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Hydrological changes following restoration of the Bois-des-Bel Peatland, Quebec, 1999–2002

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Summary Restoration efforts at peatlands drained for peat extraction attempt to return the hydrological conditions necessary for *Sphagnum* moss regeneration. One year of pre-restoration monitoring (1999) and three years of post restoration monitoring were done at the Bois-des-Bel peatland near Riviere-du-Loup, Quebec, to evaluate hydrological changes that occurred at a managed section (restored site) relative to an adjacent abandoned section of the same peatland (unrestored site). Restored site evaporation was 74%, 74%, and 98% of unrestored site evaporation in 2000, 2001, and 2002, while runoff at the restored site was 83%, 30%, and 12% of unrestored site runoff over the same period. Seasonal soil volume change (swelling and shrinking of the peat) was evident at the restored site indicating rewetting of the peat profile despite the prolonged period between site abandonment and the initiation of the restoration measures (19 years). Site rewetting may have benefited from the relatively deep layer of residual peat (around 1.5 m). Higher seasonal mean water table and soil moisture were observed at the restored site relative to the unrestored site in 2000 through 2002 along with increased seasonal variability at the former location. Mean soil–water pressure was also higher than at the unrestored site and the range decreased, both spatially and on a seasonal and daily basis. The restoration techniques contributed to the recovery of hydrological conditions necessary for *Sphagnum* recolonization, though successful application at different sites may be limited by specific peat and climate characteristics.

Introduction

Successful large-scale restoration of mined North American peatlands has not been achieved. Early reports on the implications of restoration measures on hydrological (Price, 1996, 1997; Price et al., 1998) and ecological (Campeau and Rochefort, 1996; Rochefort et al., 2003; Lavoie et al.,

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2001) processes have greatly improved the understanding of the short-term response of relatively small-scale systems, ranging from plots to sections of peat fields.

Restoration procedures attempt to accelerate the return of the hydrological conditions necessary for *Sphagnum* moss recovery, specifically a high and stable water table (>−40 cm) (Schouwenaars, 1988), high soil moisture (>50%), and soil–water pressure above −100 mb (Price and Whitehead, 2001). The strategies employed must overcome the dramatic alterations in natural peatland hydrological processes caused by site preparation for peat extraction. Changes include the removal of living vegetation resulting in a bare, unstable peat surface (Price, 1997) and the installation of drainage ditches to lower the water table, which leads to increased subsidence (Schothorst, 1977; Hillman, 1992; Prevost et al., 1997), and alters water retention (Oleszczuk et al., 2000) and water transmission characteristics (Chow et al., 1992; Silins and Rothwell, 1998).

Seasonal plot-scale experiments have identified important techniques for improving site hydrology including the use of straw mulch for reducing evaporation (Price et al., 1998) and the blocking of drainage ditches to limit runoff (Price, 1997). Combining the work on improving hydrological conditions at cutover peatlands with details of *Sphagnum* regrowth has resulted in the development of a general approach for peatland restoration in Eastern North America (Rochefort et al., 2003), and have culminated in a system-scale restoration at Bois-des-Bel peatland, near Rivière-du-Loup, Quebec (GRET-PERG, 2003 ⟨www.gret-perg.ulaval.ca⟩) prior to the 2000 growing season.

Initial site scale research at the Bois-des-Bel peatland has confirmed the importance of various aspects of the restoration approach. The addition of the straw mulch contributed to a 13% and 8% decrease in evaporation relative to an adjacent unrestored section in 2000 and 2001, respectively (Petrone et al., 2004b). The construction of bunds have also contributed to increased retention of snowmelt water which prolongs soil wetness during the summer, though bunds become ineffective at storing water once the water table drops below the peat surface (Shantz and Price, in press). At this site, higher soil moisture is also associated with greater density of straw mulch application (Petrone et al., 2004a).

Previous research at the Bois-des-Bel peatland has been valuable for helping to verify the importance of specific restoration measures, but the collective impact of these changes has not been fully evaluated. Identifying patterns in the hydrological characteristics is critical for evaluating the impact of restoration activities, and the potential for long-term restoration success. This includes the effect of new surface vegetation and moss cover (Groeneveld and Rochefort, 2002), loss of straw mulch by decomposition (Waddington et al., 2003a), and peat substrate changes through rewetting (von Waldow, 2002; Price, 2003). This research documents the hydrological changes by evaluating conditions prior to restoration (1999) and for three post-restoration years (2000 to 2002) to (1) identify how restoration techniques have influenced within-summer and year-to-year patterns of soil moisture, water table, soil–water pressure and peat volume change, and (2) consider factors that may influence the broad application of the current restoration approach.

Study site and restoration approach

Bois-des-Bel peatland is located approximately 10 km north of Riviere-du-Loup, Quebec (47°53′ N, 69°27′ W) at an elevation of 20 m asl. Climate data (1971–2000) (Environment Canada, 2003) recorded 5 km south (St. Arsene) indicates mean annual total precipitation is 962.9 mm (29% falling as snow) and the mean annual temperature is 3.2 °C. The entire ombrotrophic peatland covers an area of approximately 200 hectares. The peat is up to 3 m deep (though only around 1.5 m in the harvested area) and the site is underlain by a layer of marine clay that restricts vertical flow through the base of the peat deposit. Further details of site conditions and vegetation distribution within the undisturbed area of the Bois-des-Bel peatland are provided in Lavoie et al. (2001).

