Transient peat properties in two pond-peatland complexes in the sub-humid Western Boreal Plain, Canada

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SUMMARY

In the Canadian Western Boreal Plain (WBP), wetlands (ponds and peatlands) comprise up to 50% of the landscape and represent unique habitat where summer precipitation is often outpaced by evapotranspiration and hillslope groundwater position does not follow topography. In this sub-humid location, groundwater fluxes and stores in riparian peatlands influence pond water levels and root zone moisture sources for forested uplands. To accurately describe the transport and retention of water in peat, it is important to consider peat subsidence. This paper quantifies the amount and effect of seasonal subsidence in a riparian peatland in the Utikuma Lake region in north-central Alberta, Canada. Results demonstrate that the deep and poorly decomposed peat deposits are resistant to compression, and that thick (and persistent) ground frost hinders pore collapse (shrinkage) above the water table until late summer when the ground has thawed. Even then, subsidence is still limited to the top 50 cm and is not closely related to changes in peatland water table or pond water level. Thus the water balance of these ponds and riparian areas appears to be less sensitive to peat volume changes than it is to the persistence of a substantial frost layer well into the snow-free period.

KEY WORDS: compression, disturbance, ground frost, shrinkage, subsidence, wetland hydrology.

INTRODUCTION

In the Western Boreal Plain (WBP) of Canada (Figure 1), wetlands and peatlands comprise up to 50% of the landscape, providing valuable habitat for wildlife (Zoltai & Vitt 1995) and a significant store of water and carbon for Canada (Kuhry *et al.* 1993, Krinner 2003). They are threatened by land use change associated with the encroachment of oil and gas exploration, petroleum industry, intense forestry, agriculture and recreational activities (Schneider 2002); and they are potentially vulnerable to future changes in climate (Li *et al.* 2000). An understanding of moisture retention and transport mechanisms in these wetlands is required to inform assessments of how they will respond to such changes.

Most Western Boreal Forest wetlands have developed in depressions left in thick mineral deposits by receding glaciers (Vitt *et al.* 2000). They consist of ponds ringed by deep peat deposits, known as pond-peatland complexes (Ferone & Devito 2004). Hydrologically, they present themselves as wetlands in a sub-humid region where precipitation is often outpaced by potential evapotranspiration (PET) (Bothe & Abraham 1993, Petrone *et al.* 2006) and hillslope groundwater position does not reflect topography. Thus the wetlands exist as large water (and carbon) stores in a region where droughts are frequent (Yu *et al*. 2001), low runoff rates are common, and water contributions to low-lying areas (i.e. ponds and wetlands) may not be controlled by topography but rather by climate patterns and regional geology (Devito *et al*. 2005a,b). Their overall water budgets are dominated by vertical fluxes (Smerdon *et al.* 2005) and at local scale the exchange of water between peatlands, ponds and uplands can be dynamic, shifting between wet and dry seasons (Ferone & Devito 2004). Therefore, although groundwater plays a relatively minor part in the water balance, the mechanisms by which the peatlands retain water and exchange groundwater with adjacent ponds or uplands are nonetheless important to their maintenance. Moreover, these mechanisms play a role in determining the quantity (and quality) of water in the ponds and hillslopes. These are key factors in determining long-term trends in carbon accumulation and are thus relevant to the long-term survival of the extensive wetlands

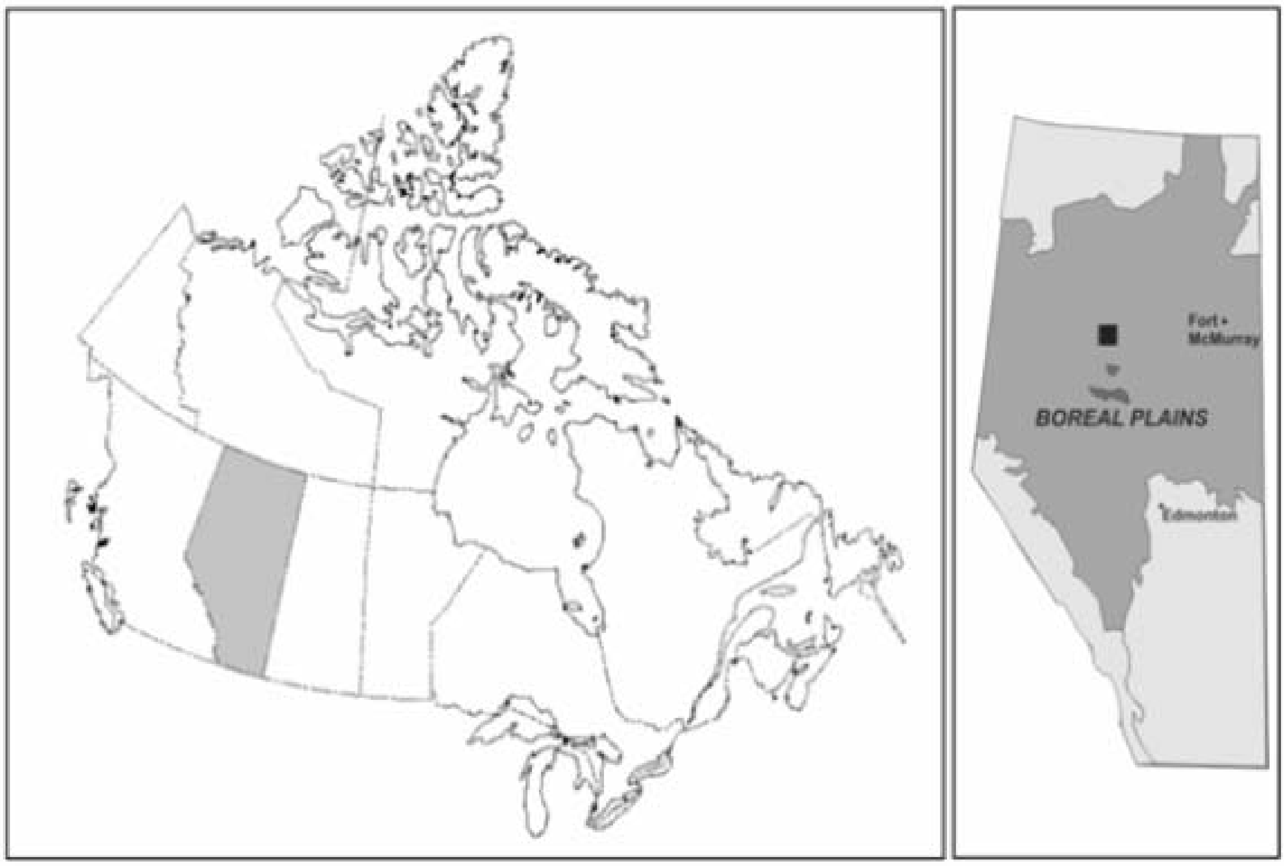

Figure 1. Location of the Utikuma Region Study Area (URSA). Left: location of Alberta (shaded) in Canada; right: enlarged map of Alberta showing major settlements, the Boreal Plains (dark shading) and URSA (the black square).

