Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands

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[1] This paper describes the nature and magnitude of peat soil volume changes and its relation to seasonal changes in water table at an undisturbed bog peatland and on two cutover sections of the same peatland and its effect on hydraulic conductivity. In the latter two sites, operations had ceased 2 and 7 years prior to this study, respectively. The water table dropped to a maximum depth of 40, 50, and 68 cm, respectively, at the undisturbed, 2-year, and 7-year abandoned sites and a resulted in subsidence of 0.96, 3.84, and 2.65 cm m^{-1}, respectively. At the undisturbed site, surface elevation changes did not always correspond to water table changes, but peat underwent a period of swelling even as the water table fell, probably due to the accumulation of methane in soil pores. At all sites most volume change occurred in the upper 50 cm layer, with maximum strain of 5, 15, and 5% at the undisturbed, 2-year, and 7-year abandoned sites, respectively, and was strongly related to water table decline. A model of peat deformation in the zone of saturation (100 cm depth), based on changes in saturated soil moisture (6%), grossly overestimated strain (1%) in the saturated zone, and again methane accumulation was the suspected cause of the soil moisture decrease. Peat compression (and perhaps methane accumulation) caused hydraulic conductivity to decrease over two orders of magnitude at 75, 125, and 170 cm depth. The decrease in hydraulic conductivity as a peatland dries may be an important self-preservation mechanism (i.e., against further water loss). *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1824 Hydrology: Geomorphology (1625); 1829 Hydrology: Groundwater hydrology; 1866 Hydrology: Soil moisture; 1890 Hydrology: Wetlands; *KEYWORDS:* peat, subsidence, compression, hydraulic conductivity

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1. Introduction

[2] Peatlands are a hydromorphic feature of the landscape [*National Wetlands Working Group*, 1988], whose genesis are strongly linked to hydrological processes from the pore-space to landscape scale. Water flow and retention in peatlands are crucial to peatland ecological and edaphic development [*Hilbert et al.*, 2000], so it is important these processes are known. Furthermore, given the wide interest in restoring and conserving wetlands [*National Research Council*, 2001], it is essential that management prescriptions are based on a proper understanding of the theory and its practical application.

[3] Long-term changes in the physical and hydraulic properties of peat are a function of decomposition and consolidation processes [*Al-Khafaji and Andersland*, 1981]. Indeed, it is well established that hydraulic conductivity [*Boelter*, 1969], pore size [*Romanov*, 1968] and thus storativity [*Ingram*, 1983] decrease with depth, due to the state of decomposition of the organic plant material that has become oxidized over centuries [*Clymo*, 1984]. In drained peatlands where subsidence results from an increase in effective stress associated with a lower water table [*Hobbs*, 1986] and from enhanced oxidation due to increased soil aeration [*Zeitz and Kosov*, 1988], changes to peat properties occur over a period of years [e.g., *Schothorst*, 1977]. Oxidative changes are irreversible, and consolidation only partly reversible (i.e., that which is not "creep", or plastic deformation) [*Hobbs*, 1986]. However, peat has a high elasticity, so changes in peat volume can occur on the timescale of water table change [*Price and Schlotzhauer*, 1999]. Concomitant changes to the hydraulic properties should also be expected. Lab experiments [*Chow et al.*, 1992; *Heiskanen*, 1995; *Oleszczuk et al.*, 2000] have demonstrated a significant increase in water retention capacity (i.e., at a specific matric potential) and a decrease in saturated hydraulic conductivity (K_{sat}). However, to the knowledge of this author, this has not been demonstrated at the field scale.

[4] Seasonal water table changes resulting in subsidence and swelling ("mooratmung" or "mire breathing") in undisturbed peatlands [*Roulet*, 1991; *Kellner and Halldin*, 2002; *Koerselman*, 1989] and cutover bogs [*Schlotzhauer and Price*, 1999] have not considered the temporal variability in hydraulic parameters. Since significant changes in surface elevation thus peat volume, can occur on a timescale of days the estimate of hydraulic conductivity, for example, may be sensitive to when it is measured. Consequently, evaluation of the time-variant behavior of hydraulic param-

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eters caused by "mire-breathing", if important, should be considered in hydrological modeling of highly compressible soils like peat.

[5] The hydraulic properties of peat are also affected by the genesis of methane. Methane is produced under anaerobic conditions, primarily below the water table [*Dunfield et al.*, 1993]. In laboratory experiments *Beckwith and Baird* [2001] showed that the accumulation of methane in saturated peat caused a 5 to 10% decrease in the volumetric water content in a "saturated" peat soil, and caused a 60% reduction in K_{sat}. The presence of soil gas also increases the soil's compressibility [*Yager and Fountain*, 2001].

[6] Understanding the processes that control water flow and storage in peatlands is important, particularly with respect to restoration, where water storage and soil-water pressure are crucial to the survival of *Sphagnum* mosses [*Price*, 1997] that dominate ecological and hydrological functions. Restoration of organic soils that have undergone subsidence is particularly difficult because of changes to hydraulic gradients and water storage capacity [*Ingebritsen et al.*, 1999]. Therefore the specific objectives of this field study, with respect to undisturbed and cutover peatlands, are to determine (1) the magnitude of peat volume change and its relationship with water storage changes and stress-strain relationships, (2) the influence of peat volume changes on hydraulic conductivity, and (3) the role of soil gas content on deformation of the peat.

2. Soil Volume Change Theory

[7] The compressibility of soil is related to its mechanical strength [*Hobbs*, 1986]. The soil's volume changes under the stress encountered when the weight of the overlying soil and water are transferred to the matrix when the water table drops. The total stress (σ_T) is given as

$$\sigma_T = \rho_T g h, \tag{1}$$

where g is gravitational acceleration, ρ_T and h are the total density and thickness, respectively, of the column of peat, water and air in the soil above the point of interest. However, σ_T is countered by the buoyancy provided by pore water pressure (ψ) below the water table, thus the effective stress (σ_e) is

$$\sigma_e = \sigma_T - \psi, \tag{2}$$

Consequently, σ_e increases when peat drains, the small decrease in σ_T being offset by the large reduction in ψ, causing the soil to subside. As pores collapse, water is expelled. In the initial stage of collapse, the volumetric change is equivalent to the volume of water lost, and this is called "normal shrinkage" [*McLay et al.*, 1992; *Pyatt and John*, 1989], or "primary consolidation" [*Terzaghi*, 1943]. An increase in pore water pressure (ψ) associated with a water table rise will have the reverse effect, as long as the strain is less than some preconsolidation pressure [*Terzaghi*, 1943] defined by a previous strain limit. Otherwise, consolidation is only partly reversible.

