

Fen restoration on a bog cut down to sedge peat: A hydrological assessment of rewetting and the impact of a subsurface gyttja layer

by

Shannon Malloy

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Vacuum harvested peatlands do not easily regain their hydrological function after peat production therefore restoration is required to create hydrological conditions appropriate for the growth of peat producing fen plant species. Peat extraction at Bic-Saint-Fabien peatland by the block-cut method began in 1946, converted to vacuum harvesting in the early 1970's and ceased in 2000. After exploitation, about 0.04-1 m of residual minerotrophic sedge peat remained; therefore Bic-Saint-Fabien was restored as a fen. Research occurred in 2008-2011 and restoration began fall 2009 so we have two pre-restoration and two post-restoration study years. Rewetting consisted of blocking active drainage ditches, contouring the peat surface into level terraces to even out elevation differences, and building peat ridges (bunds) to retain runoff. Vegetation was introduced to some recontoured parts of the site by the surface layer transfer method. A straw mulch treatment was applied to minimize evapotranspiration. A water budget was created for the harvested cutover area and an adjacent undisturbed section of Bic-Saint-Fabien for all study years. Data collection for the water budget occurred June 2-August 7 (day of year 153-219). Water table, volumetric soil moisture content and soil-water pressure were also examined to better understand the impact of reconfiguration on the hydrology of the system. A 1-1.5 m thick layer of gyttja (a low permeability, high porosity lake-bed sediment) underlies the residual peat; it was parameterized and assessed to see if it could potentially compress and supply water to the overlying peat when the system is stressed. In 2011, the volumetric moisture content and thickness of gyttja were monitored in the field to estimate the strain placed on the gyttja by seasonal water table variability. Gyttja samples were collected and brought back to the laboratory for parameterization and compressibility tests.

A water budget was completed annually for the cutover and undisturbed areas of the peatland. There were no distinguishable differences between study years except that 2008 and 2009 were climatologically wetter. During the water budget period surface and groundwater run-on into the cutover area were negligible making precipitation the principle water input. The dominant water loss from the cutover area was evapotranspiration since runoff was only 2 and 9 mm in 2010 and 2011, respectively. Rewetting did not result in a uniform wetness across the cutover site chiefly due to local differences in peat surface elevation. An interior section of Bic-Saint-Fabien remained saturated for nearly all of 2011; it had mean seasonal water table of +2.8

cm, and volumetric soil moisture content and soil-water pressure, 5 cm below the peat surface were 86% and +4 mbar. At a peripheral section (~100 m away) the values were -14.4 cm, 67% and -13 mbar, respectively. While the interior was generally wetter than the peripheral regions, there were some exceptions, notably near where dams were installed on peripheral drainage ditches. The markedly different spatial patterns of wetness suggests that a uniform prescription regarding vegetation re-establishment in the rewetted section may not be warranted.

The bulk density, particle density and porosity of gyttja averaged 0.12 g cm^{-3} , 1.57 g cm^{-3} and 92%, in the top 40 cm of the layer. The organic matter content of gyttja decreased with depth from about 70% at a 5 cm depth to 45% at a 45 cm depth. Laboratory compression tests showed 9 and 72% total strain at effective stresses of 3.5 and 200 kPa, respectively, demonstrating the potential for releasing water upon compression, which in the field is caused by water table lowering. From day of year 192 to 202 in 2011, when a ~8 cm water level change occurred (effective stress range ~0.8 kPa), the volumetric moisture content and thickness of the top 30 cm of gyttja decreased by 0.4%, and 0.5 cm, respectively, representing 0.1% and 1.7% strain, respectively, as determined from these two different approaches. The compression of gyttja after Bic-Saint-Fabien was rewetted (2011) was small but might have been significant under drier conditions with greater water table variability, such as during the early stages of site drainage when it was being prepared for peat extraction or after peat production ceased. The release of water to the peat layer from the compression of gyttja after peat production finished and before rewetting occurred, might have been an important self-preservation mechanism, eventually making it easier to rewet. Water table drawdown in 2011 produced very small strain rates suggesting gyttja compression in this year had no important role; hence rewetting success was more reliant on other rewetting techniques implemented at this site.

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1.0 Introduction

Peat harvesting for horticultural materials in Canada is very regionalized and most production occurs in New Brunswick and Québec (Daigle & Daigle, 2001). Since the early 1970's vacuum harvesting has been the common method of peat extraction. Vacuum harvesting is more efficient, yet causes larger disturbances than the older block-cut method. Peat harvesting involves intentionally lowering the water table and the removal of peat, leaving a residual peat layer of variable thickness. Exploited peatlands have a reduced storativity because they comprise more decomposed peat with smaller pore spaces; they have a lower specific yield than undisturbed peatlands (Schlotzhauer and Price, 1999; Price, 2003). The deeper (Price, 1996; 1997) and more variable (Schouwenaars, 1993) water table after peat harvesting activity causes more subsidence (shrinkage, oxidation and compression), which further reduces the pore size (Hobbs, 1986), specific yield (Price, 1996; Van Seters and Price, 2002) and thus, storativity. Lower soil-water pressures (Price, 1997) and soil moisture contents (Price and Whitehead; 2001) in the cutover peat also occur after drainage. These harsh hydrological conditions deter peat-forming bryophytes from colonizing the peat surface (Campeau et al., 2004).

In North America, restoration techniques (Quinty and Rochefort, 2003; Rochefort et al., 2003) have been developed (moss layer and straw mulch transfer, ditch blocking, etc.) to restore the ombrotrophic conditions of bog ecosystems. Such techniques have been practiced at a large-scale and monitored (Shantz and Price, 2006a, 2006b; McCarter and Price, in press) in bog systems. Minerotrophic conditions can exist post-harvesting because the lower peat surface after harvesting allows nutrient rich water to access the disturbed regions and enrich the residual peat; peat removal can also expose minerotrophic peat. In such cases it may not be appropriate to try to restore to a *Sphagnum* dominated system (Wind-Mulder and Vitt, 2005). Fens are differentiated from bogs based on their water inputs, geochemistry and vegetation communities. Fens have a wider range of hydrogeochemical conditions, generally more base-rich and vegetation community type, which complicates restoration. European fen restoration techniques typically aim to create managed semi-natural areas, so are not appropriate for North American goals of restoring natural fen functions (Graf and Rochefort, 2008).

Some research exists in North America pertaining to fen restoration (Cobbaert et al., 2004; Cooper et al., 1998; Cooper and MacDonald, 2000, 2002; Graf and Rochefort, 2008, 2010; Graf et al., 2008) however much of it is at the plot scale. Plot-scale studies have begun to link hydrological conditions to target plant growth. For *Tomenthypnum nitens*, a brown moss commonly found in fen systems, Busby and Whitfield (1977) established growth did not require fully saturated conditions and most growth occurred when the water table was ~10 cm below the peat surface. Little growth of *Tomenthypnum nitens* occurs when the water table drops 40 cm below the peat surface (Graf and Rochefort, 2008). Restoration techniques (surface layer transfer and straw mulch applications) are also effective at increasing the richness of target fen species (Cobbaert et al., 2004). Cooper et al. (1998) established that blocking drainage ditches in a fen drained for agriculture was effective at raising and reducing the variability of the water table; however, we do not know if restoration techniques are effective at restoring natural fen conditions in vacuum harvested peatlands.

Peat harvesting can leave very little residual peat therefore the hydrological connection to underlying geology becomes more important. High porosity, saturated clay and gyttja soils can exist under residual peat and could undergo compression (Price, 2003) and release water to the overlying peat, possibly ameliorating the harsh hydrological conditions, aiding restoration. Gyttja is a lake-bed sediment that accumulates underwater by the deposition of materials (dead planktonic organisms and inorganic particles) suspended in the water column (Hansen, 1959) that can infill aquatic systems and be terrestrialized by a covering peat layer (Rydin & Jeglum, 2006, Łachacz et al., 2009, Dempster et al., 2006 and Campbell et al., 1997). Research has previously been done in rewetted peatlands where a gyttja layer exists (Kieckbusch et al., 2006; Kieckbusch & Schrautzer, 2007; Tiemeyer et al., 2006); however gyttja was considered to be impermeable due to its low hydraulic conductivity, and its potential to compress and release water was not considered.

Bic-Saint-Fabien peatland near Rimouski Québec was exploited for horticultural peat from 1946-2000. Vacuum harvesting on an 11 ha section of Bic-Saint-Fabien exposed minerotrophic sedge peat ~0.4-1 m thick and lowered the surface elevation, and allowed for nutrient-rich water to access the site; therefore it was restored as a fen. Restoration at Bic-Saint-Fabien is the first ecosystem scale fen peatland restoration project on a vacuum harvested peatland in Canada.

Restoration began in autumn 2009 following techniques developed for bog restoration but using the surface transfer method with materials collected from a nearby-undisturbed fen. Gyttja soil (1-1.5 m thick) underlies the residual peat at Bic-Saint-Fabien. Little is known about the compressibility and water storage properties of gyttja. We are uncertain of the implications gyttja has on rewetted peatlands. The specific objectives of this project are to:

1. Understand the implications of site reconfiguration on the hydrology of the restored fen system at Bic-Saint-Fabien
2. Quantify the fluxes of the a water budget for an undisturbed and harvested section of Bic-Saint-Fabien peatland before and after rewetting, to identify the main determinants of rewetting success
3. Assess the hydrophysical and mechanical properties of gyttja, and its behaviour under peat harvesting and restoration activity
4. Determine the strength of hydrological connection between gyttja and the overlying peat

1.1 Thesis Organization

This thesis consists of two manuscripts. My contribution was to organize and conduct field research (2010 and 2011) and laboratory experiments. I was also responsible for writing the first edition of both manuscripts. The first manuscript (Fen restoration on a bog harvested down to sedge peat: A hydrological assessment) covers the first two objectives. It examines the response to rewetting of the first ecosystem-scale fen restoration project in Canada. The latter 2 objectives pertaining to gyttja are included in the second manuscript (Influence of gyttja on the hydrological response to rewetting in a fen peatland). This manuscript involves parameterizing and testing the compressibility of gyttja through field and laboratory experiments. This thesis is a comprehensive hydrological assessment of the first vacuum harvested peatland being restored as a fen by the North American peatland restoration approach and provides a detailed examination of gyttja soils.

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

2.1 Outline

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 was moister than peripheral regions. Bic-Saint-Fabien was cut down to minerotrophic sedge peat; therefore it was restored as a fen.

Rewetting began in fall 2009. Hydrological data exist for two years before (2008 and 2009) and two years after (2010 and 2011) rewetting. Note: rewetting was not complete until early in the 2010 study year due to late dam installation in the peripheral drainage network. A water budget was completed annually for the harvested cutover section and an undisturbed section of the peatland. The main differences between study years were that 2008 and 2009 were climatologically wetter. Before-after-control-impact design ANOVA indicated the water table was significantly higher at the cutover area after rewetting (2010 after dam installation+2011) compared to before rewetting (2008+2009). In 2011 a wetness gradient remained evident within the cutover section; 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 +2.8 cm, and volumetric soil moisture content and soil water pressure, measured 5 cm below the surface, of 86% and +4 mbar, respectively, compared to -14.4 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.