of the Western Boreal Forest (Vitt *et al*. 2000). They also give insights towards understanding how land use change associated with e.g. forestry and oil exploration will alter the hydrological cycle in these catchments.

Groundwater participates in many peatland water budgets, but its role is difficult to quantify (Scanlon *et al.* 2002, Waddington *et al.* 1993). The quantity and source of groundwater in a wetland can affect vegetation (Zoltai & Vitt 1995), pore water chemistry (Warren *et al*. 2001) and biogenic gas production (Moore & Knowles 1990). In the sub-humid WBP, groundwater storage and movement in riparian peatlands may also influence pond water levels and root-zone moisture sources for adjacent forested uplands (Devito *et al*. 2005b), as observed in prairie pond systems by Hayashi *et al*. (1998). Therefore, accurate description of the transport and storage of groundwater in peat is relevant to all components of the WBP landscape mosaic.

Peat subsidence, which involves reversible collapse and expansion (shrinking and swelling) of the peat matrix with changes in water table depth, provides one mechanism for water retention in WPB peatlands. The ability of peat to retain water is a function of its internal pore structure (Clymo 1983) and its compressible nature (Hobbs 1986). The effect of peat compression (shrinkage) in reducing pore sizes and thus increasing water retention by matric forces was studied by Silins & Rothwell (1998) and has been noted as a possible mechanism by which wetlands conserve water when subjected to environmental stress involving drainage (Price 2003). In any wetland, the compression process is generally reflected by a change in surface level (e.g. Glaser *et al*. 2004, Whittington & Price 2006). However, the changes in internal pore structure that accompany it in peat can alter fundamental physical and hydraulic properties such as bulk density, porosity and hydraulic conductivity (Baird & Gaffney 1995, Minkkinen & Laine 1998, Price 2003). These changes lead in turn to change in larger-scale variables such as evaporation and oxidation, and can thus affect the cycling not only of water but also of nutrients and gases through these environments.

Given the significance of the sensitive WBP peatlands in regional water and carbon cycling, it is essential to quantify the transient behaviour of the peat in these systems. The objectives of the study reported here were to:

1. quantify seasonal subsidence in a riparian peatland in the WBP;
2. determine whether transient peat properties may influence hydrological linkages in the WBP; and
3. determine whether natural resource exploration can affect water retention properties within these peatlands.

METHODS

Study sites

The study was conducted between 18 May and 30 September 2004 (Julian Day, JD, 138–273) within the Utikuma Region Study Area (URSA) (56° 6’ N, 116° 32’ W) which is located in the WBP ecozone (Figure 1) of Northern Alberta, Canada (Devito *et al*. 2005b). URSA is located approximately 150 km south of the discontinuous permafrost zone (Woo & Winter 1993) and is characterised by extensive bogs with spruce, and aspen-dominated mineral uplands.

The WBP is composed largely of shale bedrock overlain by up to 240 m of glacial deposits that include sandy outwashes, till moraines and clay plains (Vogwill 1978). Long-term climate data indicate that 30-year mean annual precipitation (P) and potential evapotranspiration (PET) are almost equal at 515 mm and 517 mm respectively (Bothe & Abraham 1993, Devito *et al*. 2005a,b).

The study focused on two adjacent pond-peatland complexes located on an ice disintegration moraine in the north-central region of URSA (Figure 1 inset, see Devito *et al*. 2005b). These specific pond-peatland complexes were chosen because moraine sites are traditionally areas of local and regional groundwater recharge (Waddington *et al*. 1993, Ferone & Devito 2004) and thus the parts of the landscape whose water balance is likely to respond first to changes in climate (Petrone *et al.* 2006). They are included in a larger regional study of 208 ponds in URSA, for which they have been designated Pond 43 and Pond 40 (Figure 2). Pond 43 lies less than 200 m east of Pond 40. Peat thickness is 3.5 m at Pond 43 and up to 5.5 m at Pond 40, and the substratum is saturated heavy unoxidised clay. Both ponds have shallow open water (<1 m deep) with approximately 1 m of loose gyttja sediment at Pond 43 and 3 m at Pond 40 (Figure 3). Their shorelines are lined by sedges (*Carex* spp.) and graminoids. Surrounding the ponds are wooded poor fen/bog peatlands (Zoltai & Vitt 1995) that are dominated by black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) and tamarack (*Larix laricina* (Du Roi) K. Koch) with leatherleaf (*Chamaedaphne calyculata* (L.) Moench) Labrador tea (*Ledum groenlandicum* Oeder) and mosses (*Sphagnum* spp.).

