The hydrology of the Bois-des-Bel bog peatland restoration: A tale of two scales

by

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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.

I understand that my thesis may be made electronically available to the public.

Abstract

Vacuum harvested peatlands typically do not spontaneously regenerate peatland species and more importantly the peat-forming *Sphagnum* mosses. Thus harvested and abandoned peatlands require restoration to return the peat-forming *Sphagnum* moss to the ecosystem. Restoration can create a hydrological environment that is suitable for peatland species' regeneration and results in substantial *Sphagnum* moss growth. Bois-des-Bel was restored in the winter of 1999 and studied in the following three years (2000-2002), then again after 10 years (this study). Immediately following restoration the conditions were deemed favourable for *Sphagnum* regeneration (i.e. soil water pressures and water tables, > -100 cm and -40 cm respectively) (~ 15-20 cm in 10 years), while evaporation from the surface was reduced due to the straw mulch that was applied as part of the restoration measures. Although the hydrological conditions were suitable for peat revegetation, Bois-des-Bel was still a net exporter of carbon during first three years. The purpose of this thesis is to understand the hydrological evolution of Bois-des-Bel since the initial assessments and document the hydrophysical properties that could limit net carbon sequestration. This is done with a combination of field and laboratory (monolith) experiments through comparison of its hydrology and hydraulic parameters to that of a natural reference site.

Since the initial assessment a water table rise of ~ 5-10 cm has occurred at the Restored site with an average water table of -27.3 (± 14.9) with respect to the cutover peat (pre-restoration surface) and ~ -42.3 (± 20.9) cm with respect to the regenerated *Sphagnum* surface. This water table is still much further from the capitula and more variable than at the Natural site (33.2 ± 9.0 cm). Both evapotranspiration (242 mm) and runoff (7 mm) from the Restored site maintained the same relationships in 2010 as during the initial assessments, compared to the Unrestored site (290mm and 37 mm, respectively). Although lower evapotranspiration equated to less water lost from the system, evapotranspiration at the Restored site was not indicative of the Natural site (329 mm), chiefly due to limited surface *Sphagnum* moisture at the Restored site. After ten years following restoration, the large scale hydrological processes are still controlled by the cutover peat and not the regenerated *Sphagnum* moss; thus the Restored site is still divergent from the Natural site.

Wells paired with the soil moisture measurements resulted in average water tables of -53.7 ± 17.8 cm at the Restored site and -31.9 ± 8.3 cm at the Natural site. In addition to much lower water tables, the upper layers of regenerated *Sphagnum* ($\theta_{2.5\ cm}$ – 0.12 and $\theta_{7.5\ cm}$ – 0.11) on average were far drier than the same species at the Natural site ($\theta_{2.5\ cm}$ – 0.23 and $\theta_{7.5\ cm}$ – 0.32) under only *Sphagnum*. Furthermore the Restored site was very dry just above the cutover peat ($\theta_{17.5\ cm}$ – 0.19), compared to the same probe depth at the Natural site (0.57). At the Natural site under ericaceous and *Sphagnum* the soil moisture contents were generally double that of the *Sphagnum*-only site. In addition to poor soil water retention at the Restored site, high specific yield was observed in the Restored site (0.44) monoliths while the water table fluctuated within the *Sphagnum* compared to both the Natural (0.10) and Unrestored (0.05) monoliths. These retention characteristics at the Restored site are due to far lower fraction of water filled pores for a given pore diameter than the same species (*S. rubellum*) at the Natural site. The high abundance of large pores do not generate the necessary capillary force to draw water from the relatively wet cutover peat into the *Sphagnum* moss, resulting in a capillary barrier.

Although after ten years the Restored section of Bois-des-Bel had somewhat representative bog peatland ecology, the hydrological conditions needed for net carbon sequestration were not present. The lack of water transmission from the cutover peat to the regenerated *Sphagnum* moss due to large pores and the inability of the *Sphagnum* moss to retain water are both retarding the restoration. For Bois-des-Bel to become a net carbon sequestering further lateral infilling of the *Sphagnum* leaves and branches along with decomposition of the basal layer will be need. In addition to these two processes, planting of ericaceous shrubs could lower the water loss through evaporation, thus increasing the capitula moisture content and creating healthier mosses. If Bois-des-Bel continues on its current ecohydrological trajectory it is likely that it will self-regulate and make the necessary structural changes to become a net carbon sequestering system.

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Lastly, I want to thank my girlfriend Katharine. Without you I would not be where I am today doing what I love.

