

Moisture dynamics and hydrophysical properties of a transplanted acrotelm on a cutover peatland

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Abstract:

The natural carbon storage function of peatland ecosystems can be severely affected by the abandonment of peat extraction, influencing peatland drainage, leading to large and persistent sources of atmospheric CO₂. Moreover, these cutover peatlands have a low and variable water table position and high tension at the surface, creating harsh ecohydrological conditions for vegetation re-establishment, particularly peat forming *Sphagnum* moss. Standard restoration techniques aim to restore the peatland to a carbon accumulating system through various water management techniques to improve hydrological conditions and by reintroducing *Sphagnum* at the surface. However, restoring the hydrology of peatlands can be expensive due to the cost of implementing the various restoration techniques. This study examines a peat extraction-restoration technique where the acrotelm is preserved and replaced directly on the cutover peat surface. An experimental peatland adopting this acrotelm transplant technique had both a high water table and peat moisture conditions providing sufficient water at the surface for *Sphagnum* moss. Average water table conditions were higher at the experimental site (-8.4 ± 4.2 cm) compared to an adjacent natural site (-12.7 ± 6.0 cm) suggesting adequate moisture conditions at the restored surface. However, the experimental site experienced high variability in volumetric moisture content (VMC) in the capitula zone (upper 2 cm) where large diurnal changes in VMC ($\sim 30\%$) were observed, suggesting possible disturbance to the peat matrix structure during the extraction-restoration process. However, soil–water retention analysis and physical peat properties (porosity and bulk density) suggest that no significant differences existed between the natural and experimental sites. Any structural changes within the peat matrix were therefore minimal. Moreover, low soil-water tensions were maintained well above the laboratory measured critical *Sphagnum* threshold of 33% (-100 mb) VMC, further indicating favourable conditions for *Sphagnum* moss survival and growth. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS peatland; acrotelm; restoration; water table; moisture dynamics

Received 3 January 2007; Accepted 1 May 2007

INTRODUCTION

Northern peatlands cover approximately 364×10^6 ha (Gorham, 1991) of the Earth's surface. Peatlands often have a two-layered soil structure within the peat profile, referred to as the acrotelm and catotelm (Ingram, 1978, 1992). The acrotelm is the upper layer of peat where water table fluctuations occur and is characterized by a high organic content that is poorly decomposed with high specific yield and porosity (Ingram, 1983). In natural peatlands, the large pore structure of the acrotelm contributes to a high water storage capacity (Boelter, 1968), particularly specific yield, which aids in limiting water table fluctuations to the near surface (Price, 1996). Hydraulic conductivity in the acrotelm is also high and generally decreases with depth (Boelter, 1965). In contrast, the catotelm is the lower and deeper layer that is permanently saturated containing highly decomposed organic material. Since catotelmic peat is degraded and consists of smaller pores, less water can be drained through gravity, resulting in low specific yield therefore higher water retention. Hydraulic conductivity is also

low; however, porosity can remain high due to the number of smaller pores within the peat (Boelter, 1965). Consequently, the structural differences of the acrotelm and the catotelm are important in determining the storage of water in peatlands (Romanov, 1968).

The high water storage capacity of the acrotelm and its ability to shrink and swell means that it acts as a regulatory function. It minimizes water table fluctuations, maintaining the water table close to the surface (Ingram 1983). In a natural peatland, the water table position generally remains very close to the surface and so the peat is able to maintain relatively wet conditions (Price, 1996; Holden and Burt, 2003). The diplotelmic structure is therefore important in terms of both water transport and water storage where disturbance to this structure can cause significant changes to the hydrological functions. Disturbances such as peatland drainage and/or peat extraction can have a large impact on the hydrophysical properties of peatlands (Holden *et al.*, 2006).

Within North America, approximately two-thirds of the peat extraction for horticultural purposes occurs within Canada and the demand for horticultural peat over the past century has led to the drainage and extraction of over 12 000 ha of peatlands (Cleary *et al.*, 2005). In areas such as the St Lawrence lowlands in Québec, loss of peatlands for peat extraction exceed 70% (Van Seters

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and Price, 2001). Block-cutting and vacuum extraction (dry harvest) techniques have been used primarily for the peat horticulture industry in Canada. Early peat extraction was typically performed by block-cutting where drainage of the peatland occurred with a series of ditches and subsequent extraction trenches. The acrotelm of the peatland was removed and discarded at the side, exposing the catotelmic peat used for horticulture. The extraction of this deeper peat was cut by hand into ~60 cm blocks (Girard *et al.*, 2002), thereby leaving the landscape in an arrangement of alternating baulks (raised mounds) and trenches (e.g. Robert *et al.*, 1999; Girard *et al.*, 2002). The remaining acrotelm material discarded at the side was generally moved to the centre of the extracted trench as more trenches were cut (Girard *et al.*, 2002). Although rarely used today in commercial peat extraction, remnants of these systems still remain in Europe and eastern North America (Price *et al.*, 2003). By the mid-1970s, mechanized cutting became the dominant peat extraction practice for commercial use. Occurring at a larger scale than block cutting, deeper and more frequent drainage ditches were used in order to facilitate adequate drainage to support heavy extraction machinery (Price *et al.*, 2003). Similar to block-cutting, the acrotelm was removed, but rather than being discarded adjacent to the extraction site, the stripping spoil or skag (i.e. vegetation layer) was completely discarded (Heathwaite *et al.*, 1993). The peat surface is then milled to facilitate drying and peat fragments are typically vacuumed from the surface (i.e. vacuum extraction) using heavy machinery to a depth of ~75–100 cm (Price *et al.*, 2003). Consequently, this dry harvest peat extraction process creates unfavourable conditions at the peat surface, especially for the re-establishment of species such as *Sphagnum* moss, the main peat forming vegetation.

Peatland drainage and dry harvest peat extraction generates harsh ecological and microclimatic conditions, hindering the re-establishment of peatland vegetation following peat extraction and abandonment. During this abandoned stage, the water table position in the now cutover peatland becomes more variable. Volumetric moisture content (VMC) of the peat is lowered and soil–water tension increases (Price, 1996), leading to an increase in peat decomposition (Waddington *et al.*, 2002) and low vegetation productivity (Greenwood, 2005). As soil moisture and soil water tension decrease, water is held more tightly within small pores of decomposed peat, limiting water availability to plants, especially non-vascular peat forming *Sphagnum* mosses (Price and Whitehead, 2004). In order for *Sphagnum* moss to re-establish on the cutover surface, water management techniques such as the blocking of drainage ditches (Eggelsmann, 1988) peat dyke construction (Eggelsmann and Blankenburg, 1993) and straw mulch application (Price 1997, Quinty and Rochefort, 1996) are required to significantly improve the hydrological conditions on cutover peatlands. However, restoring the hydrology of a cutover peatland can be very expensive due to the costs

of implementing the various restoration techniques, and is often delayed until many years after abandonment. Consequently, this leads to a large and persistent source of atmospheric CO₂ due to the decomposing peat and the unvegetated surface (Waddington *et al.*, 2002). The restored peatland hydrology does not resemble that of a natural peatland within the first few years post restoration (Shantz and Price, 2005), and it has been suggested that this will not occur until an acrotelm (upper peat layer) is established on the cutover peatland surface (Shantz and Price, 2005).