Approximately 11.5 hectares of the peatland were drained in 1972 for peat extraction and subsequently abandoned in 1980. The peat extraction area consisted of 11 fields numbered west to east (Fig. 1), each bounded by drainage ditches. Restoration measures were undertaken in the fall of 1999 on fields 1–8 (restored site, 8.1 ha) while field 9 was left as a buffer and fields 10–11 remained in their abandoned state for comparison purposes (unrestored site, 1.9 ha). At the restored site, vegetation and woody debris that had grown or become exposed in the time (Waddington and McNeil, 2002) since abandonment was removed. Old drainage ditches were blocked with well-decomposed peat approximately every 30 m along their length and a new collector ditch was dug along the south-east edge of the restored site perpendicular to the blocked ditches to allow monitoring of site runoff (see Fig. 1). Bunds were built perpendicular to the slope of the peat surface to block and store site runoff. Finally, *Sphagnum* diaspores collected at a nearby donor site were introduced, straw mulch was spread (4000 kg/ha), and a phosphorus fertilizer applied throughout the site (15 g/m^2) (Stephanie Boudreau, personal communication). For the purposes of this study, the ''restored'' site represents peat fields 1–8, for all years of study (i.e. even pre-restoration).

Methods

Monitoring occurred in the summer months (May–August) of 1999 through 2002. Specific monitoring start and end dates for all measured processes are listed in Tables 1 and 2. Evaporative fluxes were determined at both the restored and unrestored sites' micrometeorological stations (met stations) (Fig. 1) for all four annual monitoring periods. In 1999, the Priestley and Taylor (1972) approach was used. Soil lysimeters (see Van Seters and Price (2001) for details) were used to calibrate the Priestley and Taylor (1972) model. In all three monitoring years following restoration, the unrestored site micrometeorological instrumentation remained the same (the Priestley and Taylor approach) while restored site evaporation was determined using the eddy covariance approach. Set up details for both approaches are outlined in detail by Petrone et al. (2001) and Petrone et al. (2004a,b). Rainfall was measured at the restored site met station for all years with a manual rain gauge and

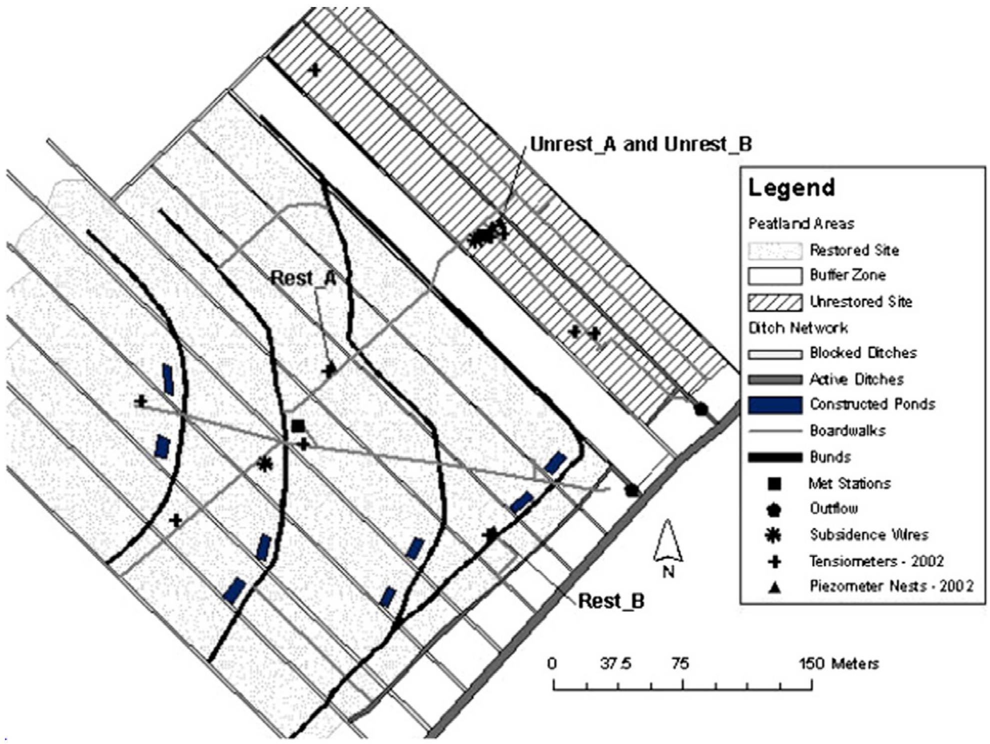

Figure 1 Map of the Bois-des-Bel peatland and location of hydrological monitoring locations for the 1999 through 2002 summer sampling periods.

Table 1 Precipitation, evaporation, and runoff at the restored (Res) and unrestored (Unres) sites of the Bois-des-Bel peatland for the summer (May to August) periods of 1999 through 2002

	1999		2000		2001		2002	
Monitoring dates (DOY)	178—243		138—243		138—243		138—243	
Site	Res	Unres	Res	Unres	Res	Unres	Res	Unres
Precipitation (mm)	167[a]		220		254		210	
Evaporation (mm)	164		248	334	374	501	253	257
Runoff (mm)	31	13	15	18	13	43	2	17

[a] Rainfall was measured from Day 152 in 1999 with total rainfall of 236 mm between Day 152 and Day 243. Evaporation was restricted to Day 178—243 and that is the precipitation component used in the analysis.

Table 2 Seasonal mean water table (wt), soil moisture at 5 cm depth ($\theta_{5\,cm}$), and soil—water pressure at 5 cm depth ($\psi_{5\,cm}$) for the 1999 through 2002 summer periods at the Bois-des-Bel restored (Res) and unrestored (Unres) sites (seasonal standard deviation in brackets)

	Site	Monitoring period (DOY)	1999		2000		2001		2002	
			μ (σ)	n	μ (σ)	n	μ (σ)	n	μ (σ)	n
wt (cm)	Res	128—243	−65.4 (6.9)	48	−30.0 (9.5)	41	−30.4 (10.5)	95	−37.2 (14.3)	74
	Unres	128—243	−55.5 (7.4)	46	−45.5 (6.0)	35	−40.4 (6.4)	96	−44.3 (6.6)	72
$\theta_{5\,cm}$	Res	130—243[a]	0.51 (0.03)	47	0.80 (0.06)	34	0.72 (0.03)	13	0.69 (0.09)	25
	Unres	130—243[a]	0.47 (0.02)	47	0.41 (0.03)	33	0.37 (0.02)	24	0.41 (0.04)	26
$\psi_{5\,cm}$ (mb)	Res	140—242	−63.6 (26.9)	42	−6.8 (8.3)	36	−8.7 (9.7)	57	−24.8 (15.9)	45
	Unres	140—242	−45.7 (14.2)	42	−41.8 (17.3)	33	−29.8 (19.7)	58	−39.9 (16.8)	44

[a] In 2000, sampling was limited to days 170—243.

a tipping bucket rain gauge (Texas Electronics model TE525) logged every half hour.

