyl chloride pipe that extended approximately 1 m into the peat, and was slotted the entire depth. The water table height at each well was measured approximately weekly throughout the growing season, 2005–2008 (1895 individual measurements). Eighteen additional wells were installed and monitored in 2007–2008 to measure changes in water table position between the three plots, as well as water level changes ~40 m north and south of the plots. All water table position data were measured relative to the surface of the peat, and therefore negative values denote the distance of the water table beneath the peat surface.

[12] Throughout the growing seasons of 2007–2008, thaw depth (relative to peat surface) was also measured at each well location with a tile probe. Continuous temperatures recorded at the peat surface by the Bonanza Creek Long-term Ecological Research station (LTER II; www.lter.uaf.edu), located in close proximity to the site in the Tanana River basin, were used to determine summed degree days (SDD), or the summed mean daily temperatures >0°C. The heat sum for the study site (SDD) was used as a predictor variable in determining changes in the recession of seasonal ice across the plots for a given year [see also *Wright et al.*, 2009]. Peat temperatures at the study sites were monitored with thermistors located 25 cm beneath the peat surface (6 per plot), and were recorded hourly throughout the growing season with Campbell CR10x data loggers (Campbell Scientific, Logan, UT). When interpolation was not possible to gap-fill missing data (extensive flooding period in 2008 resulted in 46% of data missing), empirical relationships between surface and 25 cm depths developed at LTER II were used in gap filling.

2.3. Peat Pore Water Measurements and Analysis

[13] Peat pore water was sampled for chemical analysis with a group of three piezometers installed at each plot. Piezometers had a 20 cm slotted region centered around a depth of 20, 40, or 80 cm, which was covered with a 40 μm Nitex nylon mesh to prevent clogging. Samples were collected approximately biweekly throughout the growing seasons of 2007 and 2008. During the period of flooding in 2008, the piezometers were overtopped and therefore sample collection only included surface water during that period. Deep piezometers could only be sampled later in the growing season when the depth to seasonal ice allowed (e.g., Tables 1 and 2).

[14] Prior to sampling for chemical analyses, the piezometers were pumped dry and allowed to recharge. The time required for recharge depended on depth, as hydraulic conductivity was much lower in the deeper peat [*Macheel*, 2010]. A small amount of pore water was pumped into the collection flask as a prerinse for sample collection in acid-rinsed dark polyethylene Nalgene bottles. Approximately 150 mL of sample was collected, and then samples were kept on ice packs in a cooler and brought back to the laboratory where they could be filtered through sterile Whatman 0.45 μm membrane filters (less than a day from time of collection). After filtration, samples were then split into three parts: (1) 50 mL was acidified (pH 2) and refrigerated prior to DOC and TDN analysis, (2) 50 mL was kept frozen prior to anion and cation analysis (in year 2007 only), and (3) 10 mL was diluted (1:10) and its ultraviolet absorbance at $\lambda = 254$ nm was immediately determined on a spectrophotometer to determine relative aromaticity of

Table 2. Changes in Cation and Anion Pore Water Chemistry Across the Three Water Table Treatments[a]

Plot	Depth (cm)	Months	pH (Pore Water)		DO[b] (mg L^{-1})		Ca^{++} (mg L^{-1})		Mg^{++} (mg L^{-1})		NH_4 –N (mg L^{-1})		NO_3 –N (mg L^{-1})		Cl^- (mg L^{-1})	
Control	20	May–Jun	6.29	(0.23)	10.28	(0.44)	4.89	(2.42)	2.94	(0.40)	1.06	(0.11)	bdl	-	1.07	(0.45)
	20	Jul–Aug	6.14	(0.02)	7.76	(0.44)	17.98	(0.38)	3.74	(1.47)	0.60	(0.50)	0.73	(0.03)	0.28	-
	20	Sep					14.49	(1.27)	4.50	(0.33)	0.30	(0.07)	0.78	(0.001)	0.20	(0.03)
	40	Jul–Aug	6.04	(0.08)			15.53	(1.46)	3.96	(0.55)	0.35	(0.19)	0.87	(0.09)	0.29	(0.01)
	40	Sep					20.65	(1.84)	6.63	(0.67)	0.14	(0.08)	1.02	(0.02)	0.29	(0.05)
	80	Sep					11.31	(0.91)	3.44	(0.26)	1.34	(0.05)	1.00	(0.28)	0.40	(0.004)
Lowered	20	May–Jun	6.23	0.15	11.55	(0.50)	7.05	(1.53)	2.72	(0.40)	bdl	-	bdl	-	0.79	(0.33)
	20	Jul–Aug	6.21	0.08	8.28	(2.32)	14.86	(6.68)	4.45	(1.39)	1.49	(0.60)	0.83	(0.17)	0.48	(0.12)
	20	Sep					18.13	(0.16)	5.60	(0.06)	0.57	(0.04)	0.91	(0.23)	0.34	(0.03)
	40	Jul–Aug	6.01	0.01			10.53	(1.00)	3.24	(0.32)	0.43	(0.10)	0.69	(0.12)	0.30	(0.07)
	40	Sep					12.64	(0.67)	2.92	(0.68)	0.69	(0.39)	0.87	(0.3)	0.21	(0.02)
	80	Sep					9.50	(2.91)	5.68	(2.04)	2.68	(0.86)	1.00	(0.12)	0.25	(0.02)
Raised	20	May–Jun	6.27	0.13	10.16	(0.11)	2.15	(2.15)	4.32	(0.94)	1.13	(1.07)	bdl	-	0.58	(0.26)
	20	Jul–Aug	6.27	0.02	6.61	(0.53)	10.09	(2.56)	3.76	(0.90)	bdl	-	0.58	(0.08)	0.10	(0.05)
	20	Sep					10.92	(0.48)	3.90	(0.22)	0.08	(0.01)	0.78	(0.20)	0.08	(0.01)
	40	Jul–Aug	6.03	0.09			11.04	(2.26)	6.00	(1.76)	bdl	-	0.59	(0.07)	0.23	(0.02)
	40	Sep					12.42	(0.39)	2.92	(0.09)	0.03	(0.03)	0.79	(0.21)	0.18	(0.005)
	80	Sep					9.29	(3.76)	3.34	(0.57)	2.31	(0.11)	0.88	(0.14)	0.19	(0.04)

[a]Standard errors of the mean values are in parentheses. Total sample n = 40 for anions and cations. Sample concentrations below detection limit are denoted by “bdl.”
[b]Dissolved oxygen measured in surface pore water only (above water table to 5 cm depth).

DOC. Blanks of deionized water (with and without acidification) were run with all analyses (approximately one for every nine samples). DON and TDN were run with a TOC-V Analyzer with TDN module, (Shimadzu Scientific Instruments, Columbia, MD, USA), and calcium (Ca^{++}), magnesium (Mg^{++}), ammonium (NH_4^+), nitrate (NO_3^-) and chloride (Cl^-) were determined with an ICS-2000 ion chromatograph (Dionex Corporation, Bannockburn, IL, USA). Dissolved organic N (DON) was determined as the difference between TDN and dissolved inorganic N (DIN; NH_4 –N plus NO_3 –N). We analyzed samples for ultraviolet absorption at λ = 254 nm with a DU-640 Spectrophotometer (Beckman Coulter, Inc., Fullterton, CA, USA) in 2007 and with a UV-Mini 1240 Spectrophotometer (Shimadzu Scientific Instruments, Inc., Columbia, MD, USA) in 2008. We calculated specific ultraviolet absorbance (SUVA) by dividing absorbance at λ = 254 nm by DOC concentration, and reported $SUVA_{254}$ of DOC in units of L mg C^{-1} m^{-1}. A subset of samples run on both instruments exhibited similar absorbance values (R^2 = 0.99, p = 0.01, n = 10). While $SUVA_{254}$ could not be corrected for changes in soluble iron content [*Weishaar et al.*, 2003], seasonal fluctuations in iron are likely to be low owing to the high cation exchange capacity of deep peat, and the constancy of a pH above ~6 [e.g., *Vitt et al.*, 1995].

[15] Throughout the growing season of 2008, surface water (within 5 cm of the peat surface) across the three plots was analyzed for dissolved oxygen (DO) using a Hach HQ 40d luminescent DO probe (Hach Company, Loveland, CO, USA); four points per plot were averaged for every sampling day. In July of 2008, 0.5 L of pore water (20 cm depth) was collected from each plot and filtered as previously described for use in an incubation experiment to determine relative differences in potential DOC and TDN mineralization. Initial DOC and TDN concentrations on the bulk samples were determined as previously described, and then 50 mL of filtered sample was put into 130 mL pre-cleaned amber glass bottles (six replicates per plot). One mL of common innoculum of pore water filtered through a 1.6 μm glass fiber filter (sequentially diluted to 10^{-3}) was pipetted into each bottle, following methods described by *Wickland et al.* [2007]. Bottles were then gently shaken and incubated in the dark at 20°C for 30 days, acidified to pH = 2, and then remeasured for DOC and TDN concentrations.

2.4. Statistics and Analysis

[16] Changes in the water table position were experimentally manipulated at two plots, but also changed seasonally across all plots. Therefore, all statistics concerning water table include both seasonal changes (across all plots) and experimental changes (at two plots). All statistical analyses of changes in pore water chemistry were performed using general linear models (GLM) in SAS 9.2 (SAS Institute Inc., Cary, NC, USA), with water table treatment (control, lowered, raised) as a fixed effect. Analysis of covariance was used to ascertain changes in the significance of DOC versus ice depth and DOC versus water table position relationships as a function of the water table treatments. Since there is autocorrelation between the depth to ice and the progression of the growing season, the GLM procedure was used in repeated measures analysis of variance tests for within subject effects of day of year, seasonal ice depth, and water table position on DOC concentrations. One-way analysis of variance multiple comparisons (least significant difference) tests were used to determine differences among treatments (α = 0.05), and descriptive statistics were calculated with Analyze-It statistical module (Leeds, UK).