2.2 Introduction

In Canada, approximately 160 km² (<0.002%) of the 1.136 million km² 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 & 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 increased load caused by the lower water table compresses 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 and Rochefort, 2005). Without restoration, abandoned peatlands with a deepened water table continue to oxidize for decades and are a source for carbon dioxide to the atmosphere (Nykanen et al., 1995). Carbon dioxide fluxes out of the system can be 300-400% higher post-drainage (Nykanen et al., 1995; Waddington and Price, 2001).

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 run off 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, 2006b; McCarter and Price, in press). 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).

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, 2002; Graf and Rochefort, 2008, 2010; Graf et al., 2008). 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). 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). In a fen drained for agriculture, ditch blocking was effective raising and stabilizing the water table, yet the water table position remained sensitive to the presence of sufficient precipitation in summer (Cooper et al., 1998).

European restoration techniques are not easily transferable to North American systems largely due to differences in historical uses and restoration goals (Graf and Rochefort, 2008), as well as climate. European fen restoration goals focus on establishing a semi-natural fen system or land reclamation for agriculture, while in North America the goal is more typically to restore natural fen functions (Graf and Rochefort, 2008).

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, with the specific objectives of creating a water budget for an undisturbed and harvested section of the abandoned peatland before and after rewetting understanding 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 and carbon exchanges.

2.3 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 1971-2000) 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 Goldthwaite Sea during the last glaciation (Dionne, 1977). The marine clay sediments and a low permeability gyttja layer (see Ch. 3.0) 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 Québec, 2012; Fortin & 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 1970's 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 (Ch. 3.0). The total cutover area (CUT) is ~11 ha. CUT is composed of 16 drainage ditches and 15 peat fields (Figure 2-1). It was evident that the peat extraction process left the cutover area with topographic elevation differences. The southwest edge of CUT was the least elevated and the surface elevation gently increased towards the northeast across CUT (along transect B) (Figure 2-1). In 2011 there was approximately a 2.5 m difference in surface elevation between peat field 1 and 15 (unpublished 2011 data). 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 a thicker layers of residual peat. 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). The northwest boundary was approximately 1-1.5 m higher than the southeast for the eastern section of the peatland and the saddle-like topography barely evident (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 & Strack, 2011; Bérubé et al., 2009).

Research at BSF occurred from 2008-2011. In fall 2009, peripheral regions at CUT were contoured to flatten out the landscape into a series of terraces (Figure 2-1). Peat ridges (bunds) were constructed to help retain runoff 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 Figure 2-1). However, the only active drainage outlet is to the west, bounded by bund #1 (see Figure 2-1). 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 (Figure 2-1) using the surface layer and straw mulch transfer methods (Rocheffort et al. 2003). Plant material and straw mulch was also applied by hand to a smaller area (0.4 ha) south of bund 2a (Figure 2-1). On June 22, 2010 (day of year 173), 6 dams were installed to raise the water tables along the peripheral drainage network at the north-east margin

of CUT (Figure 2-1). 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 (Figure 2-1) was selected as a reference site; it is dominated by *Thuja occidentalis*, *Larix laricina*, with brown mosses such as *Campyllum stellatum* and *Tomenthypnum nitens* forming the moss carpet (Mahmood & 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).

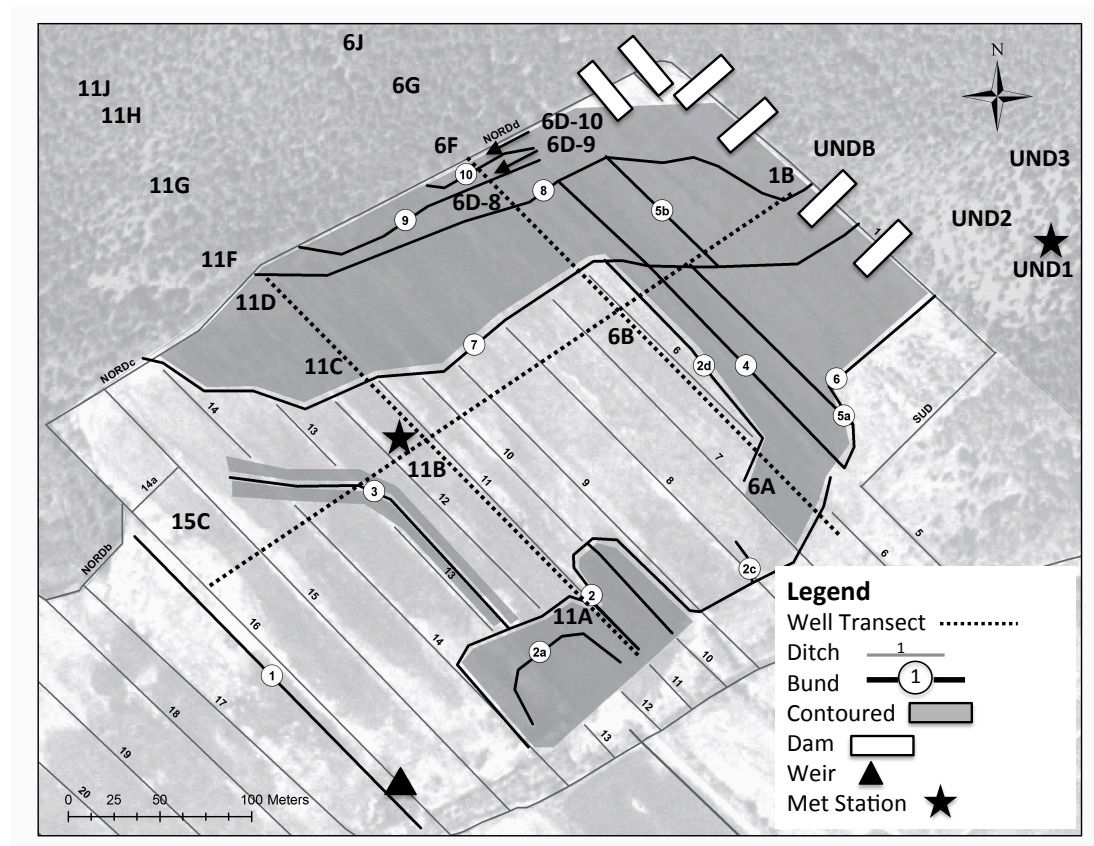


Figure 2-1 Map of Bic-Saint-Fabien.

2.4 Methods

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

2.4.1 Meteorological Conditions

A meteorological station was set up at CUT (11B) and UND (UND1) (Figure 2-1). In 2008 the UND meteorological station was at UND3 (Figure 2-1). Campbell Scientific Inc. (CSI) 10X data loggers measured sensor values at 60-second intervals, averaged, then logged at 20-minute intervals unless otherwise stated. Net radiometers approximately 1 m above the ground surface measured net radiation (Q^* ; REBS Q7.1). Ground heat flux plates were installed approximately 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,

$$ET = \alpha \left(\frac{s}{s+q} \right) \left(\frac{Q^* - Q_g}{L_v \rho} \right), \quad [2-1]$$

where s is the slope of the saturation vapour 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°C), L_v is the latent heat of vapourization (J kg^{-1}), and ρ , which is the density of water (kg m^{-3}). Q^* (J day^{-1}), Q_g (J day^{-1}) and T_a ($^\circ\text{C}$) obtained from each meteorological station in addition to s , q , L_v , and ρ were used to calculate ET . The α 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) (Figure 2-1). The α parameter was determined in 2011, and was used in equation [2-1] 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 (θ_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 θ_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.

2.4.2 Groundwater Flux, Storage Change and Runoff

Polyvinylchloride (PVC) wells (i.d. 2.5 cm; o.d. 3.3 cm) slotted in their entirety were installed to a depth of 1 m at CUT and UND (Figure 2-1; e.g. 11A, 11B, etc.) to monitor water table positions and variability approximately twice weekly. PVC pipes (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 (Figure 2-1; e.g. 11A, 11B, etc.) to measure pressure at said depths and were measured approximately twice weekly. A total of eight horizontal hydraulic conductivity (K) tests were performed on each piezometer from 2008-2011 following the method described by Hvorslev (1951). Lateral 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

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

where ΔS 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 equation 2-2. A Wardenaar sampler was used to cut peat profiles (12 cm x 10 cm x 40 cm) that were analyzed for S_y and bulk density (ρ_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 (Figure 2-1). 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-hour 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 ρ_b .

A v-notch weir installed April 2010 in ditch 16 (see Figure 2-1) 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-minute intervals. A stage-discharge relationship was created to determine total CUT discharge for 2010 and 2011.

2.4.3 Pattern of Rewetting

At CUT, one W-E and two S-N well transects were defined, transect B, transect 11, and transect 6, respectively (Figure 2-1). 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 transect 6 (6A, 6B, 6D) data are only available for post-restoration study years as some 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 Figure 2-1).

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 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 θ_v and soil-water pressure (ψ) were also measured on transect 11 (11B and 11D) and UND1 at 5 cm below the peat surface (Figure 2-1). Time Domain Reflectometry (TDR) probes (CSI TDR100) were used to determine θ_v hourly based on the method of Kellner and Lundin (2001). Tensiometers installed 5 cm below the peat substrate were used to determine ψ and were measured bi-weekly with a TensicorderTM pressure transducer (Soil Measurement Systems) with 1 mbar sensitivity.

2.5 Results

2.5.1 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 Figure 2-1). 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 Figure 2-1).

The highest water tables at all sites for all years were in response to summer storms (Figure 2-2). The water table at CUT was significantly ($p < 0.05$) higher after rewetting. The mean water table difference between CUT and UND before and after rewetting (2010 after dam installation+2011) was 17.1 and 0.8 cm, respectively (Table 2-1). The mean water tables at CUT in 2008-2011 were -33.1, -22.6, -21.8, and -8.0 cm, respectively and -13.0, -8.0, -15.3 and -9.1 cm, respectively at UND (Table 2-1). The mean daily water table position at CUT was significantly ($p < 0.05$) lower than UND in 2008 and 2009 based on 27, and 31 measurements, respectively (Table 2-1). It was not significantly different than UND in 2010 and 2011 from 11

and 21 measurements, respectively ($p=0.13$ and 0.44 , respectively) even though CUT was not completely rewet until the dams were installed in 2010 (Table 2-1).

Table 2-1 BACI design ANOVA comparing before and after rewetting study periods and ANOVA comparing the water table at CUT and UND annually. Note: * indicates not significant.

		Sample Size	Mean	Variance	P Value
Before Rewetting		57	17.1	84.9	0.00
After Rewetting		28	0.8	22.1	
2008	CUT	27	-33.1	135.0	0.00
	UND	27	-13.0	20.6	
2009	CUT	31	-22.6	146.7	0.00
	UND	31	-8.0	7.0	
2010	CUT	11	-21.8	115.5	*0.13
	UND	11	-15.3	68.9	
2011	CUT	21	-8.0	30.3	*0.44
	UND	21	-9.1	11.3	

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 (Figure 2-2), 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 (Figure 2-2). The position and range of the water table at CUT (interior) and UND were similar for all years of study (Figure 2-2). 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 -15.1 -10.8 -15.1 and -3.2 cm, respectively and for the peripheral region they were -42.7, -31.6, -26.8 and -11.6 cm, respectively.