[8] The volume-change versus water-content relationship expected when the soil is saturated and volume change occurs by dewatering only, is given by

$$V = \theta_g V_w + V_s, \tag{3}$$

where V is specific volume of the soil (dm kg^{-1}), V_w is the specific volume of water (1 dm^3 kg^{-1}), V_s is the specific volume of the solid fraction of peat (the reciprocal of particle density, about 0.64–0.69 dm^3 kg^{-1} [*McLay et al.*, 1992; *Pyatt and John*, 1989]), and θ_g is the gravimetric water content (mass of water over mass of solids). In extensive beds of fibric peat horizontal strain manifest as cracking is unimportant [*Pyatt and John*, 1989] so the volume change occurs as a vertical displacement of the layer with thickness *t*, expressed as a proportion of the original thickness (t_i) of the layer under consideration, where

$$\frac{t}{t_i} = \frac{\theta_g V_w + V_s}{\theta_{g,i} V_w + V_s} \tag{4}$$

and $\theta_{g,i}$ is the initial gravimetric water content of that layer [*Pyatt and John*, 1989]. Equation 4 assumes V_s constant, i.e., that the solid fraction of peat fragments is incompressible. In practice, this is of minor importance, because of the small solid fraction of peat, which typically ranges from 5–15% by volume [*Clymo*, 1983].

[9] Above the water table where lower moisture contents occur (i.e., after air-entry) residual shrinkage may take place [*McGarry and Malafant*, 1987] at a slower rate with respect to changes in θ_g. Nevertheless significant volume change can occur when pore water pressure (ψ) is much less than atmospheric ($\psi \ll 0$); for example when evaporation losses at the surface outpace the rate of capillary rise [*Price*, 1997]. This can be realized through equation 2 when σ_e increases as ψ becomes negative.

[10] With subsidence there is a decrease in the void ratio, and an increase in bulk density, hence a shift in pore size distribution. These changes affect K_{sat} and water retention (ψ versus θ). In lab experiments [*Chow et al.*, 1992] noted that K_{sat} decreased up to three orders of magnitude as bulk density increased from 0.124 to 0.24 kg m^{-3}, and water retention at about -100 mb was 50% higher. Lower K_{sat} and higher water retention result from the increase in the proportion of small pores, since the large pores are the first to collapse. This study investigates these changes in the peat at a wetland site and explores the consequences to the hydrological behavior of the system.

3. Study Area

[11] The study was performed near Lac-Saint-Jean, Québec, Canada (48°47′N, 72°10′W). The peatland is part of a 4315 ha bog-poor fen complex, classified as "plateau bog" [*National Wetlands Working Group*, 1988]. The peat deposit has developed over permeable deltaic sands [*Morin*, 1981] where a well-developed iron pan limits seepage losses [*Price*, 1996]. This study examined an undisturbed section of bog (undisturbed site) and two cutover sections in 1998. The cutover sections were drained and the upper 0.35 to 0.6 m of peat removed by block cutting with heavy machinery using the Haku technique [*Money*, 1995]. The cutover sites in this study (1998) are identified by the number of years elapsed since peat-harvesting operations were abandoned. At one cutover site, drainage took place in 1990, peat cutting occurred in 1991 and the ditches were blocked with peat dams set every 100 m along the drainage system, in the fall of 1992 (7 years abandoned). The second cutover site was drained in the autumn of 1995, peat was cut in 1996 and ditches were blocked in 1997 (2 years abandoned). Peat

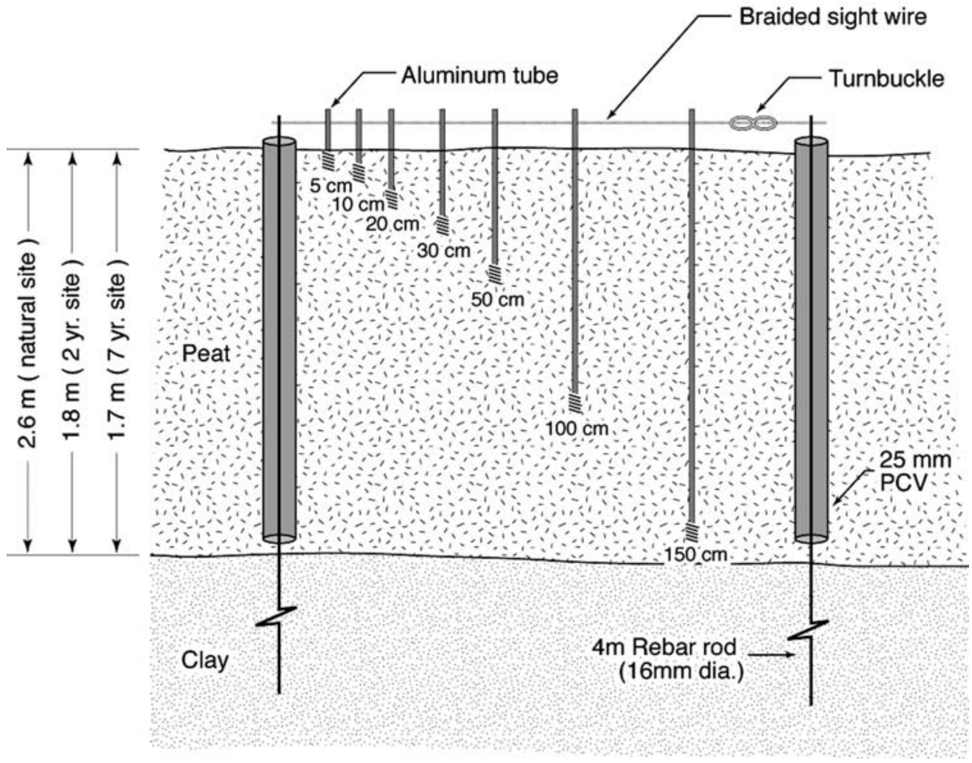

Figure 1. Soil deformation sensor setup.

thickness was 2.6 to 2.9, 1.8 to 1.95 and 1.66 to 1.7 m at the undisturbed, 2 and 7 year abandoned sites, respectively. Peat at this site is fibric, and the peat is relatively undecomposed, with von Post number no greater than 4, even at depth.