The restored and unrestored sites represent unique watershed areas of 8.1 and 1.9 ha, respectively. Runoff was measured at both sites in all annual monitoring periods. Manual measurements were taken at the culvert (10 m length) outlet (see Fig. 1) using a calibrated bucket and stopwatch (average of three tests). Rating curves were developed using a flume in 1999 and 2000. The flumes were located just upstream of the culverts at both sites and stage was logged half hourly using a float and potentiometer connected to a Campbell Scientific™ CR10x datalogger. In 2001 and 2002, v-notch weirs were fastened directly to the outlet end of the culvert and the stage was measured using a Remote Data Systems (RDS) well. Relationships were developed between logged stage measurements (i.e. potentiometer and RDS wells) and manual measurements taken during discharge sampling.

Peat bulk density (ρ_b) was determined for all sampling years with the exception of 2001. Field samples of a known volume were weighed, oven dried, and re-weighed using standard methods of Klute (1986). Spatially distributed peat samples in the upper 50 cm were collected in cylindrical sample rings (volume 84.8 to 66.5 cm^3) either directly in the field or as subsamples from a Wardenaar™ peat corer (12 cm $\times$ 10 cm $\times$ 100 cm). In all cases, care was taken to ensure minimal compression during sampling. Seasonal peat subsidence and swelling was measured in the field at the restored and unrestored sites for all post-restoration monitoring years with rods anchored in the peat at 5, 10, 20, 30, 50, 100, and 150 cm depths, following the method of Price (2003). Readings of rod movement were taken relative to a level datum anchored in the underlying clay substrate at a frequency of 3–7 days in 2000 and 1–3 days in 2001 and 2002. Changes in peat volume for various layers were determined based on the movement of the anchors relative to the fixed datum. This method assumes volume change is occurring exclusively in the vertical direction which appears valid at the Bois-des-Bel site since there was no evidence of large scale vertical cracking in the peat.

Depth to water table (wt) was monitored manually every 1 to 3 days at the restored and unrestored met stations in all summers. wt was measured from the peat surface to account for any seasonal subsidence or swelling. Soil moisture (θ) was measured using the time domain reflectometry (TDR) technique (Topp et al., 1980). TDR probes were installed horizontally into the undisturbed wall of a pit, at depths of 2, 5, 10, 20, 30, and 50 cm. The pits, located near the two met stations, were then backfilled with peat. To ensure a solid position within the peat profile, probes were reinstalled at the beginning of each field season as the peatland thawed. Measurements were made using a Tektronix 1502B unit with waveforms saved to a laptop running the WATTDR program (Redman, 2000) and later used to determine the dielectric constant (Ka). θ values were calculated from the determined Ka measurements using the temperature dependent calibration function described by von Waldow (2002).

Soil–water pressure (ψ) was measured in all monitoring seasons at the met stations using straight and L-shaped porous cup tensiometers (Soil Moisture Systems, Tucson) installed at the beginning of each field season. Measurements were made manually every 3–5 days using a pressure transducer (accuracy of ±1 mb) (Soil Moisture Systems, Tucson). Measured pressure values were converted to actual pressure and total head (cm) based on the height of the water column in each tensiometer and its depth below the peat surface.

In 2002, more detailed spatial sampling of ψ occurred. Sampling locations are provided in Fig. 1 with equipment and sampling procedures the same as those described previously for the met station locations. Sampling frequency was every 3 to 5 days. In addition, intensive sampling occurred on Day of Year (DOY) 240 (a hot and dry day) starting at 06:00 and repeated every 2 hours until 18:00. Spatially distributed tensiometers (5 at each site) were measured at the 5 and 10 cm depths for both the restored and unrestored sites.

Horizontal saturated hydraulic conductivity (K_h) was measured weekly in 2002 at the restored and unrestored sites using the bail test method of Hvorslev (1951). While K_h measurements were also made in 1999 through 2001, the sample size was small and measurements were not used for interannual comparisons. Piezometers were emptied using a syringe and plastic tubing with recovery measured to a minimum of 80%. At the restored site, piezometer nests were located in the middle of an old peat field. Rest_A was located halfway between two blocked ditches in field 6 (see Fig. 1) while Rest_B was located 17 m into the peatland from the collector drainage ditch (see Fig. 1). At the unrestored site, piezometer nests were located close to the met station at a distance of 2 m (Unrest_A) and 8 m (Unrest_B) from the active north–south oriented drainage ditch (see Fig. 1). Piezometers were constructed from 2.5 cm internal diameter PVC pipe. Mean intake depths were 50, 75, 100, 125, and 150 cm (where the peat was deep enough) and the intake length was 15 cm. All piezometers were covered with Nitex screening (250 μm) to prevent clogging. Piezometers were inserted into pilot holes of similar dimension. Their elevation was surveyed relative to the site benchmark following restoration.