3. Results

3.1. Water Table and Seasonal Ice Depth

[17] The drained plot had a consistently lower water table height relative to the surface of the peat than did the reference control plot, while the raised plot was consistently wetter throughout all 4 years of manipulation (Figure 1).

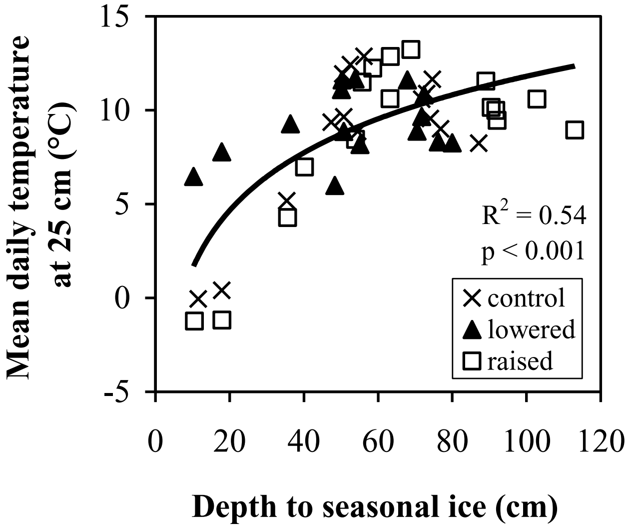

Figure 2. Mean daily peat temperatures (25 cm) increased as the depth to seasonal ice increased with the progression of the growing season. Coefficients describing the natural logarithmic trend are $\beta_0 = -8.66 \pm 2.46$, $\beta_1 = 4.44 \pm 0.62$.

The mean (±standard error) monthly water table position during the growing season for the control and drained plots across all 4 years of manipulation was 7.2 ± 3.2 and 10.0 ± 3.8 cm beneath the surface of the peat, respectively, whereas the raised water table treatment had water 0.1 ± 2.2 cm above the peat surface on average. The water table position at the drained treatment was also more variable than at the control plot, whereas experimentally raising the water table depth relative to the peat surface at the raised plot reduced fluctuations in water table height within the months of June, July, and August (Figure 1, inset). During the flooded period (August–September 2008), the mean water table height was 28.8 ± 2.4 cm above the peat surface across all of the plots (Figure 1).

[18] While the experimental treatments were effective in altering the water table position among the three plots, seasonal ice dynamics largely controlled water table changes throughout the growing season. The distance to water table relative to peat surface increased as the depth to seasonal ice increased with the progression of the growing season across all plots ($R^2 = 0.38$, $p < 0.001$, $F_{1,45} = 27.33$). As the depth to seasonal ice increased with the progression of the growing season, mean daily peat temperatures (25 cm) also increased (Figure 2). There was an interaction between water table height and mean daily peat temperatures (25 cm) in explaining depth to seasonal ice across all plots ($F_{1,45} = 7.29$, $p = 0.01$).

[19] The thawing of seasonally frozen ground with increasing summed degree days (SDD, >0°C) at the peat surface varied across treatment plots and years ($F_{2,54} = 6.25$, $p = 0.004$). The water table height was maintained at a higher position relative to the peat surface at the raised treatment, and the rate of ice recession with time was the fastest at this plot (Figure 3c). Throughout 2007 and 2008, the rates of ice recession with increasing heat sums (SDD) at the peat surface (cm of thaw per increase in SDD) were 0.04 ± 0.006, 0.03 ± 0.006, and 0.05 ± 0.008 (cm of thaw per increase in SDD) for the control, lowered, and raised plots, respectively ($R^2 = 0.75$, 0.64, and 0.68, and $p < 0.001$, respectively).

3.2. Pore Water Composition

[20] Throughout the growing seasons of 2007 and 2008, pore water DOC and TDN measured at 20 cm depth both increased as the growing season progressed (Figure 3). This seasonal pattern was not evident in samples obtained from 40 and 80 cm, though the deeper pore water generally had higher DOC and TDN solute concentrations than the shallower depths (Table 1). $SUVA_{254}$ values recorded in the surface piezometers were variable throughout the growing season, with high values occurring early in the season following snowmelt (Table 1). When differences in year of sampling were accounted for, $SUVA_{254}$ values increased with the progression of the growing season in the 40 and 80 cm piezometers ($R^2 = 0.30$, $p < 0.001$) (Table 1). $SUVA_{254}$ increased as the water table position declined relative to the peat surface across all plots and measurement depths ($R^2 = 0.10$, $p = 0.01$), with the strongest relationship occurring in the 40 and 80 cm piezometers ($R^2 = 0.41$, $p < 0.001$). As the $SUVA_{254}$ increased across all plots, the percentage of [DIN] increased in pore water at all depths ($r = 0.40$, $p = 0.04$), while [DON] had a weak negative correlation with $SUVA_{254}$ ($r = -0.36$, $p = 0.06$).

[21] Patterns of TDN concentrations closely followed DOC concentrations in peat pore water, mostly tracking changes in DON with DOC across all plots and measure-

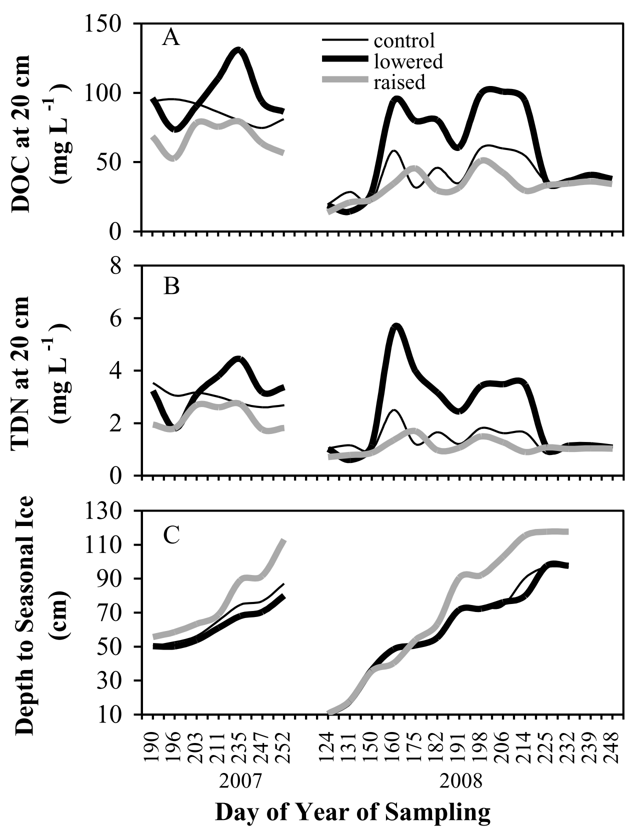

Figure 3. Seasonal patterns of (a) DOC, (b) TDN, and (c) depth to seasonal ice across the three water table treatments.

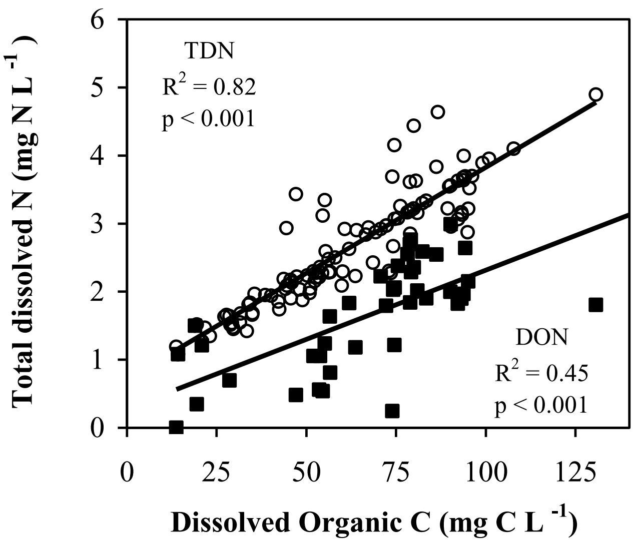

Figure 4. Total dissolved N (circles) and dissolved organic N (squares) both increased with pore water [DOC] measured at all depths across the three treatments. Coefficients describing the trend for TDN are β_0 = 0.71 ± 0.09, β_1 = 0.031 ± 0.001 and for DON are β_0 = 0.28 ± 0.26, β_1 = 0.020 ± 0.004.

ment depths (Figure 4). DON comprised approximately 46% of the total TDN pool (DON = 0.32 ± 0.39 + TDN × 0.46 ± 0.13; R^2 = 0.25, p = 0.001). While NO_3 –N concentrations also increased significantly with DOC concentrations at all depths (R^2 = 0.42, p < 0.001), this trend was driven mostly by the absence of detectable NO_3 –N early in the season (Table 2), when the depth to ice was shallowest. NH_4 –N concentrations were not related to pore water DOC concentrations ($F_{1,39}$ = 0.26, p = 0.62), and were consistently highest in the deep 80 cm piezometers (Table 2). Pore water concentrations of base forming cations (Ca^{++} and Mg^{++}) generally increased with the progression of the growing season, but were consistently lowest in the 80 cm piezometers (Table 2). In the 20 and 40 cm piezometers, [Ca^{++}] was correlated with depth to seasonal ice across all plots (r = 0.49, p = 0.001). Concentrations of Cl^-, which is thought to come solely from precipitation and snowfall and is biologically inert [*Hayashi et al.*, 2004; *Jones et al.*, 2005], were highest early in the season following snowmelt, but then did not change across the growing season (Table 2), or with depth ($F_{1,39}$ = 0.85, p = 0.36). Mean Cl^- concentrations were higher in the lowered plot than in the raised plot (F = 5.48, p = 0.03), but neither were different from the control plot. After snowmelt, there were no trends between Cl^- and water table position measured at the plots throughout the growing season.

[22] Dissolved oxygen (DO) measured at the peat surface (±5 cm) declined with the recession of seasonal ice (R^2 = 0.68, p < 0.001, n = 12) as the growing season progressed across all plots (Table 2). The lowered water table plot exhibited marginally higher DO values than the control or raised treatment plots early in the season ($F_{2,11}$ = 3.95, p = 0.06), but there were no differences in surface water DO across the treatments late in the season (Table 2).