[12] The average annual temperature is 2.2°C, with average January and July temperatures of −15.9 and 18.1°C, respectively [*Environment Canada*, 1992]. Mean annual total precipitation is 909 mm (36% falling as snow).

4. Methods

[13] Rather than a simple estimate of peat surface elevation change [e.g., *Cahoon and Lynch*, 1997], peat subsidence was determined with 5 mm diameter aluminum elevation sensor rods protruding above the surface and anchored into the peat at depths of 5, 10, 20, 30, 50, 100, and 150 cm (Figure 1). Motion of an individual sensor occurs when the peat beneath it rises or falls. Volume change was assumed to be manifest entirely as vertical movement, since no cracking occurred. Therefore to determine the change in thickness of an individual layer (strain), the changes to layers below the one of interest was deducted at each time step, and the result expressed as a proportion equivalent to t/t_i (i.e., thickness with respect to the initial thickness). The anchors of the three upper sensors were 2.5 cm long plastic drywall screws into which the rods were fixed. To provide stability for the 5 cm sensor, the rod protruded 5 cm below the anchor in a premade hole of the same diameter. The aluminum rods of the upper three sensors were hollow. The four deeper anchors were 5 cm sections of flighted aluminum auger. The anchors were augured into place with a 2 cm o.d. removable hollow shaft, and were placed 30 cm apart. The hollow shaft was removed after installation, leaving an opening of similar diameter in the peat above the sensor, through which the aluminum rods passed. It is possible that the holes collapsed at depth, but the aluminum rods were coated with dry silicone lubricant to reduce potential friction. All rods extended approximately 30 cm above the surface, adjacent to a sight-wire stretched tightly between two posts set approximately 10 m apart that were sunk into the substrate below the peat (Figure 1). The posts were 4 m long 16 mm (5/8 inch) concrete reinforcing rods that were pushed through a 2.5 cm i.d. PVC tube that itself extended to within 50 cm of the mineral substrate. The PVC tube was used to minimize friction caused by the immobile rod against the subsiding and swelling peat (the PVC was free to move). The wide spacing was to ensure that any such friction was well removed from the sensors. The upright aluminum sensor rods were graduated and read to the nearest mm with binoculars that rested on a fixed post about 5 m from the wire.

[14] At all three sites a series of three piezometer nests were installed along the center-line of the cutover peat fields (i.e., parallel to the blocked ditches), and along a straight transect in a lawn section of the undisturbed bog. Individual pipes were spaced approximately 1 m apart, and nests had approximately 2 m spacing. Piezometers were 1.9 cm i.d. PVC set at depths of 0.75, 1.25 and 1.75 m, and had slot lengths of 50 cm. Bail tests [*Hvorslev*, 1951] were done weekly, and the water level before testing was recorded. Most tests had 90% water level recovery, and all had 2/3 or greater recovery. Water table was also recorded continuously with a float-potentiometer device, at the undisturbed and 7-year abandoned site.

[15] Soil moisture was monitored continuously with Campbell™ CSI615 probes set 5, 20 and 100 cm beneath the surface at the undisturbed and 7-year cutover site. Unexpectedly, the probes did not share a common calibration for the well-saturated peat. Laboratory calibration revealed a common slope, but variable intercept. However, since detailed destructively sampled peat cores were taken at each site, the water content at saturation following snowmelt was known, and used for the initial estimate of soil moisture, representing the condition on 6 May when the water table was above all sensors. The intercept of the sensor output was matched to this value. Therefore the absolute value of soil moisture could be ±5%. However, the change in soil moisture is expected to be much better (about ±0.5%).

[16] Soil-water pressure at the cutover sites was measured at −1, −5, −10, −20, −30 and −50 cm with tensiometers. All but the 30 and 50 cm tensiometer were 1 cm o.d. porous ceramic cup tensiometers inserted horizontally into a pit wall, connected to a partially water filled L-shaped tube protruding above the peat surface. The pit was backfilled with peat. The 30 and 50 cm tensiometers had a 2.5 cm porous cup attached to a straight tube inserted into a predrilled hole. Pressure was measured with a Tensimeter™ pressure transducer accurate to 1 mb, and adjusted to account for the height of the water column above the ceramic cup. Values herein are expressed in cm of water (1cm = mb).

[17] Meteorological data including measurements of rainfall, temperature and evaporation [*Priestley and Taylor*, 1972] method were made at the 7-year cutover site, and methods are described in detail by *Price* [1997].

[18] Sensor motion was related to stresses imparted by the overlying peat mass. Total stress (σ_T) was determined for the height of material (water plus peat) above the point of interest. Here σ_T was calculated for two situations, (1) the 10–20 cm layer and (2) the 100–150 cm layer, using a form of equation 2. The total density of the peat and water (ρ_T) can be determined from the sum of the masses of peat solids (M_s) and water (M_w) per unit volume (V) where

$$\rho_T = \frac{M_s + M_w}{V}. \quad (5)$$

Since $M_w = \theta_g \bullet M_s$, equation 5 can be rewritten as

$$\rho_T = \frac{M_s}{V} + \frac{\theta_g M_s}{V} \quad (6)$$

and since ρ_d (dry bulk density) = M_s/V, equation 6 can be reduced to

$$\rho_T = \rho_d(1 + \theta_g). \quad (7)$$

However, ρ_d is not constant, since the peat undergoes strain (ε) during drying, so the adjusted bulk density (ρ_d') was determined as

$$\rho_d' = \frac{\rho_d}{1 - \varepsilon} \quad (8)$$

Therefore total stress at the 10 cm sensor (σ_{T_10}) was determined by substituting equation 7 into equation 1, so

$$\sigma_{T\_10} = \rho_d'(1 + \theta_{g(AVG)})gh, \quad (9)$$

where $h = 10$ cm, $\theta_{g(AVG)}$ was the average of gravimetric soil moisture measured 5 cm below the surface, and ρ_d' is dry bulk density adjusted on the basis of strain (ε) at the 10 cm layer. At the 100 cm sensor σ_{T_100} was calculated as

$$\sigma_{T\_100} = \rho_d'(1 + \theta_{g(AVG)})gh_u + \rho_d'(1 + \theta_g)gh_s \quad (10)$$