Dedication

I dedicate this thesis to my girlfriend Katharine Hajdur.

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1.0 Introduction

Canadian peatlands occupy 113 million ha, which is approximately 12% of Canada's landmass (Daigle and Gautreau-Daigle, 2001) and sequesters ~ 70 million tonnes of carbon per year (Gorham, 1991; Daigle and Gautreau-Daigle, 2001). Carbon sequestration in peatlands depends on high water tables (Hayward and Clymo, 1983; Strack *et al.*, 2004; Strack *et al.*, 2006; Strack and Waddington, 2007; Dimitrov *et al.*, 2010; Dimitrov *et al.*, 2011), high soil moisture contents (Waddington *et al.*, 2001; McNeil and Waddington, 2003; Petrone *et al.*, 2003; Lafleur *et al.*, 2005; Strack and Price, 2009; Dimitrov *et al.*, 2010; Waddington *et al.*, 2010; Dimitrov *et al.*, 2011) and decay resistant plant material (i.e. *Sphagnum*) (Clymo, 1984; Clymo, 1987; Clymo *et al.*, 1998; Belyea and Clymo, 2001). The water table (and associated capillary fringe) create oxygen reduced conditions (Rydin and Jeglum, 2009), which limits microbial activity and plant material is left in a relatively undegraded state, resulting in lower carbon emissions (Rydin and Jeglum, 2009). Besides sequestering carbon, peatlands can have a regionally important economic impact (e.g. St. Lawrence Lowlands, Quebec) through horticultural peat harvesting (Daigle and Gautreau-Daigle, 2001). As of 2001, an estimated one million tons of peat was harvested throughout Canada annually, which corresponds to < 0.02% of the total peatlands in Canada (Daigle and Gautreau-Daigle, 2001). Harvesting peatlands for horticultural peat is a $CDN 170 million business in Canada (Daigle and Gautreau-Daigle, 2001), especially important in Eastern Quebec. In this region, the vacuum peat harvesting method has been the primary harvesting method since 1960 (Lavoie and Rochefort, 1996; Girard, 2000; Girard *et al.*, 2002), which increased the size and rate of extraction operations compared to the block cut method (Price *et al.*, 2003). Gorham (1991) estimated that 0.0085 Pg of CO_2 and 0.046 Pg of CH_4 are released from drained and harvested peatlands in Canada annually.

The vacuum harvesting method requires ditches to be dug ~ 30 m apart and connected to a main drainage channel, which is used to export the water off site; resulting in low water tables and a dry peat surface. The extraction process removes the existing vegetation (including the peat forming *Sphagnum* moss), acrotelm and catotelm peat, resulting in relatively dense (deep) catotelm peat at the surface (Lavoie and Rochefort, 1996; Girard, 2000; Girard *et al.*, 2002; Lavoie *et al.*, 2003). Spontaneous revegetation of post vacuum harvested peatland is often limited to vascular and non-peatland species (Girard *et al.*, 2002; Lavoie *et al.*, 2003; Poulin *et al.*, *in press*); whereas block-cut peatlands have a larger viable seed bank and more suitable micro-habitats resulting in a higher diversity of peatland specific species (Price *et al.*, 2003). Vacuum harvesting is more damaging to the ecosystem as nearly all the plant material and the seed bank are removed and thus requires extensive restoration measures (Gorham and Rochefort, 2003; Price *et al.*, 2003; Rochefort *et al.*, 2003).