3.3. Water Table and Seasonal Ice Controls on DOC and TDN

[23] Throughout the growing seasons of 2007 and 2008, mean monthly DOC concentrations measured at 20 cm depth increased as the standard deviations in mean monthly water table positions increased acrossplots (R^2 = 0.30, p = 0.036). Pore water DOC concentration measured at 20 cm depth increased as both the water table and the seasonal ice receded beneath the peat surface with warmer temperatures as the growing season progressed (Figure 5). [DOC] at 20 cm also increased as mean daily peat temperatures at 25 cm increased (R^2 = 0.28, p < 0.001), as expected because of the high correlation among peat temperatures, heat sums, and seasonal ice depths (e.g., Figure 2). There was no significant difference in the DOC concentration versus water table height ($F_{2,52}$ = 9.22, p = 0.97) relationship as a function of water table treatment in analysis of covariance, and pore water [DOC] increased by 2.26 ± 0.37 mg L^{-1} for every cm of decline in water table position below the peat surface across all plots (Figure 5a). There were drainage treatment effects on the relationship between pore water [DOC] and seasonal ice depth ($F_{2,45}$ = 3.59, p = 0.04), with the lowered water table plot exhibiting the greatest change in pore water [DOC] with changes in seasonal ice (Figure 5b). TDN concentrations followed patterns similar to [DOC], with water table position explaining 73% of the variance (p < 0.001) and seasonal ice depth explaining 44% of the variance (p = 0.002) in [TDN] at 20 cm depth across all plots.

[24] As expected from the seasonal patterning of data in Figure 3, there were significant interactions between the timing of sampling and the recession of seasonal ice in affecting DOC concentrations throughout the growing season (Table 3). As such, date of sampling was accounted for in determining significant environmental effects on changes in pore water [DOC] (Table 4). When day of year was considered, the significance of seasonal ice depth and peat temperature as predictors of [DOC] were negated (Table 4). However, there was a strong interactive effect between depth to seasonal ice and water table position in explaining changes in [DOC] (Table 4), and this interaction term alone explained 45% of the variance in DOC concentrations at 20 cm across all plots ($F_{1,45}$ = 35.40, p < 0.001). Similarly, the peat temperature × water table position interaction term explained 48% of the variance in DOC concentrations at 20 cm across all plots ($F_{1,45}$ = 40.73, p < 0.001). The decline in [DOC] observed with increasing water table height was not solely due to dilution effects, as DOC:Cl^- ratio trends between water table position and depth to seasonal ice were maintained (Figure 6).

[25] A seasonal hysteresis pattern in pore water [DOC] was evident with changes in water table position during late season flood (Figure 7). The increase in pore water [DOC] at 20 cm as water table position declined in the early part of the year in 2008 was not significantly different from 2007 (Table 4), but with late season flooding the DOC concentration was markedly higher than that measured early in the season at the same water table position (Figure 7). With early season drainage, [DOC] doubled in the month of July, with relatively little change in water table position but a large increase in the depth to seasonal ice (from 10 to 55 cm)

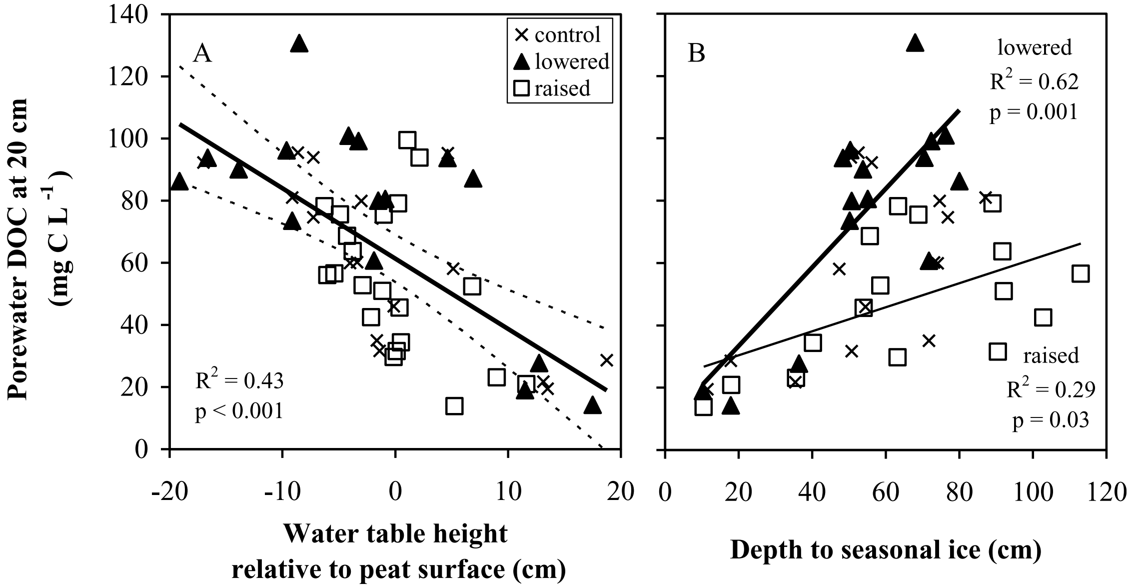

Figure 5. (a) Pore water [DOC] concentrations measured at 20 cm depth as a function of water table height (data from period of flooding in 2008 not shown). Coefficients are β_0 = 61.37 ± 3.04, β_1 = −2.26 ± 0.37. (b) Pore water [DOC] at 20 cm depth as a function of depth to season ice. Coefficients are (lowered) β_0 = 8.14 ± 15.83, β_1 = 1.26 ± 0.27; (raised) β_0 = 22.72 ± 11.46, β_1 = 0.39 ± 0.16. There was no significant difference in the DOC versus water table height (F = 9.22, p = 0.97) relationship as a function of water table treatment in analysis of covariance. Dotted lines represent a 95% confidence interval about the regression line.

(Figure 7). The higher concentrations of DOC and TDN observed at the lowered water table plot, and lower concentrations (relative to the control) measured at the raised water table plot (Table 1) were maintained even during the period of extensive flooding, with [DOC] means of 42.0 ± 3.4 (control), 49.1 ± 11.4 (lowered), and 33.5 ± 1.1 (raised) mg L^{-1} being measured at 20 cm throughout August–September in 2008.

3.4. Mineralization Potential of DOC and TDN

[26] Pore water collected at the control, lowered, and raised treatment plots for an incubation experiment differed in their initial DOC (51.1 ± 0.3, 89.8 ± 0.6, and 33.4 ± 0.3 mg L^{-1}) and TDN (1.57 ± 0.01, 3.08 ± 0.02, and 0.94 ± 0.01 mg L^{-1}) concentrations, respectively. Following 30 days, the reduction in [DOC] and [TDN] owing to mineralization was greatest at the lowered plot, which exhibited the highest initial solute concentrations (Figure 8). However, reductions in [DOC] as a percentage of initial concentrations were not significantly different across treatments (7.2 ± 0.9%; $F_{2,17}$ = 0.78, p = 0.48), which suggests that DOC quality may not have differed across the experimental treatments. Reduction in [TDN] as a percentage of initial concentration was significantly higher at the raised plot (4.7 ± 0.5%) than the lowered (2.8 ± 0.4%) or control (3.5 ± 0.4%) plots ($F_{2,17}$ = 4.33, p = 0.04).

[27] The depth to water table affected the transformation of different N species in peat pore water measured across-plots (Figure 9). NO_3 –N was not detectable until the water table had receded to just below the peat surface across all plots. When the water table had receded to approximately 5 cm below the surface of the peat, there was a marked increase in NO_3 –N production relative to NH_4 –N (Figure 9a), and also a marked increase in DIN concentrations (Figure 9b). With continued water table drawdown across plots, NO_3 –N concentrations declined (Figure 9a). The DIN:TDN ratio increased as the water table position declined relative to the peat surface across all plots (R^2 = 0.15, p = 0.02); however, there was considerable variation within the treatments, and this trend was driven mainly by the lowered water table plot data (Figure 9b).

4. Discussion

4.1. Interactive Controls of Water Table and Seasonal Ice

[28] In this study there was a significant interaction between water table position and depth to seasonal ice in explaining variance in pore water [DOC] and [TDN]. It is perhaps not surprising that pore water [TDN] and [DOC]

Table 3. Results From Repeated Measured Analysis of Variance (General Linear Model) Analyzing Changes in Pore Water [DOC] at 20 cm Depth Across All Experimental Treatments, Using Data From All Sampling Times

Source	DF	SS	MS	F	p Value
Day of year	1	25146.61	25146.61	222.62	<0.0001
Day of year × [DOC]	1	2277.46	2277.46	20.16	<0.0001
Day of year × depth to ice	1	19698.33	19698.33	174.39	<0.0001
Day of year × water table	1	0.70	0.70	0.01	0.9375
Error (day of year)	51	5760.74	112.96		

Table 4. Results of a General Linear Model Utilizing Experimental Treatments and Environmental Parameters to Predict Changes in Pore Water [DOC] at 20 cm (Data From the Period of Flooding Not Included)[a]

Source	DF	SS	MS	F	p Value	R^2
Water table treatment[b]	2	6004.33	3002.17	16.10	<0.0001	
Year	1	126.88	126.88	0.68	0.4148	
Day of year	1	517.24	517.24	2.77	0.1045	
Mean temperature at 25 cm	1	1.09	1.09	0.01	0.9395	
Depth to seasonal ice	1	6.78	6.78	0.04	0.8499	
Mean water table position	1	256.70	256.70	1.38	0.2483	
Water table × temperature at 25 cm	1	1444.65	1444.65	7.75	0.0085	
Water table × depth to ice	1	2907.78	2907.78	15.60	0.0003	
Model	9,45	31795.76	3532.86	18.95	<0.0001	0.83

[a]DF, degrees of freedom (source, model total); SS, type III sum of squares; MS, mean square error.
[b]Grouped by three class variables (drained, raised, control). There was no significant difference in the DOC versus water table (F = 9.22, p = 0.97) relationship when water table treatment was accounted for in analysis of covariance.