where h_u and h_s represent the distance from the water table to the surface, and water table to the point of interest beneath, respectively, and where ρ_d' is the strain (ε) adjusted ρ_d for the zones above and below the water table, respectively. When the water table depth (h_u) was below 30 cm, $\theta_{g(AVG)}$ was determined from gravimetric soil moisture measured at 5, 10, and 100 cm, as

$$\theta_{g(AVG)} = \frac{\theta_5 \cdot 10 + \theta_{20}(h_u - 25) + \theta_{100} \cdot 15}{h_u} \quad (11)$$

where it was assumed that θ_{100} represented the gravimetric water content of a 15 cm capillary fringe [see *Price and Whitehead*, 2003], θ_5 represents θ_g the 0–10 cm layer, and θ_{20} represents θ_g in the layer from 10 cm to the top of the capillary fringe. When the water table was above 30 cm

$$\theta_{g(AVG)} = \frac{\theta \cdot 10 + \theta_{20} \cdot (h_u - 10)}{h_u} \quad (12)$$

[19] Effective stress (σ_e), determined from equation 2 accounts for the role of pressure. In the peat layer between 5 and 10 cm (h_u) the average pressure (ψ) was determined from tensiometers 5 and 10 cm below the surface. Below the water table pressure was determined as the distance (h_s) in cm below the water table (expressed as kPa).

[20] Laboratory shrinkage tests were performed using a peat sample (approximately 8 cm sided cube) coated with Saran F310 resin, using the method described by [*Brasher et al.*, 1966]. The resin-coated sample was allowed to dry over a 50-day period, and the water loss was determined gravimetrically. The resin permits vapor to escape, but blocks liquid water transfer. Hence the sample was immersed in water to find its displacement volume. Measurements of mass and volume change were made approximately every 3 days, except for the second last measurement, which was separated by a period of about 3 weeks from the preceding measurement. Peat particle density (ρ_s) was determined in the laboratory using standard methods [*Blake and Hartge*, 1986]. Plotting and analysis follows from [*Bronswijk*, 1988] with void ratio (φ) (volume of voids/volume of solids) plotted against moisture ratio (ω) (volume of water/volume of solids).

5. Results

[21] Rainfall between 6 May and 27 August 1998 totaled 286 mm (Figure 2). Most of the rain fell in June and July, with only one storm greater than 20 mm (30 June; 27.1 mm). Rain for the months of May to August registered at Peribonca, Quebec was −50, +69, −22 and −45% of the 30-year normal [*Ministère de l'Environnement*, 1998]. Published data from 1–14 May 1998 are missing, but they were supplemented (6–14 May) with rain recorded at this study site to determine the deviation reported above. Evaporation, ranging from 0.8 to 6.9 mm d^{-1}, averaged (±standard deviation) 3.0 ± 1.5 mm d^{-1}, and totaled 438 mm. Follow-

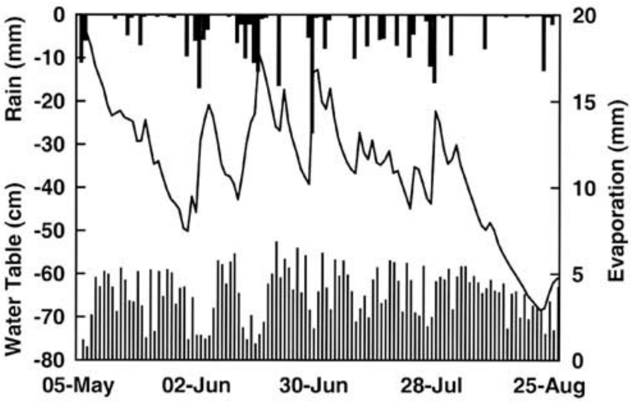

Figure 2. Rain, evaporation, and water table depth in 1998, at the meteorological station on the 7-year abandoned site.

ing snowmelt, the water table in the 2-year and 7-year abandoned sites was at the ground surface. At the undisturbed site it was 8 cm below the surface. May and August were comparatively dry, and in these months the water table at the 2-year and 7-year abandoned sites, and undisturbed site, dropped to 50, 68 and 40 cm below the ground surface, respectively.

[22] Soil moisture was highly temporally variable 5 cm below the surface (Figure 3). At 20 cm depth soil moisture was also highly variable at the 7-year abandoned site. These locations and depths all experienced a general decline in soil moisture but were punctuated with increases corresponding to moisture recharge from rain events. At both the undisturbed and 7-year abandoned sites at 100 cm depth, and at the undisturbed site at 20 cm depth, soil moisture experienced a general decline (5% and 6.5%, respectively, between 6 May and 27 August), but did not exhibit marked short-term temporal variability.

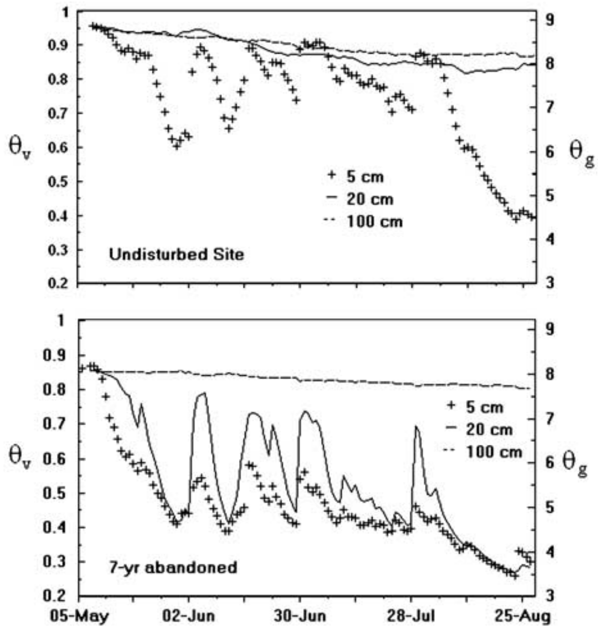

Figure 3. Volumetric soil moisture (θ_v) and gravimetric soil moisture (θ_g) at the undisturbed and 7-year abandoned sites at 5, 20, and 100 cm below the surface. No data were collected at the 2-year abandoned site. Note that θ_v is based on calibration of a fixed peat volume and thus is greater than the actual volumetric soil moisture (i.e., expressed against the changing peat volume [*Oleszczuk et al.*, 2000].