In this study, a peatland restoration technique is examined in which ~20–30 cm of the upper acrotelm with vegetation intact is retained during the peat extraction process and transplanted directly on a cutover peat surface. It is hypothesized that the retention and replacement of the upper acrotelm layer in this restoration technique will maintain close to natural hydrological conditions post extraction. More specifically, it is hypothesized that the water table would remain close to natural near-surface level conditions, thereby stabilizing soil moisture content. However, due to the movement and disturbance of the peat surface during extraction and replacement of the peat, it is expected that structural changes could occur in the transplanted acrotelm peat. This causes large pores within the peat to collapse, affecting moisture retention and water movement properties. The aim of this study, therefore, is to characterize the moisture dynamics and hydrophysical conditions of a transplanted acrotelm onto a cutover peat surface and compare it to that of an adjacent natural peatland. If the hydrology of the transplanted acrotelm is similar to a natural site then this restoration technique would potentially result in lower CO₂ emissions to the atmosphere and decrease the time and cost to restore a dry harvested peatland ecosystem to a functioning peatland.

STUDY AREA

This study was conducted at the Point-Lebel peatland, ~20 km south of the town of Baie Comeau, Québec (49°7'N, 68°12'W). The average annual temperature at the Baie Comeau airport (~3 km from the research site), is 1.5 °C with a mean January and July temperature of –14.4 °C and 15.6 °C respectively. The 30 year normal (1971–2000) annual precipitation is 1014.4 mm, of which 684.1 mm is rain (Environment Canada, 2006).

The Pointe-Lebel peatland is situated on top of deltaic sands adjacent to the St Lawrence River forming a 92 ha shrub (*Chamaedaphne calyculata*, *Kalimia angustifolia*, *Picea mariana* and *Ledum groenlandicum*), *Sphagnum* moss (*S. rubellum*, *S. fuscum*) and scattered open water bog complex. The peat depth in the peatland ranges from 5–6 m. At the southern end of this complex, a small section of the peatland was subdivided into two sites for this study: natural and experimental. The natural site served as the control site and comprised a pristine section of the peatland that had not been

impacted by any peat extraction or peatland drainage. In June 2005, an experimental site ($\sim 6 \times 12$ m), set-up parallel to a ($\sim 2 \times 1$ m) drainage ditch within the peat extraction zone was used to test the acrotelm transplant procedure.

Acrotelm transplant technique

The acrotelm transplant and peat extraction-restoration technique has been recently developed by Premier Tech Lte. (Riviere-du-Loup, Quebec). This technique increases peat extraction while attempting to minimize ecosystem impact by incorporating restoration (acrotelm transplant) into the process. This trench extraction-restoration technique removes peat similarly to traditional block-cut methods (e.g. Girard *et al.*, 2002). Extraction of the peat is performed mechanically with a back-hoe by creating extraction trenches parallel to a long and deep ($\sim 4 \times 3$ m) cut drainage ditch (Figure 1a). Initially a ~ 20 – 30 cm deep section of the acrotelm containing

the surface vegetation (mosses and shrubs) within a $\sim 5 \times 5$ m plot is removed and placed beside the extraction zone (Figure 1b). Peat is then mechanically removed to the depth of interest (~ 2 m) containing the viable peat for horticultural purposes (Figure 1c). The extracted peat is then transported to a processing facility. Once extraction is complete, the acrotelm that was retained is then transplanted over the older and more decomposed catotelm peat in the cutover peatland (Figure 1d). This creates a trench topography in which the surrounding natural peatland is higher than the extraction zone. The process is then repeated along the transect, thereby expanding the trench. Subsequent trenches are created parallel to the initial trench, decreasing the overall elevation of the peatland over time (Figure 1e). The transplanting of the acrotelm vegetation onto the cutover peatland in the trench is considered the restoration or rehabilitation process since the acrotelm structure is retained.

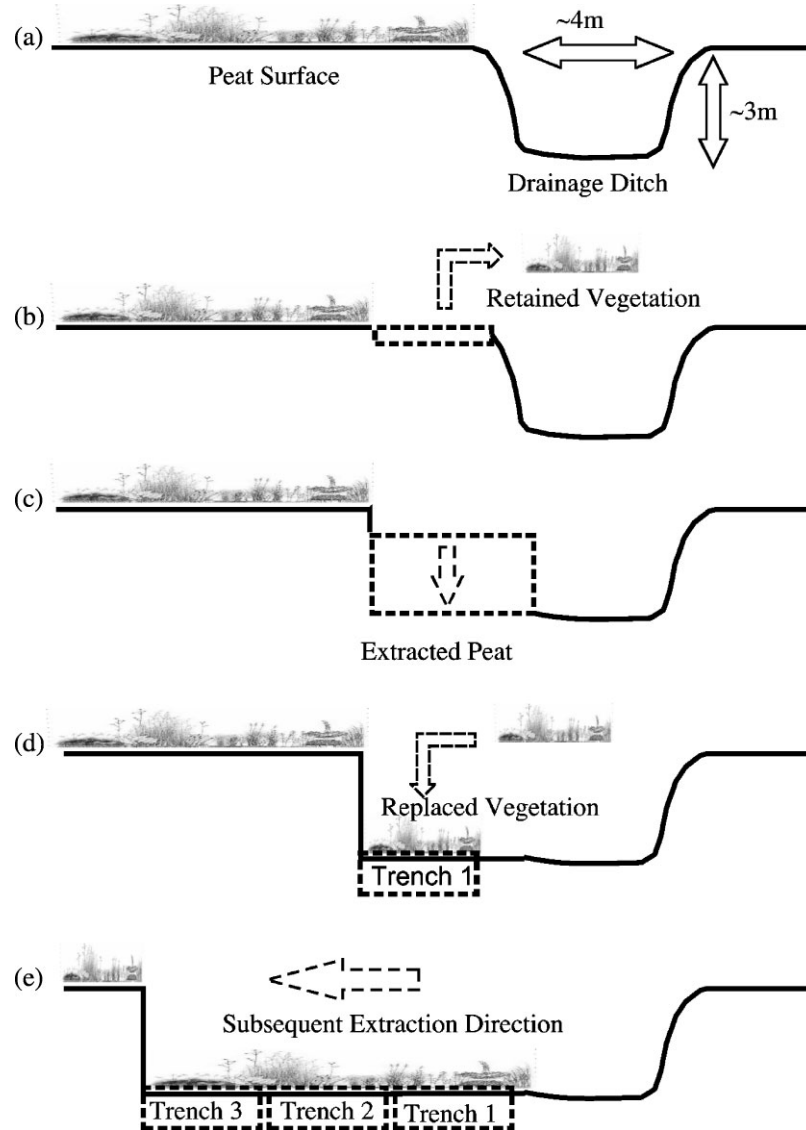


Figure 1. The trench extraction-restoration technique. (a) A natural peatland prior to extraction adjacent to a large drainage ditch. (b) ~ 20 – 30 cm of surface vegetation-acrotelm is removed and retained. (c) Extracted peat. (d) Retained vegetation-acrotelm replaced on cutover surface. (e) Extraction-restoration continues parallel and away from the ditch and moves into the peatland as subsequent trenches are created

METHODOLOGY

Measurements of peatland hydrology were undertaken from May 20th to August 18th, 2005 (day of year 140–230) representing the spring and summer growing periods.

