

## Fen restoration on a bog harvested down to sedge peat: A hydrological assessment



Shannon Malloy\*, Jonathan S. Price

University of Waterloo, 200 University Ave West, Waterloo, Ontario, Canada N2L3G1

### ARTICLE INFO

#### Article history:

Received 10 June 2013

Received in revised form 5 November 2013

Accepted 19 December 2013

#### Keywords:

Peatland  
Hydrology  
Restoration  
Rewetting  
Minerotrophic

### ABSTRACT

Peatlands abandoned after being exploited for horticultural materials can be characterized by soil–water deficits that challenge the establishment of appropriate plant species, thus rewetting is an important step to restoring them to naturally functioning ecosystems. A bog section of Bic-Saint-Fabien peatland near Rimouski, QC was vacuum-harvested for peat production and abandoned in 2000. Harvesting activity left topographic elevation differences across the harvested area, creating wetness gradients. In general, the site interior had more available water than peripheral regions. Bic-Saint-Fabien was cut down to minerotrophic sedge peat; therefore it was restored as a fen. Research for this study lasted four years, 2008–2011. A water budget was created for every year of study to determine the importance of different hydrological parameters at Bic-Saint-Fabien.

The main loss of water was through evapotranspiration and the principal input was precipitation. The main difference in the water budget between study years was that pre-rewetting was climatologically wetter than post-rewetting. Despite more available water before rewetting, before-after-control-impact design ANOVA indicated the water table was significantly higher at the cutover area after rewetting. In 2011 a wetness gradient remained evident within the cutover section of the peatland; however the mean seasonal water table was close (within 20 cm) to the peat surface at all measured wells. An interior section of Bic-Saint-Fabien remained saturated for nearly all of 2011 and had mean seasonal water table of +2.4 cm, and volumetric soil moisture content and soil water pressure, measured 5 cm below the surface, of 86% and +4 mbar, respectively, compared to –15.4 cm, 67% and –13 mbar, respectively, at a nearby (~100 m) peripheral section. Systematic differences in wetness across the site suggest that a uniform prescription for vegetation re-establishment in the rewetted section may not be appropriate.

© 2014 Elsevier B.V. All rights reserved.

### 1. Introduction

In Canada, approximately 160 km<sup>2</sup> (<0.002%) of the 1.136 million km<sup>2</sup> of peatland have been exploited for horticultural peat (Keys, 1992; Tarnocai, 2006). The area of harvested peatland is small compared to total peatland area in Canada, however the peat production industry is very localized, occurring predominantly in New Brunswick and Québec (Daigle and Gautreau-Daigle, 2001). Without intervention these disturbed systems rarely return to naturally functioning ecosystems, due to changes in site hydrology and peat hydraulic character (Price, 1996); therefore, restoration measures are required.

Peat extraction with the vacuum harvesting method presents uniformly poor conditions for spontaneous regeneration of peat-forming mosses characteristic of bogs (Price et al., 2003).

Preparation for vacuum harvesting includes the creation of artificial drainage networks that intentionally lower the water table to allow heavy machinery to be supported by the peat surface (Mulqueen, 1989), and to reduce moisture content for processing. The peat above the water table becomes oxidized and shrinks causing the peat to lose volume (Schothorst, 1977). The buoyant forces in the peat matrix created by a high water table (and high soil water pressures) are lost due to water table drawdown, compressing the deeper peat; both processes reduce the ability of the peatland to store water (Price and Schlotzhauer, 1999). When the peat is compressed and oxidized the specific yield is lowered (Price, 1996) resulting in increased water table variability (Schouwenaars, 1993) and rate and extent of decline during summer (Price, 1996, 1997). Reduced water availability inhibits colonization of bryophytes on the bare peat surface (Campeau et al., 2004), and frost-heave can inhibit the colonization of vascular species (Groeneveld, 2002; Groeneveld and Rochefort, 2005). Without restoration, abandoned peatlands with a deepened water table continue to oxidize for decades and are a source for carbon

\* Corresponding author. Tel.: +1 5198884567x35397.

E-mail address: [shannonmalloy@gmail.com](mailto:shannonmalloy@gmail.com) (S. Malloy).

dioxide to the atmosphere (Nykänen et al., 1995). Carbon dioxide fluxes out of the system can be 300–400% higher post-drainage (Nykänen et al., 1995; Waddington and Price, 2001). A lower water table generally reduces methane emissions in vacuum harvested peatlands (Strack et al., 2004). However, a lower water table favors the colonization of vascular species over mosses, which can act as a substrate for methane production (Bellisario et al., 1999) or vent methane to the atmosphere through the aerenchyma (Schutz et al., 1991; Greenup et al., 2000).

Successful restoration is contingent on returning disturbed systems into carbon sinks, which can be achieved through a combination of rewetting to halt oxidation, and revegetation with peat forming plants (Waddington et al., 2010). Rewetting is typically the first step in peatland restoration and it aims to improve the hydrological conditions necessary for ecological development. Rewetting chiefly involves blocking active drainage ditches, re-profiling the peat surface to eliminate small-scale changes in surface elevation, creating peat ridges called bunds along contour lines while producing level terraces to retain water and applying a straw mulch treatment to reduce water loss by evaporation (Price et al., 1998). Until recently, efforts have been focused on the large-scale restoration of *Sphagnum* dominated bog peatlands and the hydrological changes that occur as a result of restoration (Spieksma, 1999; Shantz and Price, 2006a,b; McCarter and Price, 2013). In contrast there has been little research on the response to rewetting in peatlands that have been cut down to minerotrophic sedge peat, for which the goal of restoring fen plants may be more appropriate. Bogs have a relatively narrow range of ecohydrological conditions including pH and vegetation community type, whereas fens have a larger range in pH, nutrient conditions and vegetation community types (Zoltai and Vitt, 1995), making restoration more complex. However, vascular species may be more likely to spontaneously recolonize where fen-like conditions occur, although not necessarily desirable species (Mahmood and Strack, 2011). A major challenge to restoring minerotrophic systems is planning for natural succession.

Campbell et al. (1997), Dempster et al. (2006) and Nicholson and Vitt (1990) documented lake basin infilling and peatland development through terrestrialization, which can give rise to peat overlying gyttja. Peat accumulates when production exceeds decomposition; accumulation occurs due to slow decomposition rather than high productivity (Damman, 1979). If precipitation is sufficient (increasing production), the surface of the peatland will rise, isolating the system from minerotrophic groundwater inputs, favoring a natural transition from minerotrophic to ombrotrophic conditions, hence *Sphagnum* mosses over brown mosses and vascular plants (Damman, 1979). Consequently, successional pathways in peatlands commonly progress from rich fen, to poor fen and finally to ombrotrophic bog conditions (cf. Kuhry et al., 1993).

Several North American studies have examined the target fen plant assemblages and restoration techniques most effective at transitioning mined peatlands into peat accumulating systems (Cobbaert et al., 2004; Cooper et al., 1998; Cooper and MacDonald, 2000; Graf and Rochefort, 2008, 2010; Graf et al., 2008). Techniques developed for North American bog restoration including the application of donor seed bank, straw mulch and fertilizer have also been effective at increasing the richness of target fen species (Cobbaert et al., 2004). Such studies have begun to link hydrological conditions to target plant growth. It has been established that brown mosses common in fen ecosystems (e.g. *Tomenthypnum nitens*) do not require full saturation to recolonize yet show more growth when the water table is ~10 cm below the peat surface (Busby and Whitfield, 1977). Little growth occurs when the water table exceeds 40 cm below the peat surface (Graf and Rochefort, 2008). Cooper et al. (1998) showed ditch blocking in a fen drained for

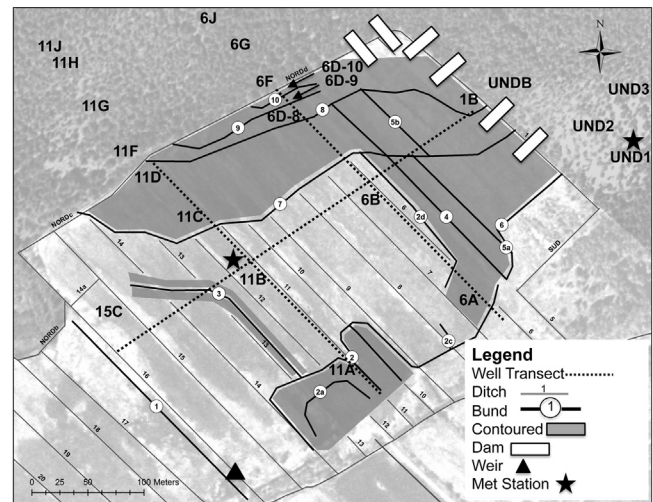


Fig. 1. Map of Bic-Saint-Fabien.

agriculture was effective at raising and stabilizing the water table, yet the water table position remained sensitive to the presence of sufficient summer precipitation.