exhibited similar trends with depth-to-seasonal-ice and water table position (Figure 4), owing to the dominance of DON in the TDN pool [see also *D'Amore et al.*, 2009]. The increase in pore water DOC concentrations observed in the lowered water table treatment, as well as across all plots as the water table declined, was consistent with numerous other studies that have shown increases in the accumulation of water soluble products of decomposition with water table drawdown in peat, as the zone of aeration increases [*Blodau and Moore*, 2003; *Blodau et al.*, 2004; *Strack et al.*, 2008; *Höll et al.*, 2009] in proportion to the zone of anaerobic or submerged peat. Moreover, depth of seasonal thaw was highly correlated with peat degree-day heat sums and peat temperatures as expected, and its utility as a predictor of pore water [DOC] agrees with previous studies showing increased DOC production with warmer temperatures in boreal organic soils [*Moore and Dalva*, 2001; *Neff and Hooper*, 2002; *Prokushkin et al.*, 2005; *Kane et al.*, 2006; *Moore et al.*, 2008]. Interestingly, seasonal ice depth and peat temperature were weak predictors of variability in pore water [DOC] in the raised water table treatment, but seasonal ice depth had strong explanatory power in the lowered water table treatment (Figure 5b). In contrast, the effect of water table position was consistent across the treatments in its ability to explain variation in pore water [DOC] (Figure 5a). These findings suggest that water table position may be a more limiting factor than seasonal ice depth (or peat temperature) in mediating DOC concentrations [*Strack et al.*, 2008]. Notwithstanding, with combined effects of drying and warming or the recession of seasonally frozen peat, these findings suggest the potential for even greater DOC production than from just drought or thaw alone (Table 4).

[29] The singular effects of changes in ice depth and water table position on pore water [DOC] are hard to disentangle throughout a growing season. For example, changes in water table height affect microbial activity and DOC production, but may also alter solute concentrations by dilution. By using the conservative ion Cl^- to account for changes in water added or removed from the treatments, we were able to determine if variation in water table and seasonal ice controls on pore water [DOC] concentrations could be explained by mechanisms other than dilution [*Hayashi et al.*, 2004]. DOC:Cl^- still increased as both the water table and the depth to seasonal ice declined beneath the peat surface, and

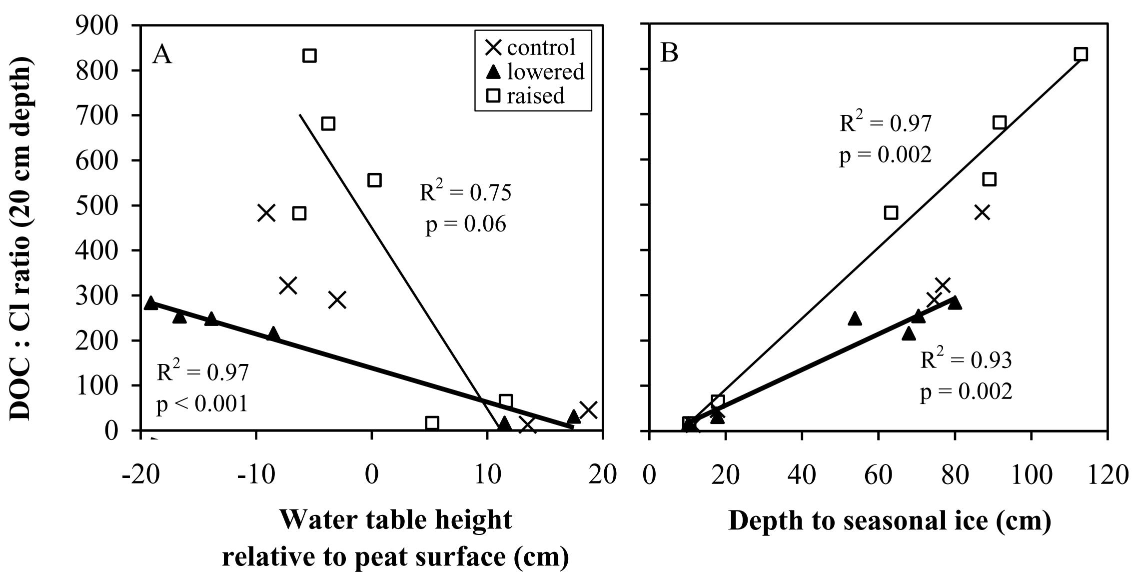

Figure 6. Pore water [DOC: Cl] concentrations (a) measured at 20 cm depth declined with increasing water table height and (b) increased as depth to seasonal ice increased across the water table treatments.

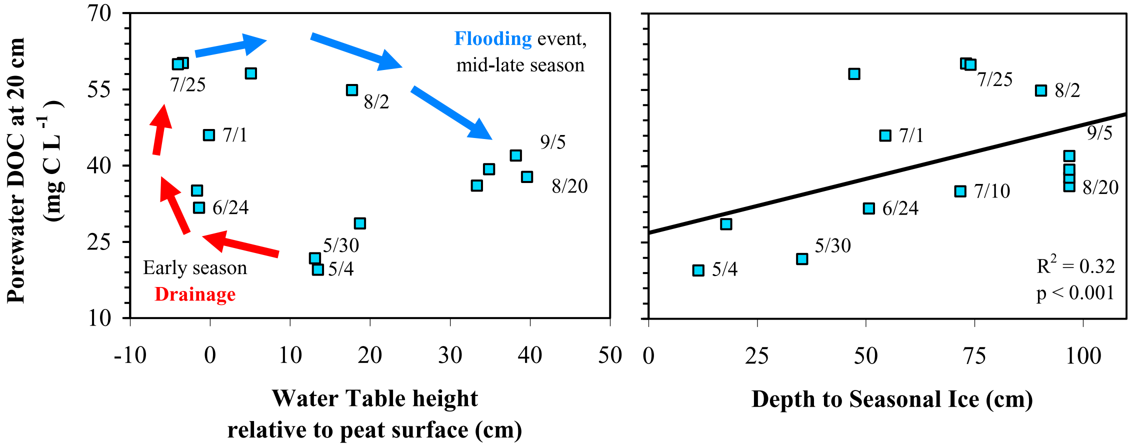

Figure 7. Seasonal pattern of [DOC] changed dramatically during a flooding event in 2008. (left) Pore water [DOC] increased with early season drainage as expected, but was much slower to decline with flooding, likely owing to (right) a concomitant increase in the depth to seasonal ice and warmer temperatures. Data are shown for the control plot only.

responses differed by water table treatment type. While it is worth noting that recent research has raised questions on the conservative behavior of chloride in organic soil [*Oberg and Sanden*, 2005], these data indicate that the changes in pore water [DOC] were not due to dilution or evaporative concentration effects alone (see discussion by *Waiser* [2006]).

[30] Manipulating the water tables and altering peat moisture also have a secondary effect on seasonal thaw depth by altering the thermal conductance of the peat [*Sharratt*, 1997; *Yi et al.*, 2009; *O'Donnell et al.*, 2009]. As such, the raised treatment plot had a more rapid rate of ice recession (Figure 3c). Adding to this complexity, peat water content at the time of freezing late in the fall largely influences its ice content [*Kane*, 1980], which in turn influences peat temperatures and the perching of runoff in the following spring season [*Bonan*, 1992; *Wright et al.*, 2009]. Drained experimental plots have exhibited early spring warming relative to control plots in previous studies examining mineral soil horizons [*Steenhuis and Walter*, 1986; *Jin et al.*, 2008]. In this system, water table and depth to ice at the lowered and raised water table plots were the most distinguished from the control plot later on in the growing season, which likely reflected changes in peat thermal conductance occurring with changes in water table when air temperatures (and heat sums) were higher [*Bonan et al.*, 1990].

[31] The experimental treatments also exhibited different responses in DOC concentrations with seasonal changes in depth to ice and water table height. The raised water table treatment exhibited the lowest sensitivity of [DOC] to changes in seasonal ice depth (Figure 5b), which suggests that temperature was not as large a constraint to DOC production as was the lack of oxygen, when the water table position was high. However, when the water table position was relatively low across all plots (July; Figure 7, left) pore water [DOC] changed rapidly in response to a relatively small change in water table height, likely owing to a rapid decline in the depth to seasonal ice also occurring when there was aerobic peat (Figure 7, right). In fact, pore water [DOC] did not exhibit any marked changes across the drainage treatments until the depth to seasonal ice reached approximately 60 cm; at this point in the growing season [DOC] increased sharply at the lowered treatment in both sampling years (Figure 3). These data illustrate how the interactive effects of water table position and seasonal ice depth on pore water [DOC] can change throughout the growing season.

[32] Another change cooccurring with the thawing of seasonal ice was the increase in primary production and microbial respiration as the growing season progressed [*Chivers et al.*, 2009]. Increased vegetation production has been linked to DOC generation (e.g., seasonal root leachates and rhizodeposition [*Kang et al.*, 2001; *Fenner et al.*, 2007], leachates from litter production [*Schiff et al.*, 1997; *Kalbitz et al.*, 2000; *Cleveland et al.*, 2004; *Blodau et al.*, 2004], and

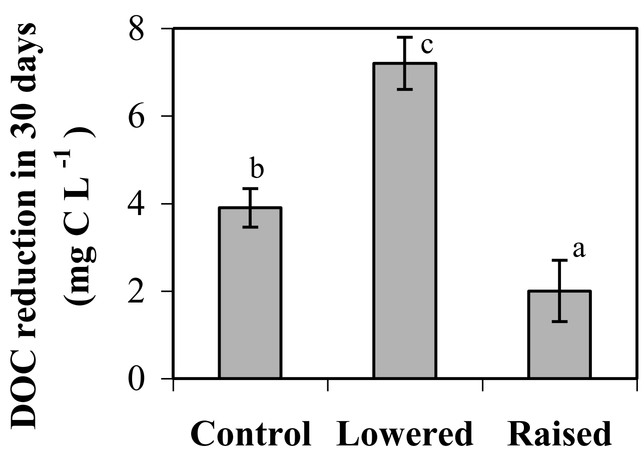

Figure 8. The amount of DOC mineralized over a 30 day laboratory incubation from the three water table treatments. The percent of DOC mineralized was the same across the three treatments (7.2 ± 0.9% loss over 30 days). Different letters denote significant differences across treatments (one-way ANOVA between subjects).

