Improving Conceptual Models of Water and Carbon Transfer Through Peat

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Northern peatlands store 500×10^{15} g of organic carbon and are very sensitive to climate change. There is a strong conceptual model of sources, sinks, and pathways of carbon within peatlands, but challenges remain both in understanding the hydrogeology and the linkages between carbon cycling and peat pore water flow. In this chapter, research findings from the glacial Lake Agassiz peatlands are used to develop a conceptual framework for peatland hydrogeology and identify four challenges related to northern peatlands yet to be addressed: (1) develop a better understanding of the extent and net impact of climate-driven groundwater flushing in peatlands; (2) quantify the complexities of heterogeneity on pore water flow and, in particular, reconcile contradictions between peatland hydrogeologic interpretations and isotopic data; (3) understand the hydrogeologic implications of free-phase methane production, entrapment, and release in peatlands; and (4) quantify the impact of arctic and subarctic warming on peatland hydrogeology and its linkage to carbon cycling.

1. INTRODUCTION

Peatlands [landscapes accumulating peat soils >40 cm thickness; *National Wetland Working Group*, 1997] constitute a major global carbon repository. Northern peatlands store 500×10^{15} g of organic carbon [*Gorham*, 1991], equivalent to ~100 years of current fossil-fuel combustion [*Moore et al.*, 1998]. The interactions of peatlands with the Earth's atmosphere are dynamic and complex; on an annual basis, peatlands are a source of methane to the atmosphere, but on a longer timescale, they serve as net repositories of carbon dioxide [*Roulet et al.*, 1994]. Although many studies quantify carbon cycling in peatlands [e.g., *Siegel et al.*, 2001; *Rivers et al.*, 1998], how they will respond to climate change remains uncertain [e.g., *Waddington et al.*, 1998] because conceptual models of these systems are usually based on specific case studies and are difficult to generalize to all northern peatlands.

Peatlands were originally assumed to have effectively stagnant pore water due to highly decomposed layers of

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peat with very low permeability at depth [e.g., *Boelter and Verry*, 1977; *Ivanov*, 1975; *Verry and Boelter*, 1978]. These results led to a view that the exchange of atmospheric carbon with peatlands is essentially only through the peat surface [*Clymo*, 1984]. However, *Ingram* [1982] suggested that horizontal flow throughout a peat profile is a vital component of peatland hydrogeology and can partially explain a bog's size and morphology.

Current research shows that the movement of water and carbon through peatlands is variable, as there are many spatial and temporal factors that can control the movement of water and solutes. First is peat accumulation. Bogs and fens accumulate carbon and grow vertically and horizontally. Vertical peatland accumulation rates in North American peatlands range from 18 to over 100 cm per 1000 years [*Glaser et al.*, 2004a; *Gorham et al.*, 2003]. Second is permeability and porosity. The permeability and porosity of peat soils are temporally and spatially variable and dependant on numerous factors, including peat substrates, compaction, and decomposition. Changes in the pore water solute concentrations also can affect permeability by interacting with organic acid functional groups and dilating larger pores [*Ours et al.*, 1997]. *Price* [1997] found considerable hysteretic changes in permeability of near-surface peat driven by seasonal water table lowering and peat compaction. Third is macroporosity. Peatland soils can have extensive networks of macropores that control the movement of water. Networks of macropores within the peat soils (e.g., decayed roots) create preferential pathways by which water is rapidly transmitted [*Beven and Germann*, 1982] and create a dual porosity peat matrix. Additionally, macropores in the upper, aerobic layer (acrotelm) control the runoff of surface water [*Holden et al.*, 2001], and can be enhanced by desiccation [*Strack et al.*, 2008].

This chapter examines the connections between hydrogeology and carbon cycling in peatland systems and presents four future challenges for research in large northern peatlands. Discussion in this chapter is based on observations over the past 20 years at the patterned glacial Lake Agassiz peatlands (GLAP) in northern Minnesota, which has sufficient size and hydrologic variability to serve as a possible template for circumboreal peatlands, in general. The discussion herein is primarily focused on processes at depth within the peat profile and largely excludes research questions related to processes in the very top few tens of centimeters of the peat profile [e.g., *Belyea and Baird*, 2006].

2. GLACIAL LAKE AGASSIZ PEATLANDS

GLAP are a 7000-km^2 expanse of sub-boreal patterned peatlands in Northern Minnesota and Southern Manitoba (Figure 1). The patterned ecosystems at GLAP alternate between bogs that have total dissolved solids (TDS) less than 15 mg L^{-1} and pH less than 4.0, and fens with surface-water TDS greater than 50 mg L^{-1} and pH greater than 6.0 [*Glaser et al.*, 1981]. The raised bogs of the GLAP are dominated by *Picea mariana*, *Carex oligosperm*, and ericaceous shrubs with a continuous mat of *Sphagnum*, whereas fens are dominated by sedges, such as *Carex lasiocarpa* and *Rhynchospora alba* and various *Amblystigeaceae* mosses [*Glaser et al.*, 1981; *Heinselman*, 1970]. The peat thickness in the GLAP ranges from 2 to >4 m, reflecting mainly less than 5000 years of accumulation [*Glaser et al.*, 1997; *Janssen*, 1968]. The research summarized in this chapter is primarily from two sites (Figure 1), the Red Lake Bog which has an area of 151.4 km^2 and a basal depth of 341–345 cm, and the Lost River Bog which has an area of 16.3 km^2 and a basal depth of 320–325 cm [*Glaser et al.*, 1997]. The Red Lake bog is referred to as the Red Lake II bog in some publications [e.g., *Glaser et al.*, 1997, *Hogan et al.*, 2000].

The regional climate is more arid to the west and colder to the north. Average precipitation declines from 63.5 cm in the eastern part of GLAP to 55.8 cm in the west, whereas evapotranspiration increases from east to west [*Glaser et al.*, 1997]. The entire region is subject to extreme multiyear droughts [*Glaser et al.*, 1997]. The annual mean temperature ranges from 2.2° to 2.7°C (NCDC/NOAA Waskish Meteorological Station data from 1997 to 2000), and the GLAP is typically covered by at least 15 cm of snow 70 to 100 d a^{-1}. The peatlands straddle a north-south climate divide along which average annual evapotranspiration equals average annual precipitation. Evapotranspiration exceeds precipitation to the west and is less than precipitation to the east of the line [*Siegel et al.*, 1995]. Consequently, the peatland is highly sensitive to changes in regional climate.