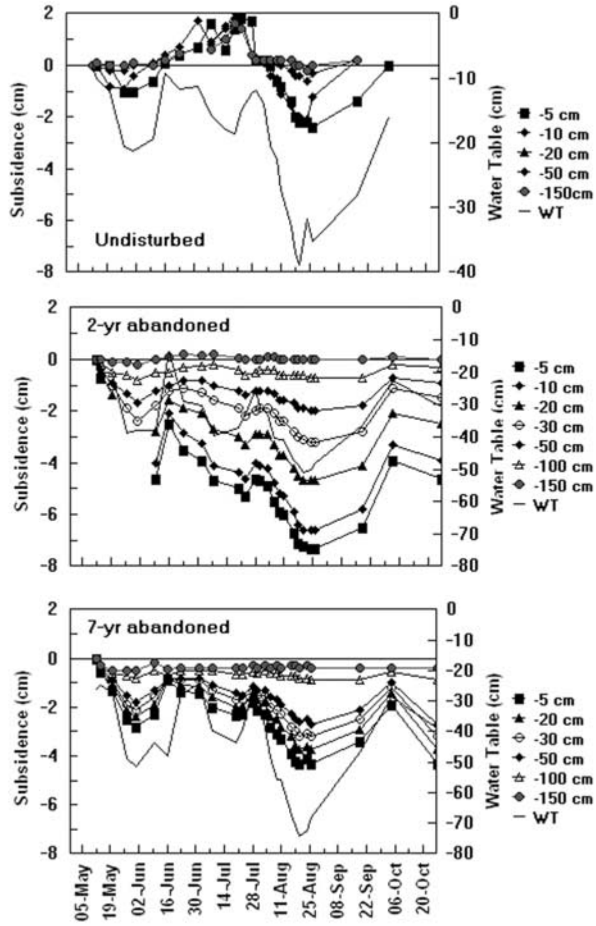

Figure 4. Sensor displacement plotted relative to initial position on 15 May for (top) undisturbed, (middle) 2-year, and (bottom) 7-year abandoned sites. Water table at each site is also shown. See color version of this figure in the HTML.

[23] Changes in peat thickness measured by the peat elevation sensors at the 2-year and 7-year abandoned sites were closely related to fluctuations of the water table (Figure 4), rising and falling in unison. This was not the case in the undisturbed site between 17 June and 31 July, when this trend reversed. The maximum subsidence recorded (at the sensor 5 cm below the surface) at the undisturbed, 2-year abandoned and 7-year abandoned sites was 2.5, 7.2 and 4.5 cm, respectively. Since the movement of the sensors was cumulative in the sense that those closer to the surface were dependent on the movement of all peat below them, the relative change in volume of the peat layer represented by each sensor was determined by deducting the elevation change in the next deepest sensor (Figure 5). In all cases the greatest volume change occurred near the surface (for example, see the 5 cm sensor that represents the 5–10 cm layer). At this level volume change was approxi-

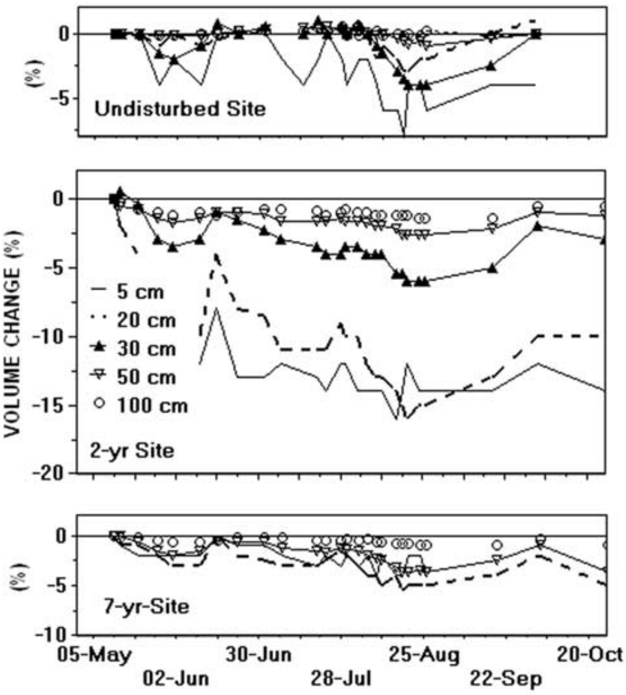

Figure 5. Volume change (strain) in individual layers at the (top) undisturbed, (middle) 2-year, and (bottom) 7-year abandoned sites. The sensor level identified indicates the top of the layer it represents. The bottom of the layer is identical to the top of the next deepest layer (note that not all levels are shown).

mately 5% at both the undisturbed and 7-year abandoned sites, and up to 15% at the 2-year abandoned site. At 100 cm depth, the volume change at the undisturbed, 2-year and 7-year abandoned sites was 0.5, 1.4, and 1%, respectively. Most of the volume change occurred in the top 50 cm. While the greatest rate of change occurred near the surface, this represented a relatively small proportion of the peat deposit.

[24] Hydraulic conductivity increased and decreased corresponding to increases and decreases in water table. The (geometric) mean hydraulic conductivity at 0.75 m depth varied closely (r^2 = 70–80%) with water table position (Figure 6). K_{sat} decreased two orders of magnitude (10^{-3} to 10^{-5} cm s^{-1}) at the 2-year and 7-year abandoned sites as the water table dropped. The change at the undisturbed site decreased by only one-half, at this depth, from 2.1×10^{-3} to 1.1×10^{-3} cm s^{-1}. Order-of-magnitude decreases occurred in 2-year abandoned and 7-year abandoned sites at 1.25 and 1.75 m depths, but again, by lesser amounts in the undisturbed site.

[25] Peat volume change (strain) of the 7-year abandoned site was positively correlated to changes in effective stress ($\Delta\sigma_e$), shown in Figure 7 for the 5–10 cm layer (r^2 = 0.69) and 100–150 cm layer (r^2 = 0.63). Greater strain occurred in the 5–10 cm layer, where negative pore water pressures dominated effective stress. The slope of this relationship, which represents the compressibility of the medium, was greater (0.5) in the shallower peat, compared to that in the deep peat (0.3). Absence of θ_g data for the 2-year abandoned site, and ψ for the undisturbed site precluded similar analyses there. However, it seems clear from Figures 4 and 5 that peat compressibility at the 2-year abandoned site was considerably greater than at the 7-year abandoned site.