1.1 Post Vacuum Harvesting Conditions

The vegetation that returns spontaneously after harvesting ceases is a reflection of the hydrological conditions caused by draining and drying a peatland (Lavoie and Rochefort, 1996; LaRose *et al.*, 1997; Lavoie *et al.*, 2003). The exposed peat has a much higher bulk density (Price, 1996; Schlotzhauer and Price, 1999) and water retention (Price, 1997; Schlotzhauer and Price, 1999; McNeil and Waddington, 2003; Waddington *et al.*, 2011), lower specific yield (Price, 1996; Price, 1997; Schlotzhauer and Price, 1999; Price, 2003; Waddington *et al.*, 2011), hydraulic conductivity (Price, 1996; LaRose *et al.*, 1997; Price, 2003), and smaller pore sizes (Schlotzhauer and Price, 1999; Price, 2003) than the typical surface peat (*Sphagnum*) in an un-harvested peatland (Price, 2003). Furthermore, harvested peatlands will irrevocably oxidize (Price, 2003) and partially compress (Schothorst, 1977; Schouwenaars and Vink, 1992) as the peat dries resulting in a further decrease in the average pore size (Hobbs, 1986). Low water tables (< -50 cm) are typical in harvested and abandoned peatlands due to the drainage network installed for harvesting, which are generally still active post harvesting (Hobbs, 1986; LaRose *et al.*, 1997; Van Seters and Price, 2001). The low water tables in conjunction with hydrophysical properties of the post harvested peat results in low soil water pressures, which is the primary deterrent to *Sphagnum* regeneration and thus peat formation (Price and Whitehead, 2001; Schouwenaars and Gosen, 2007). Unlike natural peatlands, which typically sequester carbon (Gorham, 1991; Gorham, 2008), harvested peatlands emit carbon due to the altered hydrological conditions (Waddington and Roulet, 1996; Waddington *et al.*, 2001; Petrone *et al.*, 2003; Petrone *et al.*, 2004a; Petrone *et al.*, 2004b; Waddington, 2008; Waddington *et al.*, 2010). It is unlikely that peatlands will spontaneously regenerate the necessary hydrological condition post harvesting to support natural peatland vegetation and sequester carbon; thus restoration measures are critical to restore these peatland functions (Lavoie and Rochefort, 1996; Girard, 2000; Girard *et al.*, 2002; Gorham and Rochefort, 2003; Rochefort *et al.*, 2003; Lavoie *et al.*, 2005).

1.2 North American Peatland Restoration

Rochefort *et al.* (2003) proposed a specific set of restoration measures for North American bog peatlands. These measures include ditch blocking and constructing bunds along elevation contour line to retain and direct water flow over the site (Rochefort *et al.*, 2003); and creating microtopography variation to give the reintroduced vegetation localized habitat for regeneration (Rochefort *et al.*, 2003). Depending on the size of the restoration site, the donor material is either grown in a greenhouse (smaller restoration sites) or the top ~ 10 cm are harvested from one or several peatlands (larger restoration sites) (Gorham and Rochefort, 2003; Rochefort *et al.*, 2003). The donor material is spread over the site (Rochefort *et al.*, 2003). Lastly straw mulch and phosphorus fertilizer are added on top of the donor material to reduce evapotranspiration from the restoration surface (Price *et al.*, 1998) and to increase the nutrient availability in the peatland (Campeau and Rochefort, 1996; Rochefort *et al.*, 2003).

Blocking the ditches and the creation of bunds raises the water table (LaRose *et al.*, 1997; Shantz and Price, 2006a) and subsequently the soil water pressures (Price and Whitehead, 2001) creating conditions which can support typical peatland vegetation (Gorham and Rochefort, 2003; Rochefort *et al.*, 2003; Waddington *et al.*, 2003). Price and Whitehead (2001) determined that water tables > -40 cm and soil water pressures > -100 mb are required for successful establishment of *Sphagnum* on a cutover peat surface. Initially, soil moisture increases and evapotranspiration decreases due to the straw mulch cover (Petrone *et al.*, 2004b). However, CO_2 emissions remain high because the decomposition of the straw mulch increases the total soil respiration (Petrone *et al.*, 2003; Petrone *et al.*, 2004b). A peatland can be considered successfully restored when there is a dominance of peatland species and a net sequestration of carbon (Poulin *et al.*, *in press*).

1.3 Study Site: The Bois-des-Bel Peatland and Restoration

The Bois-des-Bel (BdB) peatland is located ~ 10 km northwest of Riviére-du-Loup, Quebec in the Bas-Saint-Laurent region of the St. Lawrence Lowlands. BdB is located on a narrow agricultural plain underlain by sand, silt and clay marine deposits (Fulton, 1995). These deposits originated from the Goldthwait Sea which covered the region until ~9500 BP (Dionne, 1977). The marine clay underlies the majority of BdB (Lavoie *et al.*, 2001). The peatland is ~ 189 ha with a mean elevation 28 m above sea level. Mean annual precipitation is 962.9 mm

(29% snowfall) (Environment Canada, 2012) and the average temperature is 3.2°C with a minimum average temperature in February of -10.9°C and a maximum average temperature in August of 16.5°C (Environment Canada, 2012).