Research over more than 20 years has shown that the evolution of the GLAP is closely controlled by local climate variability within the study area and regional-scale hydrogeologic systems. The importance of regional groundwater that discharges at the base of these peatlands, and which comprises a major component of their annual water budget, cannot be overstated. This upwelling is confirmed by (1) upward vertical hydraulic gradients at the base of many peat profiles [e.g., *Rosenberry et al.*, 2003], (2) elevated dissolved-ion species in pore water near the base of peat profiles [*Siegel et al.*, 1995], and (3) regional hydrogeologic models that elucidate the connection between regional groundwater flow systems and peatlands [*Siegel*, 1993].

The peatland hydrogeology within the GLAP, while moving relatively small amounts of water in terms of total flux, is dynamic. As in most groundwater systems, the flow of water through the GLAP is primarily horizontal, but there is also complex variability in vertical flow. At raised ombrotrophic

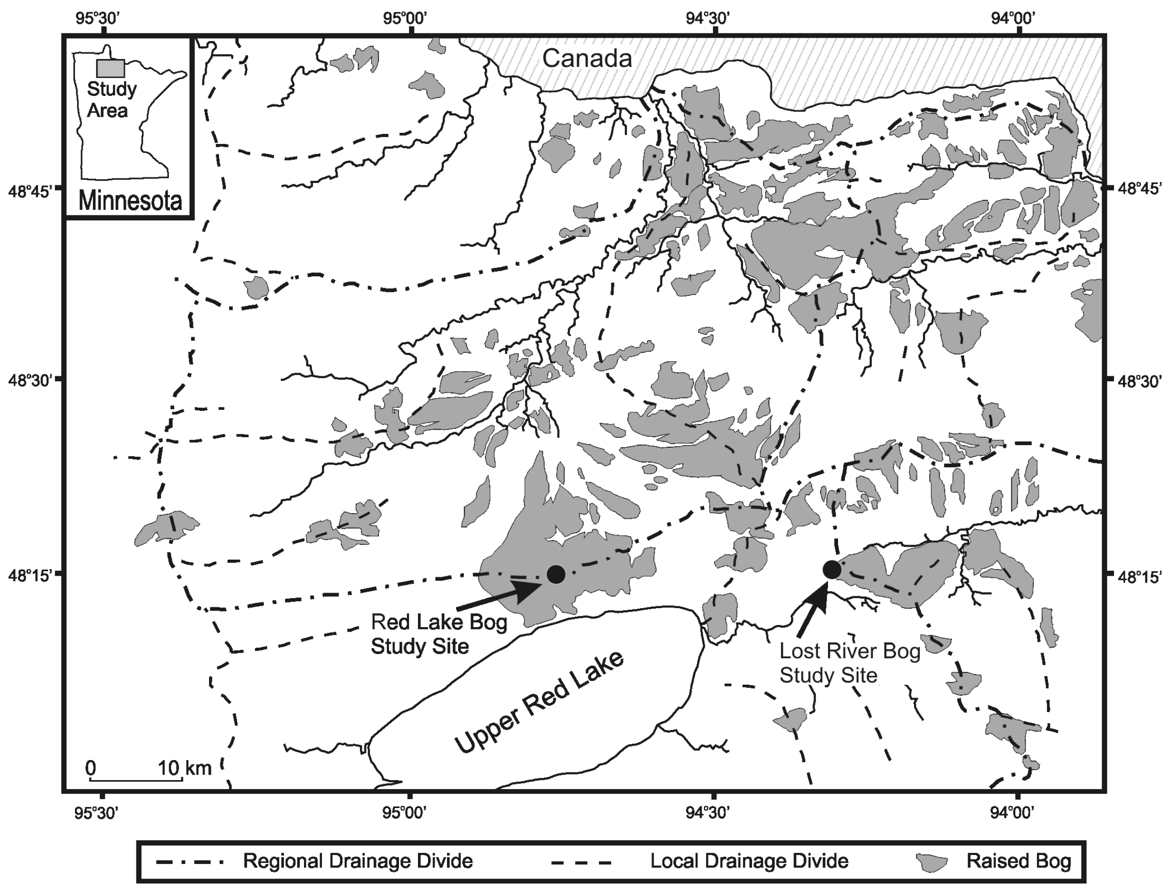

Figure 1. Map of the glacial Lake Agassiz peatlands (GLAP) with the three study sites indicated [*McKenzie et al.*, 2006].

bogs, such as Lost River, there is flow downward from the water table of the bog and upward flow from the base of the peat profile. These two vertical flow systems meet at an intermediate depth within the peat profile that varies over time (Figure 2). These groundwater flow systems connect to fens and water-track landforms originating on the bog flanks. Here, bog vegetation is succeeded by fen plants at what appear to be seepage faces. The fens are primarily dominated by the upward and lateral flow of minerotrophic groundwater [*Siegel and Glaser*, 1987]. Numerical modeling simulations by *Reeve et al.* [2000] show hydrologic interactions among local to intermediate scale groundwater flow systems beneath these peatlands and demonstrate the importance of the permeability of these underlying sediments.

Within this GLAP hydrogeologic framework, the direction and velocity of pore water flow in peatlands varies over seasonal, annual, and longer timescales. The interaction of meteorological events (such as drought) with regional groundwater flow systems creates a dynamic hydrogeologic flow system [*Siegel and Glaser*, 1987; *Reeve et al.*, 2006].

For example, flow reversals, when the vertical direction of pore water movement changes seasonally, have been documented at GLAP as well as in many peatland morphologies and locations [*Devito et al.*, 1997; *McKenzie et al.*, 2002; *Siegel et al.*, 1995]. At GLAP, detailed studies in the Lost River bog site show that groundwater flows upward into large, raised bogs during droughts, but in temperate years, groundwater moves predominately downward [*Glaser*, 1992; *Romanowicz et al.*, 1993; *Siegel*, 1983; *Siegel and Glaser*, 1987]. During long droughts, almost the entire peat column can be flushed by upwelling mineral water, and during long wet periods, surface water can penetrate almost to the mineral soil because of vertical recharge downward under developing water table mounds [*Siegel et al.*, 1995]. In general, the degree to which advective flow within raised bog peat occurs is related to the kind of subsurface mineral