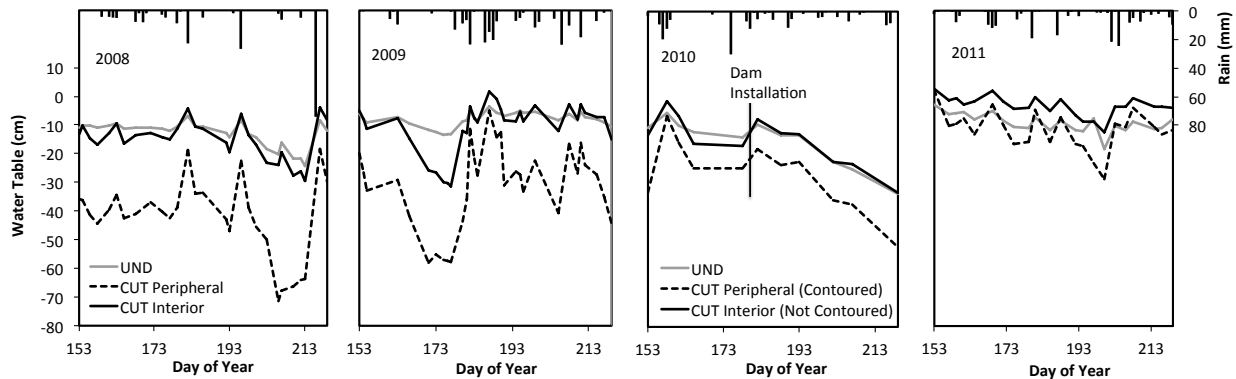


Figure 2-2 Precipitation (recorded at CUT) and mean water table at UND, CUT – Peripheral (11A, 11C, 11D, 1B) and CUT – Interior (15C, 11B, 6B) for all study years.

On transect B the 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 except in 2011 where the mean seasonal water table at 1B was ~1 cm closer to the surface than 6B (Figure 2-3). Transect B had the largest range in water table before rewetting at ~50 cm in 2008 and 2009 (Figure 2-3) largely due to the low water table at 1B, which was -59.5 and -51.9 cm, in 2008 and 2009 respectively (Figure 2-3). 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 20 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 -12.0 and +2.8 cm. At 11D it was -30.4 and -14.4 cm, respectively (Figure 2-3).

The surface elevation with water tables on transects 11 and 6 for 2011 is illustrated in Figure 2-4. The remnant saddle-like topography remained evident on transect 11 and was less obvious on transect 6. The change in surface elevation was greatest on transect 6. 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 (Figure 2-4). 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 (Figure 2-1). 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 (Figure 2-1).

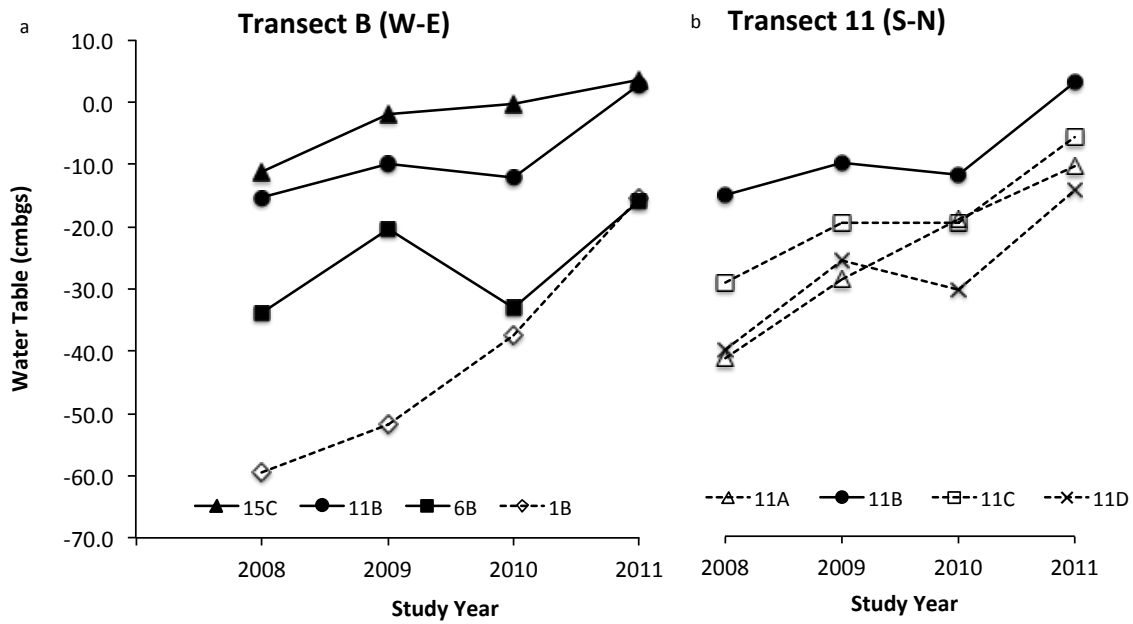


Figure 2-3 Mean seasonal water tables on transect B and transect 11. Note: Dashed lines with open symbols represent peripheral wells.

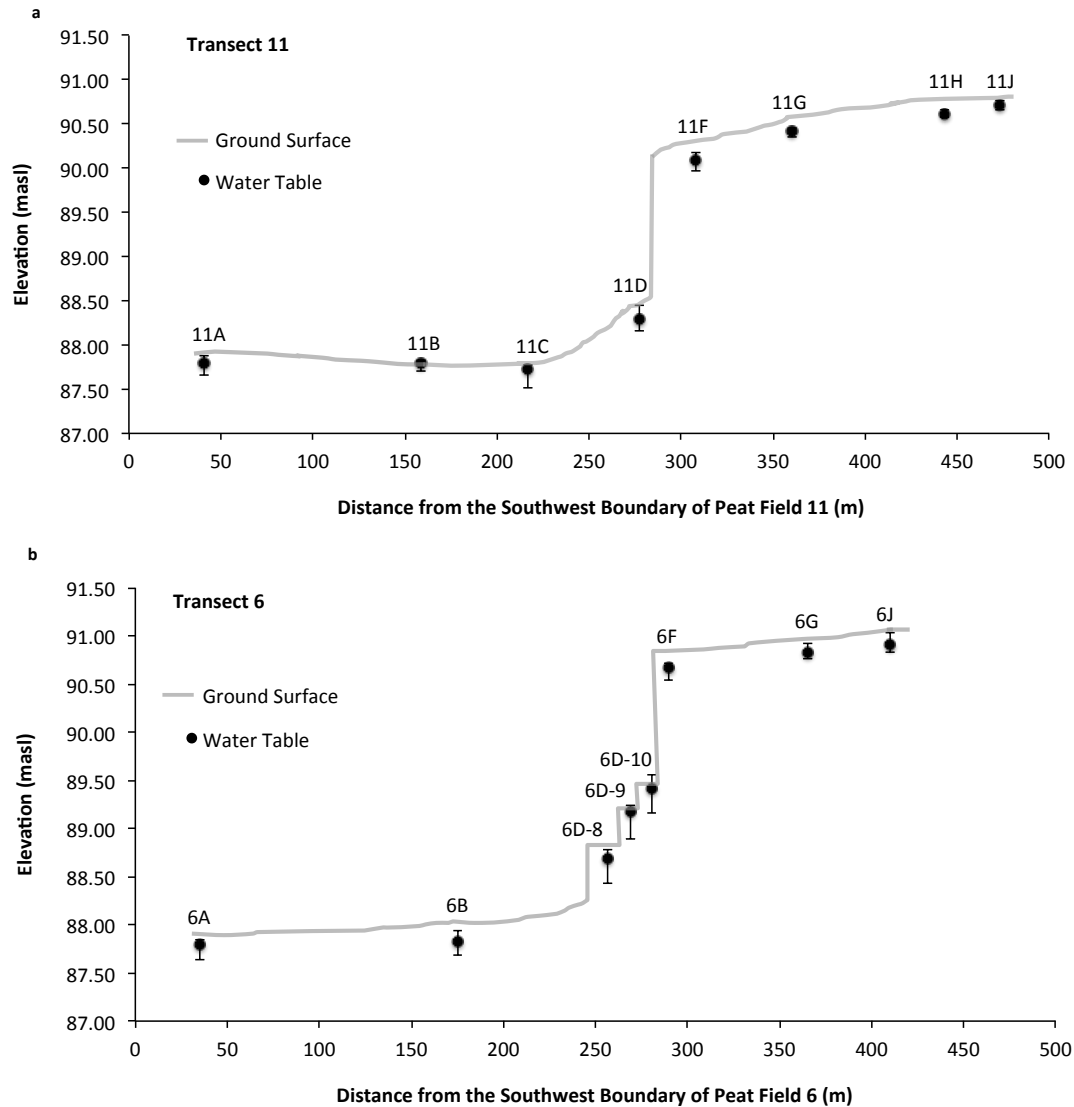


Figure 2-4 2011 surface elevation and water table for transect 11 and transect 6. Error bars represent range.

The average θ_v at CUT measured 5 cm below the peat surface at 11B and 11D in 2011 was 85.8 and 67.0%, respectively (Figure 2-5a) and ψ was +4 and -13 mbar, respectively (Figure 2-5b). In 2011 the average θ_v and ψ at UND (Figure 2-5) was 89.9% and -3 mbar, respectively. UND θ_v data were sporadic due to in-field power supply issues.

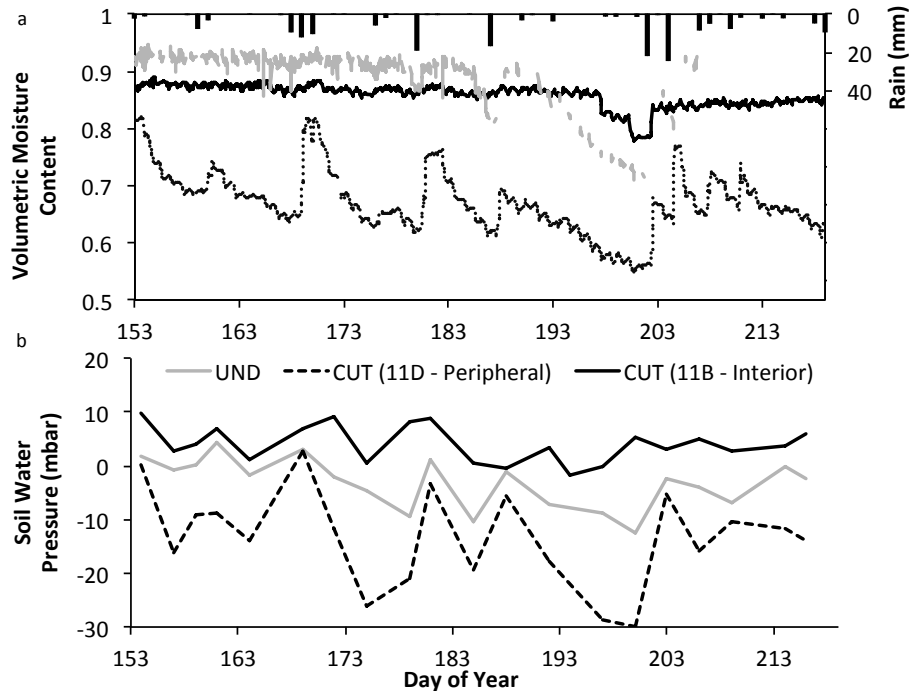


Figure 2-5 Volumetric soil moisture and soil-water pressure 5cm below the peat surface in 2011. CUT interior is 11B and CUT peripheral is 11D.

2.5.2 Water Budget

The annual data sets span June 2-August 7 (day of year 153-219), 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, 204, 243, 174 and 199 mm of rainfall, respectfully, were recorded at CUT meteorological station. In comparison there was 207, 224, 164 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 (DOY 143-152).