[26] Shrinkage tests performed in the laboratory were done with peat from the 7-year abandoned site that had particle density (ρ_s) of 1.45 Mg m^{-3}. The initial volumetric water content was 85%. The sample shrank 7.3% by volume, and 14% by mass, over 50 days. Shrinkage data initially plotted parallel to the "normal" (primary) consolidation line (1:1 line between ω and φ, in Figure 8), where the moisture ratio (ω) was greater than 7.4. All points plotted above the 1:1 line. At lower moisture ratios, the void ratio (ε) did not change (with ω), meaning some voids emptied. Shrinkage may be underestimated because a small portion of water may have been lost during the coating process.

[27] Changes in peat layer thickness (t/t_i) calculated from changes in soil moisture (equation 4) were made at 20 and 100 cm depths at the undisturbed site, and at 100 cm only at the 7-year abandoned site, where (from Figure 3) it seems apparent that air-entry did not occur. In these cases normal consolidation was assumed. At all depths and sites the volume change predicted from changes in θ_g were notably overestimated (Figure 9). There was a general trend of decreasing layer thickness predicted and observed, but the patterns of temporal variability were not well matched.

6. Discussion

[28] As is typical in bogs, a summer water deficit developed because evaporation (438 mm) was much greater than precipitation (286 mm). The result was a decline in water table. As the water table dropped, air entered the overlying peat, and consequently there was a drop in soil moisture above the water table (Figure 3). The loss of peat buoyancy and the negative pressures that developed in this zone resulted in an increase in effective stress that significantly compressed the peat. Below the water table a smaller effective stress (see Figure 7) resulted in a small but important decrease in soil moisture there (see soil moisture curves for 100 cm sensors in Figure 3). Over the summer period the changes were manifest as a lowering of the peat surface.

[29] Volume change is directly linked to changes in effective stress (σ_e) that is associated with changes in the water table and soil moisture, thus careful attention to water content is needed. The high soil moisture variability at the 5 and 20 cm depths at the 7-year abandoned site, and at 5 cm at the undisturbed site was a consequence of pore water drainage and air-entry. Soil moisture was not recorded for the 2-year abandoned site. At the undisturbed site the water table was above the 20 cm sensor until about 8 August, but no evidence of gravitational drainage was apparent at the 20 cm level (Figure 3) because of capillary fringe effects [*Price and Whitehead*, 2003]. At 100 cm depth at both sites, the soil moisture declined gently but steadily, but was not due to air-entry, in the conventional sense. The decrease in moisture content at these depths was in large part a response to the general increase in effective stress over the summer, resulting in strain (deformation) (Figure 7) in which the proportion of solid material in a given volume increased. This increase in σ_e required a dissipation of excess pore water pressure, which in this system propels water toward

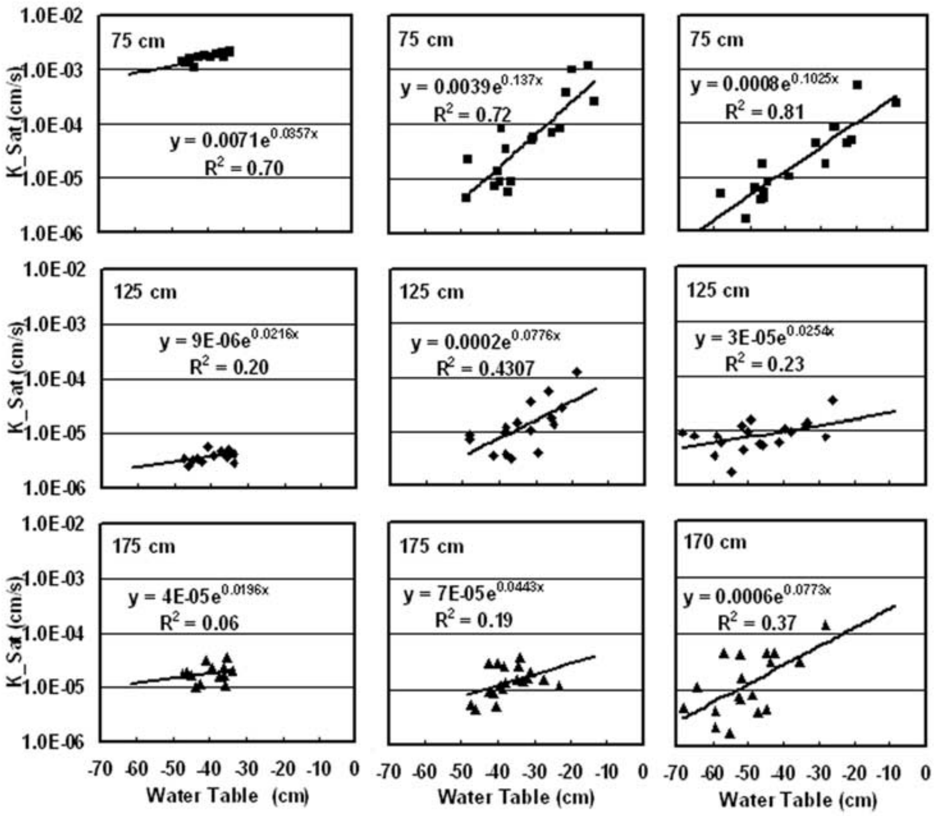

Figure 6. Saturated hydraulic conductivity at 75, 125, and 175 cm depths at the (left) undisturbed, (middle) 2-year, and (right) 7-year abandoned sites. Values are the geometric mean of measurements made in each of the three piezometers at each depth, at each site, on the same day.

the surface. Evapotranspiration was the main water sink, and drove this process.

[30] At the cutover sites the greatest changes in peat volume occurred in the upper peat layers (i.e., above the water table). The greater change at the 2-year abandoned site (about 15% at 5 cm depth) compared to the 7-year abandoned site (about 5%) is likely because the older abandoned site has undergone more irreversible consolidation due to the longer period it has experienced this additional overburden pressure caused by site drainage, thus preconsolidation [*Hobbs*, 1986], and time for peat oxidation [*Waddington et al.*, 2002]. A greater volume change near the surface was a consequence of the negative pore water pressures that increased the effective stress (equation 2). Furthermore, the soil compressibility of peat in the unsaturated zone was greater (Figure 7), possibly due to the inclusion of (highly compressible) gas bubbles [*Yager and Fountain*, 2001] that inevitably occur there. Below the water table (e.g., between 50 and 100 cm depth) the change in peat volume was relatively small (a few per cent). Nevertheless, significant changes in peat hydraulic properties occurred at these depths (discussed below). *Price and Schlotzhauer* [1999] demonstrated that the magnitude of water storage change at this site (7-year abandoned) was mostly (63%) due to the storativity associated with aquifer compression, compared to 37% caused by water table variability.