Results

Water balance components

Not including 1999 (shortened sampling period), 2002 had the lowest summer rainfall followed by 2000 and 2001 (210, 220, and 254 mm, respectively) (Table 1). Complete data are available for June, July, and August during all years monitored. In all years, total precipitation for June through August period was 85%, 66%, 82%, and 66% of the long term average, in 1999 through 2002, respectively. Following restoration, rainfall was below the monthly average for all summer months with the exception of May 2000 and July 2002. Evaporation (Table 1) was less at the restored site (which had straw mulch added as part of the restoration), in all post-restoration summers. In both 2000 and 2001, restored site evaporation was only 74% of that at the unrestored site. In 2002, evaporation at the restored site was 98% of that at the unrestored site.

Runoff was greater at the restored site (31 mm) than the unrestored site (13 mm) in 1999. After restoration, the unrestored site runoff was greater by 3, 30, and 15 mm, in

2000, 2001 and 2002, respectively (Table 1). For all post restoration summers, baseflow at both sites was negligible, particularly during dry periods (see Shantz and Price (in press) for more detail). The ratio of runoff relative to rainfall for the restored site decreased from 1999 through 2002 (0.186, 0.068, 0.051, and 0.010, respectively) while the unrestored site ratios were 0.078, 0.082, 0.169, and 0.081 for the comparable years.

Peat characteristics

Prior to restoration (1999), ρ_b in the 30—60 cm peat layer ranged from 0.101—0.161 g/cm^3 throughout the entire site (average = 0.130 g/cm^3, n = 9). Following restoration (excluding 2001 where no sampling was done), average ρ_b in the peat layer between 30 and 50 cm depth was 0.138 g/cm^3 (n = 18) at the restored site and 0.146 g/cm^3 (n = 18) at the unrestored site, both with a standard deviation of 0.013 g/cm^3. The 30—50 cm depth range was used to compare sites since there was less within season variability in density caused by shrinkage and swelling. A T-test (α = 0.05) indicated ρ_b was not significantly different between the two sites for this depth range.

Following restoration, bulk density near the surface of the restored site varied as evidenced by seasonal changes in peat surface elevation. The restored site surface elevation dropped 4.7, 2.6, and 5.2 cm from its starting elevation in the 2000, 2001 and 2002 field seasons, respectively, while the unrestored site surface elevation change was less than 0.5 cm in each of the three years. Peat volume change at the restored site was strongly related to wt fluctuations with similar relationships for all post restoration years (Fig. 2). The greatest change occurred in the upper 30 cm zone where volume decreased 6.2%, 4.8%, and 9.6% in 2000, 2001, and 2002, respectively. In the layer between 30 and 150 cm, 1.9%, 1.1% and 2.4% change in volume occurred over the respective periods. In all three years, the greatest volume change with respect to wt in the upper 30 cm zone occurred in the early part of the monitoring period (prior to DOY 161) (Fig. 2) with the rate of change slowing later in the monitoring period (to day 243).

K_h was seasonably variable, decreasing during corresponding periods of low wt and greatest subsidence. Changes (monitored in 2002) were more evident in the −75 cm piezometers vs. those at −100 cm (Fig. 3). For example, K_h at Rest_B −75 cm piezometer decreased from 3.4×10^{-5} cm/s to 6.7×10^{-6} cm/s from day of year 142 to day of year 239. At the unrestored site, some variability in K_h associated with wt fluctuation was evident at the −75 cm depth but this was not associated with any measurable peat volume change.

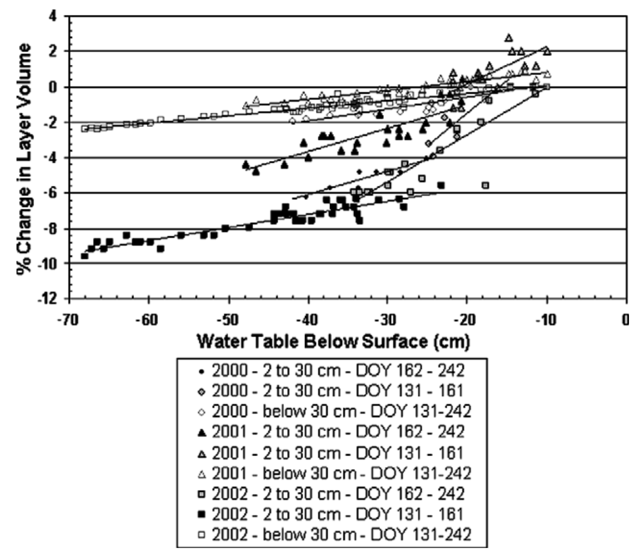

Figure 2 Restored site wt below surface vs. % change in layer volume in zones of 5—30 cm and 30 cm and below for the 2000, 2001, and 2002 summer periods.

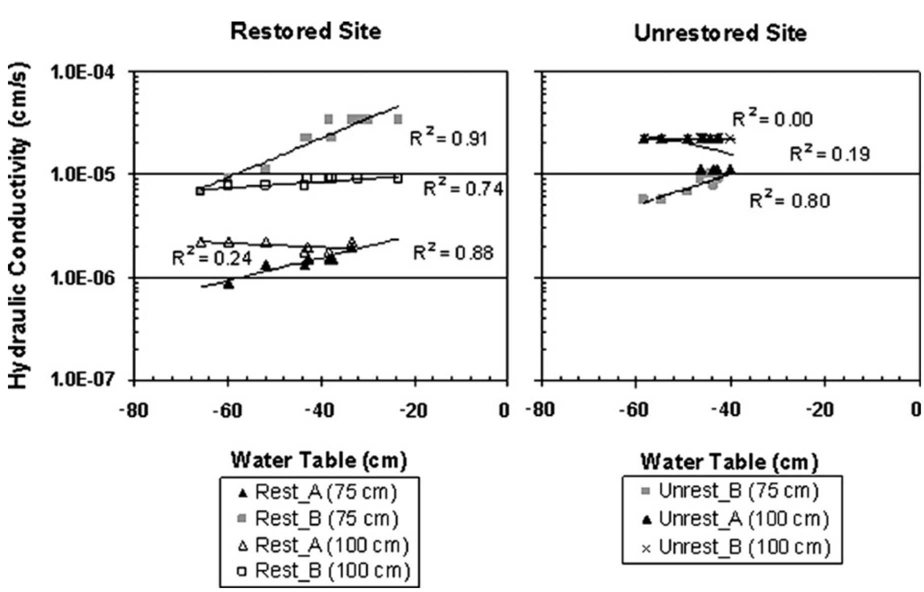

Figure 3 Changes in K_h relative to water table (wt) fluctuations during the 2002 summer field season.