BdB is the last and largest peatland in Bas-Saint-Laurent region that has not yet been extensively harvested (Lavoie *et al.*, 2001). Peat harvesting occurred within an 11 ha area in the northeast area of BdB and ceased in 1971. The harvested area was left abandoned and vascular vegetation often found in forests or ruderal ecosystems dominated the site pre-restoration (Poulin *et al.*, *in press*). The residual peat depth at the post harvested site was ~1.8 m where high concentrations of woody debris prohibited further peat extraction (Lavoie *et al.*, 2001). A domed section of the bog is located ~2 km away within BdB and has an average peat depth of ~2.2 m with a maximum peat depth ~3.2 m (Lavoie *et al.*, 2001). In the winter of 1999 restoration measures were implemented on 8.1 ha of the 11 ha harvested site, with 1.9 ha left unrestored as a comparison and a 30 m buffer strip was created between the restored and unrestored sections. It was originally estimated it would take between 20-30 years for complete restoration (net carbon sequestering) based on ecological succession (Rochefort *et al.*, 2003), while Lucchese *et al.* (2010) predicted complete restoration would occur in ~17 years based on peat decomposition rates, net primary productivity and accumulation of organic matter.

As a result of the restoration measures, the water table increased ~30 cm to an average water table of -32.5 cm during the growing seasons of 2000-2002 (Shantz and Price, 2006a). The resulting soil water pressures were well above the limit of -100 mb (Price and Whitehead, 2001) and had an average of -13 mb over the first three years (Shantz and Price, 2006a). Surface soil moisture (-5 cm below surface) also increased to an average of 0.74 as a result of the restoration, which is an increase of ~0.4 compared to the unrestored site (Petrone *et al.*, 2004a; Petrone *et al.*, 2004b; Shantz and Price, 2006a). These hydraulic properties created conditions suitable for the successful reintroduction of peatland vegetation at BdB (Shantz and Price, 2006a; Poulin *et al.*, *in press*). The addition of bunds and blocking ditches led to an ~38 % decrease in total runoff from the Restored site (Shantz and Price, 2006a; Shantz and Price, 2006b). Evapotranspiration decreased by 25 % (Petrone *et al.*, 2004b; Shantz and Price, 2006a) and these changes were attributed to the presence of straw mulch decreasing the net radiation on the restoration surface (Petrone *et al.*, 2004a; Petrone *et al.*, 2004b). BdB remained a net exporter of carbon during the first three years due to high levels of total soil respiration caused by straw mulch decomposition

(Petrone *et al.*, 2003; Petrone *et al.*, 2004a; Petrone *et al.*, 2004b). Seven years post restoration (2007) Waddington *et al.* (2011) systematically sampled the upper (0-4 cm) and lower (8-12 cm) of the ~15 cm regenerated *Sphagnum* carpet. Compared to a natural site located in BdB, the restored section's *Sphagnum* had lower bulk density, residual water contents, poorer water retention properties and higher specific yields; particularly in the lower samples (Waddington *et al.*, 2011). As of 2010 the restored section of BdB was dominated by peatland species; however had a much higher biodiversity than the natural site due to the presence of non-peatland wetlands species (Poulin *et al.*, *in press*). Furthermore the site remained a net carbon exporter, indicating the restoration is yet to be successful (Strack, *unpublished data*).

1.4 Objectives

Although the majority of the vegetation is peatland vegetation, including a complete layer of *Sphagnum* moss, the site does not sequester carbon and the ecohydrological conditions of BdB are poorly understood. It is unclear which hydrophysical processes are retarding carbon sequestration and how the ecohydrology of the *Sphagnum* functions. Furthermore, it is also unknown how the site hydrology has evolved since the initial assessments of Shantz and Price (2006a) and how divergent the Restored site is from the Natural site. Therefore the objectives are:

1. Determine the current hydrological state of the Bois-des-Bel restoration and how it has evolved since the initial assessments.
2. Determine the hydrological progression of Bois-des-Bel toward a natural system.
3. Characterize the ecohydrological properties of the regenerated *Sphagnum* moss and compare to natural *Sphagnum* moss.
4. Define the limiting ecohydrological process preventing carbon sequestration.
5. Speculate on the hydrological trajectory and the implications for the outcome of the restoration of Bois-des-Bel.