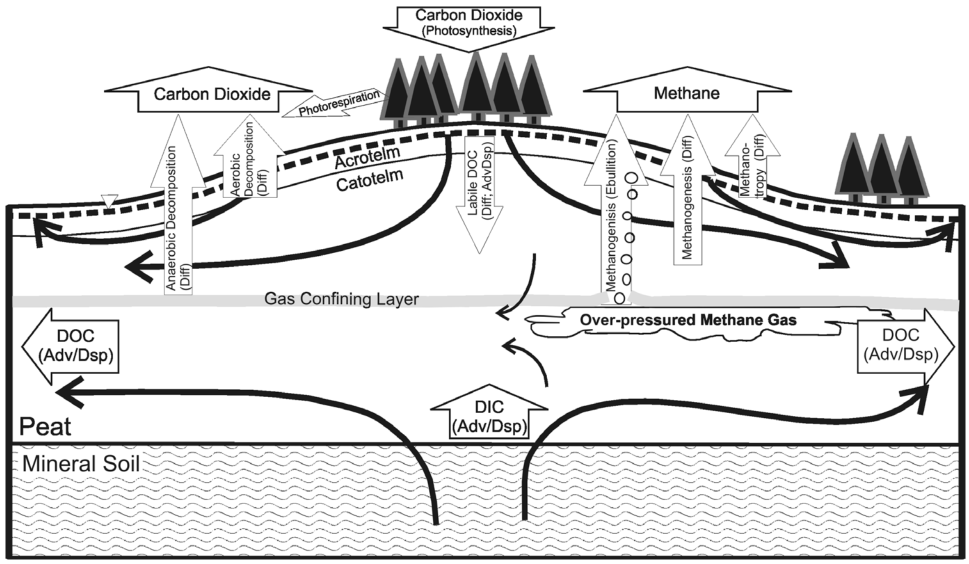

Figure 2. Conceptual model of the hydrogeology and carbon cycling of a representative peatland in the glacial Lake Agassiz peatlands. The dashed line represents the water table, and the line arrows indicate idealized groundwater flow paths. Image adapted from *Siegel et al.* [1995] and *Glaser et al.* [2004b]. Abbreviations are DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; Diff, diffusion; and Adv/Dsp, advection/dispersion.

soil beneath them. *Reeve et al.* [2000] used heuristic numerical modeling experiments to suggest that where bogs are underlain by permeable mineral soil, such as is in parts of the GLAP, their water table mounds can efficiently drive downward vertical flow. However, where bogs evolved over clayey low-permeable soils, such as in the Hudson Bay Lowlands, vertical flow in inhibited.

Advection may also be affected by hydraulic conductivity that varies temporally in response to changing volumes of biogenic gas trapped beneath semielastic, semipermeable layers of woody debris in the peat [*Rosenberry et al.*, 2003]. Trapped gas can occlude pores in the peat and locally reduce hydraulic conductivity, preventing vertical flow of water in a finite volume of the peat beneath the trapped gas. Sudden releases of trapped gas could result in near instantaneous changes in direction of flow within the peat in response to rapidly changing pressure fields that occur as gas is released, either to a shallower depth within the peat column or to the atmosphere.

3. CARBON CYCLING

The simplest view of peatlands is a two-layer system where the acrotelm is responsible for the majority of organic matter decomposition (90% of total organic carbon decomposition), and the lower, anaerobic layer (catotelm) stores the bulk of undecomposed carbon and has very slow decomposition rates [*Clymo*, 1984]. Active and alive vegetation at the surface of the peat column sequesters carbon dioxide from the atmosphere, photorespires carbon dioxide back to the atmosphere, and produces organic litter. This organic litter is either oxidized in the oxic zone above the water table or is buried and stored below the water table [*Clymo*, 1984]. *Blodau* [2002] and *Limpens et al.* [2008] provide thorough reviews of carbon cycling and carbon budgets in peatlands. While thorough in terms of surface-water runoff and water table fluctuation, they present little information regarding subsurface hydrogeology and carbon cycling of peatlands.

Hydrogeology and carbon cycling are connected by solute transport, the process by which dissolved substances are transported via advection, dispersion, and diffusion. The peat matrix presents particular challenges for studying solute transport because of its dual porosity nature and changing bulk density in response to water table changes [*Hoag and Price*, 1997; *Price*, 1997]. Decomposed peat has a high total porosity (>90%) but a low effective porosity and permeability [*Ours et al.*, 1997]. Advection is the primary process that moves solutes vertically through peat profiles, which is easily confirmed by looking at pore water chemistry profiles. For example, in the Red Lake bog, increasing total dissolved solids is observed near the base of profiles in conjunction with upward hydraulic gradients. These are interpreted to be the result of upward advection of minerotrophic waters from underlying inorganic sediments. Work by *Reeve et al.* [2001] has shown that transverse dispersion along long horizontal flow paths can also move solutes upward from underlying, solute-rich waters in mineral soils into peat profiles. Although dispersive mixing is important, the low flux of water through some peatland systems, especially in non-domed systems, creates situations where the diffusive flux of solutes may be more important than advection. At millennial scales, changing degrees of diffusion and advection of solutes from underlying sediments, coupled to the accumulation of peat, can significantly impact how water and solutes move in peat. *McKenzie et al.* [2002] found that the vertical accumulation of 3.5 m of peat in ~7000 C^{14} years in an alpine bog in Switzerland created downward hydraulic head gradients and forced a change from diffusive to advective vertical solute transport as the bog grew.

Although many of these processes happen on decadal or longer timescales, there are short, potentially more significant processes that control the flux of carbon into and out of the peatland system. Although dissolved organic carbon is removed from both the catotelm and acrotelm by runoff, and moved to deeper systems through groundwater recharge, the aerobic and anaerobic decomposition of organic carbon also leads to the loss of carbon to the atmosphere by diffusion of dissolved CO_2 and CH_4. Some gas emissions are sufficient to alter the elevation and horizontal position of the peat surface [*Glaser et al.*, 2004b]. CO_2 and CH_4 can also escape to the atmosphere through buoyancy-driven ebullition fluxes, potentially releasing large amounts of carbon [*Rosenberry et al.*, 2003; *Glaser et al.*, 2004b; *Baird et al.*, 2004; *Kellner et al.*, 2004; *Strack et al.*, 2006]. These episodic carbon emissions from boreal peatlands have largely gone undetected and have only recently begun to be quantified [*Rosenberry et al*., 2006].

4. CHALLENGES

Previous and ongoing research has provided many key observations and hypotheses that lead to an improved understanding of many of the hydraulic and biogeochemical processes in peatlands. Research, both at the GLAP and at other northern peatlands, shows that the connections between hydrogeology and carbon cycling remain somewhat disjointed and site specific. Following are four suggested major scientific challenges for future research of large northern peatlands, in general. These challenges are by no means encompassing all research challenges, but are developed based on questions arising from GLAP research that are applicable to northern peatlands, in general. Generalized process-based solutions to these problems will help lead to a unified theory connecting hydrogeology and carbon dynamics.