Water table, soil moisture, and soil—water pressure

Prior to restoration, the mean wt depth at the restored site, and the unrestored site met stations was −65.4 and −55.5 cm, respectively. Both sites showed little variability throughout the field season (Fig. 4 and Table 2). Following restoration, the wt in the restored site was closer to the soil surface than at the unrestored site, by an average of 15.5, 10.0 and 7.1 cm, in 2000, 2001 and 2002, respectively. However, the seasonal variability increased at the restored site, with standard deviation almost doubling from approximately 7 cm to 14 cm (Table 2). Mean wt was significantly closer to the surface in 2000 and 2001 but not 2002 (based on Mann—Whitney test and $\alpha = 0.01$).

Seasonal mean volumetric soil moisture at 5 cm ($\theta_{5\,cm}$) depth showed little variability at both the restored and unrestored sites in 1999 (SD of 0.03 and 0.02, respectively)

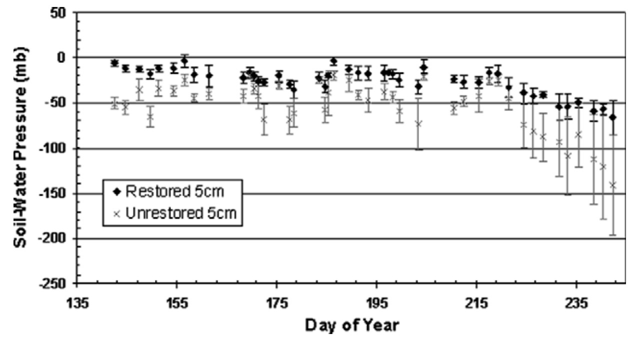

Figure 5 Seasonal soil—water pressure ($\psi_{5\,cm}$) trends at the restored and unrestored sites for the 2002 field season (each value represents daily average of all spatially distributed tensiometers at each site with error bars representing one standard deviation of all spatial samples).

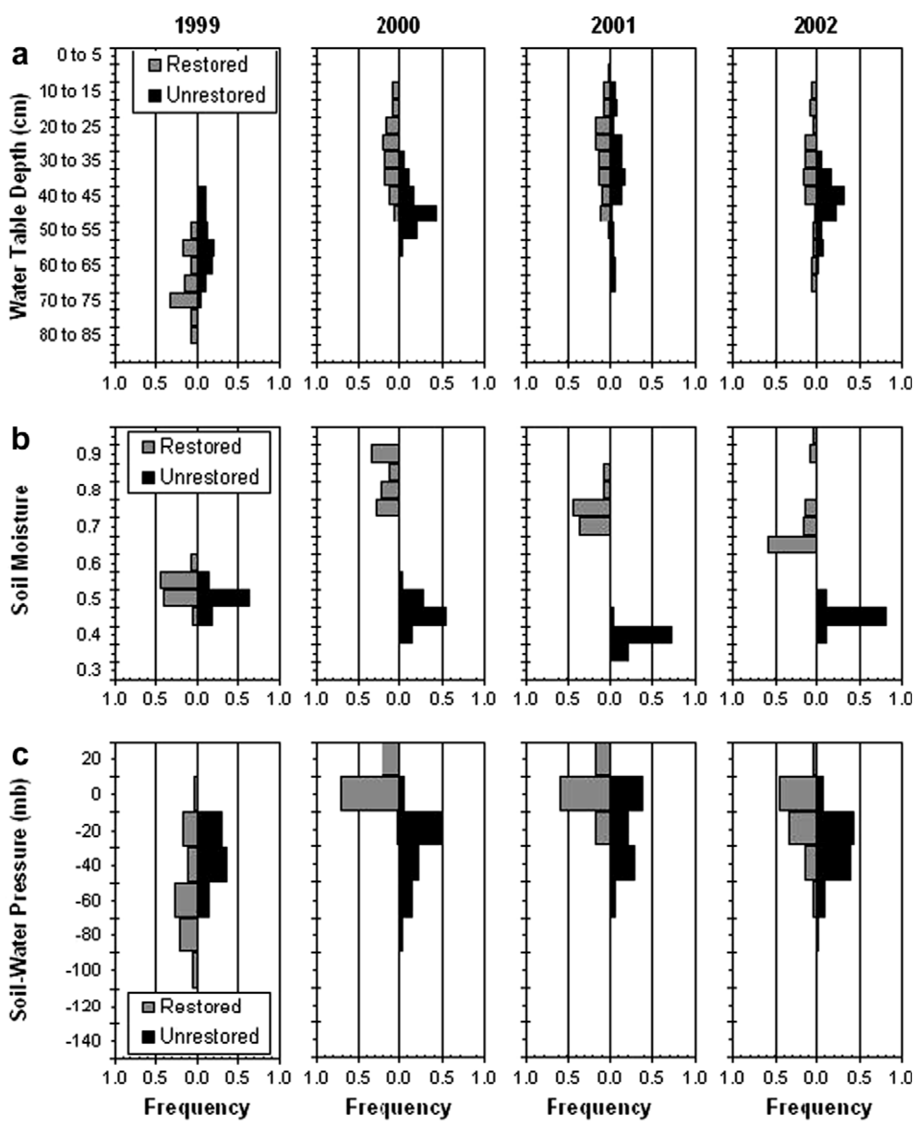

Figure 4 Frequency distributions during the 1999 through 2002 summer monitoring period for (a) restored and unrestored tower water table (wt) below surface, (b) restored and unrestored tower soil moisture at 5 cm ($\theta_{5\,cm}$), and (c) restored and unrestored met station soil—water pressure at 5 cm depth ($\psi_{5\,cm}$).