Meteorological variables

Precipitation was measured using a Texas Electronic (Campbell Scientific Inc.) tipping bucket rain gauge at the natural site and additional precipitation data was collected from the adjacent Baie Comeau airport weather station (Environment Canada, 2006). Photosynthetically active radiation (PAR) was measured using a Li-COR (Lincoln, Nebraska) quantum light sensor ($\mu\text{mol m}^{-2} \text{s}^{-1}$). These variables were logged every 20 minutes at both the natural and experimental sites using Campbell Scientific CR10X dataloggers (Alberta, Canada).

Hydrological measurements

Water table levels were measured at two locations (natural and experimental) using a pulley system potentiometric water level recorder and logged every minute and averaged every 20 minutes using the dataloggers.

Within the ~ 25 cm deep acrotelm, two depths were chosen to represent VMC, specifically the *Sphagnum* capitula (0–4 cm) where surface moisture content changes have been shown to affect photosynthesis (Rydin and McDonald, 1985) and a lower acrotelm depth chosen to represent the mean acrotelm moisture condition (10–14 cm). These measurement depths (zones) are hereafter referred to as *capitula* and *mid-acrotelm*.

VMC in the capitula zone θ_c was determined using dual pulse heat probes (DPHP) (East 30 Sensors, Washington) attached to a multiplexer (Campbell Scientific AM16/32, Alberta, Canada) and a datalogger logging at 60 minute intervals. The DPHP sensors consisted of a pair of 30 mm steel needles spaced 6 mm apart. One end contained an Evanohm heater and the other a chromel-constantan (Type E) thermocouple (East 30 Sensors, Washington). A current was applied to the heater for a specified time and the temperature rise of the thermocouple was monitored. The specific heat of the material (e.g. peat) is inversely proportional to the height of the recorded temperature rise, and the thermal diffusivity of the material is related to the time taken for the heat pulse peak to pass the temperature sensor (East 30 Sensors, Washington). Properties such as thermal diffusivity, specific heat and VMC can be calculated from the output of the measurement. A DPHP was installed at a lawn and hummock microform at each site to determine temporal changes in θ_c over the season. Campbell Scientific CS615 (Alberta, Canada) water content reflectometers were used to measure VMC in the mid-acrotelm zone (θ_a) at each site. The probe consists of two 30 cm long steel probes, using time-domain measurement methods that are sensitive to dielectric permittivity, to calculate moisture content (Campbell Scientific, Alberta).

Spatial variability of VMC surveys were taken at a 10×10 m plot at the natural site and a 12×1 m plot at the experimental site. Measurements were taken over three periods at the natural site (June–August) and two periods at the experimental site (July–August) with an instantaneous portable Campbell Scientific Hydrosense (CD620) soil moisture Time Domain Reflectometer (TDR) (12 cm probe length and $\pm 3\%$ accuracy, Campbell Scientific, Alberta, Canada), which integrated the upper 5 cm surface layer and was calibrated in the laboratory for peat soils. A total of 400 VMC measurements were made at each plot (during each period) and these point measurements were then input to a contour surface mapping program (Surfer 8.0, Golden Software, Colorado) to map the spatial distribution of VMC.

Soil-water retention curves

Large intact peat blocks ($\sim 26 \times 33 \times 24$ cm) were removed from the natural and experimental sites in August 2005. The samples were carefully placed in coolers, transported back to the laboratory within 48 h, and frozen. The soil blocks were then cut into several cylindrical capitula and mid-acrotelm cores (8 cm diameter, 4 cm deep) with a hole-saw while frozen, thus preventing compression and disturbance to the physical structure during cutting. Capitula cores were taken from 0–4 cm and mid-acrotelm were taken from 10–14 cm. Replicates of eight sub-samples at each depth for both sites were analyzed to determine differences between sites and depths in soil–water retention curve characteristics and to evaluate the spatial variability. Soil-water retention curves were determined using a methodology fully described by Dane and Hopmans (2002) and Klute (1986). Briefly, the frozen soil samples (contained in PVC rings) were saturated and thawed in de-aired water for 48 h prior to testing to achieve full saturation of the peat. Samples were then placed on top of a high flow 0.5 bar porous ceramic plate cell (effective pore size 6.0 micron, hydraulic conductivity $3.1 \times 10^{-5} \text{ cm s}^{-1}$ and approximate porosity 50% by volume) within a 5 bar pressure plate extractor (Model 1600, Soil Moisture Equipment Corp., Santa Barbara) and sealed. Various tensions were applied (20, 40, 60, 80, 100 and 120 mb) using a pressure manifold ($\pm 1\%$ accuracy) (Model 700-3, Soil Moisture Equipment Corp. Santa Barbara) until equilibrium of the samples was reached within the pressure cell. A water outflow tube was connected from the pressure extractor into a graduated glass beaker to measure the water outflow from the samples. Equilibrium of the samples at each tension increase was reached when the outflow of water had ceased (generally 1–3 days). Samples were weighed prior to moisture extraction (100% saturation) and after each tension change once equilibrium was observed.

RESULTS

Precipitation and water table position

Precipitation during the study season totalled 253 mm, which was much lower than the long-term precipitation

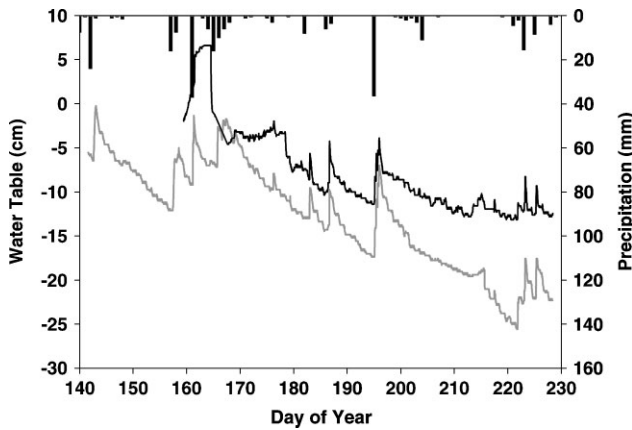


Figure 2. Daily precipitation (upper panel) and water table position at the experimental (black line) and natural (grey line) sites

normal (1971–2000) for the Baie Comeau meteorological station of 340 mm over the same period (Environment Canada, 2006). Frequent precipitation events occurred during the first half of the study season (days 140–180) where 153.5 mm of rain fell compared to 100.5 mm during the latter half of the study season (days 181–230) (Figure 2). Major precipitation events occurred on days 142, 161 and 195 with rainfall depths of 24, 37 and 36.5 mm, respectively. Additionally, from days 160–165, a total of 60 mm of precipitation fell within a 5 day period. During this time, the experimental site experienced a large flooding event shortly after the trench extraction process was complete. Water table position (wt) reached above surface levels due to a backup of water at the site until adequate draining occurred post harvesting, after which wt levels returned to close to surface conditions. The experimental site wt declined throughout the season and ranged from a depth of -13.1 cm to $+6.6$ cm with a mean of -8.4 ± 4.2 cm. The natural site wt reached a maximum and minimum depth of -25.6 cm and -0.2 cm respectively, with a mean of -12.7 ± 6.0 cm.