There is a lack of research pertaining to the hydrological response of fen restoration, especially on the ecosystem-scale and on harvested bogs cut down to minerotrophic peat. Hence, we do not know if restoration techniques are effective at restoring natural fen conditions. Understanding the effect of restoration techniques on the hydrologic regime is important because the peat industry is under increased pressure to restore these systems when production finishes. The goal of this research is to evaluate the hydrological changes associated with the restoration of the cutover area of Bic-Saint-Fabien peatland to a fen. The specific objectives are to create a water budget for an undisturbed and harvested section of the abandoned peatland before and after rewetting and to understand the implications of site reconfiguration on the hydrology of the system. This will provide information essential for evaluating the response of the system to plant reintroduction, carbon exchanges and insight on the fen-to-bog transition process.

## 2. Study site

The Bic-Saint-Fabien (BSF) peatland (48°19' N, 68°50' W) lies within the boundaries of Parc National du Bic in a synclinal valley at the northern extent of the Appalachian Mountains. The average annual precipitation and temperature (from 1971 to 2000) was 915 mm (with approximately 30% fall as snow) and 3.9 °C, respectively (Environment Canada, 2011). BSF formed over marine clay sediments deposited from the former Goldthwait Sea during the last glaciation (Dionne, 1977). The marine clay sediments and a low permeability gyttja layer (unpublished data) limit exchanges of water with the regional aquifer. An approximately 350 m high ridge of Paleozoic sedimentary rock borders the north edge of BSF (Government of Quebec, 2012; Fortin and Belzile, 1996). BSF was prepared for block-cut peat extraction by the creation of drainage ditches in 1946 (Bérubé et al., 2009). Vacuum harvesting began in the early 1970s and operations ceased in 2000 when the bog peat resource was exhausted. Peat production left ~0.4 to >1 m of mostly fen peat dominated by sedges, overlying 1–1.5 m of gyttja (unpublished data). The total cutover area (CUT) is ~11 ha. CUT is composed of 16 drainage ditches and 15 peat fields (Fig. 1). It was evident that the peat extraction process left the cutover area with topographic elevation differences. In general the westernmost peat fields were harvested for a longer period of time than the eastern

section of CUT. This caused the southwest edge of CUT to be the least elevated and the surface elevation gently increased toward the northeast across CUT (along transect B) until about peat field 6; from peat fields 6 to 1 there was a steeper elevation gradient (Fig. 1). Recall the abrupt elevation change at peat field 6 as a result of being harvested for a shorter length of time. In 2011 the surface elevation of peat field 1 was approximately 2.5 m higher than peat field 15 (Fig. 4). The elevation differences southeast to northwest across CUT (transect 11 and transect 6) were more complex. CUT was characterized by saddle-like topography where the interior portion of the site was slightly depressed with less residual peat compared to the more elevated peripheral regions northwest and southeast of the interior section, which had thicker layers of residual peat. The saddle like topography was evident in peat fields 10–16. In general, at the western section of the peatland (west of peat field 10) the northwest boundary was typically less than ~0.5 m higher than the southeast, and the peat field surface elevation remained concave in character (unpublished 2011 data). For peat fields 1–10, the northwest boundary was approximately 1–1.5 m higher than the southeast for the eastern section of the peatland. The saddle-like topography was barely evident in peat fields 1–10 (unpublished 2011 data).

Even before rewetting, CUT was a relatively wet site, notably in the interior portions, where inflowing water along with the fen-peat substrate resulted in fen-like conditions with pH averaging ~6.5–7 (Sararas, E., unpublished 2010 data). Hence, the decision was made to restore this system to a fen. Prior to restoration CUT had become spontaneously revegetated with *Scirpus cyperinus*, *Equisitum arvense*, *Calamagrostis canadensis*, *Eriophorum vaginatum*, *Drosera rotundifolia* and *Typha latifolia* (concentrated near drainage ditches); there was very little moss regeneration (Mahmood and Strack, 2011; Bérubé et al., 2009).

Research at BSF occurred from 2008 to 2011. In fall 2009, peripheral regions at CUT were contoured to flatten out the landscape into a series of terraces (Fig. 1). Peat ridges (bunds) were constructed to help retain water and prevent erosion. Interior drainage ditches were blocked at their south end but peripheral ditches remained active. The interior section had insufficient bearing capacity to support machines, so was not cleared of vegetation or contoured; however, this section was indirectly affected by drain-blocking and the adjacent enclosing bunds. The lowest elevation in the central portion of CUT is near the meteorological station (see Fig. 1). However, the only active drainage outlet is to the west, bounded by bund #1 (see Fig. 1). A weir was installed to measure outflow, most of which was derived from seepage onto the site in the northwest corner. Plant material milled from a nearby undisturbed fen was applied to CUT northeast of bund 4 (Fig. 1) using the surface layer and straw mulch transfer methods (Rochefort et al., 2003). Plant material and straw mulch was also applied by hand to a smaller area (0.4 ha) south of bund 2a (Fig. 1). On June 22, 2010 (day of year 173), six dams were installed to raise the water tables along the peripheral drainage network at the north-east margin of CUT (Fig. 1). At this time leaky ditches were re-blocked and breached bunds were repaired. Therefore we have two study years before rewetting (2008 and 2009), and two study years after rewetting (2010 and 2011); however note that CUT was not completely rewet until partially through the 2010 study year due to the late installation of the dams.

A natural section of BSF remains northwest and northeast of CUT. The undisturbed section (UND) east of CUT (Fig. 1) was selected as a reference site; it is dominated by *Thuja occidentalis*, *Larix laricina*, with brown mosses such as *Campylopus stellatum* and *T. nitens* forming the moss carpet (Mahmood and Strack, 2011). Sedge species at UND include *Trichophorum cespitosum*, *Trichophorum alpinum*, *Carex interior* and *Carex prairea* (Mahmood and Strack,

2011). The peat at UND is about 3.3–3.8 m thick (Sararas, E., unpublished 2010 data).

### 3. Methods

Data were collected at BSF peatland from 2008 to 2011; data from day of year 153–219 (June 2–August 7) are available for all years.

#### 3.1. Meteorological conditions

A meteorological station was set up at CUT (11B) and UND (UND1) (Fig. 1). In 2008 the UND meteorological station was at UND3 (Fig. 1). Campbell Scientific Inc. (CSI) 10× data loggers measured sensor values at 60-s intervals, averaged, then logged at 20-min intervals unless otherwise stated. Net radiometers ~1 m above the ground surface measured net radiation ( $Q^*$ ; REBS Q7.1). Ground heat flux plates were installed ~2 cm below the ground surface to measure ground heat flux ( $Q_g$ ; REBS HFT-3.1). Precipitation ( $P$ ) was measured using a tipping bucket rain gauge (Texas Electronics, Inc. TR-525M). A manual rain gauge was installed within ~1 m of the tipping bucket at 11B to data check logged values. Due to logging problems in 2008 and 2009, manual rain data were used. Air temperature ( $T_a$ ) was measured with a copper-constantan thermocouple placed in a well-ventilated, shielded chamber.