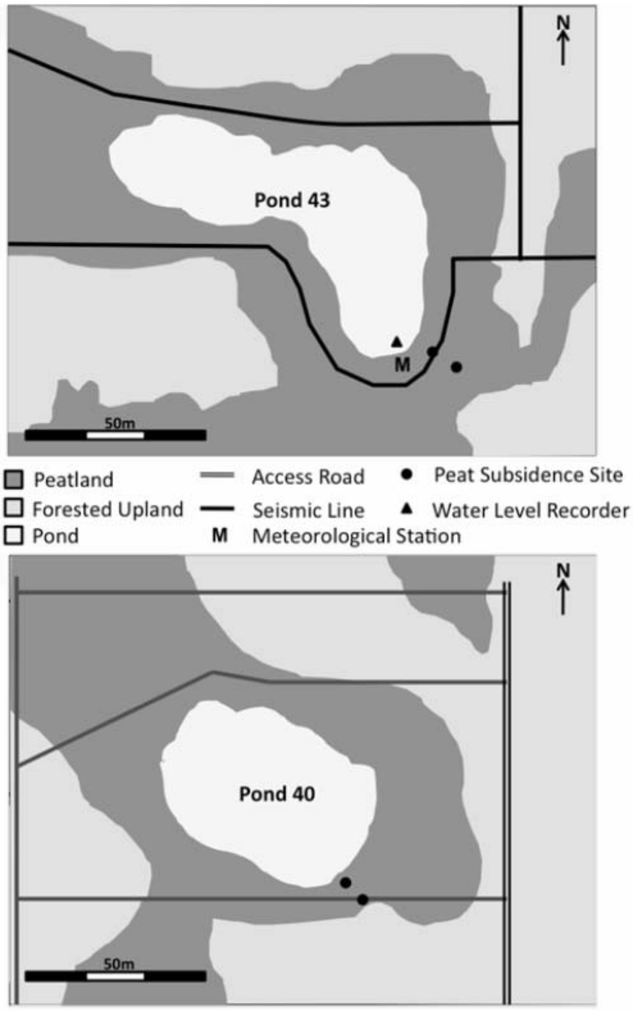

Figure 2. Maps of the two pond-peatland complexes studied, showing instrument locations.

Uplands adjacent to the peatlands are dominated by trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) with an understorey consisting mainly of prickly rose (*Rosa acicularis* Lindl.) and low bush-cranberry (*Viburnum edule* (Michx.) Raf.). The upland soils are mostly clay till with occasional thin bands (<50 cm) of sand and silt.

Oil exploration surveys in this landscape frequently necessitate the removal of all woody vegetation from so-called ‘seismic lines’ which, although subsequently left to regenerate, persist for some time as linear disturbances (MacFarlane 1999). At each pond-peatland complex, two representative pairs of nearby sites were chosen, one pair being on undisturbed mire and the other on a seismic line (eight sites in total). The sites are designated by pond-peatland complex number and landscape unit, such that the duplicate mire sites at Pond 43 are referred to as “P43-Bog” and the duplicate seismic line sites at the same complex as “P43-Seismic”. The corresponding duplicates at Pond 40 are “P40-Bog” and “P40-Seismic”.

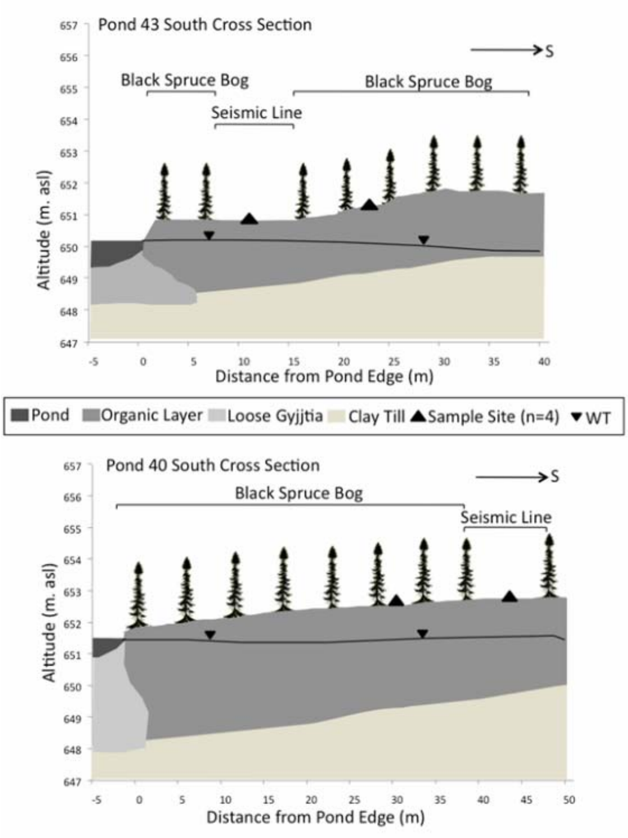

Figure 3. Cross-sections of the study areas in Ponds 43 and 40, illustrating average seasonal water table depth, vegetation cover/landscape delineations, and main substrate strata. Sampling locations at both ponds are also indicated.

Peat properties

A column of peat (70 mm x 120 mm) was collected from each of the eight sites using a Wardenaar type coring device (Wardenaar 1987). Degree of humification on the von Post scale (von Post & Granlund 1926) was determined in the field immediately after extraction (Damman & French 1987). The cores were then transported to the laboratory and sectioned into 5 cm slices such that at least two samples per depth increment (Table 1) were obtained. One sample was analysed for specific yield (S_y) (saturated for 24 hr then drained for 24 hr, Brady & Weil 1999), soil moisture (θ) (weight loss on oven drying at 105°C for 24 hr from field condition), bulk density (ρ_b) (oven-dry weight per unit field volume of sample) and particle density (D_p) (Pansu & Gautheyrou 2006). The other was used to determine horizontal and vertical saturated hydraulic conductivity ($Ksat_x$, $Ksat_y$) in a constant head permeameter (Hoag & Price 1997).

Ground frost position

Depth to ground frost was recorded at five random locations at each of the eight sites by probing through peat to the ice surface with a 1 cm diameter welding rod of known length, then measuring the length of rod protruding above the surface. Depth of frost was determined by pounding the rod through the ice using a hammer until resistance to the pounding suddenly decreased, at which point the lower limit of frost was assumed to be reached and the length of rod protruding was again measured. The thickness of the ice layer was calculated by subtracting the second measurement from the first. These measurements were made in triplicate at each site and checked periodically by drilling holes and measuring ice thickness. They were also compared with temperatures at 5, 10, 25 and 50 cm depth indicated by thermistor strings at each site.

Peat subsidence

The experimental setup for peat subsidence followed Price (2003). At each of the eight sites, two steel reference rods were placed in lined holes augured to mineral soil, then pounded into the substrate for approximately 50 cm. Smaller 6.3 mm (1/4 inch nominal) diameter aluminium rods with scales attached to their upper ends were anchored vertically at depths of 50, 100 and 200 cm in the peat between the reference rods using 5 cm (2 inch nominal) plastic drywall anchors. Changes in position of these smaller anchored rods were measured without disturbance by reading their scales against a sightwire strung tightly between the reference rods from a distance of at least 5 m through tripod-mounted binoculars. Reading inconsistency due to parallax effects was avoided by installing tripods permanently for the season.