Seasonal variability in mid-acrotelm VMC

Volumetric moisture content in the mid-acrotelm θ_a at 10 cm depth was significantly greater ($p < 0.05$) at the natural site ($90.4 \pm 1.6\%$) than the experimental site ($89.2 \pm 7.0\%$). A decline in θ_a occurred throughout the season at both sites. However, the temporal variability of θ_a at the experimental site was much larger over the season (Figure 3). The experimental site was very sensitive to precipitation events, enhancing the moisture variability throughout the season, increasing variability. Precipitation events (e.g. days 183 and 195) allowed moisture content to rise significantly after large rainfall events followed by a rapid decline during dry periods. Moreover, θ_a at both sites remained above 50% throughout the season.

Seasonal variability in capitula VMC

VMC in the capitula zone θ_c was $76.8 \pm 5.6\%$ and $65.2 \pm 4.0\%$ for the natural site lawn and hummock, respectively. Similarly, the experimental site lawn and

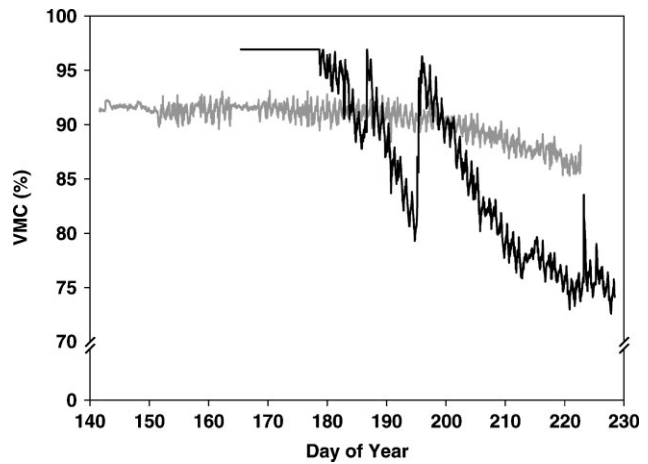


Figure 3. Mid acrotelm VMC at the natural (grey line) and experimental (black line) sites

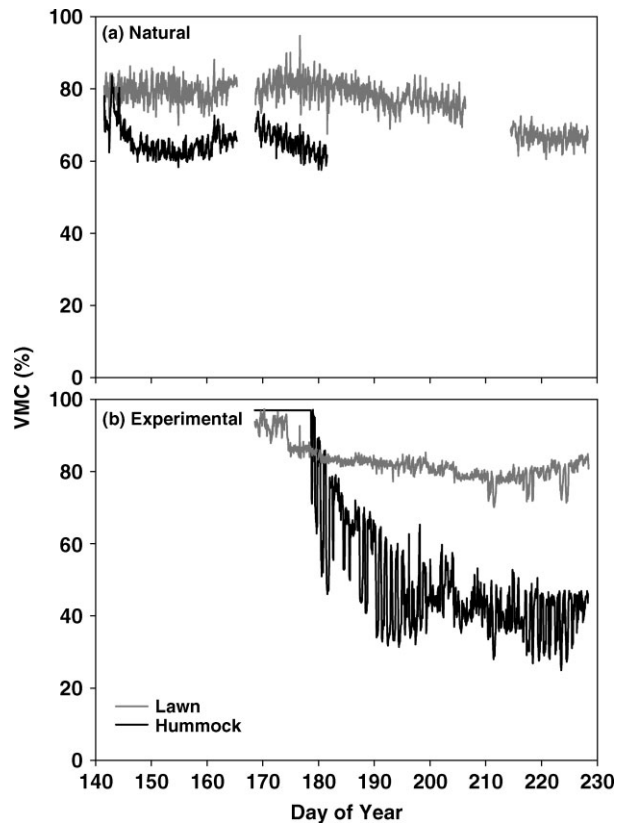


Figure 4. Capitula VMC at (a) natural and (b) experimental lawn (grey line) and hummock (black line) microforms

hummock averaged $82.4 \pm 5.0\%$ and $56.2 \pm 22.1\%$ over the season. VMC in the capitula zone θ_c at the natural site was higher at the hummock, however, the lawn was larger at the experimental site over the season.

The natural site lawn θ_c ($76.8 \pm 5.6\%$) was significantly higher ($p < 0.05$) than the natural site hummock ($65.2 \pm 4.0\%$) (Figure 4a). Lawn capitula maintained a stable moisture content that slowly declined as the season progressed. Furthermore, a moderately rapid decline in θ_c was observed at the natural site hummock followed by more stable moisture conditions. The variation in θ_c at

both microforms remained low due to a fairly stable moisture content over the season, however the lawn appeared to have a slightly greater daily θ_c change compared to the hummock. Additionally, the hummock appeared to be more sensitive to rain events since large increases in θ_c corresponded to large precipitation events.

At the experimental site lawn, θ_c ($82.4 \pm 5.0\%$) was significantly higher ($p < 0.05$) than hummock θ_c ($56.2 \pm 22.1\%$) (Figure 4b). Both the experimental hummock and lawn θ_c began the season under saturated conditions during the flooding event and declined rapidly as the season progressed. The hummock, however, experienced a much greater decline after flooding and remained variable throughout the season. The θ_c variability at the experimental hummock was quite large, where considerable changes in VMC were observed on a daily basis. Furthermore, θ_c at the natural site never dropped below 50% whereas the experimental site experienced surface moisture levels below this level at the hummock microforms.

Diurnal variability in capitula VMC

A time series spectral plot with a Tukey-Hamming spectral window (SPSS, Chicago, Illinois) revealed that a 24 h diurnal cycle for θ_c existed at all microforms at the natural and experimental sites over the season. Spectral density and frequency plots showed that the signal strength of the diurnal cycles differed between microforms and sites. Generally, the natural lawn showed stronger diurnal signals compared to the experimental lawn. However, the experimental hummock exhibited much stronger daily diurnal cycles than the natural hummock. A well-defined moisture pattern at the experimental hummock existed during periods of days with high light conditions where pronounced wetting and drying cycles were evident (Figure 5a). During days with low light conditions, the diurnal cycle was much more suppressed and patterns in θ_c were not very apparent (Figure 5b). A post rainfall period revealed a different pattern with θ_c moderately stronger than the low light days (Figure 5c). Moreover, the experimental lawn microform showed a much lower suppressed diurnal signal compared to the experimental hummock. Conversely, the natural site hummock revealed a lower diurnal signal than the experimental hummock during the high light periods (Figure 6a). The low light period responded similarly to the high light period with moderately less variation (Figure 6b) and a slightly stronger diurnal pattern emerged during a post wetting event compared to a full light period (Figure 6c). Moreover, the natural site lawn microform responded very similarly to the natural hummock diurnal patterns.