Evapotranspiration ( $ET$ ) was determined using the Priestly–Taylor method (1972) as,

$$ET = \alpha \left[ \frac{s}{s+q} \right] \left[ \frac{Q^* - Q_g}{L_v \rho} \right], \quad (1)$$

where  $s$  is the slope of the saturation vapor pressure vs. temperature curve ( $\text{Pa}^\circ\text{C}^{-1}$ ),  $q$  is the psychrometric constant ( $0.0662 \text{ kPa}^\circ\text{C}^{-1}$  at  $20^\circ\text{C}$ ),  $L_v$  is the latent heat of vaporization ( $\text{J kg}^{-1}$ ), and  $\rho$ , which is the density of water ( $\text{kg m}^{-3}$ ).  $Q^*$  ( $\text{J day}^{-1}$ ),  $Q_g$  ( $\text{J day}^{-1}$ ) and  $T_a$  ( $^\circ\text{C}$ ) obtained from each meteorological station in addition to  $s$ ,  $q$ ,  $L_v$ , and  $\rho$  were used to calculate  $ET$ . The  $\alpha$  term represents the calibration coefficient and is the slope of the line when equilibrium evaporation ( $\alpha = 1$ ) is plotted against actual evapotranspiration ( $ET_a$ ).  $ET_a$  was measured in 2011 by five weighing lysimeters in all surface types at CUT (11A, B, C, D, and 6B), and two lysimeters at UND in moss/sedge ground cover (UND1 and UND2) (Fig. 1). The  $\alpha$  parameter was determined in 2011, and was used in Eq. (1) for all study seasons. The lysimeters consisted of a peat monolith placed in a bucket that was open only at the top, and weighed about twice weekly. Volumetric soil moisture ( $\theta_v$ ) was monitored inside the lysimeter and outside within ~50 cm of the lysimeter with a Delta-T Devices HH2 moisture meter to ensure that  $\theta_v$  in the lysimeter was similar to the surrounding conditions; water was added/removed accordingly. Lysimeter data were rejected when  $P \geq 5$  mm between weighing periods; thus a total of eight lysimeter measurement periods were used to calibrate  $ET$  in 2011.  $ET$  was not determined at UND in 2009 due to insufficient meteorological data.

#### 3.2. Groundwater flux, storage change and runoff

Polyvinylchloride (PVC) wells (i.d. 2.5 cm; o.d. 3.3 cm) were installed to a depth of 1 m at CUT and UND (Fig. 1; e.g. 11A, 11B, etc.). The portion of the well that extended below ground surface had circular slots (drill holes) approximately 1 cm in diameter spaced about 3–5 cm apart. PVC piezometers (i.d. 2.5 cm; o.d. 3.3 cm; slotted intake 15 cm) were installed at 0.75, 1.5 m below the peat surface at CUT and UND (Fig. 1; e.g. 11A, 11B, etc.) to measure pressure at said depths (i.e. the middle of the slotted intakes are at 0.75 and 1.5 m). Piezometer slot dimensions are the same as the well slot

dimensions. Well and piezometer measurements were taken about twice weekly during the water budget time period (June 2–August 7). In general, wells and piezometers were installed to be near the midpoint of a peat field relative to the bordering drainage ditches. A total of eight saturated horizontal hydraulic conductivity ( $K$ ) tests were performed on each piezometer from 2008 to 2011 following the method described by Hvorslev (1951). We acknowledge that Hvorslev (1951) is a rigid soil theory. Peat is highly compressible; therefore reported  $K$  values should be regarded with caution. However, where the dimensionless recovery was non-linear (indicative of compressible soils), the appropriate time-lag adjustment was made based on the tail of the recovery curve (where water inflow to the piezometer from storage are nearly complete) (Hvorslev, 1951). Hydraulic conductivity tests were only performed on piezometers. Lateral groundwater fluxes into CUT were determined for the northwest and northeast seepage faces for the saturated zone in the upper 1 m of the soil layer. Fluxes into CUT from the northwest and northeast seepage were determined using 0.75 m deep piezometers on transect 11 and transect B, respectively.

The seasonal change in storage was calculated as

$$\Delta S = dh(S_y), \quad (2)$$

where  $\Delta S$  represents the change in storage,  $dh$  is the change in water table position and  $S_y$  is specific yield. The average  $S_y$  for the depth over which the seasonal change in water table position occurred, was used in Eq. (2). A Wardenaar sampler was used to cut peat profiles (12 cm  $\times$  10 cm  $\times$  40 cm) that were analyzed for  $S_y$  and bulk density ( $\rho_b$ ) in July 2012. Cores acquired include two and four cores extracted from UND (UND1 and UND2) and CUT (11B, 11D, 6B, and 6D-9), respectively (Fig. 1). Cores were cut into 5 cm thick segments.  $S_y$  was calculated by determining (gravimetrically) the volume of water that drained freely by gravity from the measured volume of saturated peat over a 24-h period. Samples were oven dried at 80 °C (rather than the conventional 105 °C to ensure no burning of organic matter) to determine the dry  $\rho_b$ .

A v-notch weir installed April 2010 in ditch 16 (see Fig. 1) was used to measure runoff from CUT. Discharge was measured approximately four to five times/week with a stopwatch and calibrated bucket. A mean discharge rate was determined from at least three trials. A pressure transducer (Solinst Levelogger Gold 3001) was deployed to take stage measurements at 20-min intervals. A stage–discharge relationship was created to determine total CUT discharge for 2010 and 2011.

### 3.3. Pattern of rewetting

At CUT, one W-E and two S-N well transects were defined, transect B, transect 11, and transect 6, respectively (Fig. 1). For CUT, transect 11 (11A, 11B, 11C, 11D) and transect B (15C, 11B, 6B, 1B) were used to evaluate the patterns of rewetting at BSF because on transect 6 most data are only available for post-restoration study years as most wells were not yet installed. The peripheral region at 6D is heavily terraced, therefore 6D is subdivided into 6D-8, 6D-9, and 6D-10 with the latter number representing the bund each terrace is enclosed by (see Fig. 1).

Seasonal mean water tables were determined at CUT and UND. At CUT transect B and 11 were used. On these transects, 15C, 11B and 6B were classified as interior wells. Wells 11A, 11C, 11D and 1B were considered to be peripheral as they were in the region that was eventually contoured. At UND wells UND3 11G, 11H, and 11J were used; wells from the undrained section northwest of CUT were included because UND3 was the only well that existed at UND for all years of study that was not impacted by ditch 1.

Before–after–control–impact (BACI) design one-way ANOVA with a 5% significance level was used to compare mean water

**Table 1**

BACI design ANOVA comparing before and after rewetting study periods and ANOVA comparing the water table at CUT and UND annually.

		Sample size	Mean	Variance	P Value
Before rewetting		57	17.0	82.3	0.00
After rewetting		26	2.2	30.9	
2008	CUT	26	−31.2	120.6	0.00
	UND	26	−11.7	15.3	
2009	CUT	31	−21.5	134.7	0.00
	UND	31	−6.6	4.6	
2010	CUT	11	−21.8	115.4	0.04
	UND	11	−13.2	45.2	
2011	CUT	19	−8.6	26.1	*0.76
	UND	19	−9.1	7.1	

Note:

<sup>a</sup> Indicates not significant.

tables at CUT before rewetting (2008 + 2009) and after rewetting (2010 after dam installation + 2011). BACI design eliminates the influence of environmental factors (e.g. climate variability between seasons) by pairing the impacted area to a control area. BACI design ANOVA involves determining the observed differences between simultaneous (same day) measurements from a control (UND) and impacted (CUT) site before and after an impact activity (i.e. rewetting). A change in the measured differences is assumed to be due to the impact activity. ANOVA is then performed on the differences before and after the impact activity. Since the water budget was completed annually we also compared the mean water table between CUT and UND on an annual basis.

In 2011  $\theta_v$  and soil–water pressure ( $\psi$ ) were also measured on transect 11 (11B and 11D) and UND1 at 5 cm below the peat surface (Fig. 1). Time domain reflectometry (TDR) probes (CSI TDR100) were used to determine  $\theta_v$  hourly based on the method of Kellner and Lundin (2001). Tensiometers installed 5 cm below the peat substrate were used to determine  $\psi$  and were measured bi-weekly with a Tensicorder™ pressure transducer (Soil Measurement Systems) with 1 mbar sensitivity.

## 4. Results

### 4.1. Pattern of rewetting

Prior to rewetting, runoff from the undrained peatland toward the cutover section during and shortly after the snowmelt period was intercepted by the peripheral drainage ditches to the northwest and northeast of CUT, and shunted to the regional drain. Contouring of the site, particularly along the northwest margin, lowered the CUT surface to the base-level of the drainage ditch and snowmelt water from the undrained section northwest of CUT seeped into the terraces bounded by bunds 7–10 (see Fig. 1). The drainage ditch to the northeast was more deeply incised and continued to carry water from the undrained sections so log and plywood dams with geo-cloth were installed (June, 2010) so dam backwater could raise the water level at CUT. Within CUT, general water flow was toward the met station (see Fig. 1).