Since our study period is after snowmelt, run-on to CUT was negligible. An 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 (Figure 2-6) representing 1 and 5% of ET .

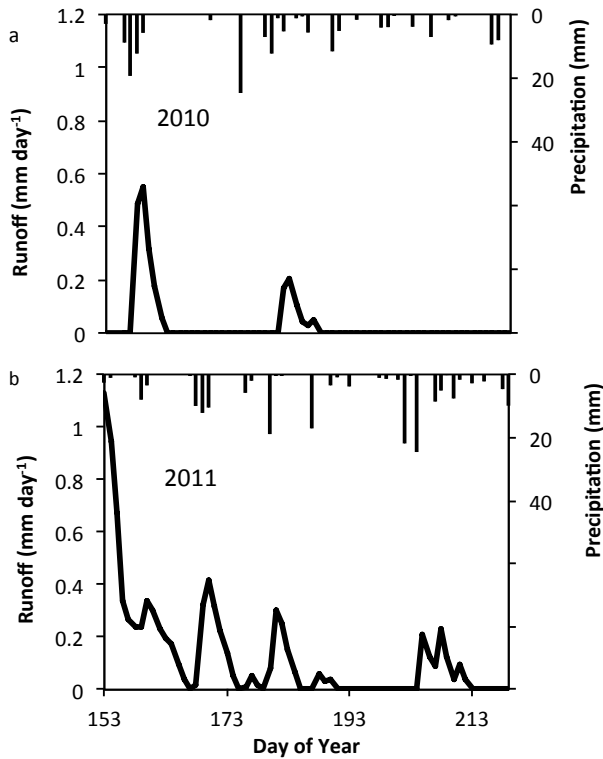


Figure 2-6 CUT runoff in 2010 and 2011.

The continuous clay base, $K \sim 0.02 \text{ cm day}^{-1}$, and low permeability gyttja layer, $K \sim 0.06 \text{ cm d}^{-1}$ (Ch. 3.0), restrict groundwater exchanges with the regional aquifer. The average four-season K for the 0.75 and 1.5 m piezometers at CUT were 0.1 and 0.07 cm day^{-1} , respectively (alternatively, at UND it was 34.6 and 3.5 cm day^{-1} , respectively). Most 0.75 and all 1.5 m 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 marginal ditches 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, totaled $< 1 \text{ mm}$ for every study year (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 (Figure 2-4). Seepage

losses into ditch 16 are accounted for by run-off. Run-on, run-off 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 α 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 2-2), all relationships having R^2 values ≥ 0.83 . The daily average *ET* rates at CUT for 2008-2011 were 2.6, 3.3, 2.9, and 2.9 mm day⁻¹, respectively, with seasonal totals being 174, 220, 193 and 193 mm, respectively (Table 2-3). At UND in 2008, 2010, and 2011, the daily average *ET* rates for sedge/moss were 1.4, 1.8, and 1.7 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 (Figure 2-1). Since the water budget is based on our measurements, we do not include an estimate of *ET* from trees/shrubs at this point, but consider it later in the Discussion section.

Table 2-2 Alpha values derived in 2011 based on 8 measurement periods at each site.

Location	Lysimeter	Water Table (cm)	Alpha	R ²
CUT	11A	-10.7	1.1	0.96
	11B	+2.8	0.6	0.83
	11C	-6.0	0.7	0.93
	11D	-14.4	1.0	0.93
	6B	-16.0	1.0	0.87
	Average	-8.9	0.9	0.90
UND	UND1	-5.4	0.4	0.84
	UND2	-6.2	0.5	0.88
	Average	-5.8	0.5	0.86

Changes in storage were mainly due to water table fluctuation since changes in θ_v and aquifer thickness (see Ch. 3.0) 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⁻³, respectively at CUT (Figure 2-7). At UND it was 0.049 and 0.13 g cm⁻³, respectively (Figure 2-7). Water storage changes for

2008-2011 calculated using equation [2-2], using the mean specific yield for the depth where the change in water table position occurred. These values at CUT were +3, -2, -10, and -5 mm, respectively and 0, -2, -9, and -3 mm, respectively at UND (Table 2-3).

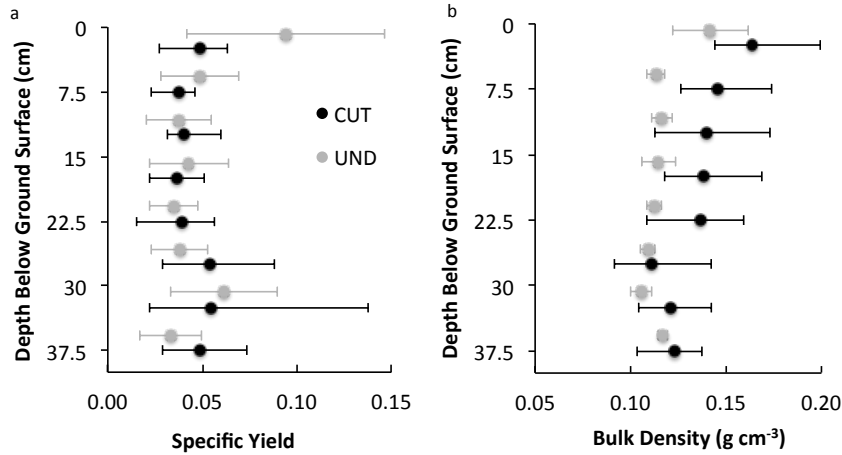


Figure 2-7 Specific yield and bulk density for CUT and UND. CUT and UND were sampled at the same depths. CUT depths are the true depths, UND was offset to clearly show range. Error bars represent range.

The water budget for BSF was calculated as

$$\Delta S = P - R - ET + \varepsilon, \quad [2-3]$$

with ε being the residual error term whose value balances equation 2-3. Seasonal water budgets are summarized in Table 2-3. Error calculated as a percentage of inputs was 13, 10, 6, and 1% for 2008-2011, respectively, at CUT. In contrast error at UND was quite high being 56, 33, and 40%, for 2008, 2010 and 2011, respectively, but the ET term did not account for water loss from trees.

Table 2-3 Water budget. * indicates ET does not account for transpiration from trees.

CUT	ΔS	P	R	ET	ϵ	% Error
2008	+3	204		174	-27	13
2009	-2	243		220	-25	10
2010	-10	174	2	193	11	6
2011	-5	199	9	193	-2	1
UND	ΔS	P	R	*ET	* ϵ	*% Error
2008	0	207		91	-116	56
2009	-2	224				
2010	-9	164		119	-54	33
2011	-3	184		113	-74	40

2.6 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). This can be ameliorated with the use of straw mulch or the establishment of a moss carpet, such as *Polytrichum strictum* (Quinty and Rochefort, 2003). Ponding behind bunds was also evident in spring, particularly behind bunds 8-10 (see Figure 2-1). 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 (Figure 2-3), 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

(Figure 2-3) 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 (Figure 2-3).

On transect 11 the water table at 11B (interior) was 17 cm closer to the peat surface than 11D (peripheral) in 2011 (Figure 2-3). Furthermore, θ , and ψ at 11B were 19% and 17 mbar higher, respectively than at 11D (Figure 2-5). 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 2-3). Water availability ($P - ET$) for the 2008-2011 study periods at CUT was 30, 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 significantly higher (Table 2-1). 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) (Figure 2-6). 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 towards the interior and is reflected by differences in water table depth relative to the surface (Figure 2-3). These discharges were small or negligible during the period of the water budget calculations.

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 ΔS . 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 α values in 2011 (which had the highest water table) 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 (~ -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 α value of 1.07 to account for ET in a treed section at nearby Cacouna bog, ~ 100 km east of BSF. Assuming α 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 -8, 100 and 72, respectively representing an error of 4%, 61% and 39%, 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 (~ 80 mm on August 6; day of year 218); 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 \sim 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.

2.7 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 were moister. 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, θ_v , ψ) 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 and a return to a carbon accumulating system.

Acknowledgements

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3.0 Influence of gyttja on the hydrological response to rewetting in a fen peatland

3.1 Outline

Water availability is a major concern when restoring degraded vacuum harvested peatlands. The seasonal expression of water from the compression of underlying organic deposits may provide a source of water. A bog near Rimouski, Quebec was harvested using the vacuum extraction method and cut down to underlying sedge peat; restoration procedures were implemented in fall 2009. The residual peat layer is 0.4 to 1 m thick, overlying a 1 to 1.5 m thick gyttja deposit. Gyttja is lake bottom sediment high in organic content with low permeability, on which peat sometimes forms. Little is known about gyttja, its water storage properties and the implications this may have on the restoration process, particularly where overlying peat is thin. The upper 40 cm of gyttja had average bulk density, particle density and porosity of 0.12 g cm^{-3} , 1.57 g cm^{-3} and 92%, respectively. The organic matter content of gyttja decreased with depth from about 70 to 45% from 5 to 45 cm below the peat base. Oedometer test results showed 9 and 72% strain at 3.5 and 200 kPa, respectively, demonstrating the potential for releasing water upon compression, which in the field is caused by water table lowering. However, during the year of measurement (2011) the changes in effective stress caused by water table lowering were only about $\sim 0.8 \text{ kPa}$, corresponding to a water table decline of 8 cm. Under these conditions the volumetric moisture content of the top 30 cm of gyttja only decreased by only 0.4%, and we observed 0.5 cm of gyttja deformation; this represents 0.1% and 1.7 % strain, respectively. On the basis of these strains, we conclude that the release of water due to the consolidation of gyttja in 2011 had little impact on rewetting the overlying peat. However, it may be important under drier conditions with a larger seasonal water deficit, and may have been important prior to restoration when larger water table fluctuations were observed.

3.2 Introduction

Gyttja is a term presented by v. Post (1862) and re-introduced by Hansen (1959) as a combination of organic and inorganic materials precipitated from a water column via biochemical processes. It is a soft sediment with gel-like consistency that accumulates underwater by the deposition of suspended materials, and sometimes in-fills aquatic systems. This can eventually terrestrialize through the development of a covering peat layer (Rydin & Jeglum, 2006, Łachacz et al., 2009, Dempster et al., 2006 and Campbell et al., 1997). In a Southern Ontario kettle peatland, Campbell et al. (1997) determined that gyttja was low in carbonates and that its organic content ranged from about 30-80% and generally decreased with depth; basal gyttja typically contained the lowest amount of organic matter. Łachacz et al., (2009) established a range in the organic matter content of 0.19-87.5% and also found that it declined with depth; the calcium carbonate content of gyttja in their study was generally low, yet reached up to 67.5% of dry weight. Rybicki and Zurek-Pysz (1990) showed gyttja consisting of nearly 80% calcium carbonate by mass and only 16.5% organic matter. It is evident that the organic matter content and composition of minerals in gyttja is highly variable, which can result in a large range of mechanical (e.g. compression) and hydrological properties.

Peat extraction for horticultural purposes is common in eastern Canada, specifically in the St. Lawrence lowlands (Keys, 1992). Peatlands are frequently abandoned after exploitation and often have too little residual peat to support the hydrological conditions necessary for natural ecological recovery. Sites that were intentionally drained and vacuum harvested have a hydrological regime that is characterized by a lower water table that is more variable (Price et al., 2003). Ultimately peatland drainage and peat extraction alters the system's ability to store water. The post-drainage landscape is devoid of vegetation cover and the first plants that tend to recolonize are vascular plants rather than peat-forming plants such as *Sphagnum* and brown mosses (Price et al., 2003, Rochefort et al., 2003, Rochefort, 2000) because of the harsh hydrological conditions typical on the relatively decomposed peat (Price and Whitehead, 2004; Price and Ketcheson, 2009).