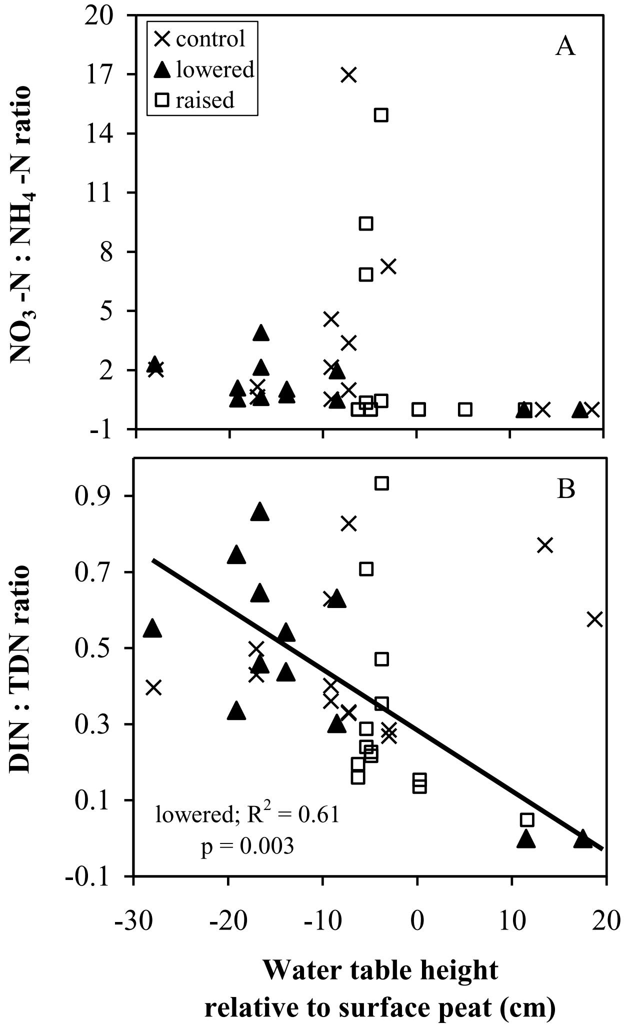

Figure 9. (a) The ratio of [NO_3 –N: NH_4 –N] in pore water collected at all three treatments exhibited a threshold change with changes in water table height, and (b) the proportion of dissolved inorganic N to total dissolved N increased as the water table height receded beneath the surface in the drained water table treatment. The regression line is through the drained plot data, and is described by the coefficients β_0 = 0.284 ± 0.068, β_1 = −0.016 ± 0.004.

moss leachate effects on pore water chemistry [*Moore*, 2003; *Wickland et al.*, 2007]). As such, seasonal changes in primary production (cooccurring with ice recession) were likely significant factors affecting peat pore water chemistry across all plots [*Harrison et al.*, 2008], but changes in primary production did not track changes in pore water [DOC] within the different experimental treatments. In a previous study, vegetation C uptake was greatest in the raised treatment and lowest in the drained treatment, suggesting sensitivity of vegetation in this system to an interaction between drought and temperature [*Chivers et al.*, 2009]. It is therefore interesting that the raised treatment (with the highest vegetation C uptake) had the lowest pore water [DOC], which may suggest that DOC production was more tightly linked with microbial activity (particularly with increased aerobic activity in nonsaturated peat) than with changes in net primary production, at least within this short timeframe across treatment plots. It is also likely that enhanced variability in water table position at the lowered treatment was more effective in DOC generation (with alternating aerobic and anaerobic conditions [*Kalbitz et al.*, 2000]) and the flushing of pore water DOC [see also *Worrall et al.*, 2008], which could uncouple DOC production from patterns of biological activity on short timescales [*Blodau and Moore*, 2003]. Continued study of vegetation changes across the treatment plots, and a better understanding of microbial processing of plant-derived DOC, is required to better understand seasonal changes in pore water DOC.

4.2. Pore Water Constituents

[33] Other pore water constituents also reflected changes in the depth to ice and water table position throughout the growing season, and across the experimental plots. For example, higher SUVA values generally reflect the presence of higher molecular weight dissolved organic matter (DOM) (at 280 nm [*Chin et al.*, 1994]) that is more aromatic [*Weishaar et al.*, 2003; see also *Novak et al.*, 1992]. DOC with higher SUVA has been shown to be less labile than lower molecular weight DOC [*Kalbitz et al.*, 2003], such as hydrophilic OM which has lower SUVA [e.g., *Croue*, 2004; *Wickland et al.*, 2007], though a broad range in SUVA may be observed within chemical fractions [*Weishaar et al.*, 2003]. The SUVA of DOM has been shown to increase over time in incubation experiments [*Chow et al.*, 2006] and with the progression of the growing season in a field wetland experiment [*Pinney et al.*, 2000]. In these studies, more labile (aliphatic) DOM was preferentially mineralized and there was an increase in the relative proportion of aromatic DOM [*Qualls and Haines*, 1992; *Ma et al.*, 2001; *Kalbitz et al.*, 2003; *Höll et al.*, 2009]. In our study, $SUVA_{254}$ in the shallow piezometers remained relatively low, even late in the growing season (Table 1). The higher $SUVA_{254}$ values observed with increasing water table drawdown across the treatment plots likely reflects the accumulation of more aromatic $SUVA_{254}$ and/or the mineralization of lower molecular weight DOC, as suggested in previous research showing increased SUVA in peatland pore water following 20 years of drainage [*Höll et al.*, 2009]. Higher $SUVA_{254}$ also likely reflected the progression of thaw into sapric basal peat which has undergone a greater degree of decomposition. While perhaps not surprising, these data suggest water soluble products from more recent microbial activity accumulate in the shallow peat depths, whereas more degraded and more aromatic DOC accumulates deeper in the profile. While we have not yet observed changes in $SUVA_{254}$ with experimental water table drawdown, seasonal change in DOC aromaticity across the plots was apparent (Table 1). In addition, the increase in $SUVA_{254}$ with depth likely reflects a decline in DOC bioavailability, which has implications for heterotrophic mineralization at different depths.

[34] The pore water [Ca^{++}], [Mg^{++}] and pH values measured at the different plots (Table 2) are consistent with other descriptions for rich fen ecosystems of North America [*Glaser*, 1992; *Vitt et al.*, 1995] and northern Sweden [*Sjors and Gunnarsson*, 2002], and as such, this system is influenced by surface runoff and groundwater. In the expanse of groundwater-fed wetlands in the Tanana Flats region, located between the plots in this study and the Tanana River

to the south, *Racine and Walters* [1994] reported high surface water [Ca^{++}] (43.7 ± 2.6 mg L^{-1}), which reflected groundwater inputs (and connectivity with the Tanana River, which has a mean growing season [Ca^{++}] of 32.2 ± 1.7 mg L^{-1}; National Stream Water Quality Network, station 15515500; 2001–2005). In this study, [Ca^{++}] in the 80 cm piezometers was consistently lower than in the shallower depths (Table 2), and hydraulic conductivity through the deeper peat was an order of magnitude lower than that measured at the surface ($k = 2–3 \times 10^{-2}$ cm s^{-1} at 20–40 cm versus $k = 2 \times 10^{-3}$ cm s^{-1} at 80 cm [*Macheel*, 2010]). Moreover, seasonal ice prevented connectivity between surface pore water and the underlying mineral soil for most of the year (e.g., Figure 3). These data suggest that the extent of groundwater influence at this site is limited, and most likely reflects flooding events or off-site upwelling and lateral transport over seasonal ice early in the season [*Hopkins et al.*, 1955; *Racine and Walters*, 1994].

4.3. Mineralization Potential of DOC and TDN

[35] Concentrations of DOC in peat pore water are constrained by rates of production, DOC mineralization, and dilution. Previous research has suggested increased aerobic conditions (as increases with water table drawdown) should favor mineralization (CO_2 production) over the preservation of DOC as an end product of decomposition [*Freeman et al.*, 2004]. In addition, a fluctuating water table can increase DOC concentrations by enhanced mineralization in aerobic conditions and flushing of DOC and preservation in saturated anaerobic peat [*Easthouse et al.*, 1992; *Kalbitz et al.*, 2000; *Strack et al.*, 2008]. We observed higher [DOC] in the lowered water table treatment, which also had the greatest variability in water table position. Water table variability increases following peat drainage and subsidence due to a decrease in specific yield and hydraulic conductivity. The total amount of DOC mineralized in a 30 day incubation was also highest in pore water from the lowered treatment (Figure 8), but this reflected a higher starting DOC concentration, as the percent DOC mineralized was not significantly different across treatments, and fell within the range reported by *Kalbitz et al.* [2003] for DOM extracted from peat and sapric material (4–9%). There was also no difference in $SUVA_{254}$ measured across treatments, which supports the incubation data. However, across all treatments there were changes in $SUVA_{254}$ with changes in water table position over the course of the growing season and with changes in pore water depth, which suggests that the biodegradability of DOC changes seasonally. In addition, while pore water DOC:Cl^- consistently increased as the depth to water table beneath the peat surface increased at all plots, there were marked differences in the slope of this response across the water table treatments (Figure 6a), which suggests differences in the mechanisms of DOC production versus mineralization across treatments [see also *Waiser*, 2006]. In fact, the lower DOC:Cl^- with changes in water table position observed for the lowered water table plot might suggest higher DOC mineralization rates occurred in this plot, whereas DOC preservation was higher in the raised plot throughout the growing season (Figure 6a). Clearly, more research is needed to determine exactly how changes in drainage may affect the biodegradability of DOC throughout the growing season.