The highest water tables at all sites for all years were in response to summer storms (Fig. 2). The water table at CUT was significantly ( $p < 0.05$ ) higher after rewetting (Table 1) using the BACI difference approach. The mean difference in water table position between CUT and UND before and after rewetting (2010 after dam installation + 2011) was 17.0 and 2.2 cm, respectively (Table 1). The mean water tables at CUT in 2008–2011 were −31.2, −21.5, −21.8, and −8.6 cm, respectively and −11.7, −6.6, −13.2 and −9.1 cm, respectively at UND (Table 1). The mean daily water table position at CUT

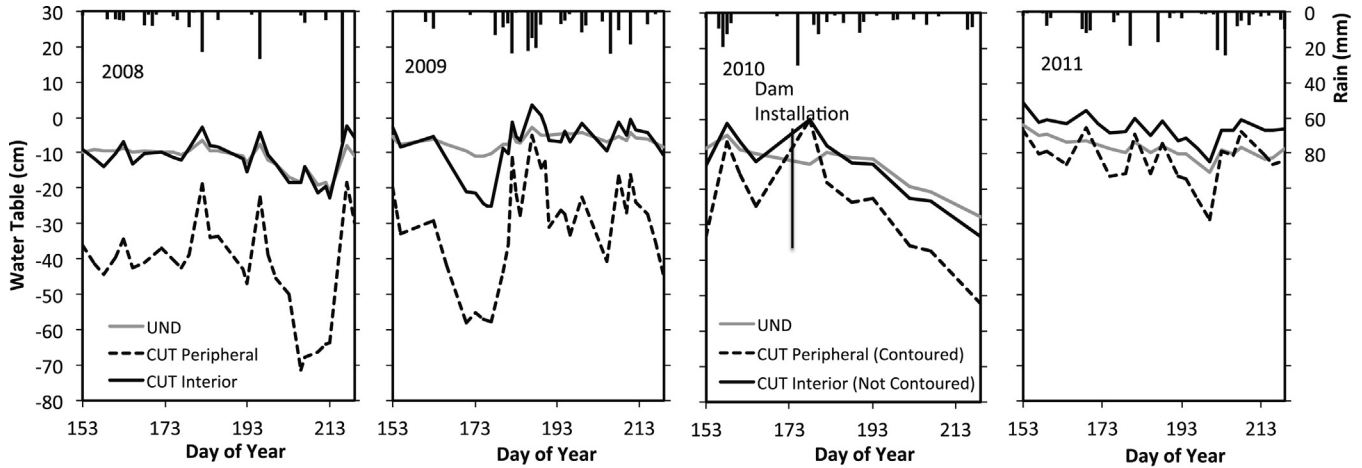


Fig. 2. Precipitation (recorded at CUT) and mean water table at UND, CUT – peripheral (11A, 11C, 11D, 1B) and CUT – interior (15 C, 11B, 6B) for all study years.

was significantly ( $p < 0.05$ ) lower than UND in the 2008–2010 study years based on 26, 31, and 11 measurements, respectively (Table 1); however the water table at CUT was the closest to that of UND in 2010. The BACI difference approach was not applied for the annual comparison of mean water tables. After dam installation in 2010 the mean daily water table at CUT was not significantly different than UND. In 2011 the average daily water table was not significantly different than UND from 19 measurements ( $p = 0.76$ ) (Table 1).

There were differences in water table depth within CUT. In general the interior water table was higher and less variable than at the peripheral area for all years of study (Fig. 2), especially in 2008 and 2009 when peripheral ditches were fully operating. Before rewetting the CUT (peripheral) water table was lower relative to the ground surface and more variable than CUT (interior) and UND (Fig. 2). The position and range of the water table at CUT (interior) and UND were similar for all years of study (Fig. 2). Following restoration the water table at CUT (peripheral) was more similar to CUT (interior) and UND. At CUT in 2008–2011 the mean water tables for the interior region were  $-11.7$ – $8.0$ – $14.9$  and  $-3.4$  cm,

respectively and for the peripheral region they were  $-42.9$ ,  $-31.6$ ,  $-27.0$  and  $-12.6$  cm, respectively.

On transect B the mean water table was closest to the ground surface at 15C and became further from the peat surface along the transect from west to east in every year of study, but in 2011 the mean water table at 1B was only  $\sim 1$  cm lower than 6B (Fig. 3). Transect B had the largest range (the difference between the well with the shallowest and deepest mean water table) before rewetting at  $\sim 60$  cm in 2008 and 2009 (Fig. 3) largely due to the low water table at 1B, which was  $-59.7$  and  $-51.9$  cm, in 2008 and 2009 respectively (Fig. 3). In comparison, the water table range before rewetting on transect 11 in 2008 and 2009 was 26 and 19 cm, respectively. The range in water table position on both transects decreased after rewetting and was less than 25 cm in 2011. On transect 11 the water table at 11B was the closest to the surface for all study years. The deepest water table on transect 11 was 11A in 2008–2009 and 11D in 2010–2011. In 2010–2011 the average seasonal water table at 11B was  $-12.2$  and  $+2.4$  cm. At 11D it was  $-32.4$  and  $-15.4$  cm, respectively (Fig. 3).

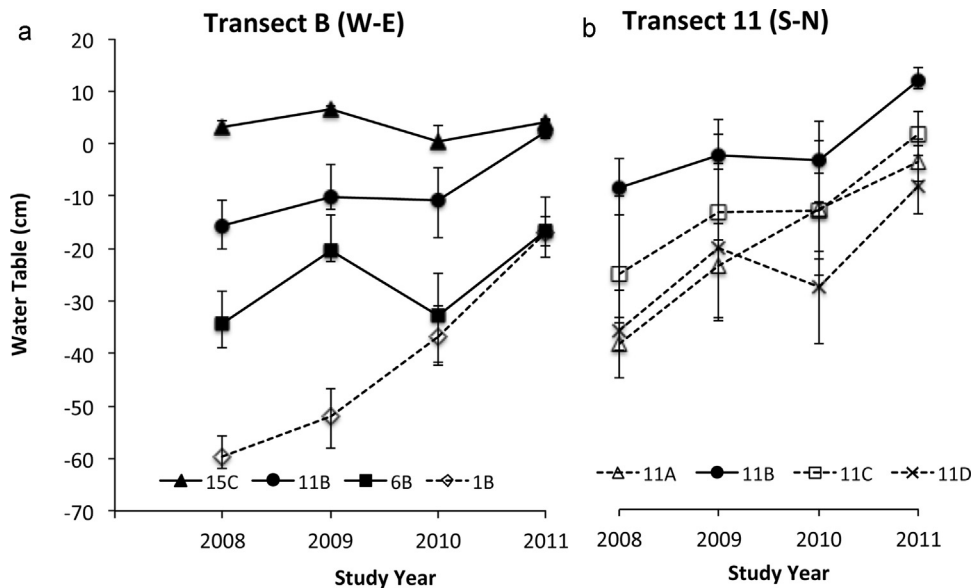


Fig. 3. Mean seasonal water tables and interquartile range (error bars) on transect B and transect 11. Note: Dashed lines with open symbols represent peripheral wells.