1.5 General Methods

This thesis comprises two distinct yet related manuscripts regarding the ecohydrology of the Bois-des-Bel bog peatland restoration. I was primarily responsible for implementing and carrying out the field work; designing, implementing and running the laboratory experiments;

and the writing of the manuscripts. The first manuscript (The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post restoration) details the changes in the large scale processes (water table fluctuations, evapotranspiration, runoff, soil water pressure and soil moisture content) since the initial assessments of Shantz and Price (2006a) and Shantz and Price (2006b). Furthermore the first manuscript questions the connectivity between the cutover peat and the regenerated *Sphagnum* moss, which is the focus of the second manuscript. The second manuscript (The hydrology of the Bois-des-Bel peatland restoration: Hydrophysical properties retarding restoration) further expands upon the limited connectivity theory of the first manuscript and systematically evaluates the hydrophysical properties (specific yield, soil water retention, saturated and unsaturated hydraulic conductivity, bulk density, porosity and pore size distribution) of the cutover peat and *Sphagnum* moss and determines the ecohydrological controls effecting the restoration. This thesis gives the first complete ecohydrological assessment of a bog peatland restored using the North American peatland restoration approach beyond the studies identifying the initial hydrological changes due to the restoration measures.

2.0 The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post restoration

2.1 Overview

Restoration measures (ditch blocking, bund construction, etc.) were applied to the Bois-des-Bel (BdB) peatland in autumn 1999; since then a complete cover of *Sphagnum rubellum* (~15 cm) has developed over the old cutover peat, along with a suite of bog vegetation. This research assesses the Restored site's (RES) hydrological condition after 10 growing seasons (May 15th – August 15th, 2010) through comparison with an Unrestored site (UNR) and a Natural site (NAT) located elsewhere in the peatland. Evapotranspiration (ET) from RES (242 mm) has not noticeably changed since the first three years post-restoration (2000-2002) still maintaining lower ET rates than UNR (290 mm). The highest ET occurred at NAT (329 mm), dissimilar to RES despite similar vegetation cover. UNR generates more runoff (37 mm) than RES (7 mm), similar to the initial assessments. However, since the initial assessments the average water table has continued to rise, from -35.3 (± 6.2) cm (2000-2002) to -27.3 (± 14.9) cm (2010) below the cutover peat surface but still fluctuates predominantly within the cutover peat and not the regenerated *Sphagnum*. The regenerated *Sphagnum* at RES has increased the surface elevation by ~ 15-20 cm, and with respect to its surface the average water table was at ~ -42.3 (± 20.9) cm. However, its water table was still lower (and more variable) than at NAT (33.2 ± 9.0 cm), with respect to the moss surface. Average soil water pressures in 2010 were similar to the early post-restoration condition at depths of 10 cm (-43.0 ± 12.2 and -44.1 ± 13.1 mb) and 20 cm (-41.4 ± 13.0 and -40.6 ± 10.5 mb) below the cutover surface at RES and UNR, respectively. Volumetric soil moisture contents (θ) at 2.5, 7.5 and 17.5 cm depths were higher in the *Sphagnum* moss at NAT (0.23, 0.31, 0.71) compared to RES (0.12, 0.11, and 0.23), where the underlying cutover peat had a relatively high θ of 0.74. The low moisture in the new moss overlying the relatively moist cutover peat indicates there was restricted connectivity between the two layers. Ten years following the implementation of restoration measures and the development of a more-or-less complete 15 cm thick *Sphagnum* moss layer, further time is required for the moss layer to develop and more consistently host the water table, so that the average water content more closely mimics NAT.

2.2 Introduction

Peatlands depend on a combination of large scale (water table, evapotranspiration, runoff, etc.) and small scale (capillary flow, soil water retention, etc.) processes to function and sequester carbon (Waddington *et al.*, 2001; Waddington, 2008). The removal of *Sphagnum* and peat through peat harvesting disrupts the hydrology (Price, 1996) that supports carbon sequestration; turning a carbon sink into a source (Waddington *et al.*, 2001). Spontaneous re-vegetation can occur; however, this is often relegated to vascular plants and not the more important peat forming *Sphagnum* mosses (Girard *et al.*, 2002; Lavoie *et al.*, 2003). Successful peatland restoration is defined by not only the successful return of target species (generally identified through the use of a natural reference site), but also the net sequestration of carbon within a peatland (Poulin *et al., in press*). Both of these restoration milestones depend on specific hydrological conditions. Target peatland plants (i.e. *Sphagnum* moss) require raised water tables to suitably raise the soil water pressures for re-colonization. Price and Whitehead (2001) suggested soil water pressures greater than -100 mb are needed for successful *Sphagnum* re-colonization. To achieve this, ditch blocking, bund construction and straw mulch application (Rochefort *et al.*, 2003) has been used to raise the water table and soil water pressures to enable *Sphagnum* regeneration (Williams and Flanagan, 1996; Gorham and Rochefort, 2003; Rochefort *et al.*, 2003; Price and Whitehead, 2004; Shantz and Price, 2006a; Strack *et al.*, 2006). Lucchese *et al.* (2010) and Waddington *et al.* (2011) suggest that a critical stage in the restoration process will occur when the water table fluctuates primarily within the newly regenerated *Sphagnum* moss layer, during which the conditions will be suitable for net carbon sequestration.