[36] While there are few studies documenting changes in TDN over time in boreal peatlands [see *Vitt et al.*, 1995], it is well established that water table position exerts dominant control over DON mineralization processes and the cycling of DIN (as reviewed by *Limpens et al.* [2006] and *Rydin and Jeglum* [2006]). When anaerobic conditions persist (saturated peat), decomposition and mineralization processes are retarded and DON accumulates; this and cold temperatures account for high DON but low DIN in northern peatlands [*Crum*, 1988]. Therefore, nitrification rates are generally very low in peatlands owing to anaerobic conditions. However, NO_3^- concentrations have been shown to increase with water table drawdown [*Freeman et al.*, 1993; *Martikainen et al.*, 1993], especially in fens or riparian wetlands where N mineralization rates are higher than in ombrotrophic systems [*Chapin et al.*, 2003; *Fellman and D'Amore*, 2007], and therefore can have a greater supply of NH_4^+ for nitrification [e.g., *Regina et al.*, 1999; *Bragazza et al.*, 2003]. Ammonification is performed by aerobic heterotrophs, and is limited in part by the availability of a labile C pool [e.g., *Pastor et al.*, 1987]. It can therefore be seen that optimal conditions for TDN transformation processes are likely to change as the water table position (aerobic region) changes relative to the peat surface (carbon source) [see also *McClain et al.*, 2003; *Mitchell and Branfireun*, 2005]. This was evident in the spike in NO_3:NH_4 observed just as the water table receded below the surface of the peat in this study (Figure 9a). As the water table continued to decline, it is likely that vegetation uptake of NO_3^- occurred more rapidly, whereas when the peat was saturated (high water table) denitrification would likely be favored, and there was little DIN (Figure 9b) [*Urban et al.*, 1988]. Moreover, the proportional increase in DIN as the water table declined beneath the peat surface observed in this study (Figure 9b) likely reflected increased mineralization as the extent of aerobic peat increased. In fact, the largest increase in the percentage of DIN (especially NO_3 –N) occurred as the water table declined in the first 20 cm of peat (Figure 9), where $SUVA_{254}$ indicated DOC had relatively low aromaticity (Table 1). Taken together, these data suggest that more DON mineralization will occur with continued drying, but the forms of DIN are likely to change as both the proximity of water table position to the peat surface as well as the availability of more labile C change. Therefore, the effects of peatland drainage on the forms of DIN available for primary production are likely to be highly variable, depending on the extent and variability of water table drawdown, as well as the type and quality of surface peat.

4.4. Broader Implications for Solute Export

[37] While the findings presented and discussed herein suggest that DOC and DIN concentrations in boreal peatlands are likely to increase with drought or the thawing of seasonally frozen ground, there are conflicting accounts of whether the delivery of these solutes to river networks would likely increase or decrease in a warmer, drier climate [*Frey and McClelland*, 2009]. In Alaska, for example, TDN export was higher in streams draining watersheds with a discontinuous distribution of permafrost than in streams with a continuous distribution of permafrost [*Jones et al.*, 2005]. However, no increase in stream TDN export with

changes in permafrost distribution was observed in West Siberia. Warmer temperatures or decreased spatial distribution of permafrost may foster nitrification in aerobic peat or denitrification in saturated peat, which could account for differences in DIN export with warming in different boreal regions [*Frey and McClelland*, 2009]. Enhanced DOC produced in warmer or more aerobic peat may increase DOC concentrations in runoff to rivers in some boreal systems [*Frey and Smith*, 2005; *Strack et al.*, 2008], or infiltrate and decompose in a broadening active layer, or be transported in groundwater flow paths, resulting in a decline in [DOC] export to streams [*Striegl et al.*, 2005]. Clearly, there are complex interactions among the mechanisms of TDN and DOC production and mineralization (drainage, temperature, thaw depth and extent of perennially frozen ground) and the flow paths available for solute export from boreal peatlands. Annual flooding is common in the middle Tanana Valley alluvial plain, and is probable throughout the low alluvial terraces of the Yukon River Basin [*Hopkins et al.*, 1955]. Deep peat and the presence of seasonally frozen ground likely inhibited the infiltration of solutes and export or mineralization in groundwater in this study, but solutes could easily be flushed during flooding events, and with spring snowmelt [*Striegl et al.*, 2007]. Moreover, peat subsidence occurring with drought has been shown to exacerbate peat decay and mineralization processes [*Whittington and Price*, 2006], which suggests that with continued drainage, DOC and TDN loads in these systems would only increase. Further research exploring how flow paths from peatlands to rivers might change with changes in the extent of seasonally and perennially frozen ground is necessary to better understand the fate of these increased solute loads.

5. Conclusions

[38] In this study, there was an interaction between seasonal ice depth and water table position in explaining variance in pore water [DOC] and [TDN]. Therefore, ascertaining the effects of boreal peatland drying on dissolved C dynamics has to account for changes in seasonal ice depth in order to link both physical and biogeochemical processes. By examining changes in [DOC] during a flooding event when the depth to ice was greatest (i.e., late in the season), we determined that the controls on pore water [DOC] at this site changed seasonally. Moreover, experimental water table treatments demonstrated that the sensitivity of pore water [DOC] to changes in seasonal ice depth (and peat temperature) depends in part on water table position, as the lowered water table treatment exhibited the highest rate of [DOC] increase with seasonal thaw. The most significant changes in peat pore water chemistry occurred at relatively shallow depths (20 cm), with increases in [DOC] and [TDN] occurring with a lowering of the water table and increasing thaw depth. Together, these findings suggest that relatively small change in water table position and its interaction with seasonal ice depth and temperature can have significant effects on DOC and DIN concentrations in boreal peatland ecosystems. Relatively small changes in the solute loads of these boreal peatlands could have large-scale effects on ecosystem processes in Alaska, owing to the extensive coverage of peatland and mineral fen ecosystems in Alaska, their tremendous capacity to harbor C and nutrients, and their influence on stream water composition. We suggest that future research focusing on how drying affects DOC lability and TDN mineralization processes, as well as how seasonal ice dynamics affect solute flow paths from these peatlands, is necessary to understand consequences of altered hydrology for the functioning of these aquatic systems.

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References

Balcarczyk, K. L., J. B. Jones, R. Jaffé, and M. Nagamitsu (2009), Stream dissolved organic matter bioavailability and composition in watersheds underlain with discontinuous Permafrost, *Biogeochemistry*, *94*, 255–270.

Ball, B. A., et al. (2010), Direct and terrestrial vegetation-mediated effects of environmental change on aquatic ecosystem processes, *BioScience*, *60*(8), 590–601.

Blodau, C., and T. R. Moore (2003), Experimental response of peatland carbon dynamics to a water table fluctuation, *Aquat. Sci.*, *65*, 47–62.

Blodau, C., N. Basiliko, and T. R. Moore (2004), Carbon turnover in peatland mesocosms exposed to different water table levels, *Biogeochemistry*, *67*(3), 331–351.

Bonan, G. B. (1992), Soil temperature as an ecological factor in boreal forests, in *Systems Analysis of the Global Boreal Forest*, edited by H. H. Shugart, R. Leemans, and G. B. Bonan, pp. 126–143, Cambridge Univ. Press, Cambridge, U. K.

Bonan, G. B., H. H. Shugart, and D. L. Urban (1990), The sensitivity of some high-latitude boreal forests to climatic parameters, *Clim. Change*, *16*, 9–29.

Bourbonniere, R. A. (1989), Distribution patterns of dissolved organic matter fractions in natural waters from eastern Canada, *Org. Geochem.*, *14*, 97–107.

Bragazza, L., R. Gerdol, and H. Rydin (2003), Effects of mineral and nutrient input on mire bio-geochemistry in two geographical regions, *J. Ecol.*, *91*, 417–426.

Bridgham, S. D., J. P. Megonigal, J. K. Keller, N. B. Bliss, and C. C. Trettin (2006), The carbon balance of North American wetlands, *Wetlands*, *26*, 889–916.

Chapin, C. T., S. D. Bridgham, J. Pastor, and K. Updegraff (2003), Nitrogen, phosphorus, and carbon mineralization in response to nutrient and lime additions in peatlands, *Soil Sci.*, *168*, 409–420.

Chin, Y.-P., G. Aiken, and E. O. O'Loughlin (1994), Molecular weight, polydispersity, and spectroscopic properties of aquatic humic substances, *Environ. Sci. Technol.*, *28*, 1853–1858.

Chivers, M. R., M. R. Turetsky, J. M. Waddington, J. W. Harden, and A. D. McGuire (2009), Effects of experimental water table and temperature manipulations on ecosystem CO_2 fluxes in an Alaskan rich fen, *Ecosystems*, *12*(8), 1329–1342.

Chow, A. T., K. K. Tanji, S. Gao, and R. A. Dahlgren (2006), Temperature, water content and wet–dry cycle effects on DOC production and carbon mineralization in agricultural peat soils, *Soil Biol. Biochem.*, *38*, 477–488.

Christensen, T. R., S. Jonasson, A. Michelson, T. V. Callaghan, and M. Haystrom (1998), Environmental controls on soil respiration in the Eurasian and Greenlandic Arctic, *J. Geophys. Res.*, *103*, 29,015–29,021.

Cleveland, C. C., J. C. Neff, A. R. Townsend, and E. Hood (2004), Composition, dynamics, and fate of leached dissolved organic matter in terrestrial ecosystems: Results from a decomposition experiment, *Ecosystems*, *7*, 275–285.

Clymo, R. S., J. Turunen, and K. Tolonen (1998), Carbon accumulation in peatland, *Oikos*, *81*, 368–388.