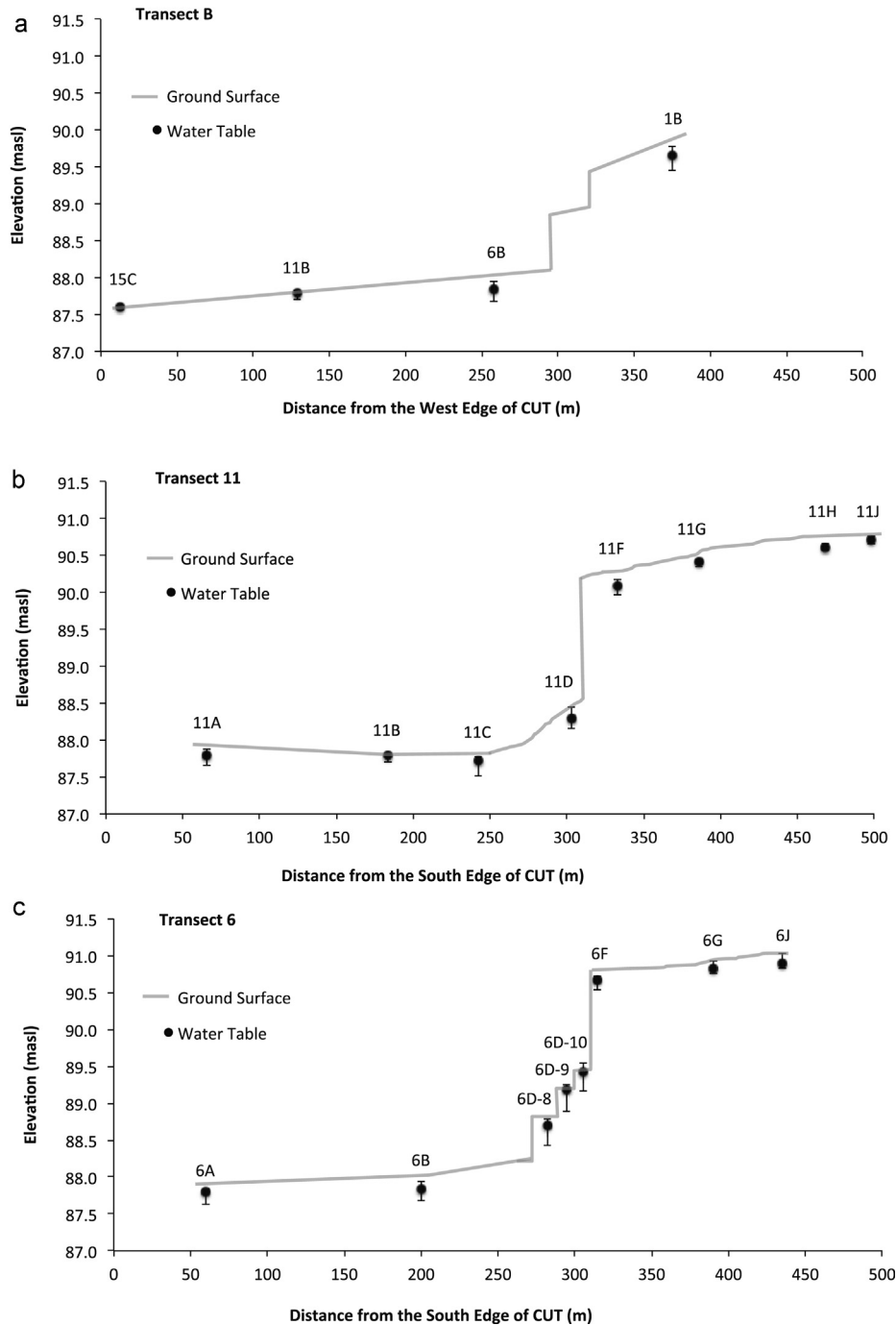
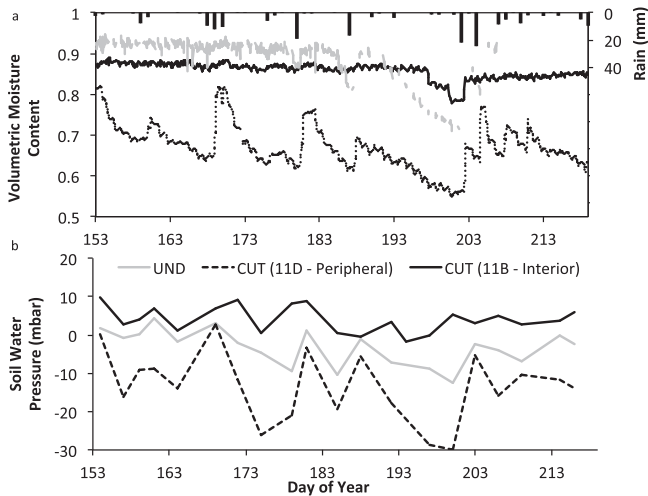


Fig. 4. 2011 Surface elevation and water table for transect 11 and transect 6. Error bars represent range.

The surface elevation with water tables on all transects for 2011 is illustrated in Fig. 4. On transect B from west to east the ground surface elevation gently increased until about peat field 6, east of field 6 the surface elevation more sharply increased (Fig. 4). Consequently the water table was closer to the ground surface and less variable in the western section CUT compared to the east (Fig. 4). The remnant saddle-like topography remained evident on transect 11 and was less obvious on transect 6. The change in surface elevation was greater on transect 6 than transect 11. Unlike transect 11; in 2011 the peripheries of transect 6 had water table closer to the peat surface compared the interior, especially at the 6D locale where several nearly level terraces were constructed (Fig. 4). The

6D region of transect 6 had a water table much closer to the peat surface than the 11D region on transect 11. Pre-rewetting data do not exist for transect 6; however these trends were likely caused by site reprofiling that lowered the peat surface in the 6D region and by the influence of backwater from the dams installed in the northernmost marginal drainage ditch early in the 2010 study season (Fig. 1). Northwest of CUT transect 6 and 11 extend into the adjacent undrained section. A gentle increase in elevation is evident on both transects in the undrained section north of CUT as they approach the ridge bordering BSF (Fig. 1).

The average  $\theta_v$  at CUT measured 5 cm below the peat surface at 11B and 11D in 2011 was 85.8 and 67.0%, respectively (Fig. 5a) and



**Fig. 5.** Volumetric soil moisture and soil–water pressure 5 cm below the peat surface in 2011. CUT interior is 11B and CUT peripheral is 11D.

$\psi$  was +4 and –13 mbar, respectively (Fig. 5b). In 2011 the average  $\theta_v$  and  $\psi$  at UND (Fig. 5) was 89.9% and –3 mbar, respectively. UND  $\theta_v$  data were sporadic due to in-field power supply issues.

#### 4.2. Water budget

The annual data sets span day of year 153–219 (June 2–August 7), as it was available for all study years (2008–2011). The mean temperatures for 2008–2011 study years were very consistent at 16.5, 16.3, 17.0, and 16.0 °C, respectively at CUT. Precipitation was the major water input to CUT. In 2008–2011, 206, 243, 174 and 199 mm of rainfall, respectfully, were recorded at CUT meteorological station. In comparison there was 210, 224, 163 and 184 mm of rain, respectively at UND. The 30-year average rainfall for these dates at Rimouski, QC (21 km northeast of study site) is 185 mm (Environment Canada, 2011) therefore all study years had above average rainfall except 2010, and near-average in 2011. In 2010 and 2011, 4 and 78 mm of rain, respectively, fell during the 10 days prior to the start of the study period (day of year 143–152).

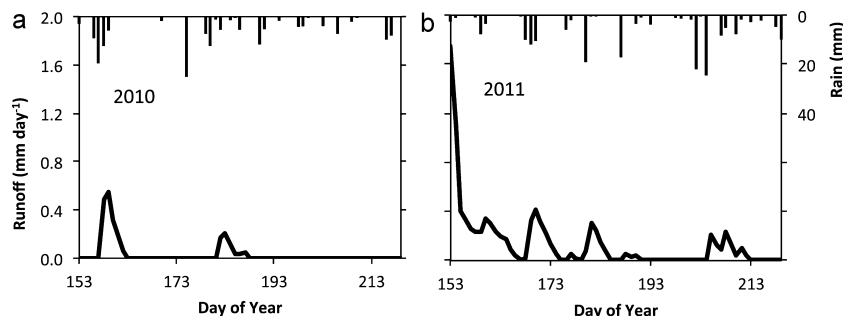
Since our study period was after snowmelt, run-on to CUT was negligible. A small but unquantified amount of water runs onto CUT from the northwest corner but is captured by a rivulet and ditch 14a that sends it to ditch 16 and out through the weir. In any case, during the main part of the study season captured by the water budget, runoff from CUT, and out through the weir, was small or nonexistent. The total runoff at this weir for the water budget period in 2010 and 2011 was 2 and 9 mm, respectively (Fig. 6) representing 1% and 5% of  $ET$ .