Drainage can also cause partially reversible and non-reversible changes to the peat structure by subsidence, impairing storativity and water transport within it (Price, 1997; 2003). In peatlands there are three primary components to subsidence: shrinkage, which occurs above

the water table, oxidation which predominately happens above the water table, and compression taking place below the water table (Schothorst, 1977). Only shrinkage and compression are partially reversible. Schothorst (1977) determined that compression of peat layers below the water table represented 35% of total subsidence due to long-term deep drainage. Compression and shrinkage account for greater than 95% of the seasonal soil volume changes where peat-harvesting activity has taken place (Kennedy and Price, 2005); over the long term oxidation may be more important (Schothorst, 1977).

Compression is a mechanical process caused by the changes in effective stress (σ_e) induced by seasonal water table fluctuations. The total stress at a point in the system caused by the weight of the soil (solids, water and air) overlying that point, is expressed as

$$\sigma_T = \rho_T g h , \quad [3-1]$$

where σ_T is total stress (Pa), g is gravitational acceleration (m s^{-2}), ρ_T is the total density of the overlying material (kg m^{-3}) of height, h (m). σ_T is countered by buoyant forces in the soil matrix that are created by high soil-water pressure (ψ) (Terzaghi, 1943), resulting in an effective stress (σ_e) of

$$\sigma_e = \sigma_T - \psi. \quad [3-2]$$

Drainage lowers the water table (ψ decreases) and increases the effective stress on the system, thus the rate and magnitude of subsidence (Hobbs, 1986). Effective stress varies largely due to seasonal changes in the position of the water table. In drained peatlands water table declines of up to 60 cm are common and the associated change in effective stress (σ_e) can thus be up to 6 kPa (Price, 2003). Changes in peat volume due to compression (and shrinkage) can be immediate and synchronous with water-level changes (Price and Schlotzhauer, 1999; Lang 2002). We do not know how the gyttja layer responds to water table fluctuations. Terzaghi (1943) states that a time-lag may be evident in volume change if a soil exhibits both a high compressibility and low-permeability (e.g., gyttja) because changes in the saturated moisture content do not occur rapidly.

The compressibility of gyttja has been assessed from an engineering point of view (foundations) rather than an environmental point of view. Hence, Zurek-Pysz (1992) examined the compressibility of gyttja but the lowest pressure tested (12.5 kPa) was greater than those typically generated by seasonal water table changes in peatlands, although possible for artificial drainage. At 12.5 and 200 kPa the strain experienced was ~5% and 35%, respectively, for detrital calcareous gyttja (Zurek-Pysz, 1992). The extent of mineral content and organic matter can influence the mechanical characteristics of gyttja soils (Becker et al., 2004), the latter being more susceptible to strain (Dingman, 1994).

Several studies exist of rewetting drained peatlands where gyttja is present (Kieckbusch et al., 2006; Kieckbusch & Schrautzer, 2007; Tiemeyer et al., 2006); however, characteristics of the gyttja layer were not assessed and it was just considered to be impermeable. There are several potential mechanisms by which seasonal peat and gyttja compression may enhance site wetness. Compression associated with subsidence of the overlying peat can lower the surface sufficiently to maintain a shallow depth to water table (Whittington and Price, 2006), and water expressed from the consolidating material (e.g. gyttja) can become available for plants, which otherwise may have been unavailable (Hillel, 1998). Recolonization of plants is highly linked to availability of water and the longer a harvested site is left abandoned, hydrological conditions become increasingly hostile, inhibiting moss growth (Kennedy and Price, 2005). To our knowledge, there is no literature linking the impact of a gyttja layer on restoration. To do this it is important to better understand the general characteristics of gyttja, especially how it functions under load, since it is unclear if it deforms sufficiently in response to seasonal variability of the water table, to express water to the overlying peat. The objectives of this research are to assess the hydrophysical and mechanical properties of gyttja, its behaviour under peat harvesting and restoration activity as well as to determine the hydrological connection between gyttja and the overlying peat. Given the dearth of information on gyttja, we also examine its behavior under higher loads than typically occur under hydrologically induced stresses, which is of value to engineering design.

3.3 Study Site

The Bic-Saint-Fabien (BSF) peatland (~20 ha) is approximately 25 km west of Rimouski, Québec (48°19'N, 68°50'W). The average annual temperature and precipitation from 1971-2000 is 3.9°C and 915 mm, respectively, with approximately 30% of the precipitation falling as snow (Environment Canada, 2011). The local geology is Paleozoic with sedimentary rock dominating (Government of Québec, 2012; Fortin & Belzile, 1996). In 1946 BSF was exploited for horticultural peat via the block-cut method; the surface was reprofiled when vacuum harvesting began in the early 1970s. Peat harvesting operations ceased in 2000 with the area harvested totaling ~ 11 ha. Harvesting activity cut down to fen (sedge) peat and left a saddle-like topography with the interior region of the site being slightly depressed with little residual peat (~0.4 m) compared to the higher elevated peripheral regions with upwards of 1 m of residual peat. The elevation differences resulted in a wetness gradient across the site with the lower interior region being wetter than most surrounding peripheral regions. The residual peat overlies a layer of gyttja soil, which ranges between about 1-1.5 m in thickness across the site.

Since the residual peat in BSF was minerotrophic sedge peat, this site is being restored as fen. Site restoration began in fall 2009 and involved the blocking of active drainage ditches, contouring the cutover section to reduce local elevation gradients (i.e. make flatter sections), constructing peat ridges (bunds) to retain runoff and the application of plant material from a donor site and a straw mulch treatment (Quinty & Rochefort, 2003) which reduces evapotranspiration, minimizes diurnal temperature fluctuations, and prevents the erosion of peat by wind (Price et al. 1998).

3.4 Methods

3.4.1 Field

Field data from June 21 to August 10, 2011 (day 172-222) are used in this paper, thus represents post-restoration conditions. Volumetric moisture content (θ_v) in the peat and gyttja were determined at an interior and peripheral site (with 40 and 75 cm of residual peat, respectively). Time Domain Reflectometry (TDR) probes (CSI TDR100) were installed at 5 and 20 cm below the peat surface and 5 and 0-30 cm below the peat base (i.e., in the gyttja). The 0-

30 cm probe was installed vertically to determine average soil moisture content of the profile, all others horizontally. The probes were installed by excavating a small pit to allow access to the peat/gyttja interface, and then the pit was backfilled. The θ_v was determined following the calibration of Kellner and Lundin (2001).

Elevation sensor rods (see Price, 2003) were installed at the interior site to measure the seasonal change in thickness of the gyttja layer. Rods were inserted at the peat-gyttja interface and 20 cm below the interface in gyttja. The reader is directed to Price (2003) for a full methods description, but briefly, wooden dowels are affixed with drywall toggle bolts and pushed down inside a tube to the required depths. The tube is removed and the toggle bolts spring open, fixing them in position. The wooden doweling is graduated above the surface and compared to a stable datum (sight wire) to determine movement. Rebar anchored into the clay substrate was used as a datum to monitor the total peat and gyttja layer movement.

A meteorological station was installed at the interior site to measure climatological variables and was outfitted with a tipping bucket (Texas Electronics, Inc. model TR-525M) to automatically measure precipitation. A manual rain gauge installed 85 cm above the ground surface with an orifice diameter of 10.4 cm was installed nearby to check the tipping bucket data.

Horizontal saturated hydraulic conductivity (K_{sat}) was determined using the method of Hvorslev (1951), based on measurements in polyvinylchloride (PVC) pipes from 2008-2011. The inside diameter, outside diameter and slotted intakes are 2.5, 3.3 and 15 cm, respectively. Pipes were installed 0.75 and 1.5 m below the ground surface into the gyttja layer at both sites. Note: the 0.75 m deep piezometer in the peripheral region is at the peat-gyttja interface, installed mostly in gyttja. A total of eight hydraulic conductivity tests were performed on each piezometer at both sites between June 2008 and June 2011. Wells constructed of PVC pipes (perforated in their entirety) were installed ~1 m below the peat surface to measure the position of the water table.

3.4.2 Laboratory

Samples of gyttja were collected in 2011 at the interior location of BSF and brought back to the laboratory to determine bulk density (ρ_b), particle density (ρ_p), porosity (ϕ), organic matter, fiber content, vertical hydraulic conductivity (K_{sat}) and compressibility. Gyttja samples were acquired by digging a small pit to the peat base and extracted using an oversized syringe-like corer constructed from 50 cm long sections of thin-walled PVC tubing with a 4.5 cm inside diameter. A larger syringe sampler (PVC pipe i.d. 7.5 cm) was used to collect samples for compressibility tests, as they required a larger diameter. Gyttja was more difficult to extract with the larger diameter sampler so only the upper ~25 cm of the gyttja layer could be acquired. A rubber bung fixed to a steel rod fitted snugly inside the piping acted as the plunger. The inside of the PVC pipe was mildly lubricated with a silicone based lubricant to maintain a seal while allowing the plunger to glide while the tube was pushed into the gyttja; the steel rod and plunger being held at a steady position thus creating the level of suction required to extract gyttja samples.

The 4.5 cm gyttja cores were cut into 5 cm segments at the depths indicated below (depths represent the sample mid-point). Vertical K_{sat} and ρ_b were determined every 5 cm for the upper 40 cm of the gyttja layer; ρ_p , ϕ were determined for 10, 20, 30 and 40 cm; organic matter content was determined for 5, 15, 25, and 35 cm; fiber content was determined for 5 and 35 cm. A mean value for all aforementioned parameters at each depth was derived from a sample size of three. Vertical K_{sat} , ρ_b , and ϕ were determined by ASTM standard F1815 (ASTM, 2011). Vertical K_{sat} was determined with Darcy's law by maintaining a constant head at the upper end while collecting the outflow to determine specific discharge. For each sample a geometric mean was obtained from three trials. Samples were oven dried at 80°C (as opposed to 105°C to prevent burning of organic matter) to determine bulk density. Particle density (ρ_p) was determined by inserting a given mass (~ 6 to 9 g) of dried, crushed soil in a graduated cylinder, which was then filled with a measured volume of a wetting fluid (kerosene) to determine sample volume. ρ_b and ρ_p , were used to calculate ϕ as

$$\phi = 1 - \frac{\rho_b}{\rho_p} \quad [3-3]$$

Organic matter and fiber content were determined according to ASTM standards D2974 and D1997, respectively. The amount of organic matter in gyttja was measured using loss on ignition (LOI) tests. Several grams of oven-dried gyttja was placed in a muffle furnace and incinerated at 450 °C for three hours then reweighed to back out the organic matter content. To determine fiber content, gyttja was wet-sieved (number 100 sieve, 150 µm) to wash away fine particulates, leaving the larger fibers. The material caught by the sieve was then incinerated to separate the mineral content and fiber content.