Croue, J.-P. (2004), Isolation of humic and non-humic NOM fractions: Structural characterization, *Environ. Monit. Assess.*, *92*, 193–207.
Crum, H. (1988), *A Focus on Peatlands and Peat Mosses*, pp. 111–140, Univ. of Mich. Press, Ann Arbor.
D'Amore, D. V., J. B. Fellman, R. T. Edwards, and E. Hood (2009), Controls on dissolved organic matter concentrations in soils and streams from a forested wetland and sloping bog in southeast Alaska, *Ecohydrology*, doi:10.1002/eco.101.
Dingman, S. L., and F. R. Koutz (1974), Relations among vegetation, permafrost, and potential insolation in central Alaska, *Arct. Antarct. Alp. Res.*, *6*, 37–42.
Dornblaser, M. M., and R. G. Streigl (2007), Nutrient (N, P) loads and yields at multiple scales and subbasin types in the Yukon River Basin, Alaska, *J. Geophys. Res.*, *112*, G04S57, doi:10.1029/2006JG000366.
Easthouse, K. B., J. Mulder, N. Christophersen, and M. Seip (1992), Dissolved organic carbon fractions in soil and stream water during variable hydrological conditions at Birkenes, southern Norway, *Water Resour. Res.*, *28*, 1585–1596.
Euskirchen, E. S., et al. (2006), Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems, *Global Change Biol.*, *12*, 731–750.
Fellman, J. B., and D. V. D'Amore (2007), Nitrogen and phosphorus mineralization in three wetland types in southeast Alaska, USA, *Wetlands*, *27*, 44–53.
Fenner, N., N. J. Ostle, N. McNamara, T. Sparks, H. Harmens, B. Reynolds, and C. Freeman (2007), Elevated CO_2 effects on peatland plant community carbon dynamics and DOC production, *Ecosystems*, *10*, 635–647.
Ford, J., and B. L. Bedford (1987), The hydrology of Alaskan wetlands, U.S.A.: A review, *Arct. Antarct. Alp. Res.*, *19*, 209–229.
Freeman, C., M. A. Lock, and B. Reynolds (1993), Fluxes of CO_2, CH_4, and N_2O from a Welsh peatland following simulation of WT drawdown: Potential feedback to climate change, *Biogeochemistry*, *19*, 51–60.
Freeman, C., N. Ostle, and H. Kang (2001), An enzymic 'latch' on a global carbon store, *Nature*, *409*, 149–150.
Freeman, C., N. Fenner, N. J. Ostle, H. Kang, D. J. Dowrick, B. Reynolds, M. A. Lock, D. Sleep, S. Hughes, and J. Hudson (2004), Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels, *Nature*, *430*, 195–198.
Frey, K. E., and J. W. McClelland (2009), Impacts of permafrost degradation on arctic river Biogeochemistry, *Hydrol. Process.*, *23*, 169–182.
Frey, K. E., and L. C. Smith (2005), Amplified carbon release from vast West Siberian peatlands by 2100, *Geophys. Res. Lett.*, *32*, L09401, doi:10.1029/2004GL022025.
Glaser, P. H. (1992), Vegetation and water chemistry, in *The Patterned Peatlands of Minnesota*, edited by H. E. Wright Jr., B. A. Coffin, and N. E. P. Asseng, pp. 15–26, Univ. of Minn. Press, St. Paul.
Goetz, S. J., A. J. Bunn, G. J. Fiske, and R. A. Houghton (2005), Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 13,521–13,525.
Gorham, E. (1991), Northern peatlands—Role in the carbon-cycle and probable responses to climatic warming, *Ecol. Appl.*, *1*, 182–195.
Guo, L., and R. W. Macdonald (2006), Source and transport of terrigenous organic matter in the upper Yukon River: Evidence from isotope ($\delta^{13}C$, $\Delta^{14}C$, and $\delta^{15}N$) composition of dissolved, colloidal, and particulate phases, *Global Biogeochem. Cycles*, *20*, GB2011, doi:10.1029/2005GB002593.
Harrison, A. F., K. Taylor, A. Scott, J. Poskitt, D. Benham, J. Grace, J. Chaplow, and P. Rowland (2008), Potential effects of climate change on DOC release from three different soil types on the Northern Pennines UK: Examination using field manipulation experiments, *Global Change Biol.*, *14*, 687–702.
Hayashi, M., W. L. Quinton, A. Pietroniro, and J. J. Gibson (2004), Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures, *J. Hydrol.*, *296*, 81–97.
Hinzman, L. D., et al. (2005), Evidence and implications of recent climate change in northern Alaska and other arctic regions, *Clim. Change*, *72*, 251–298.
Höll, B. S., S. Fiedler, H. F. Jungkunst, K. Kalbitz, A. Freibauer, M. Drosler, and K. Stahr (2009), Characteristics of dissolved organic matter following 20 years of peatland restoration, *Sci. Total Environ.*, *408*, 78–83.
Hopkins, D. M., T. N. V. Karlstrom, R. F. Black, J. R. Williams, T. L. Pewe, A. T. Fernold, and E. H. Muller (1955), Permafrost and ground water in Alaska, *U.S. Geol. Surv. Prof. Pap.*, *264-F*, 113–130.
Jin, C. X., G. R. Sands, H. J. Kandel, J. H. Wiersma, and B. J. Hansen (2008), Influence of subsurface drainage on soil temperature in a cold climate, *J. Irrig. Drain. Eng.*, *134*(1), 83–88.
Jones, J. B., 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.
Judd, K. E., and G. W. Kling (2002), Production and export of dissolved C in arctic tundra mesocosms: The roles of vegetation and water flow, *Biogeochemistry*, *60*(3), 213–234.
Kalbitz, K., S. Solinger, S. H. Park, B. Michalzik, and E. Matzner (2000), Controls on the dynamics of dissolved organic matter in soils: A review, *Soil Sci.*, *165*, 277–304.
Kalbitz, K., J. Schmerwitz, D. Schwesig, and E. Matzner (2003), Biodegradation of soil-derived dissolved organic matter as related to its properties, *Geoderma*, *113*, 273–291.
Kane, D. L. (1980), Snowmelt infiltration into seasonally frozen soils, *Cold Reg. Sci. Technol.*, *3*, 153–161.
Kane, D. L., L. D. Hinzman, M.-K. Woo, and K. R. Everett (1992), Arctic hydrology and climate change, in *Arctic Ecosystems in a Changing Climate*, edited by F. S. Chapin III et al., pp. 35–58, Academic, San Diego, Calif.
Kane, E. S., D. W. Valentine, G. J. Michaelson, J. D. Fox, and C.-L. Ping (2006), Controls over pathways of carbon efflux from soils along climate and black spruce productivity gradients in interior Alaska, *Soil Biol. Biochem.*, *38*, 1438–1450.
Kang, H. J., C. Freeman, and T. W. Ashendon (2001), Effects of elevated CO_2 on fen peat biogeochemistry, *Sci. Total Environ.*, *279*, 45–50.
Keyser, A. R., J. S. Kimball, R. R. Nemani, and S. W. Running (2000), Simulating the effects of climate change on the carbon balance of North American high-latitude forests, *Global Change Biol.*, *6*, 185–195.
Knorr, K.-H., G. Lischeid, and C. Blodau (2009), Dynamics of redox processes in a minerotrophic fen exposed to water table manipulation, *Geoderma*, *153*, 379–392.
Limpens, J., M. M. P. D. Heijmans, and F. Berendse (2006), The nitrogen cycle in boreal peatlands, in *Boreal Peatland Ecosystems*, edited by R. K. Wieder and D. H. Vitt, pp. 195–221, Springer, Heidelberg.
Ma, H., H. E. Allen, and Y. Yin (2001), Characterization of isolated fractions of dissolved organic matter from natural waters and a wastewater effluent, *Water Res.*, *35*, 985–996.
Macheel, C. A. (2010), Variably saturated flow and heat transport simulations of an interior Alaskan fen, M.S. thesis, Dep. of Min. and Geol. Eng., Univ. of Alaska, Fairbanks, Fairbanks.
Martikainen, P. J., H. Nykanen, P. M. Crill, and J. Silvola (1993), Effect of a lowered water table on nitrous oxide fluxes from northern peatlands, *Nature*, *366*, 51–53.
McClain, M., et al. (2003), Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems, *Ecosystems*, *6*, 301–312.
McClelland, J. W., M. Stieglitz, F. Pan, R. M. Holmes, and B. J. Peterson (2007), Recent changes in nitrate and dissolved organic carbon export from the upper Kuparuk River, North Slope, Alaska, *J. Geophys. Res.*, *112*, G04S60, doi:10.1029/2006JG000371.
McKnight, D., E. M. Thurman, R. L. Wershaw, and H. Hemond (1985), Biogeochemistry of aquatic humic substances in Thoreau's bog, Concord, Massachusetts, *Ecology*, *66*, 1339–1352.
Michaelson, G. J., C.-L. Ping, G. W. Kling, and J. E. Hobbie (1998), The character and bioavailability of dissolved organic matter at thaw and in spring runoff waters of the arctic tundra north slope, *J. Geophys. Res.*, *103*, 28,939–28,946.
Mitchell, C., and B. Branfireun (2005), Hydrogeomorphic controls on reduction-oxidation conditions across boreal upland-peatland interfaces, *Ecosystems*, *8*, 731–747.
Moore, T. R. (2003), Dissolved organic carbon in a northern boreal landscape, *Global Biogeochem. Cycles*, *17*(4), 1109, doi:10.1029/2003GB002050.
Moore, T. R., and M. Dalva (2001), Some controls on the release of dissolved organic carbon by plant tissues and soils, *Soil Sci.*, *166*, 38–47.
Moore, T. R., N. T. Roulet, and J. M. Waddington (1998), Uncertainties in predicting the effect of climatic change on the carbon cycling of Canadian peatlands, *Clim. Change*, *40*, 229–245.
Moore, T. R., D. Pare, and R. Boutin (2008), Production of dissolved organic carbon in Canadian forest soils, *Ecosystems*, doi:10.1007/s10021-008-9156-x.
Myers-Smith, I. H., J. W. Harden, M. Wilmking, C. C. Fuller, A. D. McGuire, and F. S. Chapin (2008), Wetland succession in a permafrost collapse: Interactions between fire and thermokarst, *Biogeosciences*, *5*(5), 1273–1286.
Neff, J. C., and D. U. Hooper (2002), Vegetation and climate controls on potential CO_2, DOC and DON production in northern latitude soils, *Global Change Biol.*, *8*, 872–884.