4.1. The Spatial Extent of Climate-Driven Flushing; the Lost River Scenario

The GLAP Lost River peatland is notable for its climate-driven flushing of pore water [*Romanowicz et al.*, 1993; *Siegel and Glaser*, 1987; *Siegel et al.*, 1995], wherein short droughts lead to changes in the vertical direction of pore water flow at depth, and a multiyear drought leads to a complete upward flushing of the dilute peat system with minerotrophic groundwater. These results have important implications for the future ecology of peatlands within a climate change framework; specifically, changes in climate may substantially alter the solute transport regime via pore water flushing. Should extended droughts persist in peatlands, groundwater mounds under bogs will likely dissipate, and the combination of advective discharge from mineral soils, diffusion, and changes in pH will logically lead to more homogeneous landscapes where fen vegetation succeeds in bogs. This process would constitute a landscape-scale reversal of bog ecosystem succession over fens in patterned peatlands that has persisted for thousands of years, since deglaciation. While the Lost River conclusions are remarkable in demonstrating the potential dynamism and adaptability of flow in a large peatland, there are many research challenges.

The principle challenge is to determine and understand the controls of the geospatial frequency of occurrence of groundwater reversals within patterned peatlands, in general. Addressing this challenge will help generalize whether these types of flow systems should be expected in other peatlands and, if so, what their net effect would be in terms of carbon cycling.

For example, the contrast between the peatlands of the Hudson Bay Lowlands and the GLAP Lost River system is indicative of the difficulty in generalizing system dynamics. In the Hudson Bay Lowlands region, pore water flushing, driven by climate change, has not yet been observed; most pore water chemistry profiles are dominated by recharge with stable distributions of total dissolved solids with depth [*Reeve et al.*, 1996]. These differences lead to a general challenge of determining if the GLAP constitutes a unique hydrogeologic setting that is essentially the result of "ideal" conditions caused by more permeable underlying sediments, allowing for more upward discharge of groundwater. Similar studies need to be done in other patterned peatlands to come to valid generalizations.

There are a range of possible climate change impacts on northern peatland systems with the common research focus being on drier conditions leading to increased methane generation at depth [*Ise et al.*, 2008; *Moore et al.*, 1998]. If, in the Lost River peatland, drought conditions are assumed without a significant lowering of hydraulic head in regional groundwater systems, there would potentially be less methane generated because labile carbon delivered by advection downward to methanogens would cease [*Chanton et al.*, 1995; *Siegel et al.*, 1995]. On a broader scientific scale, these results present a significant challenge to understand and quantify the interaction of intermediate to regional scale groundwater-flow systems on the hydrogeology of northern peatlands and the associated transport of carbon [*Siegel*, 1993].

4.2. Hydrogeologic and Isotopic Complexities and Contradictions

The measurement of physical parameters, such as permeability, in peatlands is inherently difficult because of easily deformable peat materials, scale dependency of permeability, and hydrologic heterogeneity [e.g., *Chason and Siegel*, 1986; *Beckwith et al.*, 2003; *Rosa and Larocque*, 2007]. Isotopic tracers can be used to constrain uncertainties in the source, direction, and velocity of peatland flow systems [*Clark and Fritz*, 1997]. Research using pore water isotope data in the GLAP has produced results that may contradict some of the hydrogeologic hypotheses and point to previously unobserved heterogeneities and unexplained errors in the water budget.

At the Red Lake bog, *Hogan et al.* [2000] used strontium isotopes and observed that 90–100% of pore water in the upper 2 m of peat was meteorically derived, but the lower 2+ m of pore water was a mixture of precipitation and groundwater. At both the Red Lake bog and adjacent fen sites, the chemical concentrations and isotopic values showed extensive variability, potentially indicating macropore flow as an important hydrochemical transport pathway [*Beven and Germann*, 1982; *Holden et al.*, 2001; *Holden*, 2005]. The strontium isotopic results suggest there is a source of water that does not match the isotopic signature of groundwater or precipitation and could only partially be explained by organic matter mineralization. The results also showed that the groundwater discharging into the base of the bog and the fen were isotopically distinct, indicating multiple distinct flow systems. *Sarkar et al*. [2008] found water with an evaporative isotopic signal in deep fen water, suggesting groundwater flowing across the major southern watershed divide defining the GLAP watershed. *Chasar et al*. [2000] used carbon isotopes to assess the source of mineralized carbon at depth within the Red Lake peatland. The results showed that methane produced at depth within the peat profile was a mixture of both older, more recalcitrant, carbon and modern labile carbon sourced from the active top layer of peat. The carbon isotopic results also indicate that dissolved inorganic carbon in upwelling groundwater was a major source of subsequently reduced carbon.

These types of isotopic studies show that the linkages of regional hydrogeology (i.e., areas larger than the GLAP), peatlands hydrogeology, and carbon transport within the GLAP are potentially contradictory and far more complex than previously thought [e.g., *Siegel*, 1993], even after decades of research. For example, in the Red Lake bog, the main zone of deep methane generation (approximately 2-m depth) is hydraulically overpressured with respect to the pore water above and below, yet to explain the observed methane generation, based on the isotopic observations, there needs to be a significant downward flux of labile carbon to this zone [*Hogan et al.*, 2000]. Much of this complexity is likely related to subsurface heterogeneities in the mineral soils and within the peat.

These contradictory results present an interesting research challenge. Generalization to all northern peatlands may be impossible as there may be no unique model of dissolved organic carbon (DOC) transport, hydrogeologic setting, and carbon mineralization. Fundamental to the research challenge discussed in this section is determining if the complexities in the hydrogeologic heterogeneities observed at the GLAP are common to other northern peatlands, and if so, quantifying the hydrogeologic and biogeochemical processes.