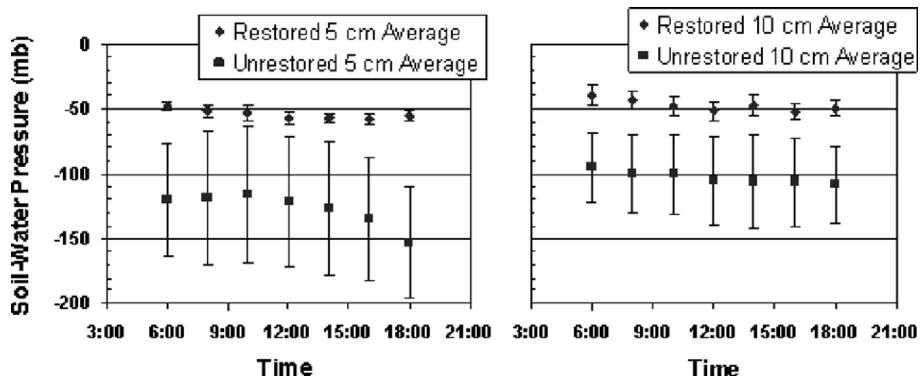

Figure 6 Daily soil—water pressure (ψ) trends at the restored and unrestored sites for 5 and 10 cm depths on Day of Year (DOY) 240 (error bars are one standard deviation).

(Table 2). In the post restoration summers, seasonal standard deviation remained relatively consistent at the unrestored site (0.03, 0.02, and 0.04 for 2000, 2001, and 2002, respectively) despite interannual differences in seasonal mean moisture content (Fig. 4). However, mean $\theta_{5\,cm}$ at the restored site was 40%—50% above that at the unrestored site. Summer restored site $\theta_{5\,cm}$ was consistently above 50%, while the unrestored site rarely had values at that level (the differences were significant in all post restoration years based on a Mann—Whitney test ($\alpha = 0.01$)).

In 1999, the mean soil—water pressure at −5 cm ($\psi_{5\,cm}$) at the restored site met station (i.e. in the pre-restoration year), was lower than at the unrestored site station (Fig. 4), and 3 of the 48 measurements during that year fell below −100 mb. Following restoration this trend reversed, and, $\psi_{5\,cm}$ at the restored met station site was consistently higher (Fig. 4) (Table 2). In all years, differences were significant based on a Mann—Whitney test ($\alpha = 0.01$). Furthermore, restored site $\psi_{5\,cm}$ never dropped below −100 mb following restoration and daily measured values were always above those found at the unrestored site. ψ in 2002 showed greater spatial variability at the unrestored site relative to the restored site for individual sampling days (standard deviation of 25.7 and 9.0 mb, respectively), as well as greater seasonal variability (Fig. 5). Spatially averaged $\psi_{5\,cm}$ fell below the −100 mb only at the unrestored site (Fig. 5). Two sampling locations used in the spatial average were below −100 mb for all sampling days following DOY 225 while the spatial average was below −100 mb for all but one sampling day following DOY 233. Greater spatial variability in ψ was also noted in diurnal measurements made in 2002 (Fig. 6). The unrestored site also had greater temporal variability in ψ relative to the restored site, particularly at the 5 cm depth where value ranges were 36.1 and 9.9 mb for the two sites, respectively. Restored site values decreased slightly towards noon but then stabilized while unrestored site $\psi_{5\,cm}$ continued to decrease throughout the afternoon.

Discussion

Water balance components

Water-balance components for the periods monitored indicated important hydrological changes occurred following restoration. Particularly, changes in storage (swelling and compression) within the peatland became a measurable component of the water balance with changes in dilation storage (as determined through volume changes below the water table) being equivalent to water losses from the site due to runoff. In all years, precipitation was the dominant water input (typical of ombrotrophic peatlands (Ingram, 1992)). However, the 1999 through 2002 summer periods were dry relative to the 30 year average. This was particularly the case for the three post restoration summers.

Evaporation dominated post-snowmelt water loss from the site with the unrestored site losing more water in all post-restoration years. In 2000 and 2001, total restored site evaporation was considerably less than the unrestored site. Petrone et al. (2004b) noted that the straw mulch affected temperature and albedo conditions near the surface of the restored site and likely reduced evaporation rates there. A comparable reduction in evaporation of a straw mulch covered peat surface was also reported by Price et al. (1998). Lower evaporation persisted at the restored site in 2002, although its effect was diminished because the mulch decomposed fairly rapidly following application in 2000 (Petrone et al., 2004b; Waddington et al., 2003a).

While three years may not be long enough to fully evaluate long-term runoff changes following restoration (Spieksma, 1999), this study shows distinct and immediate differences following restoration. Site runoff decreased in the years following restoration, both in terms of absolute magnitude and also relative to measured rainfall. The decreased runoff relative to rainfall at the restored site suggests that the restoration methods have been beneficial at retaining water on the site.