Novak, J. M., G. L. Mills, and P. M. Bertsch (1992), Estimating the percent aromatic carbon in soil and aquatic humic substances using ultraviolet absorbance spectrometry, *J. Environ. Qual.*, *21*, 144–147.
Oberg, G., and P. Sanden (2005), Retention of chloride in soil and cycling of organic matter-bound chlorine, *Hydrol. Process.*, *19*, 2123–2136.
O'Donnell, J. A., V. E. Romanovsky, J. W. Harden, and A. D. McGuire (2009), The effect of moisture content on the thermal conductivity of moss and organic soil horizons from black spruce ecosystems in interior Alaska, *Soil Sci.*, *174*, 646–651.
Oechel, W. C., S. J. Hastings, G. L. Vourlitis, M. Jenkins, G. Riechers, and N. Grulke (1993), Recent change of arctic turndra ecosystems from a net carbon dioxide sink to a source, *Nature*, *361*, 520–523.
Osterkamp, T. E., and V. E. Romanovsky (1999), Evidence for warming and thawing of discontinuous permafrost in Alaska, *Permafrost Periglac., Processes*, *10*, 17–37.
Osterkamp, T. E., L. A. Viereck, Y. Shur, M. T. Jorgenson, C. Racine, A. Doyle, and R. D. Boone (2000), Observations of thermokarst and its impact on boreal forests in Alaska, USA, *Arct. Antarct. Alp. Res.*, *32*, 303–315.
Pastor, J., M. A. Stillwell, and D. Tilman (1987), Nitrogen mineralization and nitrification in four Minnesota old fields, *Oecologia*, *71*, 481–485.
Pastor, J., J. Solin, S. D. Bridgham, K. Updegraff, C. Harth, P. Weishampel, and B. Dewey (2003), Global warming and the export of dissolved organic carbon from boreal peatlands, *Oikos*, *100*, 380–386.
Pinney, M. L., P. K. Westerhoff, and L. Baker (2000), Transformations in dissolved organic carbon through constructed wetlands, *Water Res.*, *34*(6), 1897–1911.
Prokushkin, A. S., T. Kajimoto, S. G. Prokushkin, W. H. McDowell, A. P. Abaimov, and Y. Matsuura (2005), Climatic factors influencing fluxes of dissolved organic carbon from the forest floor in a continuous-permafrost Siberian watershed, *Can. J. For. Res.*, *35*(9), 2130–2140.
Qualls, R. G., and B. L. Haines (1992), Biodegradability of dissolved organic matter in forest throughfall, soil solution, and stream water, *Soil Sci. Soc. Am. J.*, *56*, 578–586.
Qualls, R. G., B. L. Haines, and W. T. Swank (1991), Fluxes of dissolved organic nutrients and humic substances in a deciduous forest, *Ecology*, *72*, 254–266.
Racine, C. H., and J. C. Walters (1994), Groundwater-discharge fens in the Tanana lowlands, interior Alaska, U.S.A, *Arct. Antarct. Alp. Res.*, *26*(4), 418–426.
Regina, K., J. Silvola, and P. J. Martikainen (1999), Short-term effects of changing water table on N_2O fluxes from peat monoliths from natural and drained boreal peatlands, *Global Change Biol.*, *5*, 183–189.
Riordan, B., D. Verbyla, and A. D. McGuire (2006), Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images, *J. Geophys. Res.*, *111*, G04002, doi:10.1029/2005JG000150.
Roulet, N. T., and M. K. Woo (1986), Wetland and lake evaporation in the low arctic, *Arct. Antarct. Alp. Res.*, *18*, 195–200.
Rydin, H., and J. K. Jeglum (2006), *The Biology of Peatlands*, pp. 164–186, Oxford Univ. Press, New York.
Schiff, S. L., R. Aravena, S. E. Trumbore, M. J. Hinton, R. Elgood, and P. J. Dillon (1997), Export of DOC from forested catchments on the Precambrian Shield of Central Ontario: Clues from C-13 and C-14, *Biogeochemistry*, *36*, 43–65.
Serreze, M. C., J. E. Walsh, F. S. Chapin, T. E. Osterkamp, M. Dyurgerov, V. E. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159.
Sharratt, B. S. (1997), Thermal conductivity and water retention of a black spruce forest floor, *Soil Sci.*, *162*(8), 576–582.
Sjors, H., and U. Gunnarsson (2002), Calcium and pH in north and central Swedish mire waters, *J. Ecol.*, *90*, 650–657.
Slaughter, C. W., and L. A. Viereck (1986), Climate characteristics of the Taiga in interior Alaska, in *Forest Ecosystems in the Alaskan Taiga*, edited by K. Van Cleve et al., pp. 9–21, Springer, New York.
Spencer, R. G. M., G. R. Aiken, K. P. Wickland, R. G. Striegl, and P. J. Hernes (2008), Seasonal and spatial variability in dissolved organic matter quantity and composition from the Yukon River basin, Alaska, *Global Biogeochem. Cycles*, *22*, GB4002, doi:10.1029/2008GB003231.
Steenhuis, T. S., and M. F. Walter (1986), Will drainage increase spring soil temperatures in cool and humid climates?, *Trans. ASAE*, *29*(6), 1641–1645.
Strack, M., J. M. Waddington, R. A. Bourbonniere, E. L. Buckton, K. Shaw, P. Whittington, and J. S. Price (2008), Effect of water table drawdown on peatland dissolved organic carbon export and dynamics, *Hydrol. Process.*, *22*, 3373–3385.
Striegl, R. G., G. R. Aiken, M. M. Dornblaser, P. A. Raymond, and K. P. Wickland (2005), A decrease in discharge-normalized DOC export by the Yukon River during summer through autumn, *Geophys. Res. Lett.*, *32*, L21413, doi:10.1029/2005GL024413.
Striegl, R. G., M. M. Dornbalser, G. R. Aiken, K. P. Wickland, and P. A. Raymond (2007), Carbon export and cycling by the Yukon, Tanana, and Porcupine rivers, Alaska, 2001–2005, *Water Resour. Res.*, *43*, W02411, doi:10.1029/2006WR005201.
Tarnocai, C. (2009), The impact of climate change on Canadian peatlands, *Can. Water Resour. J.*, *34*(4), 453–466.
Tarnocai, C., J. G. Canadell, E. A. G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov (2009), Soil organic carbon pools in the northern circumpolar permafrost region, *Global Biogeochem. Cycles*, *23*, GB2023, doi:10.1029/2008GB003327.
Turetsky, M. R., R. K. Wieder, C. J. Williams, and D. H. Vitt (2000), Organic matter accumulation, peat chemistry, and permafrost melting in peatlands of boreal Alberta, *Ecoscience*, *7*(3), 379–392.
Turetsky, M. R., R. K. Wieder, D. H. Vitt, R. J. Evans, and K. D. Scott (2007), The disappearance of relict permafrost in boreal north America: Effects on peatland carbon storage and fluxes, *Global Change Biol.*, *13*, 1922–1934.
Turetsky, M. R., C. C. Treat, M. P. Waldrop, J. M. Waddington, J. W. Harden, and A. D. McGuire (2008), Short-term response of methane fluxes and methanogen activity to water table and soil warming manipulations in an Alaskan peatland, *J. Geophys. Res.*, *113*, G00A10, doi:10.1029/2007JG000496.
Urban, N. R., S. J. Eisenreich, and S. E. Bayley (1988), The relative importance of denitrification and nitrate assimilation in midcontinental bogs, *Limnol. Oceanogr.*, *33*, 1611–1617.
Vitt, D. H., S. E. Bayley, and T.-L. Jin (1995), Seasonal variation in water chemistry over a bog-rich fen gradient in continental western Canada, *Can. J. Fish. Aquat. Sci.*, *52*, 587–606.
Waiser, M. J. (2006), Relationship between hydrological characteristics and dissolved organic carbon concentration and mass in northern prairie wetlands using a conservative tracer approach, *J. Geophys. Res.*, *111*, G02024, doi:10.1029/2005JG000088.
Weishaar, J. L., G. R. Aiken, B. A. Bergamaschi, M. S. Fram, R. Fujii, and K. Mopper (2003), Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon, *Environ. Sci. Technol.*, *37*, 4702–4708.
Whittington, P. N., and J. S. Price (2006), The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, Canada, *Hydrol. Process.*, *20*, 3589–3600.
Wickland, K. P., J. C. Neff, and G. R. Aiken (2007), Dissolved organic carbon in Alaskan boreal forest: Sources, chemical characteristics, and biodegradability, *Ecosystems*, doi:10.1007/s10021-007-9101-4.
Worrall, F., and T. P. Burt (2008), The effect of severe drought on the dissolved organic carbon (DOC) concentration and flux from British rivers, *J. Hydrol.*, *361*, 262–274.
Worrall, F., H. S. Gibson, and T. P. Burt (2008), Production vs. solubility in controlling runoff of DOC from peat soils—The use of an event analysis, *J. Hydrol.*, *358*, 84–95.
Wright, N., M. Hayashi, and W. L. Quinton (2009), Spatial and temporal variations in active layer thawing and their implication on runoff generation in peat-covered permafrost terrain, *Water Resour. Res.*, *45*, W05414, doi:10.1029/2008WR006880.
Wyatt, K. H., R. J. Stevenson, and M. R. Turetsky (2010), The importance of nutrient co-limitation in regulating algal community composition, productivity, and algal-derived DOC in an oligotrophic marsh in interior Alaska, *Freshwater Biol.*, doi:10.1111/j.1365-2427.2010.02419.x.
Yi, S., et al. (2009), Interactions between soil thermal and hydrological dynamics in the response of Alaska ecosystems to fire disturbance, *J. Geophys. Res.*, *114*, G02015, doi:10.1029/2008JG000841.
Yoshikawa, K., and L. D. Hinzman (2003), Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska, *Permafrost Periglac., Processes*, *14*, 151–160.

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