4.3. Methane Production, Entrapment, and Release From Peatlands

A current peatland research topic is the characterization and quantification of the processes that control subsurface anaerobic production, entrapment, and release. *Weber* [1906] first reported on the phenomenon of peat land surfaces fluctuating in elevation over diurnal or longer time spans. *Fechner-Levy and Hemond* [1996] suggested that this vertical movement of a peat surface is caused by the interaction of free-phase methane gases trapped at depth within the peat column and atmospheric pressure, a now established hypothesis. At the GLAP Red Lake bog, high precision differential GPS were used to observe changes in bog surface elevation of up to 30 cm [*Glaser et al.*, 2004b] and that most of those elevation fluctuations closely correlated to daily and subweekly changes in barometric pressure [*Rosenberry et al.*, 2003]. Within these surface-elevation fluctuations, there are pronounced rapid drops and slow rises in the surface of the peat that are unrelated to barometric pressure, but are very closely related to rapid drops in pressure at 2-m depth within the peat profile. It is hypothesized that methane gas forms at or below 2 m at high enough concentrations to form free-phase methane gas and that changes in atmospheric barometric pressure compress this zone, allowing the surface of the peat to fluctuate up and down [*Glaser et al.*, 2004b]. The rapid drops in the peat surface are caused by large ebullition events when methane gas rapidly escapes to the surface, and the peat surface collapses similar to a soufflé deflating [*Glaser et al.*, 2004b].

Rosenberry et al. [2006] provide an in-depth review of much of the literature related to biogenic gas formation and escape. The ebullition pathways for methane release can be enigmatic and poses numerous research challenges including to understand the rates and mechanisms that control methane production, entrapment, and release. The primary controls on methane generation are temperature [*Hulzen et al.*, 1999; *Updegraff et al.*, 1998], carbon supply [*Chanton et al.*, 1995], and water table position [*Ise et al.*, 2008; *Moore and Dalva*, 1993]. The mechanisms that control production, entrapment, dissolution, and release of methane are not yet all understood, although researchers are using a variety of innovative techniques to image and understand the controlling processes, including geophysical methods [*Comas et al.*, 2007], time-domain reflectometry [*Beckwith and Baird*, 2001], coring [*Glaser et al.*, 2004b], differential GPS [*Glaser et al.*, 2004b], direct measurement [*Almendinger et al.*, 1986; *Roulet*, 1991], and ex situ imaging such as X-ray tomography [*Kettridge and Binley*, 2008]. Linking and scaling these disparate data to wider areas remains a major research challenge. Problems associated with scaling hydrologic data are well known, such as the scale dependency of hydraulic conductivity [*Freeze and Cherry*, 1979; *Surridge et al.*, 2005], and similar scale-dependent challenges will exist in expanding these detailed studies to the entire peatland scale, in particular, to expand to the peatland three-dimensional (3-D) landscape [*Rosenberry et al.*, 2006].

Evaluating how overpressured in situ methane at depth affects the internal hydrodynamics of bogs and the extent to which this overpressuring occurs in peatlands, in general, is another question for future research. The question of hydrodynamic trapping of overpressured methane still needs to be better quantified to determine why methane traps are being formed at depth. Why are methane traps being formed at depth? Local free-phase gas will obviously occlude pores and decrease hydraulic conductivity, but the observed cycles of trap and release is not fully understood. A possible model to explain these cycles would be elastic deformation [*Ingebritsen et al.*, 2006], though more research is required to understand the physical properties of the peat and the threshold required for accumulating and trapping gas. Although this research challenge focuses on ebullition from northern peatlands, seasonal freezing and permafrost are a dominant factor in controlling the atmospheric flux of carbon in the arctic and sub-Arctic [e.g., *Christensen et al.*, 2004; *Rivkina et al.*, 1998].

4.4. The Warming and Subsequent Thawing of the Arctic and Peatlands

As is often pointed out by research in high latitudes and in the popular press, continued climate change and warming of the arctic is leading to thawing permafrost in northern peatlands and the rapid release of carbon [e.g., *Kolbert*, 2005; *Serreze et al.*, 2000]. Observed hydrologic response to arctic warming include increasing groundwater contributions to surface-water systems [*Walvoord and Striegl*, 2007], disappearance of lakes sitting on top of permafrost [*Smith et al.*, 2005], and increases in the flux of carbon to the atmosphere [*Ise et al.*, 2008]. The net response of northern peatlands to warming is a balance between increased biological productivity and increased carbon decomposition rates, two factors that are closely controlled by soil temperature, meteorology, and surface hydrology [*Davidson and Janssens*, 2006].

A major concern with ongoing warming is that decreased moisture inputs will lead to a lowering of the water table that will consequently generate increases in methane emissions and DOC runoff due to additional aerobic peat mineralization [e.g., *Ise et al.*, 2008; *Moore and Dalva*, 1993]. An increase in surface temperatures will increase temperatures throughout the peat column [*McKenzie et al.*, 2006] leading to increased carbon decomposition rates within the catotelm [*Moore and Dalva*, 1993]. A long-term lowering of the water table will also increase vegetative activity and cause increased DOC production and runoff [*Strack et al.*, 2008]. All of these factors, on a global scale, have the potential to act as a warming feedback, reinforcing concerns regarding the warming of northern peatlands.

Increased temperatures with decreased moisture is the most commonly predicted scenario that is analyzed in terms of the peat-carbon dynamics. Increased temperatures should increase the size of the active zone. With a decrease in moisture and a thinner snowpack, greater frost penetration or a thicker accumulation of ice at the peat surface could trap free-phase gas within the peat, causing large ebullition events during spring thaw [*Rosenberry et al*., 2006]. In areas where there would be increased moisture and a thicker snow cover, increased insulation could result in higher subsurface temperatures.

Within this context of a warming arctic, there are many challenges to understanding the impact on peatlands including the impact of thawing permafrost in arctic and subarctic regions, thickening of the active zone above permafrost, and changes in the moisture.

Heat transport through peatlands is primarily dominated by conduction as opposed to advection due to low pore water flow velocities [*McKenzie et al.*, 2006; *Moore*, 1987]. The impact of freezing on hydrogeology is commonly minimized, but it can have a strong control on pore water flow by decreasing permeability and effective porosity, while increasing heat capacity and thermal conductivity [*McKenzie et al.*, 2007]. Freezing can also exert a strong control on hydrogeology through cryogenic suction, ice lensing, and chemical segregation effects [*Williams and Smith*, 1989].

These potential future changes in temperature and hydrogeology inherently will lead to feedback mechanisms with implications for carbon cycling. Higher air temperatures will increase the size of the active zone in permafrost areas, leading to greater shallow methane production through longer growing seasons and warmer temperatures. In the Siberian peatlands, these feedbacks are already observed in permafrost lakes [*Walter et al.*, 2006] and with increasing DOC runoff [*Frey and Smith*, 2005].