Restoration measures (Rochefort *et al.*, 2003) applied to the previously harvested Bois-des-Bel (BdB) bog in autumn 1999 included blocking ditches, constructing bunds along elevation contour lines and reintroducing bog vegetation (see Rochefort *et al.* (2003) for a more detailed description). Hence, we consider the first year post-reclamation (i.e. first growing season) to be 2000. The donor material used in the restoration contained approximately the same amount of *S. fuscum* and *S. rubellum*; however, *S. rubellum* dominates the site (Poulin *et al., in press*). The high water tables that occurred initially after restoration created suitable conditions for *S. rubellum* to outcompete other *Sphagnum* species (i.e. *S. fuscum*), which resulted in the current species composition (Poulin *et al., in press*). Poulin *et al.* (*in press*) believe that *S. fuscum* will become more prevalent as larger hummocks develop at the site, due to conditions becoming better suited to *S. fuscum* than *S. rubellum*. Currently BdB is dominated by peatland species (see Poulin *et al.* (*in press*) for a complete description) with some wetland species resulting in higher a biodiversity than the natural reference site.

A detailed description of the hydrology during the first three years following restoration (2000-2002) is provided by Shantz and Price (2006a). The construction of bunds and blocking of ditches led to a decrease in runoff by 25% compared to the unrestored section during the post-snowmelt period (Shantz and Price, 2006b). Although runoff decreased post-restoration, the discharge peaks were greater due to wetter antecedent conditions compared to the unrestored section (Shantz and Price, 2006b). Total growing season runoff from the restored and unrestored sites maintained an average ratio of ~1:2.6 mm during the first 3 years following restoration (Shantz and Price, 2006b) where the average growing season water tables were -32.5 cm and -42.5 cm, respectively (Shantz and Price, 2006a). Evapotranspiration decreased at the restored site by ~25% compared to the unrestored site, initially due to the straw mulch application covering the plant material (Petrone *et al.*, 2004b; Shantz and Price, 2006a). Both the soil water pressure (greater than -100 mb) and soil moisture content (0.73 ± 0.05) 5 cm below the peat surface were significantly higher in the restored section of the peatland (Shantz and Price, 2006a), thus providing greater water availability for the newly regenerated vegetation. Although only a few cm of patchy *Sphagnum* had regenerated during the initial assessment, the conditions were suitable for it to regenerate across the site in the ensuing years (Poulin *et al.*, *in press*).

Notwithstanding the successful reintroduction of bog vegetation, the site remained a net exporter of carbon in 2000 and 2001 (Petrone *et al.*, 2003; Petrone *et al.*, 2004b) and 6 years (2006) after restoration (Waddington *et al.*, 2010). Strack (unpublished data, 2012) found the restored site was still a net carbon source in 2010, but so was the natural site in this relatively dry summer. Rewetting has caused higher surface soil moisture during the growing season which has resulted in enhanced photosynthesis; however, in the early post-restoration period this was offset by high soil respiration due to low water tables and high carbon export from mulch decomposition (Petrone *et al.*, 2003; Petrone *et al.*, 2004a; Petrone *et al.*, 2004b; Waddington *et al.*, 2010).

It remains uncertain, therefore, whether the ecohydrological conditions in the moss have recovered the potential for net carbon accumulation, and how the hydrology of Bois-des-Bel has evolved since the initial assessment in 2000-2002 by Shantz and Price (2006a). With respect to this last point, this study aims to determine 1) the current hydrological state of the Bois-des-Bel restoration; 2) identify how it has evolved since the initial assessments; and 3) determine the hydrological progression toward a natural bog peatland.