Compression tests were done with an oedometer based on ASTM standard D2435/D2435M (ASTM, 2011) with minor modifications. Compression tests were performed on gyttja from 5, 10 and 20 cm below the peat base, with said depths representing the midpoint of each 19 mm sample (initial sample height). Tests for 5 and 10 cm depths were triplicated and for the 20 cm depth was duplicated. Samples were saturated for several days prior to compression tests ensuring 100% saturation to replicate field conditions; samples were kept saturated for the duration of the experiment. In addition to the standard loads typically tested (6.25, 12.5, 25, 50, 100, and 200 kPa), a load of 3.5 kPa was added to better capture the rate and magnitude of compression that gyttja would experience under field conditions. All other loads were tested despite not being in the range of seasonal water table variations, to be consistent with standard procedure. Also, testing at higher pressures provides insight on stress levels that may have been reached through initial artificial drainage and to better characterize gyttja for other practitioners. Each load was left for approximately 24 hours. The oedometer tests were one-dimensional as the specimen was constrained laterally to prevent lateral deformation. Total strain (ϵ) and void ratio (e) were calculated at the end of each 24-hour load increment. Strain was calculated as

$$\epsilon = \frac{\Delta H}{H_0}, \quad [3-4]$$

where ΔH is change in sample height and H_0 is the initial sample height (19 mm). The height of solids (H_s) and height of voids (H_v) were used to calculate the void ratio as

$$e = \frac{H_v}{H_s} . \quad [3-5]$$

The height of the void spaces was calculated as the difference between the sample height (H) and the height of the solids where

$$H_v = H - H_s . \quad [3-6]$$

The height of the solids remains the same before loading and after unloading and is given as

$$H_s = \frac{M_d}{AG_s\rho_w} , \quad [3-7]$$

where M_d is the dry soil mass respectively, A is the area of the oedometer ring, G_s is the specific gravity of gyttja and ρ_w is the density of water. Compression results were used to create strain vs. effective stress and void ratio vs. log-scale effective stress plots. The amount of water gyttja could release given a specific rate of strain was calculated (thickness of consolidating gyttja multiplied by strain) for the upper 5, 10, 20, and 30 cm of the gyttja layer for effective stresses of 1, 3.5, 6.25 kPa. The strain rates for the given pressures were derived from laboratory consolidation tests. Since consolidation was not tested for 1 kPa, the strain rate was estimated from the strain vs. effective stress curve.

The void ratio vs. log-scale effective stress plot was used to estimate the preconsolidation pressure (P_c). The P_c tells us about the stress history of the soil, as it is maximum load previously experienced, beyond which virgin compression (typically at a higher rate) occurs (Hillel, 1998; Hobbs, 1986). The P_c was estimated following the Casagrande (1936) method (see Figure 3-1a). This method involves visually estimating the point with the smallest curve radius; a line is drawn tangent (line 1) and horizontal (line 2) to this point; the angle created by these lines is bisected (line 3); the straight-line portion of the curve (virgin compression) is extended back (line 4) to intersect the bisector line; the corresponding pressure where these lines intersect is the P_c (Figure 3-1). The recompression (C_r) and virgin compression (C_c) indices were established by determining the slope of the corresponding section of the curve. The slope of the unloading curve (not shown) was used to determine C_r .

Vertical K_{sat} (m min^{-1}) was calculated from compression results for the loads of 3.5, 6.25 and 200 kPa using

$$K_{sat} = C_v m_v \gamma_w. \quad [3-8]$$

C_v is the coefficient of consolidation ($\text{m}^2 \text{min}^{-1}$), γ_w is the specific weight of water (9.81 kN m^{-3} at 20°C), and m_v is the coefficient of volume compressibility ($\text{m}^2 \text{kN}^{-1}$), which is calculated as

$$m_v = \frac{\Delta e}{\Delta \sigma_e} \frac{1}{1+e_o}, \quad [3-9]$$

for each 24-hour load increment. e_o is the initial void ratio for the load increment. Note: 1 kPa is equal to 1 kN m^{-2} . The square root time fitting method (Taylor, 1948) was used to determine C_v using

$$C_v = \frac{T_v H_{dr}^2}{t_{90}}, \quad [3-10]$$

where T_v is a dimensionless time parameter (0.848), H_{dr} for two-way drainage is half the average sample thickness for the load increment; t_{90} is the time at 90% consolidation. The t_{90} parameter is estimated from a settlement vs. square root time curve (see Figure 3-1b). A straight line (line AB) is drawn through the initial straight portion of the curve. A second line (line AC) is drawn where the abscissa is 1.15 times larger than that of line AB. The abscissa of the point where line AC intersects curve is t_{90} . We note the ambiguous nature of estimating t_{90} but this method is a standard curve fitting method and common in literature (Dananaj and Frankovská, 2004; Tai et al., 2008).

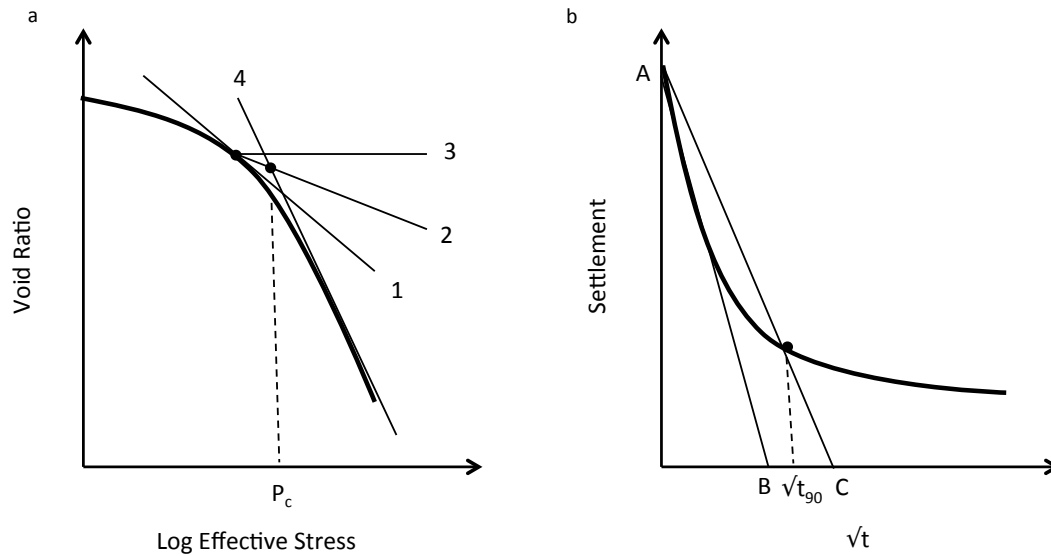


Figure 3-1 Graphical procedures for estimating a) preconsolidation pressure following Casagrande (1936), and b) time of 90% consolidation following Taylor (1948). See text for details.

3.5 Results

Between day of year 172 and 222, 2011, BSF received 159 mm of precipitation compared to the 30-year average of 144 mm for the same period. The study season followed a relatively wet spring with 70 mm of rain falling in the 20 days prior to the start of the study period (day of year 152-171). Four rain events in the study season each totaled over 10 mm. Values obtained by the tipping bucket gauge were within $\pm 9\%$ of the manual rain gauge.

The 40 cm thick peat layer at the interior site was much wetter than the more elevated peripheral site with 75 cm thick peat. The θ_v in the peat was higher and less variable at the interior site (Figure 3-2) than the peripheral site. Variability in θ_v declined with depth below the ground surface at both sites (Figure 3-2). The water table was typically at or just above the ground surface at the interior location and was lower and more variable at the peripheral site, having average seasonal values (\pm standard deviations) of 1.7 (± 3.1) and -15.1 (± 6.7) cm, respectively. Seasonal water-table ranges were ~ 13 and 30 cm at the interior and peripheral sites, respectively (Figure 3-2). The θ_v in the gyttja layer at both locations exhibited negligible short-term variation, as they were both below the water table and remained saturated for the duration of the study season (Figure 3-2). However, a gentle, yet clear seasonal decrease in θ_v

occurred. This trend is more apparent in the drier peripheral region of the site that experienced a greater water table decline (Figure 3-2). At the peripheral region the seasonal decrease in moisture content for the 5 and 0-30 cm gyttja probes was 2.6 and 1.1%, respectively; at the interior site it was 1.8 and 1.7%, respectively.

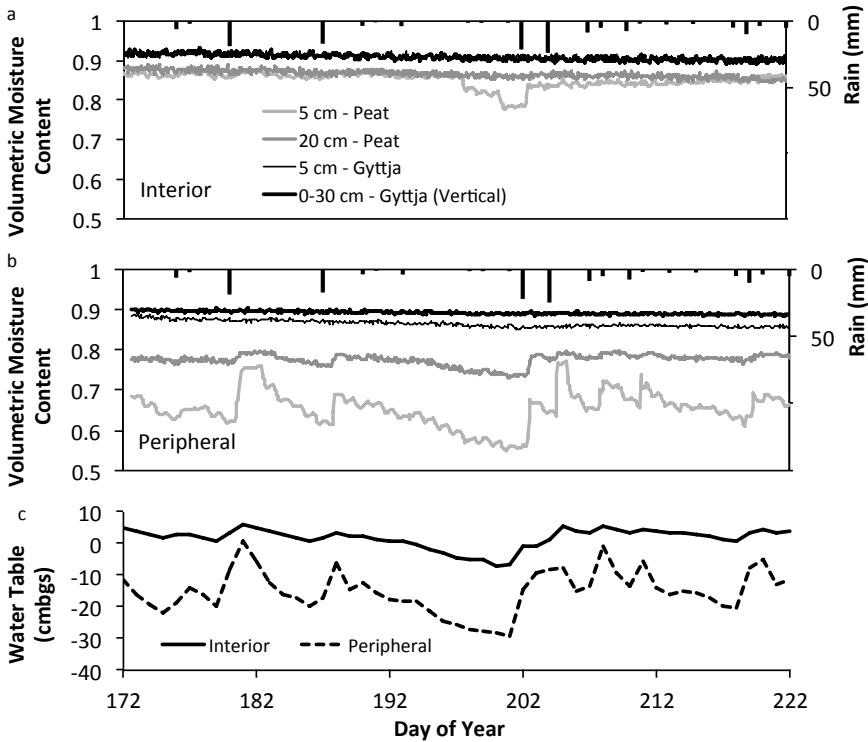


Figure 3-2 Volumetric moisture content and water table for interior and peripheral regions.

The elevation sensor rod measuring the deformation of the gyttja layer (interior site) was relatively static, with a 0.7 cm (+0.2 to -0.5 cm) range in thickness during the study period; the seasonal change in thickness was zero (Figure 3-3). The rod installed 20 cm below the gyttja surface, in gyttja was less mobile and had a seasonal range in movement of 0.3 cm (+0.2 to -1 cm); the seasonal change in thickness measured at this rod was +0.1 cm. Both rods experienced most movement when the water table recessed mid-season (Figure 3-3). In contrast, the range of deformation of the total soil column (i.e. measured at the ground surface) was 2.9 cm, exhibiting a similar but muted trend to that of the water table (Figure 3-3). This means that almost all of the soil volume-change occurred in the peat above the gyttja; strain in the peat was about 5.5% for

the 40 cm thick peat layer, much of this due to shrinkage when it was desaturated on days 192-202 (Figure 3-2c).