From 23 June (JD 174), surface movements were also measured at each site using automatic sensors (potentiometers) similar to the “bog shoe” described by Roulet (1991) connected to CR10X dataloggers (Campbell Scientific, Inc., Utah). The “bog shoe” consisted of a 30.5 cm length of capped PVC pipe (5 cm outside diameter) which was placed on the mire surface and attached by 20 gauge aircraft cable to a potentiometer mounted on a 12.7 mm (1/2 inch nominal) diameter steel rod inserted in the same way as the reference rods described above. As the "shoe" moved up and down with the peat surface, the potentiometer was moved clockwise or counter-clockwise, thereby increasing or decreasing the millivolt output monitored by the datalogger.

Hydrometric measurements

At locations within 2 m of the other instruments at each site, water table position was recorded in a dipwell (4.8 cm internal diameter, perforated over its entire length); and volumetric soil moisture content (θ) was measured periodically using a Tectronix 1502 Time-Domain-Reflectometry (TDR) unit with sensor rods installed horizontally at depths of 10 cm and 20 cm. For each duplicate pair of sites, one dipwell was read manually at intervals of at least one week and the other was fitted with an electronic water level recorder.

Pond water levels were recorded automatically every half hour, at Pond 40 with a Global WL-14 vented pressure transducer (Hoskin Scientific Ltd., Edmonton, Canada) and at Pond 43 with a vented pressure transducer (Keller AG, Switzerland) connected to a Campbell Scientific (Edmonton, Canada) CR10X datalogger, which also recorded the meteorological data required to estimate evapotranspiration. The meteorological variables measured (also half-hourly, at the location indicated in Figure 2) were net radiation 5 m above ground level (NRLite, Kipp & Zonen), ground heat flux (HFT03, Campbell Scientific Ltd.), precipitation (TE525WS, Campbell Scientific Ltd.), wind speed and direction (Wind Sentry, R.M. Young), temperature and relative humidity 1.5 m and 5 m above ground level (HMP45C, Campbell Scientific Ltd.), ground temperature at 0, 2, 5, 10, 25 and 50 cm depth (107B, Campbell Scientific Ltd.) and soil moisture at 10 and 50 cm depth (CS616, Campbell Scientific).

Potential evapotranspiration was estimated using the Priestley-Taylor formula ($\alpha = 1.26$) (Priestley & Taylor 1972), which provides a radiation-based empirical approximation to the Penman (1948) approach. It assumes that an air mass moving over a homogeneous, well-watered surface will become saturated so that the equilibrium potential evapotranspiration PET_{eq} should be attained.

$$PET_{eq} = \frac{\Delta}{\Delta - \gamma}\left(Q^* - Q_G\right) \qquad [1]$$

where Δ is the slope of the saturated vapour pressure curve (°C kPa^{-1}), γ is the psychrometric constant (Pa °C^{-1}), Q^* is net radiation (Wm^{-2}) and Q_G is the soil heat transfer (Wm^{-2}). The method was originally validated on the basis of 30 studies which showed that 95% of the annual evaporative demand on vegetated areas with negligible water deficits was imposed by radiation (Stagnitti *et al*. 1989). Actual evapo-transpiration AET is related to PET_{eq} by the Priestley-Taylor coefficient α such that

$$\alpha = AET/PET_{eq} \qquad [2]$$

The value of α adopted for many studies is 1.26, which is based on conditions of well-watered vegetation, minimum advection and no edge effects (Jacobs *et al*. 2002), under which evapotranspiration occurs at the potential rate (PET) (Davies & Allen 1973, Eichinger *et al*. 1996). Evapotranspiration rarely occurs at either the equilibrium or the potential rate in practice, however, because there is almost always horizontal advection and/or deviation from the 'ideally wet' evaporating surface (Wilson & Baldocchi 2000). Different values of α may be applied to derive estimates of AET for other conditions of moisture availability or atmospheric demand (e.g. Petrone *et al*. 2006).

Datum levels

All wells and rods placed in mineral soil were surveyed from a stable datum at least twice during the study season in order to confirm that there was no significant vertical movement.

Stress, strain, compression and shrinkage

Peat deformation occurs by three processes, namely: (1) consolidation of peat beneath the water table due to the weight of overlying material (compression); (2) shrinkage above the water table due to both overlying weight and negative pore water pressure (suction); and (3) long-term oxidative breakdown (Kennedy & Price 2005). Rather than providing a bulk estimate of peat subsidence, the measurement technique employed here distinguishes layers within the peat that may be subject to these three processes in differing degrees. For each layer of peat, strain (ε) can be described by the change in volume:

$$\varepsilon = h / h_i \qquad [3]$$

where h_i is the initial thickness of the layer and h is its thickness at a given subsequent time. Both compression and shrinkage can occur on the same timescale as water table fluctuations, and are fully reversible up to a critical level of stress (defined by the pre-consolidation pressure), after which structural changes become permanent. The effective stress (σ') placed upon peat at any point in the soil column is:

$$\sigma' = \sigma_T - \psi \quad [4]$$

where σ_T is the total stress due to the weight of the overlying material and ψ is the pore water pressure at that point, which may be positive or negative and so either offset or add to the effective stress. In the absence of direct measurements of (negative) pore water pressure, a close approximation can be calculated using:

$$\psi = \rho_w \, d \, g \quad [5]$$

where ρ_w is the density of water, d is the depth to the water table from the point of interest and g is the acceleration due to gravity.

The original placement of the subsidence meters defined four peat layers, but the presence of ground frost necessitated the addition of another boundary at the ice surface, within the uppermost 50 cm of the profile. Accordingly the 0–50 cm layer was split into two layers, termed 'peat surface–ice surface' and 'ice surface–50 cm'. The thickness of the peat surface–ice surface layer changed as the ice melted, its thickness at time t being given by:

$$h_t = h_{t-1} + \Delta z_{surf} - \Delta z_{ice} \quad [6]$$

where h_t is the layer thickness at time t, h_{t-1} is the previous thickness, Δz_{surf} is the rise in peat surface level and Δz_{ice} is the rise in ice surface level (upward movements and increase in thickness reckoned positive). Equation 6 was used to calculate the thickness of the peat surface–ice surface layer until the loss of ice allowed reversion to the original four layers.