2.3 Study Site

BdB is located 10 km northwest of Riviére-du-Loup, Quebec (47°57’47 N, 69°26’23 W, 28 masl), with an average temperature and precipitation of 14.6°C and 366 mm, respectively,

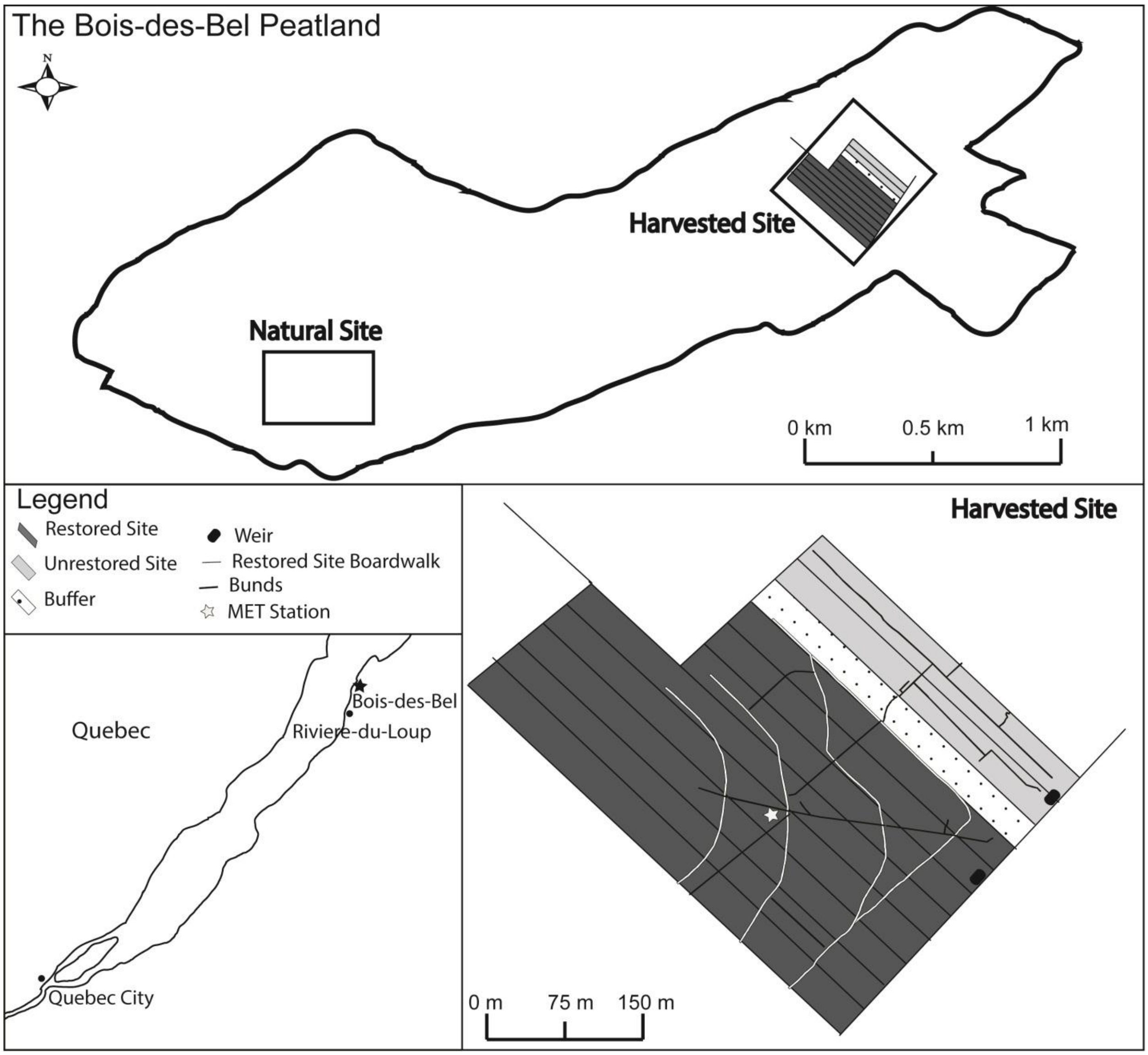

Figure 2-1 A map of the Bois-des-Bel peatland and the hydrological monitoring locations within the Restored, Unrestored and Natural sites.

from May – August (Environment Canada, 2012). The ombrotrophic peatland is approximately 189 ha with ~2.2 m of peat thickness in the Natural (NAT) site (47°57’35 N, 69°27’00 W) and

1.8 m in the cutover section (Restored (RES) and Unrestored (UNR) sites) (Lavoie *et al.*, 2001). The Unrestored (1.9 ha) and Restored (8.1 ha) sites are located adjacent to each other with a buffer of ~30 m between them, whereas NAT is ~2 km away in the same peatland (Figure 2-1). Since restoration a complete ~15-20 cm of *Sphagnum* moss, chiefly *S. rubellum*, has covered RES; NAT is also dominated by *S. rubellum* (Poulin *et al., in press*). The interface depth (i.e. where the regenerated Sphagnum and cutover peat meet) is variable over the site with small hummocks being ~ 20 cm, while other areas ~ 15 cm below the top of the *Sphagnum* moss. In contrast to NAT, where the dominant vascular vegetation are specific peatland plants, RES's vascular species are a mix of peatland and wetland plants (Poulin *et al., in press*).