**Table 2**  
Alpha values derived in 2011 based on eight measurement periods at each site.

Location	Lysimeter	Water table (cm)	Alpha	$R^2$
CUT	11A	–11.3	1.1	0.96
	11B	+2.4	0.6	0.83
	11C	–6.6	0.7	0.93
	11D	–15.4	1.0	0.93
	6B	–16.6	1.0	0.87
	<b>Average</b>		–9.5	0.9
UND	UND1	–5.4	0.4	0.84
	UND2	–6.0	0.5	0.88
	<b>Average</b>	–5.7	0.5	0.86

The continuous clay base,  $K \sim 0.02 \text{ cm day}^{-1}$ , and low permeability gyttja layer,  $K \sim 0.06 \text{ cm day}^{-1}$  (unpublished data), restrict groundwater exchanges with the regional aquifer. The average four-season  $K$  for the 0.75 and 1.5 m piezometers at CUT were 0.11 and 0.07  $\text{cm day}^{-1}$ , respectively (alternatively, at UND it was 34.2 and 3.4  $\text{cm day}^{-1}$ , respectively). Most piezometers at CUT were in gyttja, at UND all piezometers were in peat. The vertical groundwater exchanges at CUT were negligible given the low  $K$  of clay. Lateral seepage from the northwest and northeast natural areas into CUT, based on Darcy's law applied to the top 1 m (which provides seepage to the peripheral ditch) for the measured ditch length, was also negligible (low hydraulic gradients and low  $K$ ). Since groundwater exchanges were negligible at CUT they were not included in the water budget. Even after surface contouring the ground elevation southeast of the interior on transect 11 remained higher than the interior, preventing seepage losses from the southernmost edge of CUT (Fig. 4). Seepage losses into ditch 16 are accounted for by runoff. Run-on, runoff and groundwater exchanges were not quantified at UND; we believe they are negligible.

Evapotranspiration rates are based on alpha values derived in 2011.  $ET$  was only measured for the moss/sedge ground cover at UND and did not account for trees and shrubs (discussed below). For the calculation of evapotranspiration, the average  $\alpha$  values derived through the regression of actual and equilibrium evapotranspiration based on eight lysimeter measurements at CUT and UND were 0.89 and 0.47, respectively (Table 2), all relationships having  $R^2$  values  $\geq 0.83$ . The daily average  $ET$  rates at CUT for 2008–2011 were 2.6, 3.3, 2.9, and 2.9  $\text{mm day}^{-1}$ , respectively, with seasonal totals being 174, 220, 193 and 193 mm, respectively (Table 3). At UND in 2008, 2010, and 2011, the daily average  $ET$  rates for sedge/moss were 1.4, 1.8, and 1.7  $\text{mm day}^{-1}$ , respectively, representing seasonal totals of 91, 119, and 113 mm, respectively. Water losses from trees/shrubs were not measured in this study so total  $ET$  from UND is underestimated. We note that the canopy was fairly open in the vicinity of our UND measurements, as can be seen from the image underlying the site map (Fig. 1). Since the water budget is based



**Fig. 6.** CUT runoff in 2010 and 2011.

**Table 3**  
Water budget.

CUT	$\Delta S$	$P$	$R$	$ET$	$\varepsilon$	% Error
2008	+3	206		174	-29	14
2009	-7	243		220	-30	12
2010	-10	174	2	193	11	6
2011	-4	199	9	193	-1	1
UND	$\Delta S$	$P$	$R$	$^a ET$	$^a \varepsilon$	$^a$ % Error
2008	-1	210		91	-120	57
2009	-1	224				
2010	-8	163		119	-52	32
2011	-6	184		113	-77	42

<sup>a</sup> Indicates ET does not account for transpiration from trees.

on our measurements, we do not include an estimate of  $ET$  from trees/shrubs at this point, but consider it later in Section 5.

Changes in storage were mainly due to water table fluctuation since changes in  $\theta_v$  and aquifer thickness (unpublished data) were very small. The average specific yield and bulk density for the upper 40 cm of the peat deposit was 0.045 and 0.12 g cm<sup>-3</sup>, respectively at CUT (Fig. 7). At UND it was 0.049 and 0.13 g cm<sup>-3</sup>, respectively (Fig. 7). Water storage changes for 2008–2011 calculated using Eq. (2), using the mean specific yield for the depth where the change in water table position occurred. These values at CUT were +3, -7, -10, and -4 mm, respectively and -1, -1, -8, and -6 mm, respectively at UND (Table 3).

The water budget for BSF was calculated as

$$\Delta S = P - R - ET + \varepsilon, \quad (3)$$

with  $\varepsilon$  being the residual error term whose value balances Eq. (3). Seasonal water budgets are summarized in Table 3. Error calculated as a percentage of inputs was 14, 12, 6, and 1% for 2008–2011, respectively, at CUT. In contrast error at UND was quite high being 57, 32, and 42%, for 2008, 2010 and 2011, respectively, but the  $ET$  term did not account for water loss from trees.

## 5. Discussion

Peat harvesting activity at BSF has substantially altered the ecosystem function as a result of vegetation removal, intentional lowering of the water table and peat cutting. After rewetting in spring 2010 and 2011, frost heaving was evident at peripheral regions of CUT. Frost heave creates an unstable ground surface, which prevents rooting of vascular plants (Groeneveld, 2002; Groeneveld and Rochefort, 2005). This can be ameliorated with the use of straw mulch or the establishment of a moss carpet, such as *Polytrichum strictum* (Groeneveld, 2002; Groeneveld and Rochefort, 2005; Quinty and Rochefort, 2003). Ponding behind bunds was also evident in spring, particularly behind bunds 8–10 (see Fig. 1). These bunds were breached at weak points during snowmelt allowing some water to cascade over the terraces. This created small gullies formed by peat erosion. Efforts were made to manually repair leaky bunds. In summer 2011 plugs were manually planted on terraces to prevent erosion. Ponding behind bunds 8–10 was also evident during the study period especially after rain events. In 2010 vegetation growth was not evident where the diaspore plant material was applied, yet some moss growth was evident in the 2011 study year.

BSF, located in a topographically low area and underlain by low permeability clay and gyttja layers, has resulted in a naturally wet landscape, thus mean water table depths were no lower than about 40 cm from the peat surface even before rewetting (Fig. 3), except for 1B, which was in the most elevated region of the site and adjacent to the deeply incised ditch 1. In general rewetting BSF

significantly raised the average water table and reduced its variability. This is particularly evident at 1B where the water table became much closer to the peat surface (Fig. 3) following dam installation in 2010. This illustrates their effectiveness at raising the water table locally. The mean water table at CUT in 2010 was considerably lower than in 2011 as illustrated herein and visually observed in the field. This could be explained by CUT not having the peripheral drains dammed until June 22, 2010 (day of year 173). Lower water tables in 2010 compared to 2011 may also be caused by substantially drier antecedent conditions in 2010. Differences in water table position along transect B and transect 11 were reduced but remained evident after rewetting (Fig. 3).

On transect 11 the water table at 11B (interior) was 18 cm higher than 11D (peripheral) in 2011 (Fig. 3). Furthermore,  $\theta_v$  and  $\psi$  at 11B were 19% and 17 mbar higher, respectively than at 11D (Fig. 5). However, not all raised peripheral locales were drier than the interior such as at 6D, because of contouring (lowering) of the peat surface adjacent to the peripheral drain. This caused some local seepage onto CUT from the adjacent undrained section in spring; dams installed in the peripheral drainage ditch in 2010 also raised the water table locally, wetting some peripheral areas.

The water budget did not show any pronounced changes after rewetting except that 2010 and 2011 were climatically drier. The study years before rewetting had the most precipitation (Table 3). Water availability ( $P - ET$ ) for the 2008–2011 study periods at CUT was 32, 23, -19 and 6 mm, respectively, suggesting more available water in 2008–2009 (pre-restoration) than in 2010–2011 (post-restoration). Despite the lower water availability after rewetting, the water tables at CUT were generally higher, especially in 2011 (Table 1). Groundwater exchanges were negligible for all years of study. Runoff from CUT in 2010 and 2011 (not measured in 2008 and 2009) was low (2 and 9 mm, respectively) (Fig. 6). Runoff from UND and a natural area northwest of CUT provided un-quantified water inputs to the peripheral parts of the cutover site during the snowmelt periods, which drained toward the interior and is reflected by differences in water table depth relative to the surface (Fig. 3). These discharges were small or negligible during the period of the water budget calculations.

A high water table, precipitation being the predominant water input, and negligible groundwater inputs combine to create conditions favorable to peat accumulation and the transition to a more nutrient deficient system. Although the soil water at BSF is currently in a minerotrophic state (pH ~ 7), this suggests that there is potential for both CUT and UND to transition toward more ombrotrophic conditions.