Table 1. Physical properties of peat from cores extracted from natural bog and seismic line sites at Pond 40 and Pond 43, summer 2004. D_p is particle density, ρ_b is bulk density, θ is volumetric soil moisture, S_y is specific yield, $Ksat_y$ is saturated vertical hydraulic conductivity and $Ksat_x$ is saturated horizontal hydraulic conductivity. All data are means of duplicate measurements.

Pond	Site	Depth (cm)	Humification (von Post)	D_p (g cm^{-3})	ρ_b (g cm^{-3})	θ (%)	S_y	$Ksat_y$ (cm s^{-1})	$Ksat_x$ (cm s^{-1})
43	Bog	0–10	H1	1.47	0.05	96.89	0.63	0.50	0.21
		15–30	H2	1.41	0.09	93.77	0.59	0.06	0.24
		40–70	H3	1.34	0.11	91.50	0.58	0.12	0.07
		75–100	H3						
		100–200	H4						
43	Seismic	0–10	H2	1.97	0.13	93.30	0.56	0.78	0.19
		15–30	H2	1.71	0.07	96.16	0.56	0.02	0.04
		40–70	H3	1.58	0.08	94.73	0.57	0.07	0.24
		75–100	H3						
		100–200	H3–4						
40	Bog	0–10	H1	1.58	0.05	96.90	0.59	0.10	0.44
		15–30	H2	1.49	0.06	95.84	0.58	0.19	0.30
		40–70	H3	1.55	0.09	94.36	0.57	0.63	0.48
		75–100	H3						
		100–200	H3–4						
40	Seismic	0–10	H2	1.43	0.04	97.02	0.59	0.78	0.19
		15–30	H2	1.42	0.07	95.17	0.58	0.02	0.04
		40–70	H3	1.42	0.15	89.69	0.56	0.10	0.24
		75–100	H3						
		100–200	H3						

RESULTS

Peat properties

Peat characteristics are displayed in Table 1. The peat at all sites was fibric and poorly decomposed (≤ H3 on the von Post scale) to at least 100 cm depth, and below that only moderately decomposed (H3–4). The low bulk density and high specific yield and hydraulic conductivity (10^{-2} cm s^{-1}) values suggest poor water retention capability. There was no significant difference in any soil physical attribute between the seismic line and bog sites ($P<0.05$; one-tailed t-test). Redding & Devito (2006) compared wetland soils across a topographical gradient in the WBP and also found no statistical differences in soil physical properties between wetland types.

Precipitation and evapotranspiration

Total rainfall during the study period was 275 mm. The two largest rainfall events (41 mm day^{-1} and 22 mm day^{-1}) occurred in September, and these together delivered 41% of the total (Figure 4). The September precipitation total was 30 mm greater than the monthly average (Environment Canada 2005). Potential evapotranspiration (*PET*) calculated using the Priestley-Taylor formula (α =1.26) was 334 mm, 93% of which occurred before September. This created a moisture deficit of 59 mm between 18 May (JD 138) and 30 September (JD 273). Petrone *et al.* (2006) found that actual evapotranspiration (*AET*) for peatland surfaces in the WBP under dry conditions could be calculated using an α coefficient of approximately 0.7. This calculation estimated *AET* at 150 mm and placed the study peatlands in water deficit from 05 June (JD 156) to 01 September (JD 244). Cumulative rainfall exceeded cumulative evapotranspiration only after the unusually large rainfall events in the autumn (Figure 4).

Peatland water table and ground frost position

The water table at both bog sites was already at least 50 cm below the surface by 24 May (JD 144) and reached a maximum depth of -60 cm before recovering to -40 cm at P43-Bog and -30 cm at P40-

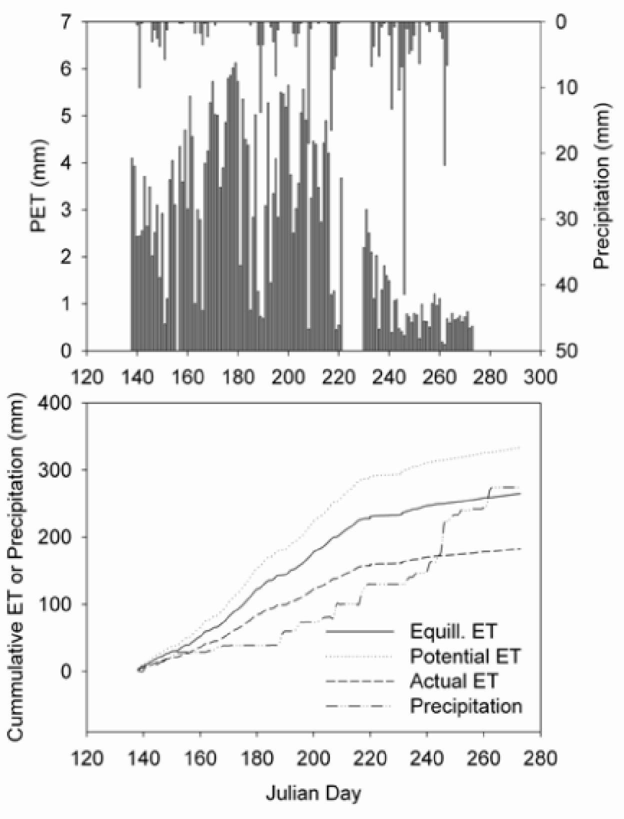

Figure 4. Daily totals of precipitation and potential evapotranspiration (*PET*) (upper diagram); and cumulative precipitation and evapotranspiration (equilibrium, potential and actual) (lower diagram) for the snow-free period of 2004.