[31] At the undisturbed site the correspondence between decreasing peat volume and water table occurred for the first

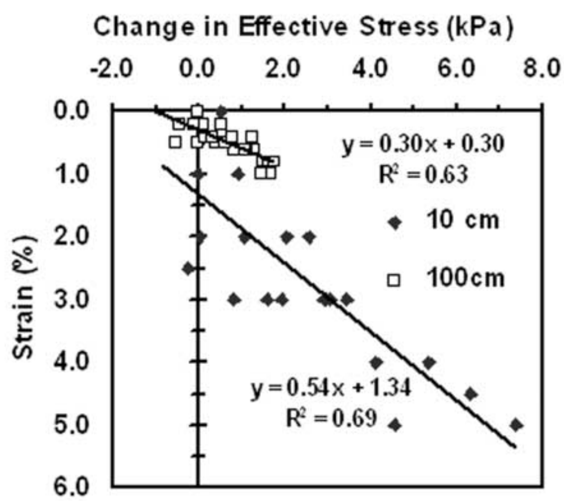

Figure 7. Changes in effective stress versus strain in the 5–10 cm layer and 100–150 cm layer in the 7-year abandoned site. Stress was determined from equation 1, and strain was derived from the soil deformation sensors. The poor resolution (0.5%) of the strain measurements is reflected in the horizontal distribution of points (range of σ_e for a given strain) in Figure 7.

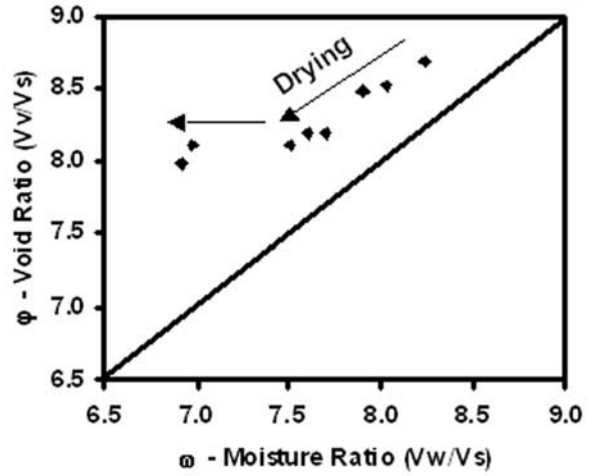

Figure 8. Laboratory results of volume change in a drying peat sample. The solid line represents normal consolidation in a completely saturated medium. The data are parallel to this line, indicating normal consolidation but incomplete saturation.

month of the study, but then the trend was reversed from 17 June (on which day 26.5 mm of rain fell) until 4 August, when a strong drying trend occurred. The erratic but parallel variation of peat elevation occurred at all sensor levels (Figure 4), indicating that either swelling took place primarily beneath the lowest sensor, or that the wire datum or anchoring rods shifted. The latter explanation seems unlikely. It seems likely that the upward movement (swelling) at depth is the production of methane in excess of equilibrium pore water pressures. Such over-pressuring [see *Romanowicz et al.*, 1993; *Siegel et al.*, 2001] has been shown to affect peatland surface elevation (and hydraulic head) [*Seigel*, 1998], and may be a cause of flow-reversals in peat bogs [e.g., *Devito et al.*, 1997; *Waddington and Roulet*, 1996; *Van Seters and Price*, 2002].

[32] To test the response of volume changes to changes in soil moisture, the model of soil compression (equation 4) was used. This model assumes normal (primary) consolidation, whereby the change in volume is entirely attributable to water displacement. These are the conditions that normally prevail below the water table. The laboratory data appear to support this (Figure 8), at least at higher moisture contents where the change is parallel to the 1:1 line (normal consolidation). However, based on the changes in soil moisture observed in the field (Figure 3), the relative volume change (t/t_i) based on equation 4 considerably over predicts the observed strain (Figure 9). While the peat underwent considerable deformation, it was much less than expected based on observed soil moisture changes. The most logical explanation is that methane production within pores displaced water, causing a decrease in moisture content, but not necessitating a volume change. This will be discussed later.

[33] The consequence of soil consolidation had an important effect on K_{sat} (Figure 6). The magnitude of the change in K_{sat} was greatest at 75 cm, and least at 175 cm, corresponding to the degree of strain at each level. It is perhaps noteworthy, however, that K_{sat} at a specific depth was better correlated to water table than strain. This is probably due to the poor sensitivity and small range of strain compared to those of the water table. The smaller change in K_{sat} at the undisturbed site was a consequence of the smaller water table drop that occurred there. Given that large pores are the first to collapse during consolidation [*Chow et al.*, 1992], the marked decrease in hydraulic conductivity (thus lateral seepage losses) is an obvious consequence, since large pores transmit most of the flow. This may be an important self-preservation mechanism in undisturbed bogs, because deeper water table drawdown is associated with enhanced peat oxidation and bog (ecological) instability [*Hilbert et al.*, 2000]. In cutover peatlands like the 2-year and 7-year sites, *Price* [1997] showed that water table position was relatively unimportant to the success of plant reestablishment, but maintaining a higher soil water pressure was the key to enhancing *Sphagnum* reestablishment. *Price* [1997] also noted that soil-water pressures at older cutover sites were more extreme (negative). It has been shown here that the older 7-year abandoned site underwent less consolidation, thus for an equivalent water loss (e.g., by evapotranspiration) pore spaces became dryer and pressures more extreme [see *Price*, 1997], than where pores can more freely collapse (e.g., 2-year abandoned site).