Much of the focus on arctic warming has used anthropogenic peat dewatering as an analog for warming scenarios and enhanced methane generation, but it is unclear that in all areas, there will be a net drying of peatlands. The prediction of peatland moisture regimes is complicated [*Koutsoyiannis et al.*, 2008], and with increased moisture, it would actually be expected to decrease decomposition rates, a situation that may occur through increased precipitation or permafrost thawing [*Davidson and Janssens*, 2006]. Additionally, the response of the peat system to drying is likely a function of the rate of drying with time, which is much faster for dewatering than for climatic scale changes to precipitation rates.

Additional impacts of permafrost melting include effects of seasonal freeze-thaw cycles on transport of solutes and organic carbon. Current research and numerical models of these processes are primarily focused in 1-D vertical profiles [*McKenzie et al.*, 2007], which need to be scaled to 2- and 3-D experiments because it is known that carbon movement through these systems is strongly controlled by regional flow patterns [*Reeve et al.*, 2001].

5. SUMMARY AND CONCLUSIONS

There are many challenges remaining for a comprehensive understanding of the impact climate change has on northern peatlands. Within this context, this chapter identifies research questions related to the hydrogeology of peatlands and its connection to carbon transport and cycling. Although the research presented here is primarily focused on the GLAP, the identified water and carbon flux challenges are applicable to other large peatland areas such as the Hudson Bay Lowland [*Roulet et al.*, 1994] and the Siberian Peatlands [*Frey and Smith*, 2005]. This transfer ability assumes that the GLAP is representative of northern peatlands, an argument that is difficult to prove. This particular issue is itself a research challenge, how to generalize and apply the more site-specific phenomena observed in the GLAP to other peatlands across the very broad northern-peatland scale.

This chapter is focused on the deeper groundwater processes within peatlands and, as such, does not give adequate treatment to methane generation or consumption near the peat surface. There are many complex feedbacks associated with water table position both seasonally and over climate timescales. These fluctuations will govern whether a given peatland is a net sink or source of carbon [*Strack et al.*, 2004], a situation with obvious implications for methane feedbacks to the atmosphere.

At the global scale, the impact of peatlands and their feedback on future climate is not well understood. There are still many unknowns regarding the rates of arctic warming and permafrost thawing, and their impact on peatlands. Global climate simulations do not include peatlands at this point [*Limpens et al.*, 2008], an omission that has important implications considering the potential feedback of peatlands for increasing carbon dioxide and methane levels in the atmosphere.

REFERENCES

Almendinger, J. C., J. E. Almendinger, and P. H. Glaser (1986), Topographic fluctuations across a spring fen and raised bog in the Lost River Peatland, Northern Minnesota, *J. Ecol.*, *74*, 393–401.

Baird, A. J., C. W. Beckwith, S. Waldron, and J. M. Waddington (2004), Ebullition of methane-containing gas bubbles from near-surface *Sphagnum* peat, *Geophys. Res. Lett.*, *31*, L21505, doi:10.1029/2004GL021157.

Beckwith, C. W., and A. J. Baird (2001), Effect of biogenic gas bubbles on water flow through poorly decomposed blanket peat, *Water Resour. Res.*, *37*(3), 551–558.

Beckwith, C. W., A. J. Baird, and A. L. Heathwaite (2003), Anisotropy and depth-related heterogeneity of hydraulic conductivity in a bog peat. I: Laboratory measurements, *Hydrol. Processes*, *17*, 89–101.

Belyea, L. R., and A. J. Baird (2006), Beyond "the limits to peat bog growth": Cross-scale feedback in peatland development, *Ecol. Monogr.*, *76*(3), 299–322.

Beven, K., and P. Germann (1982), Macropores and water flow in soils, *Water Resour. Res.*, *18*(5), 1311–1325.

Blodau, C. (2002), Carbon cycling in peatlands—A review of processes and controls, *Environ. Rev.*, *10*(2), 111–134.

Boelter, D., and E. S. Verry (1977), Peatand and water, *Gen. Tech. Rep. NC-31*, 22 pp., U.S. Dep. of Agric. For. Serv.

Chanton, J. P., J. E. Bauer, P. A. Glaser, D. I. Siegel, C. A. Kelley, S. C. Tyler, E. H. Romanowicz, and A. Lazrus (1995), Radiocarbon evidence for the substrates supporting methane formation within northern Minnesota peatlands, *Geochim. Cosmochim. Acta*, *59*(17), 3663–3668.

Chasar, L. S., J. P. Chanton, P. H. Glaser, D. I. Siegel, and J. S. Rivers (2000), Radiocarbon and stable carbon isotopic evidence for transport and transformation of dissolved organic carbon, dissolved inorganic carbon, and CH_4 in a northern Minnesota Peatland, *Global Biogeochem. Cycles*, *14*(4), 1095–1108.

Chason, D., and D. Siegel (1986), Hydraulic conductivity and related physical properties of peat, Lost River Peatland, northern Minnesota, *Soil Sci.*, *142*(2), 91–99.

Christensen, T. R., T. Johansson, H. J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B. H. Svensson (2004), Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, *Geophys. Res. Lett.*, *31*, L04501, doi:10.1029/2003GL018680.

Clark, I. D., and P. Fritz (1997), *Environmental Isotopes in Hydrogeology*, 328 pp., CRC Press Lewis Publishers, Boca Raton, FL.

Clymo, R. S. (1984), The limits to peat bog growth, *Philos. Trans. R. Soc. London, B, Biol. Sci.*, *303*(1117), 605–654.

Comas, X., L. Slater, and A. S. Reeve (2007), In situ monitoring of free-phase gas accumulation and release in peatlands using ground penetrating radar (GPR), *Geophys. Res. Lett.*, *34*, L06402, doi:10.1029/2006GL029014.

Davidson, E. A., and I. A. Janssens (2006), Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, *Nature*, *440*, 165–173.

Devito, K. J., J. M. Waddington, and B. A. Branfireun (1997), Flow reversals in peatlands influenced by local groundwater systems, *Hydrol. Processes*, *11*(1), 103–110.

Fechner-Levy, E. J., and H. F. Hemond (1996), Trapped methane volume and potential effects on methane ebullition in a northern peatland, *Limnol. Oceanogr.*, *41*, 1375–1383.

Freeze, R. A., and J. A. Cherry (1979), *Groundwater*, 604 pp., Prentice-Hall, Englewood Cliffs, N. J.

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), Peat Landforms, in *Patterned Peatlands of Northern Minnesota*, edited by H. E. J. Wright et al., p. 327, Univ. of Minn., Minneapolis.

Glaser, P. H., G. A. Wheeler, E. Gorham, and H. E. Wright, Jr. (1981), The patterned mires of the Red Lake peatland, northern Minnesota: Vegetation, water chemistry and landforms, *J. Ecol.*, *69*, 575–599.