Spatial variability in VMC

The natural site began with high surface moisture VMC at the beginning of the season which generally decreased as the summer progressed, whereas the experimental site had higher VMC than the natural site which did not vary much over the two periods post disturbance

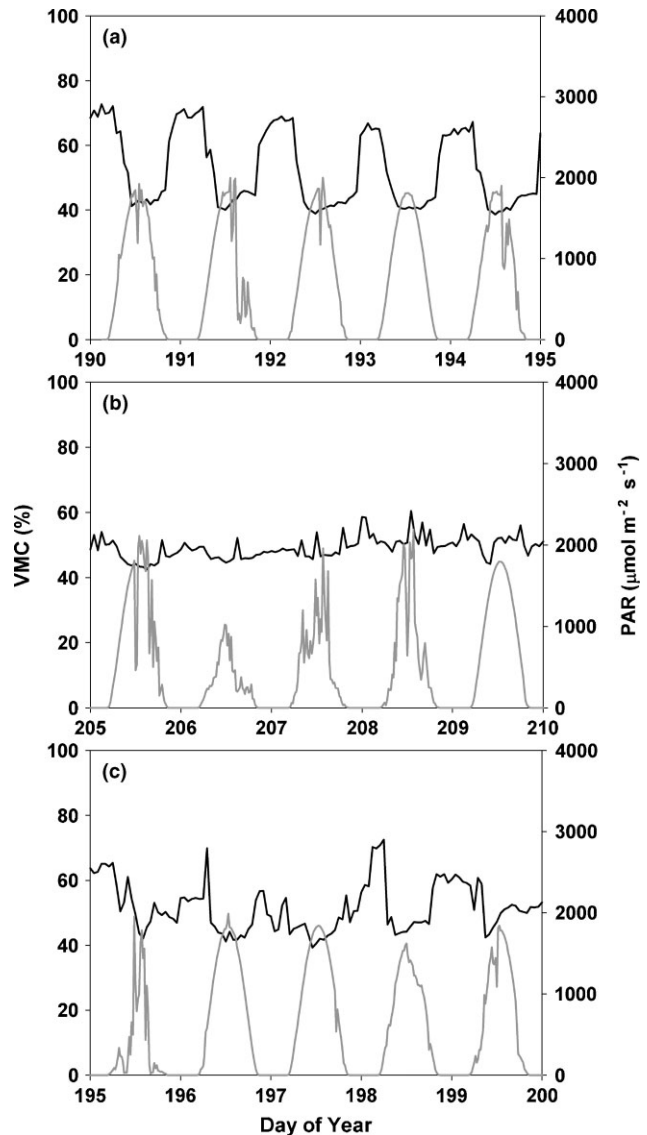


Figure 5. Experimental site diurnal variation in capitula VMC (black line) and PAR (grey line) during (a) high light; (b) low light; and (c) post-rainfall conditions

(Figure 7). During the three measurement periods, the natural site VMC averaged $52.4 \pm 22.7\%$, $39.9 \pm 17.1\%$ and $38.0 \pm 14.1\%$ respectively. The experimental site averaged $93.1 \pm 7.1\%$ and $90.6 \pm 9.9\%$ over the two periods. The spatial variability in VMC was greater at the natural site with coefficients of variation (CV) of 0.43, 0.43 and 0.37 for the three periods compared to 0.08 and 0.11 for the two periods at the experimental site (Table I). Furthermore, the wetter areas at each site commonly corresponded to lawn microforms and the drier areas corresponded to hummock microforms.

Soil-water retention curves

Capitula soil-water retention curves were similar for both the natural and experimental site (Figure 8a). However, applied tension of 80–120 mb produced slight differences in the shape of the retention curve. In particular, the average moisture content at 100 mb tension was moderately higher at the experimental site ($32.6 \pm 8.9\%$) than

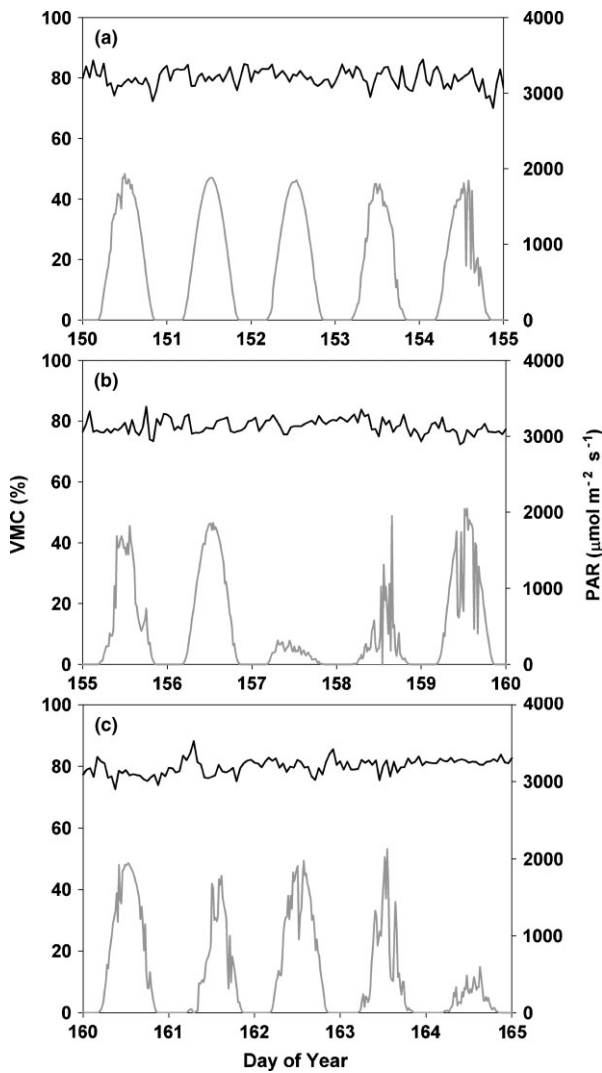


Figure 6. Natural site diurnal variation in capitula VMC (black line) and PAR (grey line) during (a) high light; (b) low light; and (c) post-precipitation conditions

Table I. θ_c and ψ_c statistics at the natural and experimental sites for June–August periods

θ_c	Average	Min	Max	CV
<i>Natural</i>				
June	52 ± 23	3	95	0.43
July	40 ± 17	3	96	0.43
August	38 ± 14	12	81	0.37
<i>Experimental</i>				
July	93 ± 7	30	101	0.08
August	91 ± 10	36	100	0.11
ψ_c	Average	Min	Max	CV
<i>Natural</i>				
June	50 ± 37	14	214	0.73
July	69 ± 39	14	214	0.56
August	70 ± 34	14	159	0.48
<i>Experimental</i>				
July	7 ± 7	0	76	0.99
August	9 ± 9	0	65	0.99

at the natural site ($30.2 \pm 4.5\%$), suggesting moderately greater θ_c at the experimental site for higher tensions.