We acknowledge the potential for human error as different researchers within and between study years took measurements. Rainfall at UND was within +8% of CUT for all years. In 2010 and 2011 the rain measured at the manual rain gauge at CUT was within 16% and 5%, respectively, of rain recorded by the tipping bucket. The error attributable to ignoring changes in peat volume were small since the elevation change of the peat surface at CUT was <3 cm in 2008, 2009 and 2011 (not measured in 2010) hence negligibly affecting  $\Delta S$ . Localized flooding was not accounted for in  $\Delta S$  therefore the estimates herein may be underestimated at CUT. It is expected error attributed to not accounting for localized flooding is negligible in 2008–2010 and negligible to low in 2011 as there was more flooding at the beginning of the 2011 study period. The  $ET$  term likely produced the most error in the water budget for CUT and UND because it was a large component of the water budget and relied on the accuracy of lysimeters and meteorological measurements. The error in  $ET$  attributable to lysimeter accuracy,  $Q^*$  and  $Q_g$  and using the Priestly–Taylor (1972) method is  $\pm 15\%$  under ideal conditions (Stewart and Rouse, 1976), thus probably greater here. Deriving  $\alpha$  values in 2011 (which had the highest water table)



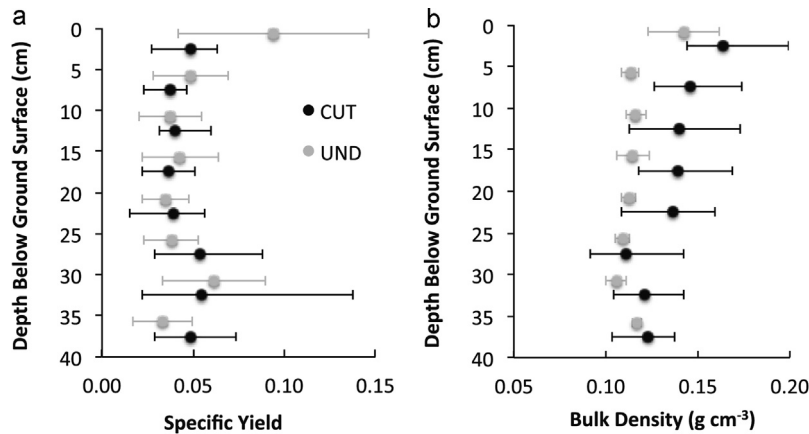


Fig. 7. Specific yield and bulk density for CUT and UND. CUT and UND were sampled at the same depths. CUT depths are the true depths, UND was offset to clearly show range. Error bars represent range.

may have over-estimated *ET* for previous study years when there was a lower water table. Since the water table at CUT was typically within the rooting zone ( $\sim 50$  cm) groundwater still contributed to *ET* (Price et al., 2003) therefore we expect the over-estimation of *ET* to be low-to-negligible. *ET* at UND did not account for tree and shrub transpiration. Van Seters and Price (2001) and Ketcheson and Price (2011) used a literature derived  $\alpha$  value of 1.07 to account for *ET* in a treed section at nearby Cacouna bog,  $\sim 100$  km east of BSF. Assuming  $\alpha$  of 1.07 at UND the seasonal *ET* totals become 208, 273, and 259 mm for 2008, 2010, and 2011, respectively. Had these values been used in the water budget then the residual term at UND for 2008, 2009 and 2011 would be  $-3$ , 102 and 69, respectively representing an error of 1%, 63% and 38%, respectively. The higher estimates of *ET* seem more probable given the strongly declining water table in 2010, as well as 2008 before the large rain event ( $\sim 80$  mm near the end of the season); the large water losses can only be explained by high *ET* losses.

There are other mechanisms that help to explain the difference in hydrological regime between UND and CUT. Ketcheson et al. (2012) examined snowpack conditions at the cutover and undrained sections of BSF in 2009. High wind speeds over the aerodynamically smooth cutover section caused the median snowpack to be about half that of the adjacent undrained section before the beginning of snowmelt. Furthermore, reduced snow pack depth has been linked to an increased frost depth (Groffman et al., 2001, 2006), suggesting deeper ground penetration of the frost layer at CUT. The frozen ground reduces the capacity for local water storage, thus encouraging runoff (Ketcheson et al., 2012), if it were not for the bunds constructed in fall 2009.

## 6. Conclusion

Rewetting Bic-Saint-Fabien has resulted in a significantly higher water table, yet differences in water table position remain within the cutover area. Peripheral locales generally remained drier than the interior after restoration; however, some peripheral locales had more available water. Given the complex variability in the distribution of water across the cutover region we suggest that the plant reestablishment program should be tailored to local conditions within the site, and not a general prescription that will be ineffective in less suitable areas. The water budget was done from late spring to summer, excluding the snowmelt period. There were no notable changes in measured water budget components following rewetting (excluding *P*), for the given water budget period. More direct hydrological measurements (water table,  $\theta_v$ ,  $\psi$ ) better

quantify the impact of rewetting through comparison with pre-rewetting periods and with the adjacent undisturbed section. Such metrics suggest that hydrological conditions at Bic-Saint-Fabien have significantly improved and should facilitate the establishment and growth of fen vegetation, return to a carbon accumulating system and possibly transition into a more ombrotrophic system.

## Acknowledgements

Funding was provided by Natural Sciences and Engineering Council of Canada (NSERC) and the peat industry through Dr. Line Rochefort's NSERC/Industrial Chair in Peatland Management, and from J. Price's NSERC Discovery Grant. We thank Sarah Scarlett for her assistance in the field and are also grateful to Joseph Lance, Tyler Lister, Colin McCarter and Evie Sararas for data collection. We gratefully acknowledge Roxane Andersen for her assistance with methods.

## References

- Bellisario, L.M., Bubier, J.L., Moore, T.R., Chanton, J.P., 1999. Controls of  $\text{CH}_4$  emissions from a northern peatland. *Global Biogeochem. Cycles* 13, 81–91.
- Bérubé, V., Rochefort, L., Lavoie, C., Poulin, M., Price, J.S., Strack, M., Waddington, M., Boismenu, C., 2009. Ecological restoration of a minerotrophic peatland in Canada. *Peatlands Int.*, 36–39.
- Busby, J.R., Whitfield, W.A., 1977. Water potential, water content and net assimilation of some boreal forest bryophytes. *Can. J. Bot.* 56, 1551–1558.
- Campbell, D.R., Duthie, H.C., Warner, B.G., 1997. Post-glacial development of a kettle-hole peatland in southern Ontario. *Ecoscience* 4, 404–418.
- Campeau, S., Rochefort, L., Price, J.S., 2004. On the use of shallow basins to restore cutover peatlands: plant establishment. *Restor. Ecol.* 12, 471–482.
- Cobbaert, D., Rochefort, L., Price, J.S., 2004. Experimental restoration of a fen plant community after peat mining. *Appl. Veg. Sci.* 7, 209–220.
- Cooper, D.J., MacDonald, L.H., Wenger, S., Woods, S., 1998. Hydrologic restoration of a fen in Rocky Mountain National Park, Colorado. *Wetlands* 18, 335–345.
- Cooper, D.J., MacDonald, L.H., 2000. Restoring the vegetation of mined peatlands in the Southern Rocky Mountains of Colorado, USA. *Restor. Ecol.* 8, 103–111.
- Daigle, J., Gautreau-Daigle, H., 2001. Sustaining Wetlands Issues Paper, No. 2001-1. North American Wetlands Conservation Council, Ottawa, Ontario, Canada.
- Damman, A., 1979. Geographic patterns in peatland development in eastern North America. In: *Proceeding of the Symposium of the International Peat Society, Hyytiala, Finland*.
- Dempster, A., Ellis, P., Wright, B., Stone, M., Price, J.S., 2006. Hydrogeological evaluation of a southern Ontario kettle hole peatland and its linkage to a regional aquifer. *Wetlands* 26, 49–56.
- Dionne, J.C., 1977. La mer de Goldthwait au Québec. *Géogr. Phys. Quater.* 31, 61–80.
- Environment Canada, 2011. National Climate Data and Information Archive. Canadian Climate Normals 1971–2000. Retrieved from: [www.climate.weatheroffice.gc.ca/climate\\_normals/results\\_e.html?stnID=5836&prov=e&lang=e&Code=1&dispBack=1&StationName=Rimouski&SearchType=Contains&province=ALL&provBut=&month1=0&month2=12](http://www.climate.weatheroffice.gc.ca/climate_normals/results_e.html?stnID=5836&prov=e&lang=e&Code=1&dispBack=1&StationName=Rimouski&SearchType=Contains&province=ALL&provBut=&month1=0&month2=12) (accessed 15.05.12).
- Fortin, D., Belzile, L., 1996. Le parc du Bic. Trécaré, Saint-Laurent, pp. 89.