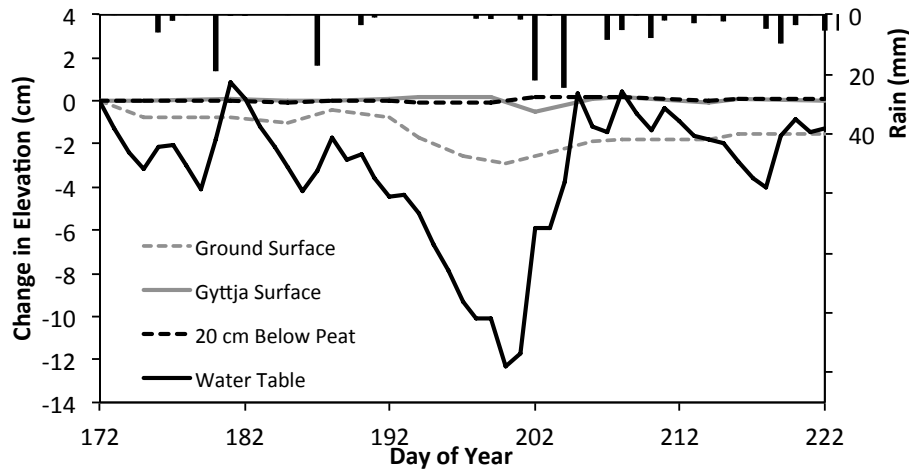


Figure 3-3 Peat and gyttja subsidence and water table movement at the interior site. Initial (day 172) water table was +5 cm.

3.5.1 Gyttja Physical and Hydraulic Properties

The mean ρ_b , ρ_p , and ϕ for the upper 40 cm of the gyttja layer was 0.12 g cm^{-3} , 1.57 g cm^{-3} , 92%, respectively (Table 3-1). A small increase in ρ_p is evident between the upper 10 and 20 cm of the gyttja layer, otherwise it was generally consistent with depth. Organic matter, fiber content both decreased with depth (Table 3-1). The organic matter content (as a proportion of the solids) 5 and 45 cm below the peat base was 70.6% and decreased to 44.8%, respectively. The fiber content was 56.4% and 49.8% at 5 and 35 cm in the gyttja layer. It is thus apparent that gyttja at BSF consists of a mineral component that increases with depth. Little to no calcium carbonate content exists in the upper 40 of the gyttja layer, as no reaction was evident when specimens were submerged in a 2% HCl solution.

Table 3-1 Gyttja properties (mean of 3 samples) Note: *Different cores used for fiber content and hydraulic conductivity and particle density. Hydraulic conductivity was calculated as a geometric mean.

Depth (cm)	Bulk Density (g cm⁻³)	*Particle Density (g cm⁻³)	Porosity (%)	Organic Matter (%)	*Fibre Content (%)	*Hydraulic Conductivity (cm day⁻¹)
5	0.11			70.6	56.4	4.1
10	0.10	1.48	93			3.5
15	0.11			58.3		2.5
20	0.12	1.60	93			2.3
25	0.12			50.7		1.3
30	0.14	1.63	91			0.9
35	0.11			47.3	49.8	1.9
40	0.12	1.58	92			3.5
Average	0.12	1.57	0.92	56.7	53.1	2.5

Vertical K_{sat} decreased with depth until 30 cm where it began to increase. At 5 cm below the peat base (Table 3-1) it was 4.1 cm day⁻¹ declining to 0.9 cm day⁻¹, 30 cm below the peat base; K_{sat} increased to 3.5 cm day⁻¹ at 40 cm below the peat base. One of the 40 cm samples had quick vertical K_{sat} (~10 cm day⁻¹) skewing the results at this depth (the other two samples were ~0.2 cm day⁻¹). Horizontal K_{sat} for gyttja in the field was lower, with a 4-year geometric mean of ~0.06 cm day⁻¹ for the 75 cm and 150 cm deep piezometers at the interior and peripheral sites (Table 3-2). Horizontal K_{sat} for the basal clay layer measured in the field was ~0.02 cm day⁻¹.

Table 3-2 Field saturated hydraulic conductivity (4 season geometric mean from 8 tests).

Location	Depth (cmbgs)	Material	Average (cm day⁻¹)
Interior	75	gyttja	0.02
	150	gyttja	0.27
Peripheral	75	peat/gyttja	0.10
	150	gyttja	0.01

3.5.2 *Laboratory Consolidation*

Unlike the in-field vertical compression tests, the laboratory tests showed a considerable amount of compression, although under much greater loads than those generated by seasonal changes in water table. Little difference in strain was observed between each depth for the same load, although the samples from 20 cm below the peat base consistently exhibited slightly less strain for all pressures tested. The mean total strain for all depths was 9, 14, and 72% at 3.5, 6.25 and 200 kPa, respectively (Figure 3-4a).

Laboratory tests also showed that gyttja compression is only partly reversible (Figure 3-4). When unloading from 200 kPa, the 10 and 20 cm gyttja swelled about 3.4 mm, or 25%, from the maximum compressed state. Unloading results (strain and void ratio) are unavailable for the 5 cm tests at 0 kPa as the consolidation cell was removed from the oedometer a day early. These data can be reasonably estimated based on measurements for 10 and 20 cm samples (Figure 3-4a). Similar to strain, little variability in void ratio existed between the three depths tested (Figure 3-4b). The mean void ratio for 0 (initial), 3.5, 6.25 and 200 kPa was 12.2, 11.0, 10.4, and 2.8, respectively. We estimate from Figure 3-4b that the average preconsolidation pressure of these gyttja samples was ~ 8 kPa. Therefore, the gyttja at the cutover section of BSF in 2011 was in an overconsolidated state. The all-depth mean recompression and virgin compression indices from the corresponding sections of Figure 3-4b were 1.3 and 6.1, respectively.

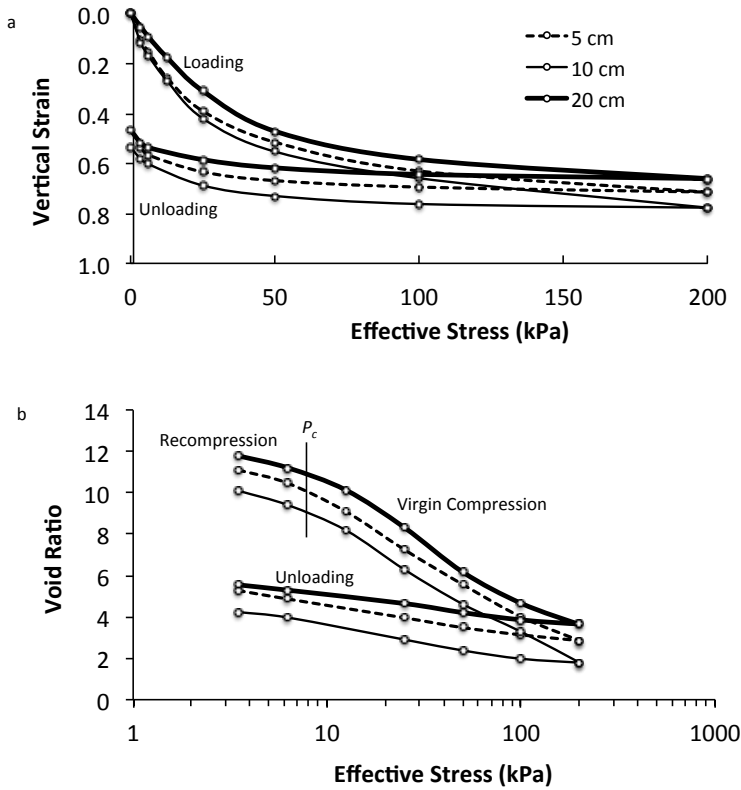


Figure 3-4 Gyttja a) strain and b) void ratio vs. log-scale effective stress loading and unloading curves.

The vertical K_{sat} with depth derived from compression tests is displayed in (Table 3-3). The vertical K_{sat} obtained from the initial load tested (3.5 kPa) should theoretically be the most representative of field conditions and therefore most comparable to K_{sat} values determined with the other methods reported herein. At 3.5 kPa the vertical K_{sat} for the 5, 10 and 20 cm tests was 1.1, 1.5, and 0.7 cm day^{-1} , respectively. A decrease in K_{sat} with depth was not evident. As expected, the vertical K_{sat} decreased as the effective stress increased. At 200 kPa the vertical K_{sat} of gyttja declined to 9.3, 6.7 and 6.2 $\times 10^{-4}$ cm day^{-1} for the 5, 10 and 20 cm tests, respectively.

Table 3-3 Hydraulic Conductivity from Compressibility Tests. Note: 1 kPa is equal to 1 kN m⁻².

Load (kPa)	Sample Depth (cm)	T_v	H_{dr} (m)	t_{90} (min)	C_v (m ² min ⁻¹)	m_v (m ² kN ⁻¹)	Y_w (kN m ⁻¹)	K_{sat} (m min ⁻¹)	K_{sat} (cm day ⁻¹)
3.5	5	0.848	9.0E-03	2.5	2.7E-05	3.0E-02	9.8	7.9E-06	1.1E+00
	10	0.848	8.9E-03	2.0	3.3E-05	3.2E-02	9.8	1.1E-05	1.5E+00
	20	0.848	9.3E-03	2.0	3.6E-05	1.4E-02	9.8	5.0E-06	7.2E-01
6.25	5	0.848	8.3E-03	16.0	3.6E-06	1.9E-02	9.8	6.8E-07	9.8E-02
	10	0.848	8.1E-03	9.3	6.0E-06	2.2E-02	9.8	1.3E-06	1.9E-01
	20	0.848	8.8E-03	4.4	1.5E-05	1.5E-02	9.8	2.3E-06	3.3E-01
200	5	0.848	3.1E-03	28.4	2.9E-07	2.3E-03	9.8	6.5E-09	9.3E-04
	10	0.848	2.9E-03	39.4	1.8E-07	2.6E-03	9.8	4.6E-09	6.7E-04
	20	0.848	3.6E-03	46.2	2.4E-07	1.8E-03	9.8	4.3E-09	6.2E-04

3.6 Discussion

The post-harvesting topography of the peatland, along with the construction of bunds to retain water, resulted in wetter conditions in the interior part of BSF compared to the peripheral part (Figure 3-2), and wetter conditions in general than pre-restoration (Ch. 2.0). The cause of seasonal differences in ground surface elevation was determined to be primarily by seasonal soil volume changes in the peat layer. The compression and hydraulic parameters were not determined for this, although Price (2003) provides a detailed discussion of peat compressibility. The ability of the peat layer to respond by subsidence to water table changes maintains the water table closer to the ground surface than it otherwise would (Whittington and Price, 2006), which is important for ecohydrological processes in peatlands. It is evident at this site that while compressible, gyttja played a lesser role in adjusting the ground surface elevation than the peat. The remainder of this paper will be focused on the potential release of water from the gyttja layer to the overlying peat, caused by seasonal compression.

The rather small water-table elevation change at the interior and peripheral sites caused only a small loading onto the gyttja. There were no measurements of subsidence at the peripheral location, but at the interior location a small loading (~0.8 kPa) when the water table dropped below the peat surface mid-season (day of year 192-202) caused minimal compression of the gyttja layer. From day 192 to our elevation sensor rod measurement on day of year 202 (the end of the dry period) the change in the thickness of the gyttja layer was 0.5 cm (Figure

3-3). If it is assumed that the volume change is primarily in the upper 30 cm of gyttja (explained below), then the strain is ~1.7%. The wet conditions and small response precluded us from developing a field-based relationship between effective stress and strain. However, this relationship was determined in the laboratory (Figure 3-4).