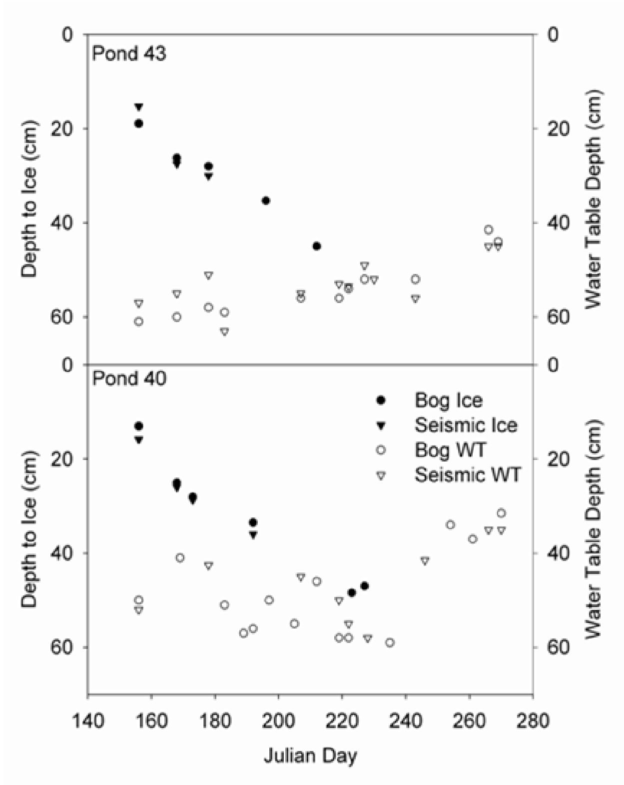

Figure 5. Depths (means of duplicate measurements) from the peat surface to the top of the ice layer and to the water table for the (natural) bog and (disturbed) seismic line sites at Pond 43 (upper diagram) and Pond 40 (lower diagram) during the snow-free period of 2004.

Bog in response to autumn rainfall (Figure 5). The patterns of water table fluctuations at P43-Seismic and P40-Seismic followed those at the bog sites, except that the water table here remained slightly (2 cm) higher during the driest periods in July (from JD 181).

Ground frost remained in the peat until the end of July (JD 212) at both of the seismic sites, and persisted into August at the bog sites (Figure 5). At all sites, the positioning of the ice was such that the water table was located below or within the ice lens so long as it persisted.

Pond water level and peat surface position

At all sites, changes in surface altitude mimicked changes in pond water level, and responded to rainfall events on the same timescale as pond water level (Figure 6). However, the magnitude of surface level change was very small when compared to the pond water level changes. For example, a 24 mm rainfall event on 26–28 July (JD 207–209) raised the water level by 3.0 cm in Pond 43 and by 2.0 cm in Pond 40; however, all peat surfaces rose by less than 1 cm (Figure 6). Only small changes in peat surface level were recorded over the entire study period, and maximum subsidence ranged from less than 1 cm at P43-Bog to 2.3 cm at P40-Seismic. Both seismic line sites displayed twice as much subsidence as their undisturbed counterparts, and the mire surface at P43-Bog showed very little movement during the first 25 days of study (Figure 6). No clear trends were displayed during the autumn re-wetting period. All sites displayed some degree of expansion following re-wetting, with the exception of P43-Bog which showed little change.

Compression and shrinkage

Compression is peat subsidence that occurs beneath the water table. Although the subsidence measurements typically have an accuracy of approximately ± 0.2 cm (Whittington *et al.* 2007), sensors placed through the deeper layers of the peat column showed small (<1 cm) changes in altitude, with no clear trend in sensor movement between sites (Figure 7). However, the inclusion of these sensors indicated a rising surface layer for all sites except P40-Seismic, which remained neutral. This result contrasts with the actual surface ('bog shoe') measurements, which all showed lowering of the peat surface, at least until the autumn rainfall events when the peat at P43-Seismic expanded above its initial altitude (Figure 6). Overall, given the accuracy of the measurements, compression was quite insignificant here.

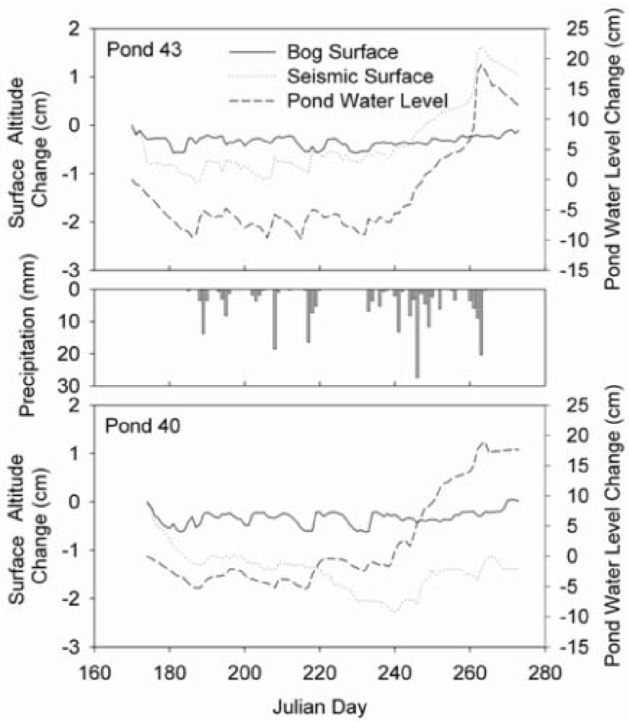

Figure 6. Daily changes in peat surface altitude (means of duplicate measurements) at the natural bog and disturbed seismic line sites at Pond 43 and Pond 40, along with pond water level and daily precipitation totals, for the snow-free period of 2004.

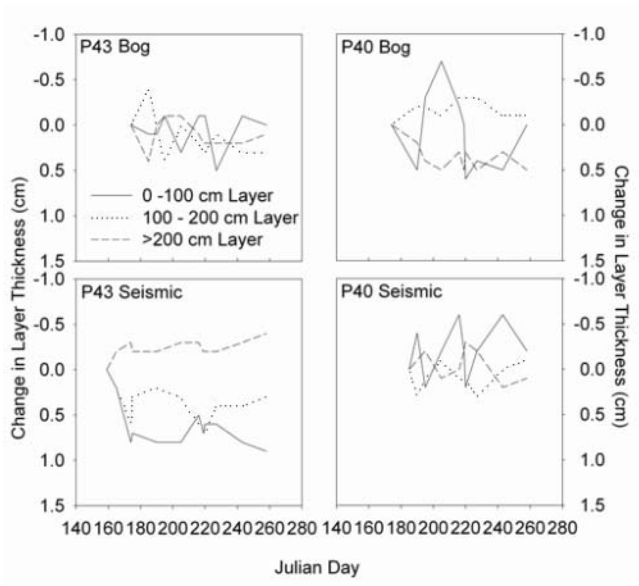

Figure 7. Changes in peat layer thickness at the bog and seismic line sites at Pond 43 and Pond 40 for the snow-free period of 2004. All data are means of duplicate measurements.