Mid-acrotelm retention curves for the natural and experimental site also displayed a similar shape (Figure 8b). Greater retention of moisture at lower applied tensions allowed for a less steep initial slope for the acrotelm samples. At 100 mb, moisture at the natural site averaged $38.0 \pm 2.0\%$ and $35.8 \pm 5.5\%$ at the experimental site. Furthermore, moisture differed for the 20 and 60 mb range where average moisture was $77.1 \pm 2.8\%$ and $45.9 \pm 2.1\%$ at the natural site and $84.3 \pm 5.1\%$ and $39.1 \pm 5.1\%$ at the experimental site, respectively. However, no significant differences existed between sites. Furthermore, variability in θ_a at a given tension at the experimental site was moderately higher than at the natural site.

Soil-water retention curves indicate that there are no statistical differences in VMC at any of the applied tensions, suggesting there are no significant structural differences between the natural and experimental sites. Nevertheless, greater variability of θ_c and θ_a at the experimental site suggests that some physical disturbance was caused with the cutting and replacement of the vegetation. However, physical properties measured from the soil water retention samples further indicate no significant structural change occurred. Bulk density at the natural site averaged 0.035 ± 0.002 and 0.040 ± 0.002 for the capitula and mid-acrotelm, respectively. Similarly, the experimental site averaged 0.048 ± 0.010 and 0.050 ± 0.017 for the capitula and mid-acrotelm, respectively. Furthermore, porosity at the natural site capitula and mid-acrotelm averaged 0.975 ± 0.001 and 0.971 ± 0.002 respectively, whereas the experimental site was comparable averaging 0.966 ± 0.007 and 0.964 ± 0.012 at the capitula and mid-acrotelm, respectively.

Spatio-temporal variability in soil–water tension

Using a simple polynomial rule describing the moisture–tension relationship, derived from the laboratory soil–water retention curves, the spatial distribution of soil–water tension c at each site was estimated. At the natural site, the soil–water tension changed throughout the season from low to higher tensions as the season progressed. Conversely, the experimental site did not experience a dramatic change, and generally experienced similar tension ranges through the season. Soil-water tension over the three periods at the natural site averaged -50 ± -37 mb, -69 ± -39 mb and -70 ± -34 mb, whereas at the experimental site results averaged -7 ± -7 mb and -9 ± -9 mb over the two periods. Soil-water tension at the experimental site did not exceed -100 mb over the two periods where the maximum tension reached was -76 mb. However, the natural site exceeded -100 mb at over 8.3%, 18.2% and 15% of the surface area at June, July and August, respectively. Moreover, a maximum tension of -214 mb was reached, suggesting greater potential for water stressed *Sphagnum* moss. The experimental site VMC was more variable

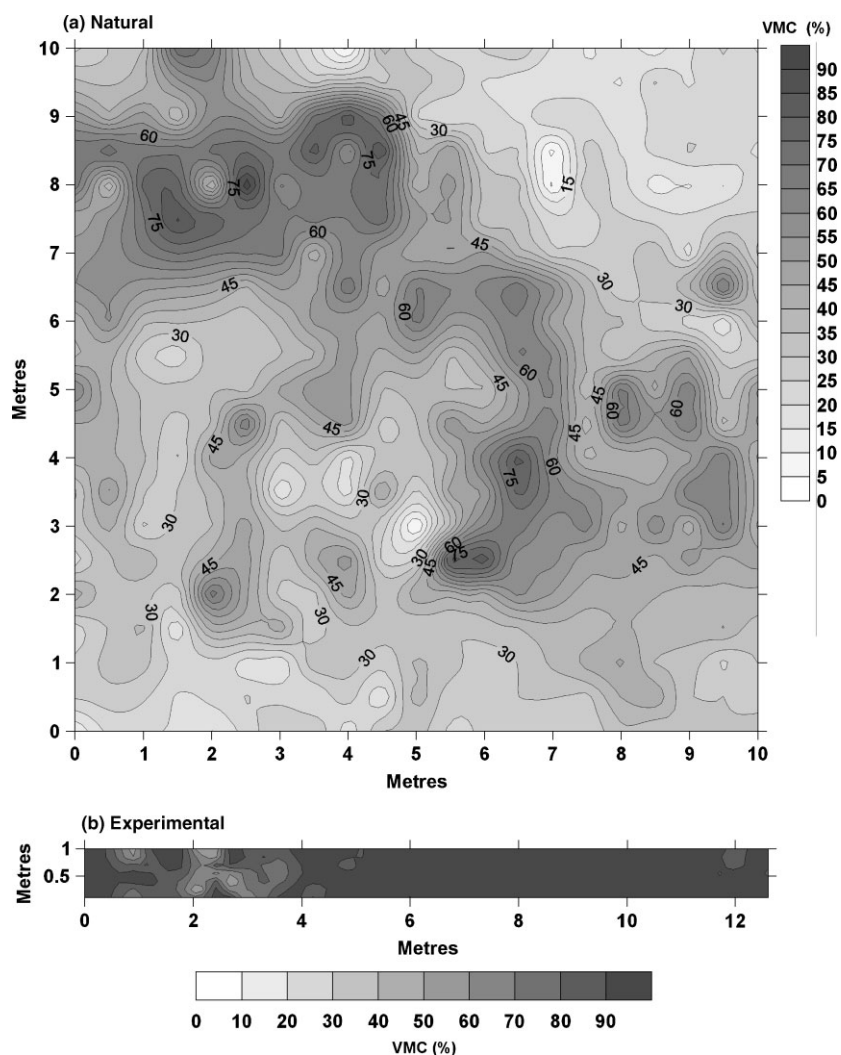


Figure 7. Spatial variability in capitula VMC for the late summer period (August) at (a) natural and (b) experimental sites

with a CV of 0.99 over the two periods. Conversely, the natural site CV was lower at 0.73, 0.56 and 0.48 over the three periods respectively. However, soil–water tension at the experimental site was quite low in most areas, except where a small area of high tension existed.