Evidence of site rewetting

Mean ρ_b in the 30—50 cm zone was slightly lower at the restored site (0.138 g/cm^3) relative to the unrestored site (0.146 g/cm^3) as expected based on the anticipated rewetting (and swelling) of the peat following restoration, although the difference was not significant ($\alpha = 0.05$). However, seasonal changes in peat volume observed at the restored site following restoration provide additional evidence of site rewetting. In the upper 30 cm zone, two distinct trends existed for each sampling year with the greatest rate of volume change occurring early in the field season during the initial drop in the wt following snowmelt (Fig. 2). A similar finding was reported by Kennedy and Price (2005). Once the wt fell below 30 cm, shrinkage and secondary compression were occurring in the upper 30 cm zone (e.g. Price, 2003). Freeze–thaw cycles of saturated soils have been found to affect soil structure (Viklander, 1998) and this process is likely impacting the peat soil at Bois-des-Bel as well. The saturated peat conditions at the site prior to freezing (Shantz and Price, in press) resulted in an expansion of the peat beyond that which would occur simply from resaturation alone (Kennedy and Price, 2005). The rapid early season subsidence reflects this structural change.

Below 30 cm, peat volume changed at a consistent and low rate relative to wt fluctuations for all post restoration summers (Fig. 2). The similarity in patterns between years suggests that recovery of the volume-change function takes place immediately following restoration. However, the prolonged period between site abandonment and the initiation of restoration (19 years) may have reduced the potential for peat rewetting through increased decomposition and decreased mean pore size (e.g. Price, 1998; Price, 2003). Greater initial rewetting may be possible at sites where restoration measures are implemented immediately following abandonment (Kennedy and Price, 2004), although the relatively deep residual peat layer at the Bois-des-Bel site may have helped offset the potential impacts of prolonged decomposition.

Since the changes below 30 cm occur in generally saturated conditions, the results indicate changes in water storage through dilation storage. In 2000, changes in dilation storage represented as much as 21 mm of water during the driest period while 18 mm and 28 mm were lost from storage in 2001 and 2002, respectively. The estimates were calculated based on observed wt patterns and the slope of the wt–volume change relationship. When the wt is at its deepest point in the season, the change in saturated layer thickness reflects the change in water storage for that layer.

Seasonal changes in peat volume also influenced K_h at the restored site, decreasing during low wt periods (times of greatest subsidence). Similar field results were observed by Price (2003) in a partially restored peatland near Lac St. Jean, Quebec. At the unrestored site, negligible seasonal changes in K_h were observed at -100 cm and changes at the -75 cm level occurred in the absence of measurable seasonal peat volume change. However, given the rewetting of the restored site, and the consequent boost in soil methane production (Waddington et al., 2003b), the presence of bubbles that block pores (e.g. Kellner et al., 2004, 2005) may contribute to more seasonally variable K_h at the restored site.

While volume change has been shown to influence peat hydraulic characteristics due to change in pore structure (e.g. Chow et al., 1992; Silins and Rothwell, 1998; Schlotzhauer and Price, 1999; Oleszczuk et al., 2000), the implications of these changes on restoration success are not clear. Price (2003) and Kennedy and Price (2004) have argued that seasonal changes in K_h may influence water transport to the surface, thus restricting vertical water losses when the wt is low and subsidence is greatest. However, since the anisotropic structure of the peat was not measured, the alteration of vertical water flows is not well understood. Further quantification of unsaturated zone K_h associated with peat volume change is also required, particularly for its importance in understanding differences in evaporation at restored and abandoned peatlands.

Differences in hydrological conditions between sites

Maintaining requisite conditions of wt, θ, and ψ is considered critical for the successful re-establishment of *Sphagnum* mosses (Price and Whitehead, 2001), particularly as a site initially undergoes the transition from mulch to vegetation cover. Measurable improvements in these conditions were observed at the restored site relative to the unrestored site.

Mean restored site wt was higher than it was at the unrestored site in all years following restoration, based on measurements made at the met station wells (with significant differences in 2000 and 2001). However, the range of wt fluctuation was also greater at the restored site than at the unrestored site, with periods where levels dropped below -40 cm at both sites (Fig. 4). An increase in the wt variability occurred at the restored site despite the moderating effects of peat volume change. The high wt variability at the restored site resulted from the enhanced snowmelt retention and flooding there (Shantz and Price, in press) which increased soil moisture and decreased available unsaturated pore space. Gillham (1984) noted the rate of wt change is strongly influenced by moisture and capillary fringe effects with small water inputs causing large changes in wt elevation. The deeper wt at the unrestored site, and the increased range of θ variability, indicates that the unsaturated zone at the unrestored site peat has more capacity to buffer wt changes than at the restored site which may contribute to the apparent hydrological disconnection between wt and surface exchanges when the wt depth exceeds 60 cm as hypothesized by Price (1997). There is a notable increase in wt at both the restored and unrestored sites, following restoration, which is difficult to explain. An average wt gradient of 0.008 between the restored site and the centre of the buffer zone suggests groundwater seepage may be occurring. However, the gradient between the centre of the buffer zone and the edge of the unrestored site is only 0.005 and with an average K_h value of 2.0×10^{-5} cm/s at the -100 cm depth at the Bois-des-Bel site, the influence was estimated to be less than 0.002 mm/day which did not result in improved $\theta_{5\,cm}$ and $\psi_{5\,cm}$ at the unrestored site.

$\theta_{5\,cm}$ was higher following restoration (Fig. 4). Despite interannual variability (which may partly be a reflection of reinstalling TDR probes each year), restored site values were consistently higher than at the unrestored site and were maintained above 50%, which Price and Whitehead (2001) argued as being important for sustaining *Sphagnum* diaspores spread during the site restoration. The greatest difference in θ between the two sites was near the peat surface, while there was very little difference beyond 20 cm depth. At the restored site, water could generally be supplied to meet evaporation demands while maintaining relatively high θ conditions. The straw mulch and vegetation cover along with ongoing shrinkage and swelling, helped to stabilize the plant water supply despite the increased variability in wt. At the unrestored site, the soil was sufficiently moist to sustain high rates of evaporation, but the drier unsaturated peat has lower unsaturated K_h, thereby limiting upward transport of water from within the peat profile, causing further drying of the peat near the surface. Further evidence of this can be seen from the exaggerated diurnal change in $\psi_{5\,cm}$, compared to $\psi_{10\,cm}$ (Fig. 6).