Glaser, P. H., D. I. Siegel, E. A. Romanowicz, and Y. P. Shen (1997), Regional linkages between raised bogs and the climate, groundwater, and landscape features of northwestern Minnesota, *J. Ecol.*, *85*, 3–16.

Glaser, P. H., B. C. S. Hansen, D. I. Siegel, A. S. Reeve, and P. J. Morin (2004a), Rates, pathways and drivers for peatland development in the Hudson Bay Lowlands, northern Ontario, Canada, *J. Ecol.*, *92*, 1036–1053.

Glaser, P. H., J. P. Chanton, P. Morin, D. O. Rosenberry, D. I. Siegel, O. Ruud, L. I. Chasar, and A. S. Reeve (2004b), Surface deformations as indicators of deep ebullition fluxes in a large northern peatland, *Global Biogeochem. Cycles*, *18*, GB1003, doi:10.1029/2003GB002069.

Gorham, E. (1991), Northern peatlands: Role in the carbon cycle and probable responses to climatic warming, *Ecol. Appl.*, *1*, 182–193.

Gorham, E., J. A. Janssens, and P. H. Glaser (2003), Rates of peat accumulation during the postglacial period in 32 sites from Alaska to Newfoundland, with special emphasis on northern Minnesota, *Can. J. Bot.*, *81*, 429–438.

Heinselman, M. L. (1970), Landscape evolution, peatland types, and the environment in the Lake Agassiz Peatlands Natural Area, Minnesota, *Ecol. Monogr.*, *40*, 235–261.

Hoag, R. S., and Price, J. S. (1997), The effects of matrix diffusion on solute transport and retardation in undisturbed peat in laboratory columns, *J. Contam. Hydrol.*, *28*, 193–205.

Hogan, J. F., J. D. Blum, D. I. Siegel, and P. H. Glaser (2000), ^{87}Sr/ ^{86}Sr as a tracer of groundwater discharge and precipitation recharge in the glacial Lake Agassiz peatlands, northern Minnesota, *Water Resour. Res.*, *36*(12), 3701–3710.

Holden, J. (2005), Piping and woody plants in peatlands: Cause or effect?, *Water Resour. Res.*, *41*, W06009, doi:10.1029/2004WR003909.

Holden, J., T. P. Burt, and N. J. Cox (2001), Macroporosity and infiltration in blanket peat: The implications of tension disc infiltrometer measurements, *Hydrol. Processes*, *15*, 289–303.

Hulzen, J. B. V., R. Segers, P. M. V. Bodegom, and P. A. Leffelaar (1999), Temperature effects on soil methane production: An explanation for observed variability, *Soil Biol. Biochem.*, *31*, 1919–1929.

Ingebritsen, S., W. Sanford, and C. Neuzil (2006), *Groundwater in Geologic Processes*, 2nd ed., 536 pp., Cambridge Univ. Press, New York.

Ingram, H. A. P. (1982), Size and shape in raised mire ecosystems: A geophysical model, *Nature*, *297*(5864), 300–303.

Ise, T., A. L. Dunn, S. C. Wofsy, and P. R. Moorcroft (2008), High sensitivity of peat decomposition to climate change through water-table feedback, *Nat. Geosci.*, *1*, 763–766, doi:10.1038/ngeo331.

Ivanov, K. (1975), *Water Movement in Mirelands*, translated from Russian by A. Thomson and H. A. P. Ingram, Academic, New York.

Janssen, C. R., (1968), Myrtle Lake: A late- and post-glacial pollen diagram from northern Minnesota, *Can. J. Bot.*, *46*, 1397–1408.

Kellner, E., J. S. Price, and J. M. Waddington (2004), Pressure variations in peat as a result of gas bubble dynamics, *Hydrol. Processes*, *18*, 2599–2605.

Kettridge, N., and A. Binley (2008), X-ray computed tomography of peat soils: Measuring gas content and peat structure, *Hydrol. Processes*, *22*(25), 4827–4837, doi:10.1002/hyp.7097.

Kolbert, E. (2005) The climate of man—I: Disappearing islands, thawing permafrost, melting polar ice. How the earth is changing, *New Yorker*, *81*, 56–71.

Koutsoyiannis, D., A. Efstratiadis, N. Mamassis, and A. Christofides (2008), On the credibility of climate predictions, *Hydrol. Sci. J*, *53*(4), 671–684.

Limpens, J., F. Berendse, C. Blodau, J. G. Canadell, C. Freeman, J. Holden, N. Roulet, H. Rydin, and G. Schaepman-Strub (2008), Peatlands and the carbon cycle: From local processes to global implications—A synthesis, *Biogeosci. Discuss.*, *5*, 1379–1419.

McKenzie, J. M., D. I. Siegel, W. Shotyk, P. Steinmann, and G. Pfunder (2002), Heuristic numerical and analytical models of the hydrologic controls over vertical solute transport in a domed peat bog, Jura Mountains, Switzerland, *Hydrol. Processes*, *16*(5), 1047–1064.

McKenzie, J. M., D. I. Siegel, D. O. Rosenberry, P. H. Glaser, and C. I. Voss (2006), Heat Transport in the Red Lake Bog, Glacial Lake Agassiz Peatlands, *Hydrol. Processes*, *21*(3), 369–378, doi:10.1002/hyp.6239.

McKenzie, J. M., C. I. Voss, and D. I. Siegel (2007), Groundwater flow with energy transport and water-ice phase change: Numerical simulations, benchmarks and application to freezing in peat bogs, *Adv. Water Resour.*, *30*, 966–983, doi:10.1016/j.advwatres.2006.08.008.

Moore, T. (1987), Thermal regime of peatlands in subarctic eastern Canada, *Can. J. Earth Sci.*, *24*, 1352–1359.

Moore, T., N. T. Roulet, and J. Waddington (1998), Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands, *Clim. Change*, *40*, 229–245.

Moore, T. R., and M. Dalva (1993), The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils, *J. Soil Sci.*, *44*, 651–664.

National Wetland Working Group (1997), *The Canadian Wetland Classification System*, 2nd ed., 69 pp., Wetland Res. Cent. Publ., Waterloo, Ont., Canada.

Ours, D. P., D. I. Siegel, and P. H. Glaser (1997), Chemical dilation and the dual porosity of humified bog peat, *J. Hydrol.*, *196*(1–4), 348–360.

Price, J. S. (1997), Soil moisture, water tension, and water table relationships in a managed cutover bog, *J. Hydrol.*, *202*, 1579–1589.