Effective stress and active layer development

The stress placed on the peat by the overlying layers is the impetus for volume change, and increases as the water table falls (Equation 4). As pore water pressure above the ice lens was always negative during the field season, effective stress was highest when the water table was lowest. As the ice melted out and the water table continued to rise after approximately 19 July (JD 200), the effective stress decreased. Thus, volume change in the peat profile should show a strong response to ice layer dynamics as well as to water table fluctuations.

Subsidence was well correlated with ice position only early in the year (Figure 8). Ice melt rates averaged 1 mm day^{-1} and were faster than the initial subsidence rates for the P40-Bog, P40-Seismic and P43-Seismic sites (Figure 9). This resulted in expansion of the peat surface–ice surface layer. Equation 3 was used to calculate the strain (ε) for the ground frost period, which was negative. The persistence of ice through to August may have slowed subsidence, as a further 1.5 cm fall in the surface at P40-Seismic occurred after the ice had disappeared even though the rate of subsidence was initially greater than the rate of ice melt.

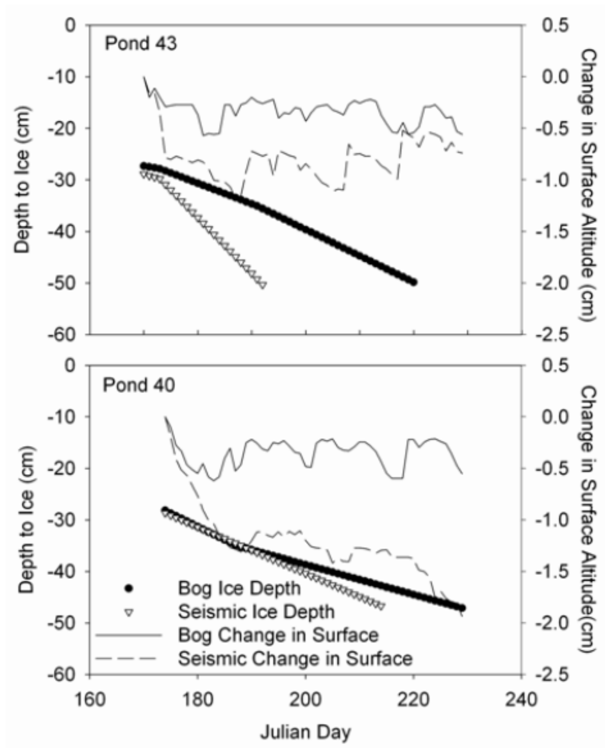

Figure 8. Daily depth from the peat surface to the top of the ice layer, and changes in peat surface altitude in the bog and seismic line sites at Pond 43 and Pond 40 during the snow-free period of 2004. All data are means of duplicate measurements.

DISCUSSION

In 2004, the water table at both pond-peatland complexes was low and beneath the ground frost lens. Low water table conditions restrict evapotranspiration (i.e. $AET < PET$), and Petrone *et al*. (2006) showed that a low water table at Pond 43 lowered the seasonal Priestley-Taylor coefficient (α) for the peatland to 0.69 in 2003. When this coefficient is applied to the 2004 data, the results indicate that the peatland remained in water deficit until the last day of August (JD 243). The water deficit and low water table were accompanied by a lowering of the peat surface; however, the surface movements also followed the pattern of water level change in the ponds.

The energy consumed during the thawing of ice should be reflected in the *PET* values shown in Figure 4, since the consumption of ground heat in thawing translates to less available energy to drive evapotranspiration. However, the decrease in available energy was more than offset by the continual supply of moisture to the upper soil layers from the melting ice (Woo & Xia 1996), and the slopes of the cumulative plots of *PET*, PET_{eq} and *AET* declined when the ice disappeared, at approximately Julian Day 210 (Figure 4). This role of meltwater is also evident in the different responses of the peat surface to the increasing depth to ice in both the bog and seismic line sites (Figure 8). The water table was confined beneath the ice layer at all sites as the season began, but water was still supplied to the surface (and was thus available for evaporation) as the ice melted. As shown in Figure 8, the ice melted out first in the seismic lines. It persisted much longer at the bog sites, further confining vertical movement of the water table whilst promoting lateral flow to the adjacent thawed areas (i.e. seismic lines, uplands or pond). Therefore, the differential ice melt rates in undisturbed bog and seismic lines enabled the former to keep the latter wetter than they would have been otherwise, and this was reflected in the lower amplitude of surface fluctuations in the seismic lines (Figure 8). A similar effect is evident in the relative fluctuations of the surface, water table and pond water levels (Figure 6).

The peat subsidence observed in these two WBP peatlands is less than previously reported in other areas. Maximum peat surface subsidence of 10 cm has been reported for a subarctic fen (Roulet 1991) and a Minnesota fen (Almendinger *et al*. 1986), and of 8 cm for a harvested peatland in Quebec (Price 2003). In this study, a maximum subsidence of 2.3 cm was found in the disturbed areas (seismic