$\psi_{5\,cm}$ was higher following restoration (consistently above −100 mb). However, Kennedy and Price (2004) have suggested that spatial variability in ψ values in abandoned peatland areas is much greater than generally accounted for in field monitoring. This was confirmed by the large spatial variability in ψ at the unrestored site (Figs. 5 and 6), particularly during prolonged periods with little precipitation. Restoration decreased spatial and temporal variability (Fig. 6) relative to the unrestored site despite greater wt variability.

Over the medium term, this study shows that θ and ψ improvements were maintained at the restored site despite decomposition of the straw mulch (Waddington et al., 2003a) and the transition to a vegetated surface. The return of vegetation (including vascular species such as *Eriophorum*) did not lead to increased drying at the restored site (see also Lavoie et al., 2005) although it may have contributed to the increased water table variability. Petrone et al. (2004a) have indicated spatial moisture patterns are related to surface vegetation cover. The role of vegetation recovery following restoration on spatial patterns in peat volume change, θ, and ψ, remains unknown.

Conclusions and recommendations

The restoration procedures applied at Bois-des-Bel peatland to enhance rewetting included the blockage of ditches and construction of bunds to retain precipitation inputs, principally snowmelt; and the application of straw mulch to reduce evaporation losses. During the construction of bunds (autumn 1999) the surface peat was reworked in part to level the surface between bunds, and partly to provide the material for bund construction. Shantz and Price (in press) reported that bunds were essential to retaining snowmelt water in the spring, but when the wt dropped below the surface, bunds provided no further hydrological function. Instead, during the summer period blocked ditches were generally effective at helping to reduce runoff losses from the restored site. Consequently, at the beginning of the growing season, the restored site had considerably more water available, and further runoff was curtailed by blocked ditches (Shantz and Price, in press). Petrone et al. (2004b) demonstrated how mulch reduces evaporation water losses from the restored site during summer. This study confirmed that evaporation from the newly restored zone was smaller than at the adjacent unrestored site, but also showed that the effect of the mulch had diminished almost completely by the third year after restoration. Nevertheless, with the additional snowmelt water retained, the net effect was to noticeably increase the summertime wt, and soil-moisture and water pressure in the near-surface zone.

This study showed that in addition to favourably adjusting the water balance components for rewetting the site, a series of other hydrological changes occurred that may be essential for successfully re-establishing an appropriate peatland plant community. Specifically, the volume-change function so important to water storage changes in many peatlands (Price and Schlotzhauer, 1999) was returned. With the ability to subside when water was lost (e.g. to evaporation), peat near the surface remained wetter relative to the unrestored site (Fig. 4). This compressible rewetted zone had higher $\psi_{5\,cm}$ (Fig. 4), thus water remained readily available to plants, particularly *Sphagnum*, which relies upon relatively weak capillary forces (Hayward and Clymo, 1982) to draw water from the soil. The stark difference between the restored and unrestored site in this regard, and the similarity of the wt–volume change relationships in all years following restoration suggests that the volume-change function was restored quickly at the site.

The changes in K_h associated with changes in soil-volume (Fig. 3), are uncertain. Potentially, greater hydrological stability results if the potential for water loss diminishes (i.e. K_h decreases) as the system becomes drier. However, horizontal water losses appear to be a relatively small component of the summer water balance following restoration and it is likely that changes in K_h caused by volume-change are much less than changes caused by variable saturation (i.e. the unsaturated K_h function). Further research is warranted to quantify differences in unsaturated K_h at the restored and unrestored sites and the implications for influencing evaporation losses.

Another important change noted in the restored site was the homogenization of ψ distributions, both spatially and temporally. Whether a consequence of site leveling, or the general increase in surface wetness (assisted by the volume-change mechanism), spatial differences in ψ were significantly reduced, and the values were consistently higher. At the restored site the ψ remained uniformly above −100 mb, the pressure threshold beyond which the survival of *Sphagnum* diaspores may be severely limited (Price and Whitehead, 2001). The improvements in ψ (and θ) occurred despite the increased wt range at the restored site suggesting that wt alone is not a strong indicator of site suitability for *Sphagnum* recovery following restoration.

The potential for peat rewetting and its influence on hydraulic functions (i.e. K_h, ψ) is in part determined by the characteristics of the residual peat at the site to be restored. For example, the effectiveness of the volume-change process as a storage mechanism is related to the depth of remaining peat, and its state of decomposition (Kennedy and Price, 2005). At the Bois-des-Bel site, the length of time between abandonment and the start of restoration (19 years) may have decreased the full potential for peat rewetting but did not appear to largely affect the success of the restoration strategies. Waddington and McNeil (2002) estimated that 730 t of carbon was lost from the Bois-des-Bel research site prior to restoration. However, the relatively thick residual peat layer (≈1.5 m) provided an advantage for rewetting over more severely mined sites. Additionally, there was little harvesting (thus use of heavy machinery) on the site which may have decreased long term compaction.

Since site specific factors in substrate conditions, climate, and (post) harvesting conditions have the potential to dramatically influence the success of restoration, it is difficult to identify a specific restoration prescription for broad application. Testing of individual and linked restoration measures under variable site conditions may only be possible with a mathematical model that fairly represents the processes and system characteristics. Despite this limitation, there are a number of general principles based on the results at the Bois-des-Bel site that have broader application in peatland restoration. The use of bunds and blocked ditches are important for retaining excess water during the snowmelt and spring period (Shantz and Price, in press). Given that the major water loss during summer is typically by evaporation, suppressing it with straw mulch is essential. Depending on the thickness of the peat deposit, and its ability to change its volume as it dries, sustaining wet conditions may be possible even after the mulch has decomposed. However, a second application of mulch may be necessary in situations where thin or rigid residual peat exists.

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