DISCUSSION

Water table position and temporal VMC within a transplanted acrotelm

It was hypothesized that the retention and transplanting of the acrotelm would assist in keeping the water table close to natural near-surface conditions, thereby maintaining stable and high soil moisture content. The experimental site maintained an elevated water table depth, which was higher relative to the natural site post-restoration. However, this may be a function of the relative position of the surface of the experimental site to the natural site water table post extraction/restoration. Nevertheless, it is believed that as the extraction and subsequent restoration reduces the surface elevation of the natural peatland, the water table position should maintain a relatively similar position as the natural

site due to the transplanted acrotelm and associated hydrological functions that it maintains. Since w_t was greater at the experimental site, it would have been expected that the VMC would have been higher compared to the natural site due to the greater availability of water; however, this was not the case (i.e. hummocks and mid-acrotelm) over the season. It is possible that the removal and replacement of the acrotelm may have damaged the peat structurally, particularly closer to the surface where variability in VMC was greatest (i.e. θ_c), potentially impeding water movement through the peat profile for atmospheric exchange processes. Price (1996) noted that as saturated moisture decreases, soil–water tension can increase where water is held tightly within the micropores of the decomposed peat, further limiting water availability to plants, particularly non-vascular *Sphagnum* mosses (Price and Whitehead, 2004).

Laboratory soil–water retention curves showed that with increasing applied tension, VMC within the peat decreased at both the natural and experimental sites; however, retention over a range of tensions (0–120 mb) were not significantly different between the sites. In fact, moisture–tension relationships in the capitula and

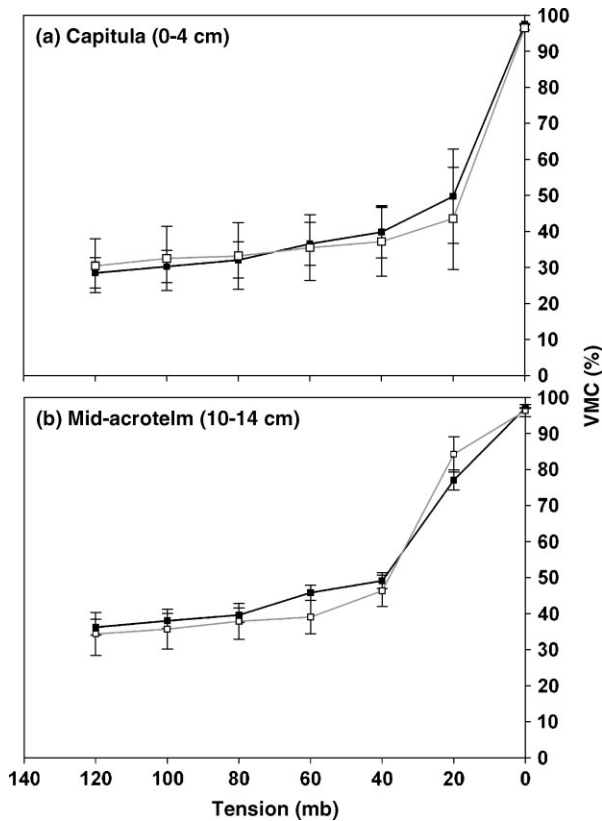


Figure 8. Soil moisture retention curves at the natural (grey line) and experimental (black line) sites for (a) capitula 0–4 cm and (b) mid-acrotelm 10–14 cm

acrotelm layers were very similar, suggesting that the cutting and movement of the acrotelm did not damage the peat structure which would impede water movement within the peat. On average, the experimental site had moderately higher variability and overall greater moisture retention relative to the natural site. This would suggest that a minor disturbance to the peat structure may have occurred, changing pore structure on some samples, allowing for the slight increase in moisture retention. However, measured physical peat properties of bulk density and porosity fell within similar ranges, further indicating that if the pore structure within the peat matrix did change (through compression, shrinkage, etc.), it would have been negligible.

Spatial variability in VMC and soil–water tension

While relatively few studies have characterized *Sphagnum* moisture–tension thresholds spatially within the field, areas where *Sphagnum* had recolonized naturally on a cutover peat surface were characterized by a high water table, VMC above 50% and soil–water tension above –100 mb (Price and Whitehead, 2001), confirming the suggestion by Price (1997) that *Sphagnum* cannot extract moisture with soil–water tension lower than this threshold. Moreover, Price and Whitehead (2001) observed that topographically wetter and lower areas within a block-cut peatland such as trenches were favourable (i.e. high moisture and low tension) to *Sphagnum* re-establishment whereas higher and drier areas such as the baulks were

less favourable (i.e. low moisture and high tension). Similarly, the microtopography at both the natural and experimental sites showed that lawns tended to have high VMC and low soil–water tension whereas hummocks had low VMC and high tension. Importantly, this study showed that the ψ_c critical to *Sphagnum* survival (–100 mb) corresponded to a θ_c of 33% at the experimental site and 30% at the natural site. This suggests that the $\psi_c - \theta_c$ relationship is species and peatland specific. Nevertheless, VMC surveys indicated that the experimental site was generally wetter on average where surface VMC ranged between 90–93% with a minimum θ_c of 30%. However, θ_c at the natural site was much more variable and lower on average. Spatial VMC across both sites suggests that the critical VMC level of 30 and 33%, corresponding to a ψ_c of –100 mb, was reached at both the natural and experimental sites at some point over the season as suggested by the spatial survey. However, the variability at the natural site indicates that VMC reached this critical soil–water tension with greater frequency.

Duration analysis of temporal VMC at the individual vegetation plots (i.e. wet and dry) within the experimental site indicates that VMC remained above the moisture–tension threshold for 100% of the season, suggesting that the variability of low moisture conditions associated with the spatial θ_c survey were likely minimal and were not captured at these individual plots. Conversely, duration analysis at a number of natural plots revealed that temporal VMC exceeded the moisture–tension threshold with durations ranging from 5–50% of the season. Price and Whitehead (2001) observed that soil–water tension fell below critical levels for 75% of the season on a cutover surface, suggesting that prolonged periods of the growing season were detrimental to both *Sphagnum* survival and re-establishment. Moreover, Price (1997) observed that soil–water tension in a bare cutover peatland could drop to values lower than –300 mb, creating an extremely hostile environment for *Sphagnum* development. Within this study, spatial variability of tension at the natural site suggests that tension exceeded –200 mb, indicating that even natural peatlands can reach significantly low tensions over the season. However, the experimental site had low soil–water tensions throughout the site, suggesting more favourable conditions for *Sphagnum*. Nevertheless, it is important to note that it has been shown that *Sphagnum* cannot survive extended dry periods (Sagot and Rochefort, 1996). It has also been suggested that even short periods of high tensions may prevent *Sphagnum* growth even within wetter conditions (Price and Whitehead, 2001).

Diurnal variation in θ_c

Although the experimental site had lower average θ_c than the natural site, the diurnal variation in θ_c was especially high at the experimental plots with observed wetting and drying cycles of ~30% in moisture change on a daily basis. In contrast, the natural site demonstrated a diurnal change in VMC of three times lower

at $\sim 10\%$. Studies have shown that evaporation can range from $2.7\text{--}2.9\text{ mm d}^{-1}$ at natural peatlands, $2.9\text{--}3.1\text{ mm d}^{-1}$ at bare/harvested peatlands and $2.6\text{--}2.9\text{ mm d}^{-1}$ at partially restored peatlands (mulch covered) (Price, 1996; Price *et al.*, 1998; Van Seters and Price, 2001). However, the daily θ_c changes at the experimental site capitula represent a daily loss of $\sim 10\text{ mm}$, over three times greater than the studied natural and standard restored sites. While a 10 mm d^{-1} change is significantly large for evaporative processes, it is more likely that the change in θ_c is partially related to structural changes within the peat as opposed to evaporation alone. However, soil–water retention and porosity properties suggest that no apparent change in structure occurred. The natural site water table was moderately lower than the experimental site; however, observed diurnal θ_c changes were only $\sim 4\text{--}5\text{ mm d}^{-1}$ and could reasonably be related to evaporation.