Reeve, A. S., D. I. Siegel, and P. H. Glaser (1996), Geochemical controls on peatland pore water from the Hudson Bay Lowland: A multivariate statistical approach, *J. Hydrol.*, *181*(1–4), 285–304.

Reeve, A. S., D. I. Siegel, and P. H. Glaser (2000), Simulating vertical flow in large peatlands, *J. Hydrol.*, *227*, 207–217.

Reeve, A. S., D. I. Siegel, and P. H. Glaser (2001), Simulating dispersive mixing in large peatlands, *J. Hydrol.*, *242*, 103–114.

Reeve, A. S., R. Evensen, P. H. Glaser, D. I. Siegel, and D. Rosenberry (2006), Flow path oscillations in transient ground-water simulations of large peatland systems, *J. Hydrol.*, *316*, 313–324.

Rivers, J. S., D. I. Siegel, L. S. Chasar, J. P. Chanton, P. H. Glaser, N. T. Roulet, and J. M. McKenzie (1998), A stochastic appraisal of the annual carbon budget of a large circumboreal peatland, Rapid River watershed, northern Minnesota, *Global Biogeochem. Cycles*, *12*(4), 715–727.

Rivkina, E., D. Gilichinsky, S. Wagener, J. Tiedje, and J. McGrath (1998), Biogeochemical activity of anaerobic microorganisms from buried permafrost sediments, *Geomicrobiol. J.*, *15*, 187–193.

Romanowicz, E. A., D. I. Siegel, and P. H. Glaser (1993), Hydraulic reversals and episodic methane emissions during drought cycles in mires, *Geology*, *21*(3), 231–234.

Rosa, E., and M. Larocque (2007), Investigating peat hydrological properties using field and laboratory methods: Application to the Lanoraie peatland complex (southern Quebec, Canada), *Hydrol. Processes*, *22*(12), 1866–1875.

Rosenberry, D. O., P. H. Glaser, D. I. Siegel, and E. P. Weeks (2003), Use of hydraulic head to estimate volumetric gas content and ebullition flux in northern peatlands, *Water Resour. Res.*, *39*(3), 1066, doi:10.1029/2002WR001377.

Rosenberry, D. O., P. H. Glaser, and D. I. Siegel (2006), The hydrology of northern peatlands as affected by biogenic gas: Current developments and research needs, *Hydrol. Processes*, *20*, 3601–3610.

Roulet, N. T. (1991), Surface level and water table fluctuations in a subarctic fen, *Arct. Alp. Res.*, *23*, 303–310.

Roulet, N. T., A. Jano, C. Kelly, L. Klinger, T. Moore, R. Protz, J. Ritter, and W. Rouse (1994), Role of the Hudson Bay lowlands as a source of atmospheric methane, *J. Geophys. Res.*, *99*, 1439–1454.

Sarkar, S., D. I. Siegel, P. H. Glaser, and J. Chanton (2008), Deep Ground Water through Stable Isotopic Analysis in a Large Circumboreal Peatland, Abstract 147296, paper presented at Joint Meeting of the Geological Society of America, Houston, Tex.

Serreze, M. C., J. E. Walsh, F. S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and Barry, G. (2000), Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207.

Siegel, D. I. (1983), Ground water and the evolution of patterned mires, Glacial Lake Agassiz Peatlands, northern Minnesota, *J. Ecol.*, *71*(3), 913–921.

Siegel, D. I. (1993), Groundwater Hydrology, Chapter 11, in *The Patterned Peatlands of Northern Minnesota*, edited by H. E. Wright, Jr., pp. 163–173, Univ. of Minn. Press, Minneapolis.

Siegel, D. I., and P. H. Glaser (1987), Groundwater flow in a bog-fen complex, Lost River peatland, northern Minnesota, *J. Ecol.*, *75*, 743–754.

Siegel, D. I., A. S. Reeve, P. H. Glaser, and E. A. Romanowicz (1995), Climate-driven flushing of pore water in peatlands, *Nature*, *374*(6522), 531–533.

Siegel, D. I., J. P. Chanton, P. H. Glaser, L. S. Chasar, and D. O. Rosenberry (2001), Estimating methane production rates in bogs and landfills by deuterium enrichment of pore water, *Global Biogeochem. Cycles*, *15*(4), 967–975.

Smith, L., C. Y. Sheng, G. M. MacDonald, and L. D. Hinzman (2005), Disappearing Arctic Lakes, *Science*, *308*, 1429.

Strack, M., J. M. Waddington, and E.-S. Tuittila (2004), Effect of water table drawdown on northern peatland methane dynamics: Implications for climate change, *Global Biogeochem. Cycles*, *18*, GB4003, doi:10.1029/2003GB002209.

Strack, M., E. Kellner, and J. M. Waddington (2006), Effect of entrapped gas on peatland surface level fluctuations, *Hydrol. Processes*, *20*, 3611–3622.

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. Processes*, *22*, 3373–3385.

Surridge, B., A. J. Baird, and A. L. Heathwaite (2005), Evaluating the quality of hydraulic conductivity estimates from piezometer slug tests in peat, *Hydrol. Processes*, *19*, 1227–1244.

Updegraff, K., S. D. Bridgham, J. Pastor, and P. Weishampel (1998), Hysteresis in the temperature response of carbon dioxide and methane production in peat soils, *Biogeochemistry*, *43*, 253–272.

Verry, E. S., and D. Boelter (1978), *Wetland Functions and Values: The State of Our Understanding*, pp. 389–402, Am. Water Resour. Assoc., Middleburg, VA.

Waddington, J., T. Griffis, and W. Rouse (1998), Northern Canadian wetlands: Net ecosystem CO_2 exchange and climatic change, *Clim. Change*, *40*, 267–275.

Walter, K. M., S. A. Zimov, J. P. Chanton, D. Verbyla, and F. S. Chapin III (2006), Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming, *Nature*, *443*, 71–75, doi:10.1038/nature05040.

Walvoord, M. A., and R. G. Striegl (2007), Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen, *Geophys. Res. Lett.*, *34*, L12402, doi:10.1029/2007GL030216.

Weber, C. A. (1906), *Uber die Vegetation und Entstehung des Hochmors von Augstumal im Memeldelta*, 252 pp., Velagsbuchhandlung, Berlin.

Williams, P. J., and M. W. Smith (1989), *The Frozen Earth: Fundamentals of Geocryology*, 306 pp., Cambridge Univ. Press, Cambridge, U. K.

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