- Government of Quebec, 2012. Quebec. Geology, Retrieved from: <http://www.gouv.qc.ca/portail/quebec/pgs/commun/portrait/geographie/geologie/?lang=en> (accessed 08.07.12).
- Graf, M.D., Rochefort, L., 2008. Techniques for restoring fen vegetation on cut-away peatlands in North America. *Appl. Veg. Sci.* 11, 521–528.
- Graf, M.D., Rochefort, L., Poulin, M., 2008. Spontaneous revegetation of cutaway peatlands of North America. *Wetlands* 28, 28–39.
- Graf, M.D., Rochefort, L., 2010. Moss regeneration for fen restoration: field and greenhouse experiments. *Restor. Ecol.* 18, 121–130.
- Greenup, A.L., Bradford, M.A., McNamara, N.P., Ineson, P., Lee, J.A., 2000. The role of *Eriophorum vaginatum* in CH<sub>4</sub> flux from an ombrotrophic peatland. *Plant Soil* 227, 265–272.
- Groeneveld, E., (M.Sc. Thesis) 2002. Le polytrichum strictum comme stabilisateur de substrat et plant compagne pour les sphaignes dans la restauration des tourbières exploitées par aspirateur. Département de Phytologie, Université Laval, Sainte-Foy, Québec, Canada.
- Groeneveld, E., Rochefort, L., 2005. *Polytrichum strictum* as a solution to frost heaving in disturbed ecosystems: a case study with milled peatlands. *Restor. Ecol.* 13, 74–82.
- Groffman, P.M., Driscoll, C.T., Fahey, T.J., Hardy, J.P., Fitzhugh, R.D., Tierney, G.L., 2001. Colder soils in a warmer world: a snow manipulation study in a northern hardwood forest ecosystem. *Biogeochemistry* 56, 135–150.
- Groffman, P.M., Hardy, J.P., Driscoll, C.T., Fahey, T.J., 2006. Snow depth, soil freezing, and fluxes of carbon dioxide, nitrous oxide and methane in a northern hardwood forest. *Global Change Biol.* 12, 1748–1760.
- Hvorslev, M.J., 1951. Time Lag and Soil Permeability in Groundwater Observations, Waterways Experimental Station Bulletin 36. US Army Corps of Engineers, Vicksburg, MS.
- Kellner, E., Lundin, L.C., 2001. Calibration of time domain reflectometry for water content in peat soil. *Nord. Hydrol.* 32, 315–332.
- Ketcheson, S.J., Price, J.S., 2011. The impact of peatland restoration on the site hydrology of an abandoned block-cut bog. *Wetlands* 31, 1263–1275.
- Ketcheson, S.J., Whittington, P.N., Price, J.S., 2012. The effect of peatland harvesting on snow accumulation, ablation and snow surface energy balance. *Hydrol. Process.*, <http://dx.doi.org/10.1002/hyp.9325>.
- Keys, D., 1992. Canadian Peat Harvesting and the Environment, Sustaining Wetlands Issues Paper. North American Wetlands Conservation Council, Ottawa, Canada.
- Kuhry, P., Nicholson, B.J., Gignac, L., Vitt, D.H., Bayley, S.E., 1993. Development of *Sphagnum*-dominated peatlands in boreal continental Canada. *Can. J. Bot.* 71, 10–22.
- Mahmood, Md., Strack, M., 2011. Methane dynamics of recolonized cutover minerotrophic peatland: implications for restoration. *Ecol. Eng.* 37, 1859–1868.
- McCarter, C., Price, J.S., 2013. The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post restoration. *Ecol. Eng.*, <http://dx.doi.org/10.1016/j.ecoleng.2013.02.003> (in press).
- Mulqueen, J., 1989. Hydrology and drainage of peatland. *Environ. Geol. Water Sci.* 9, 15–22.
- Nicholson, B.J., Vitt, D.H., 1990. The paleoecology of a peatland complex in continental western Canada. *Can. J. Bot.* 68, 121–138.
- Nykanen, H., Silvola, J., Alm, J., Martikainen, P.J., 1995. Emissions of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> from a virgin fen and a fen drained for grassland in Finland. *J. Biogeogr.* 22, 351–357.
- Price, J.S., 1996. Hydrology and microclimate of a partly restored cutover bog, Quebec. *Hydrol. Process.* 10, 1263–1272.
- Price, J.S., 1997. Soil moisture, water tension, and water table relationships in a managed cutover bog. *J. Hydrol.* 202, 21–32.
- Price, J.S., Heathwaite, A.L., Baird, A.J., 2003. Hydrological processes in abandoned and restored peatlands: an overview of management approaches. *Wetl. Ecol. Manag.* 11, 65–83.
- Price, J.S., Rochefort, L., Quinty, F., 1998. Energy and Moisture considerations on cutover peatlands: surface microtopography, mulch cover, and *Sphagnum* regeneration. *Ecol. Eng.* 10, 293–312.
- Price, J.S., Schlotzhauer, S.M., 1999. Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland. *Hydrol. Process.* 13, 2591–2601.
- Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Weather Rev.* 100, 81–92.
- Quinty, F., Rochefort, L., 2003. Peatland Restoration Guide, 2nd ed. Université Laval, Québec, Canada.
- Rochefort, L., Quinty, F., Campeau, S., Johnson, K., Malterer, T., 2003. North American approach to the restoration of *Sphagnum* dominated peatlands. *Wetl. Ecol. Manag.* 11, 3–20.
- Schothorst, C.J., 1977. Subsidence of low moor peat soil in the western Netherlands. *Geoderma* 17, 265–291.
- Schouwenaars, J.M., 1993. Hydrological differences between bogs and bog relicts as consequences for bog restoration. *Hydrobiologia* 265, 217–224.
- Schutz, H., Schröder, P., Rennenberg, H., 1991. Regulation of methane flux to the atmosphere. In: Sharkey, T.D., Holland, E.A., Mooney, H.A. (Eds.), Trace Gas Emissions by Plants. Academic, San Diego, CA, pp. 29–63.
- Shantz, M.A., Price, J.S., 2006a. Characterization of surface storage and runoff patterns following peatland restoration, Quebec, Canada. *Hydrol. Process.* 30, 3799–3814.
- Shantz, M.A., Price, J.S., 2006b. Hydrological changes following restoration of the Bois-des-Bel peatland, Québec, 1999–2002. *J. Hydrol.* 331, 543–553.
- Spieksma, J.F.M., 1999. Changes in the discharge pattern of a cutover raised bog during rewetting. *Hydrol. Process.* 13, 1233–1246.
- Stewart, R.B., Rouse, W.R., 1976. Simple models for calculating evaporation from dry and wet tundra surfaces. *Arctic Alpine Res.*, 263–274.
- Strack, M., Waddington, J.M., Tuittila, E.S., 2004. Effect of water table drawdown on northern peatland methane dynamics: implications for climate change. *Global Biogeochem. Cycles* 18, GB4003, <http://dx.doi.org/10.1029/2003GB002209>.
- Tarnocai, C., 2006. The effect of climate change on carbon in Canadian peatlands. *Global Planet. Change* 53, 222–232.
- Van Seters, T.E., Price, J.S., 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Quebec. *Hydrol. Process.* 15, 233–248.
- Waddington, J.M., Price, J.S., 2001. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Phys. Geogr.* 21, 433–451.
- Waddington, J.M., Strack, M., Greenwood, M.J., 2010. Toward restoring the net carbon sink function of degraded peatlands: short term response in CO<sub>2</sub> exchange to ecosystem-scale restoration. *J. Geophys. Res.* 11, 5, <http://dx.doi.org/10.1029/2009JG001090>.
- Zoltai, S.C., Vitt, D.H., 1995. Canadian wetlands: environmental gradients and classification. *Vegetatio* 118, 131–137.