Peat is highly compressible and elastic where changes in peat volume can occur due to water table changes (Price and Schlotzhauer, 1999). Natural and cutover peatlands undergo seasonal water table changes (e.g. Roulet, 1991; Schlotzhauer and Price, 1999; Kellner and Halldin, 2002) where shrinking and swelling can result, affecting both physical and hydraulic properties of peat (e.g. water retention and hydraulic conductivity). It is therefore possible that the overall ‘geometry’ of the transplanted acrotelm blocks can be altering θ_c . For example, when the acrotelm is extracted, retained and transplanted on the cutover peat, large spaces (gaps/fissures) are left between the acrotelm blocks which may cause significant changes to the peat structure. While there may be some natural vertical movement of the peat due to shrinking and swelling, it is likely that lateral movement of the peat may be enhancing the apparent changes in θ_c because of spaces between the acrotelm peat blocks. Daily lateral expansion and contraction into/out of these gaps may be possible, causing changes in VMC. An expansion of the capitula surface during the day can cause a decrease in moisture and a contraction during the night can lead to an increase in moisture. It is likely that the greatest amount of movement in the peat is within the upper acrotelm (0–5 cm) layer, since the loose *Sphagnum* moss at the surface would allow the necessary expansion/contraction to affect the moisture content. While a 30% change in volume is large, expansion/contraction calculations suggest that lateral movement is possible to explain these changes. For example, a lateral expansion of peat in the capitula zone of approximately 2 cm (at each side) with a subsequent increase in surface elevation (1.5 cm) can lead to an increased volume, lowering VMC ($\sim 30\%$). Conversely, a contraction of peat with a decrease in surface level (i.e. 2 cm and 1.5 cm) would decrease volume, thereby elevating VMC. It is possible that changes in volume affects pore size (expand/contract), impeding capillarity of *Sphagnum* mosses if VMC frequently varies above and below the moisture–tension thresholds due to peat volume change.

As the acrotelm resettles and regeneration of mosses and vascular vegetation occurs, the spaces between the transplanted acrotelm blocks may infill, reducing lateral movement within the peat and creating more stable moisture conditions in the capitula. Stable moisture conditions are important, especially from a gas exchange perspective where McNeil and Waddington (2003) observed that wetting and drying cycles can negatively affect *Sphagnum* primary production and consequently net ecosystem CO_2 exchange (see Cagampan, 2006).

Conclusions and implications for restoration

Cutover peatlands are important since rewetting and evaporation influence changes in VMC, water table position, soil–water tension and hydraulic properties of the peat. While current management techniques aim to rewet the cutover surface by blocking drainage ditches (Eggelsmann, 1988) to restore the water balance to more natural peatland conditions, it does not necessarily prevent a deep and variable water table (Price, 1996) or high soil–water tension at the surface (Price, 1997) from occurring. Additional restoration techniques such as seepage reservoirs (LaRose *et al.*, 1997; Price 1998), artificial topography (Price *et al.*, 1998), companion species (Ferland and Rochefort, 1997), and straw mulch application (Quinty and Rochefort, 1996; Price, 1997), can all aid in reducing surface soil–water tension, increasing VMC and improve the likelihood of *Sphagnum* re-establishment on the peat surface (Price *et al.*, 2003). However, these techniques are both costly and labour intensive to conduct where peatlands can be abandoned for many years before restoration is even considered. Moreover, as time from abandonment increases, additional changes to the peat structure occur through the processes of oxidation, compression and shrinkage (Schothorst, 1977; Schlotzhauer and Price, 1999), further promoting higher surface tensions unsuitable for *Sphagnum* survival. It is therefore important to restore a dry harvest peatland as soon as possible (Price, 1997) in order to limit harsh hydrological conditions, thereby aiding in re-establishing key vegetative species such as *Sphagnum* moss.

Results from this study indicate that the acrotelm transplant technique aided in restoring the hydrological processes at a plot scale. The transplanted acrotelm maintained both a stable and high water table and moisture conditions that were above the critical *Sphagnum* threshold (-100 mb) at the surface, thereby spatially decreasing water tension significantly compared to the natural site. Soil–water tension never exceeded -100 mb at individual plots, suggesting that conditions at the surface were generally favourable. In comparison, the natural site appeared to exceed the critical threshold more frequently due to the greater spatial variability in moisture across the site. The threshold was exceeded for up to 50% of the time over the season. Since the primary issue in restoration is water availability to prevent desiccation of *Sphagnum* (Sagot and Rochefort, 1996), it appears

that the acrotelm restoration technique maintained ideal hydrological conditions, preventing low moisture and high tension conditions at the surface. Additionally, results suggest that the peat did not undergo any major structural changes. However, a volume change at the peat surface may have enhanced wetting and drying cycles in the capitula. Due to the acrotelm removal and subsequent transplant, gap/fissures are left between the replaced surfaces that may cause lateral expansion/contraction within the peat matrix. This can lead to a volume change where large changes in VMC (30%) were observed, leading to variable moisture conditions at the surface. Unfortunately, we do not have vertical or lateral expansion data and this should be the focus of future research. However, diurnal variation may vary tension, causing unfavourable conditions for *Sphagnum* and potentially have an even greater effect on gas exchange processes at the surface.

Nevertheless, from a management perspective, the acrotelm transplant technique has great potential to be an adequate restoration method since the cutover peatland is restored almost immediately after extraction. The adverse hydrological effects of abandonment are minimized and the hydrological conditions sufficient for *Sphagnum* growth and survival are created. Moreover, the acrotelm, which is important in governing peatland water storage and *Sphagnum* growth, is present immediately. Conversely, under standard restoration techniques, it is estimated that the re-establishment of the acrotelm may take years or even decades, implying hydrological conditions may be variable for many years post restoration.

It has been suggested that if the acrotelm was replaced with greater care by positioning the blocks closer together, it may be possible to limit or even remove the spaces between the peat. This would potentially reduce the lateral movement and further stabilize surface moisture and soil–water tension conditions. From a gas exchange perspective, stable surface moisture conditions are particularly important, since highly variable moisture can negatively affect *Sphagnum* primary production and consequently net ecosystem CO₂ exchange (McNeil and Waddington, 2003).

ACKNOWLEDGEMENTS

Funding was provided by a research grant from Premier Tech Ltd. to J.M. Waddington and the Peatland Ecology Research Group. Thanks to Premier Tech Ltd. for access to the research site and to Sebastien Landry for logistical assistance at the extraction site.

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