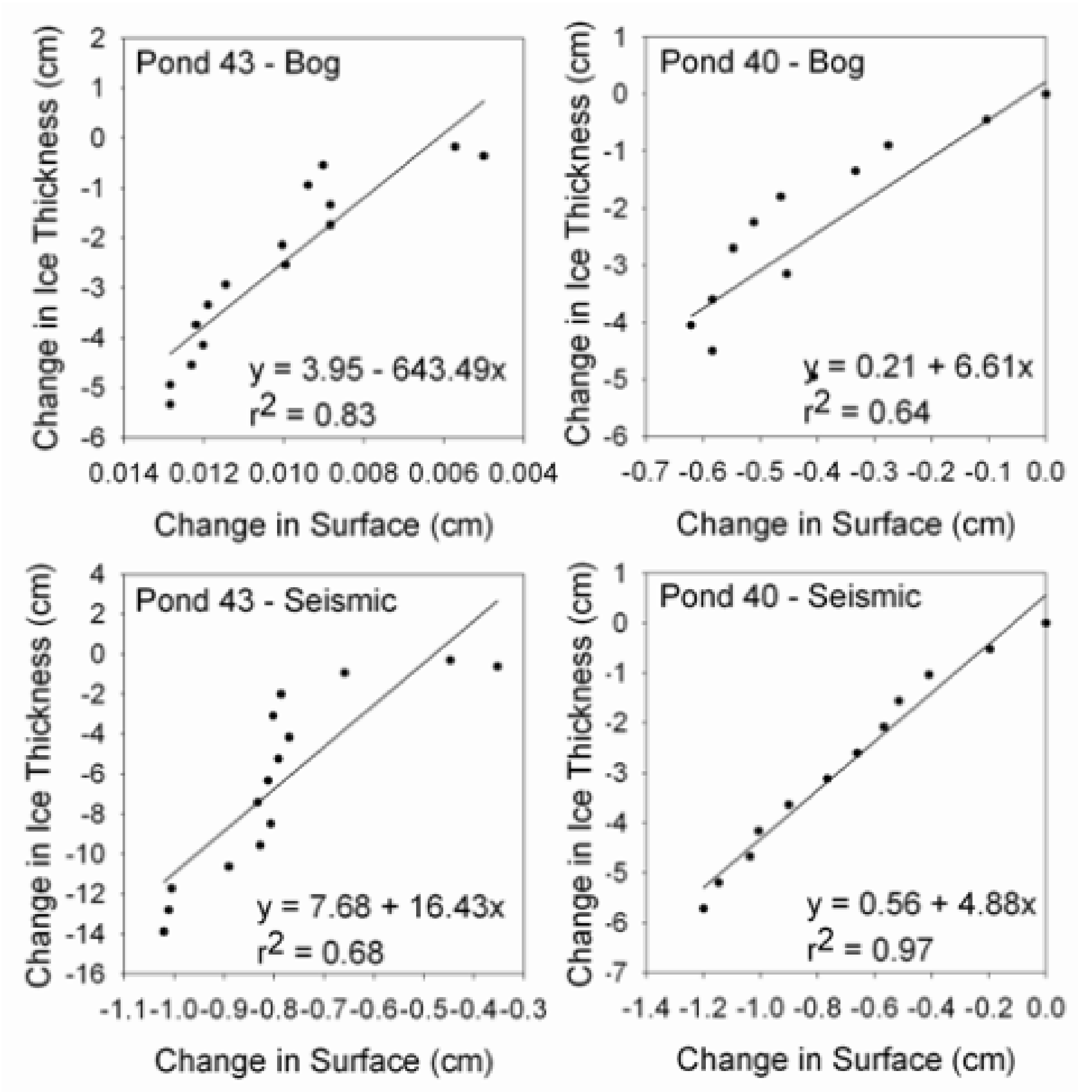

Figure 9. Relationships between the changes in ice layer thickness and peat surface altitude at bog and seismic line sites, 2004. Regression equations and correlation coefficients are shown for each set of duplicate sites.

lines) of these WBP peatlands, and this was approximately double the maximum subsidence recorded in the undisturbed areas. While these small changes are comparable to those observed in an undisturbed bog by Price (2003), the persistent ice lens appeared to restrict subsidence to the layer above the frost table so that the peat columns studied here showed no significant compression or expansion beneath 50 cm depth, whereas Price's results showed movements down to 150 cm depth. Similarly, Roulet (1991) noted that peat subsidence in a subarctic fen was linked to ice melt, and attributed most of the subsidence during melt to the collapse of ice-filled pores. This mechanism could be responsible for the relatively rapid early-season subsidence of the WBP peatlands, but although ice persisted here until August and subsidence continued at P40-Seismic, it became nearly neutral at the bog sites much earlier in the year (Figure 8). The effect of the ice was to change the thickness, and hence the volume, of the uppermost layer of peat. Ice melt occurred more rapidly than subsidence, creating a situation where the upper layer of peat was increasing in thickness as the ice melted, but the peatland surface was still subsiding. This resulted in an increase in layer thickness, but there was no accompanying decline in bulk density as might be expected (Price 2003).

The lack of movement of the deeper subsidence sensors suggests that the changes in surface altitude resulted from either ice melt or pore collapse (shrinkage) due to large negative pore water pressures. Both of these causes are probable. Ice in peat appears to keep pore sizes large and peat incompressible (Roulet 1991). However, the fibric nature and high porosity of the peat, especially in the top 50 cm (von Post H<3), also make it resistant to collapse, and the long-term oxidation of this upper layer is likely to be proceeding slowly (Petrone *et al*. 2005, Kennedy & Price 2005). This would explain why the surface subsidence values were still so low after melt-out.

Conceptually, the process of compression and shrinkage in these peatlands occurs as follows. Moisture is removed due to high atmospheric demand in the spring, but only from thawed ice and other moisture available above the ground frost (Figures 4 and 5). This, along with pore collapse due to phase change in pore water, creates surface subsidence above the ground frost (Figure 7). As the frost disappears, the weight of the dry surface peat is increasingly borne by deeper peat layers and the effective stress is controlled more directly by water table depth and the corresponding negative pore water pressures (Figures 8 and 9). Any precipitation inputs can re-expand the unsaturated peat and create an opportunity for the reformation of ground frost so that the 'cycle' starts again the following spring.

The small amounts of subsidence in the WBP peatlands could also be associated with the periodic prolonged droughts in this region (Devito *et al*. 2005). Low water table and high loading by overlying dry peat during droughts would apply more consistent stress on the entire peat column, and could push the peat beyond its preconsolidation pressure so that only small further changes in pore sizes would be possible. This would in turn result in lower spatial variability in subsidence amongst landscape units (e.g. seismic lines *vs*. natural bog).

CONCLUSIONS

The deep and poorly decomposed peat deposits in the Western Boreal Plain are resistant to compression and consolidation. This is a product of high peat porosity and internal processes within the peat column. Thick and persistent ground frost hinders pore collapse above the water table until late summer, after which compression is still limited to the topmost 50 cm and is not closely related to water level changes in either the peat or the pond. The ground frost also regulates horizontal and vertical moisture exchanges within the peatland and between the peatland and the pond. As a result, volume changes in the unsaturated layer of surface peat are less important to the water balance than are evaporative conditions (e.g. *PET* : *AET* ratios) and groundwater-surface water interactions.

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