[34] The production and oxidation of methane in peat soils has been well studied (see *Segers* [1998] for review), although its immediate hydrological consequences have not. Briefly, methanogenesis occurs under anaerobic conditions where labile carbon exists, such as in the poorly decomposed peat at this site; and is encouraged by warmer soil temperatures [*Dunfield et al.*, 1993]. The higher soil temperatures that occurred in the summer not only increased methane production, but also may have stimulated the release of dissolved gas into bubbles, expelling pore water (i.e., reducing soil moisture) but maintaining an equivalent volume. Because gas is highly compressible, increases in effective stress (σ_e) caused by a declining water table could accelerate consolidation [*Yager and Fountain*, 2001], since a reduction in bubble volume would be direct and instan-

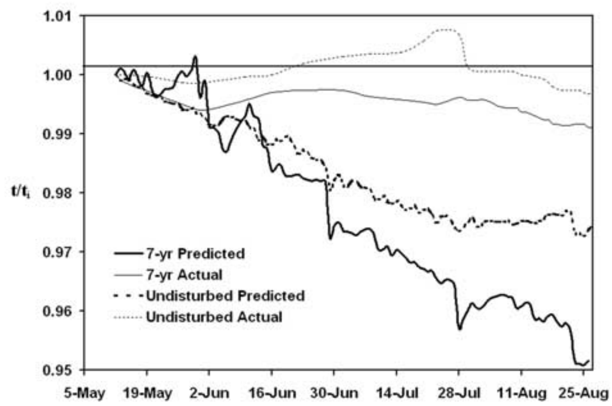

Figure 9. Predicted and actual deformation (strain) within layers assumed to be saturated (air entry had not occurred) at the undisturbed site and 7-year abandoned site. Deformation predicted on the basis of soil moisture changes (equation 4) is clearly overestimated.

taneous, at least compared to more lengthy pore water expulsion and eventual loss by evapotranspiration. Thus the slope of the consolidation relationship (Figure 7) is probably steeper than one would determine in a lab sample without significant gas inclusion.

[35] It should be noted that the presence of even a small volume of gas in the pores could also significantly decrease K_{sat} [*Beckwith and Baird*, 2001]. *Romanowicz et al.* [1995] hypothesized that methane bubbles at depth cause a confining layer to dissolved and gaseous methane flux. The observation here of large decreases in K_{sat} also corresponds to the period of increasing peat temperature, thus methanogenesis. Consequently, a portion of the observed decrease in K_{sat} could be attributable to methane development, but an important factor was changing pore architecture caused by compression. Whatever the cause, changes in K_{sat} of over two orders of magnitude have a major impact on the ability of peat to transmit water, both to the surface for evapotranspiration - moreover for plant water-supply; and to the bog margin.

7. Conclusions

[36] The significant water deficit typically experienced in continental peatlands during summer results in water table drawdown. Consequently, there is an increase in effective stress on peat that results in strain, or peat deformation. This can be observed as surface subsidence, which is largely reversible when wetter conditions return. Subsidence occurs primarily through the collapse of large pores, which are most prevalent near the surface of undisturbed peatlands. In any case, the greatest strain (e.g., 5–15% in this study) is near the surface where strong negative pressures often develop. At depths below 50 cm, strain is much less (0.5–1% in this study). The consequences of significant peat deformation in the zone above the water table, in terms of changes to hydraulic parameters, require investigation. However, even where strain is relatively small (i.e., below the water table), significant seasonal changes can occur to hydraulic conductivity. In this study, where volume change (shrinkage) of only 1% occurred, there was a change (decrease) in hydraulic conductivity of more than 2 orders of magnitude. Following rewetting, an increase in hydraulic conductivity was observed. The collapse (or refilling) of large water-conducting pores is the likely explanation. However, the genesis of methane in saturated peat can have a similar effect, albeit smaller [e.g., *Beckwith and Baird*, 2001]. While no direct measure of methane in the peat soil was made in this study, several observations point to its presence. These include (1) the irregular behavior (swelling) of peat at depth in the undisturbed site, while the water table was falling; (2) the change in saturated soil moisture content beyond that which can be explained by peat deformation; and (3) the presence of gas in a presaturated, sealed, laboratory peat sample. In spite of the probable presence of methane, changes in hydraulic conductivity were closely correlated to changes in water table position.

[37] Change in water balance caused by reduction in lateral drainage (lower hydraulic conductivity) may also be important, although at this site (ditches blocked), evaporative water loss greatly exceeded drainage losses. Perhaps more important are the effects of seasonal swelling and shrinkage on water storage changes [*Price and Schlotzhauer*, 1999], which at this same site water storage changes due to soil volume change were greater than those due to water table fluctuations (i.e., via specific yield).

[38] The presence and possible effects of methane were a surprise outcome of this study, and in the absence of direct measurements of methane concentrations, conclusions about its role must be limited. Further study is required. However, the seasonal deviation of hydraulic conductivity, whatever its cause, is an important finding. Studies in undisturbed or damaged peatlands that rely on measurement of hydraulic conductivity made at a single point in time could be in error by several orders of magnitude. Models or flux calculations based on inadequate temporal sampling will have a similar error. To correctly predict water fluxes, it is necessary to characterize changes in hydraulic conductivity on the basis of pressure changes in the system, whether above or below the water table. Here this relationship has been demonstrated for several sites within one peatland, within saturated peat only. Above the water table, volume changes are proportionally greater, yet the consequence on hydraulic conductivity remains a matter of speculation. As below the water table, large pores will collapse first, but the volume change will maintain a higher level of saturation than it would in a rigid soil. Consequently, the usual reliance of unsaturated hydraulic conductivity on the level of saturation is compounded by the reliance of saturation on volume change, as well as intrinsic differences to the peat as a conductive medium. To be able to model pressure distributions and soil-water fluxes in the unsaturated zone will require considerably more effort (parameterization) than for rigid soils, and must incorporate an explicit function of strain vs. hydraulic conductivity and water-retention.

[39] Regardless of the technical difficulty of representing the volume-change in a hydrological model, the process itself may have important ecological significance. In peatlands, nonvascular vegetation (chiefly *Sphagnum*) relies on capillary water to replace that lost to evaporation. In this deformable soil system, evaporative water losses will have less effect on water table drawdown, and the degree of soil saturation will be more elevated, than in a rigid soil system under similar conditions [*Nuttle et al.*, 1990]. Consequently, after a period of water loss, vertical moisture fluxes to nonvascular vegetation in peatlands is less restricted than it would otherwise be. At the same time, lower hydraulic conductivity in the saturated peat will restricts lateral water losses. Moreover, sustained saturation will reduce peat oxidation. Thus the changing peat volume may be an important self-preservation mechanism for undisturbed peatlands, and an important consideration for water managers planning for restoration of cutover systems.

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