The small change in gyttja volume was corroborated by a small change in its saturated θ_v (Figure 3-2) (i.e. the water table was always above the gyttja layer). This seasonal decline in θ_v despite remaining saturated suggests a decrease in the volume of pore spaces consistent with peat compression (Price, 2003). Decreases in θ_v below the water table could also be the result of methanogenic gas buildup in the soil, although this typically gives an erratic θ_v signal (Kellner et al., 2005) that was not observed here. The change in θ_v in the 0-30 cm layer occurred mostly near the top of the layer (5 – 10 cm gyttja depth) because this is where it has the highest organic content, largest fibers, highest hydraulic conductivity and highest m_v (Table 3.3) (Table 2-1). At depths below the 30 cm level these values all are substantially decreased, so taken together it is reasonable to assume that relatively little change in θ_v occurs below the 30 cm layer. From when the water table dropped 8 cm below the peat surface to the end of the dry period (day of year 192-202), the strain produced by 0.8 kPa loading on the 0-30 cm gyttja layer was 0.1% based on a change in θ_v of 0.4%, respectively, and accounting for θ_v of ~90%; the strain calculated was smaller than determined from the elevation sensor rod (1.7%).

Laboratory tests showed gyttja volume change was greatest for loads with effective stresses (σ_e) greater than P_c (8 kPa and higher) (Figure 3-4a). Assuming changes in total stress (σ_T) in the field were relatively minor compared to changes in pore-water pressure (ψ) (see eqn. 3-1 and 3-2) then the loading (σ_e) that would occur in the field as a result of a water table decline can be seen in Figure 3-4a). For a change in load (σ_e) between 0 and 1 kPa (representing a 10 cm water table decline) the strain estimated from Figure 3-4a would be ~3%. This was slightly greater than that estimated from field data (1.7 and 0.1% from elevation sensor rods and θ_v , respectively).

From the field (elevation sensor rods and changes in θ_v at the interior site) and laboratory, estimates of strain are 1.7, 0.1%, and 3%, respectively for ~1 kPa of loading. For this loading we can calculate the amount of water expressed from a 30 cm layer of gyttja as 5.1, 0.3, and 9.0 mm,

respectively. These represent a relatively small proportion of the seasonal water input to the site by rainfall (159 mm).

In the year of study gyttja at BSF was in an overconsolidated state as the range in effective stress in the field was much less than the preconsolidation stress (8 kPa). This means that any soil volume change gyttja underwent in the field was recompression where the rate of volume change is less than virgin consolidation ($C_r = 1.3$, $C_c = 6.1$). The small amount of loading and low rate of volume change during recompression was reflected in only a small amount of gyttja volume change in the field. In a dry year with much greater water table recession we expect proportionately higher compression, and therefore more water could be released. For the same study period (day of year 172-222) before restoration in 2008 and 2009 the range in water table position at the interior well was 34 and 36 cm (loading of ~ 3.4 and 3.6 kPa), respectively, which was much more than what was observed in 2011. At the peripheral well in 2008 and 2009 the range in water table position was 74, and 57 cm (~ 7.4 and 5.7 kPa), respectively compared to ~ 3 kPa in 2011 (unpublished data). Consequently, before restoration there was a larger driver for change in gyttja volume (subsidence), especially at the peripheral well. Figure 3-5 shows the potential quantity of water that could be released from the gyttja layer under different levels of effective stress. For example, with a 60 cm water table drop the change in effective stress (~ 6 kPa) could cause strain of $\sim 14\%$ based on oedometer tests, which could result in an expression of 42 mm of water if that change occurred in the upper 30 cm (Figure 3-5). Therefore, more water could have been released from the gyttja layer before restoration when the range of loading was greater. Although the laboratory and field experiments illustrate the potential for gyttja compression to deliver water to the thin overlying cutover peat in response to seasonal water table lowering, this outcome was not realized during the relatively wet conditions at the site.

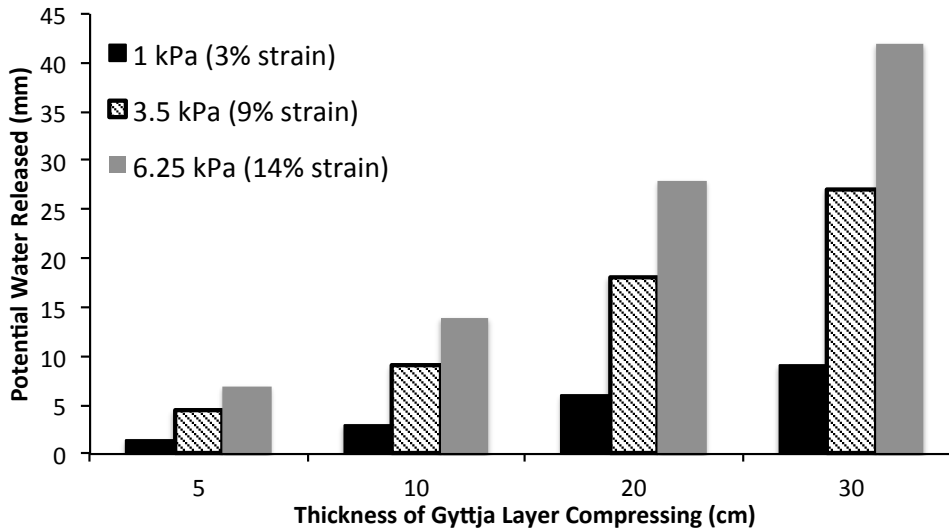


Figure 3-5 The potential amount of water that could be released from different thicknesses of consolidating gyttja under different loads.

3.6.1 Compressibility Controls

The mechanical properties of the contrasting gyttja materials are different. There was no evidence of carbonate, which is consistent with the local geology; however calcium carbonate can comprise a portion of gyttja (Rybicki and Zurek-Pysz, 1990; Łachacz et al., 2009). Strain of 12.5 kPa for gyttja tested by Zurek-Pysz (1992) was ~5% for gyttja with 25-30% organic matter content. The average strain for all depths tested here at a similar load (12.5 kPa) was 23% for gyttja with 45 – 70% organic matter (and no calcium carbonate). This indicates that gyttja with high organic matter is more compressible than gyttja dominated by inorganic materials under the same load. At higher loads (200 kPa), the strain reported by Zurek-Pysz (1992) was ~35% compared to our three depth average of 72%, suggesting organic matter impacts the compressibility of gyttja even under high loads. Our data support the notion that the extent of organic matter is directly proportional to the compressibility of gyttja.

Soil materials under progressive compression see a corresponding reduction in their permeability (Dhowian & Edil 1980; Hillel, 1998; Hobbs, 1986). This was evident from our compressibility tests as permeability of gyttja decreased by four orders of magnitude under loading from 3.5 to 200 kPa. Consequently, it took longer for the excess pore water pressure to dissipate under higher loads. The mean t_{90} for all depths tested for the 3.5, 6.25, and 200 kPa

loads were 2.4, 11.1, and 40.2 minutes; the ranges were 3, 21, and 55 minutes, respectively. The ambiguous nature of estimating t_{90} explains the large range in values. Doubling t_{90} halves K_{sat} ; therefore we note that error in estimating t_{90} impacts K_{sat} . We note, however, that our gyttja K_{sat} values determined by consolidation tests (Table 3-3) and through Darcy permeameter tests (Table 3-1) are quite similar, albeit higher than field tests (Table 3-2). To our knowledge, no studies have linked permeability with gyttja compression so we cannot compare our results with literature. Changes in hydraulic conductivity in the field season (c.f. Price, 2003) would have been small to negligible because of the low range of loading in the wet year. In a drier year, higher loading would cause a sharper decline in hydraulic conductivity, which would delay the release of water.

3.6.2 *Peat Harvesting Activity Implications*

Peat harvesting machinery can produce stress, causing compaction of the substrate (Hillel, 1998), depending on the weight of machinery, wheel size, softness of the soil, etc. (McKyes, 1978). The impact of this at BSF is unknown, but the effect of drainage can be estimated. Artificial drains in peatlands can lower the water table by at least 100 cm (Price, 1997), and seasonal water table fluctuations in cutover peatlands can be much higher as a result of artificial drainage and peat degradation (Price, 1996). A water table lowering of 100 cm represents a loading of ~10 kPa. Based on the compressibility obtained through our oedometer tests, this could result in ~20% strain, assuming deformation is vertical. In BSF, where the gyttja layer is up to 1.5 m thick, hypothetically 300 mm of water could be released. Although the K_{sat} of gyttja is low, a protracted period of drainage is likely to result in the loss of this water, and more virgin consolidation of the gyttja layer (i.e. the preconsolidation pressure of gyttja in an undisturbed system is likely much less than the ~8 kPa reported here). Both factors (water loss and continued virgin consolidation) could potentially make restoration more difficult the longer it is delayed, so restoration should proceed as soon as possible after operations cease (the same arguments can be made for the peat layer).

3.6.3 *Future Research*

In the future it would be beneficial to run oedometer tests with gyttja under lower pressures and with smaller pressure increments (e.g. testing at 1, 2, 3 kPa) in line with seasonal water table fluctuations. It would also be instructive to sample gyttja from an undisturbed site, although this

would be difficult at BSF where there is approximately 3.3-3.8 m of peat overlying gyttja (Sararas, E., unpublished 2010 data). Running oedometer tests on gyttja obtained from a natural site would help us better understand the implications of peat harvesting on the site hydrology.

3.7 Conclusion

The naturally high water and organic matter content of gyttja along with a large void ratio results in it being a highly compressible material. This means that the subsurface gyttja layer at Bic-Saint-Fabien peatland has potential to consolidate under stress and supply water to the overlying peat layer, although this was not important in the year of our study. The potential for gyttja to compress and supply water in harvested peatlands would be greatest after peat production stops and before rewetting begins. The loading in this period would likely be less than the preconsolidation pressure (recompression), yet still great enough to compress gyttja and release water. Although not studied in detail here, the release of water caused by the shrinking and swelling of the gyttja layer after Bic-Saint-Fabien was abandoned might have been an important self-preservation mechanism (c.f. Whittington and Price, 2006), eventually making it easier to rewet. Since we did not find any such detailed parameterization for gyttja in the published literature, the values provided here provide the first insight into its role in harvested and abandoned peatlands.

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4.0 Conclusions

Since restoration success requires growth of fen vegetation and a return to a carbon accumulating system it is too early to either confirm or deny restoration success. There is not a universal determinant that defines rewetting success, however the more even distribution of water, significantly higher water table, high volumetric soil moisture and high soil-water pressure at the cutover area after rewetting suggests that rewetting was successful and should be able to support peat-accumulating mosses and a return to a carbon accumulating system. Peripheral locales generally remained less moist after rewetting; however not all peripheral locales were drier than the site interior. Due to the complex rewetting patterns observed, revegetation programs should be tailored for different hydrological conditions within a site and a general revegetation prescription may not be appropriate.

The influence of gyttja in 2011 when Bic-Saint-Fabien was rewetted was negligible as little in-field compression occurred under stresses induced by seasonal water table variability. Laboratory compression tests indicate the potential for more compression (and therefore more water release) under higher loads, which might have been an important self-preservation mechanism before Bic-Saint-Fabien was rewetted. Even though the impact of gyttja on rewetting at Bic-Saint-Fabien was unimportant, our results pertaining to the hydrophysical and mechanical properties of gyttja remain relevant as our findings can contribute to the sparse body of literature on gyttja soils and can be applied to broader fields of study. Ultimately successful rewetting is more reliant on implemented restoration techniques designed for bog restoration, which are transferable to fen ecosystems and are effective at improving hydrological conditions.

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