2.4 Methods

Field monitoring at BdB occurred from day-of-year (D) 145 - 245 in 2010. Meteorological data, water table depth and volumetric soil moisture (θ) were averaged every thirty minutes (60 minutes for volumetric soil moisture) between D 145 - 245. Manual water table measurements were made twice weekly. For the comparison to early post-restoration results (2000-2002) reported by Shantz and Price (2006a), only twice-weekly manual well measurements were used to determine average water table. Samples (4) of the cutover peat and *Sphagnum* moss were taken from each site in 2.5 cm depth increments starting 1 cm below the surface to determine bulk density. The top 1 cm was taken individually to determine the evaporative surface (capitula) bulk density.

Micrometeorological stations were installed and instrumented at RES and NAT with net radiometers, tipping bucket rain gauges, temperature/relative humidity probes, and two copper-constantine thermocouples measuring soil temperature at 1 and 5 cm. Ground heat flux (Q_g) was determined using Fourier's Law (Eq. 2-1).

$$\boldsymbol{Q_g} \cong -\boldsymbol{k_s}\left(\frac{(\boldsymbol{T_2}-\boldsymbol{T_1})}{(\boldsymbol{z_2}-\boldsymbol{z_1})}\right) \qquad \textbf{Eq. 2-1}$$

Where Q_g (W m$^{2\ -1}$) is the ground heat flux, k_s (W m^{-1} K^{-1}) is the thermal conductivity, T (K) temperature, and z (cm) is the depth. θ content reported from the 2.5 cm TDR probe. k_s was determined hourly based on the 2.5 cm TDR probe and an assumed thermal diffusivity of 0.12 m^2 s^{-1} x 10^{-6} (Oke, 1987).

The Priestley - Taylor combination model (Eq. 2-2) (Priestley and Taylor, 1972) was used in conjunction with soil lysimeters (Price and Maloney, 1994) to calibrate the coefficient of evaporability (α); (Unrestored – 1.72, Restored – 1.44, Natural – 1.63) to obtain unique evapotranspiration (ET) values for all three sites;

$$\boldsymbol{ET = \alpha \left[\frac{s}{(s+q)}\right]\left[\frac{(Q^{*}-Q_{g})}{L\rho}\right]} \qquad \textbf{Eq. 2-2}$$

where Q^* is net radiation, s is the slope of saturation vapour pressure-temperature curve (Pa °C^{-1}), q is the physchrometric constant (0.0662 kpa °C^{-1} at 20 °C), L is the latent heat of vaporization (J kg^{-1}), ρ is the density of water (kg m^{-3}). Four 30 cm diameter, 40 cm deep lysimeters were installed at both NAT and RES; while two 12.5 cm diameter, 20 cm deep lysimeters were installed at UNR (due to the high volume of roots and woody debris in the peat that limited the practical size of the lysimeter). Lysimeters were weighed twice weekly.

Soil water pressure (ψ) was measured using tensiometers at both RES and UNR twice weekly. Due to the poor contact surface in the upper portion of *Sphagnum* moss, the tensiometers were unable to provide measurements at NAT or in the regenerated *Sphagnum* moss at RES. A total of 12 tensiometers (6 at each site) were installed 10 and 20 cm below the level of the cutover peat. The tensiometers were installed in 20 cm of *Sphagnum* moss at RES.

Two perpendicular ~200 m transects of 10 wells (70 m transects of 5 wells at UNR) (100 cm slotted intake, 2.54 cm I.D. PVC pipes) were measured twice weekly at RES and NAT. Averages of all manual well measurements were used to compare to Shantz and Price (2006a). One logging pressure transducer was installed per site for a continuous record of water table from D 145-245. Weirs were installed on culverts at both RES and UNR; a bucket and stopwatch were used to derive a stage-discharge relationship for each site. Due to weir malfunction UNR was unable to be measured until D 180.

θ content was measured using time domain reflectometry (TDR) with uniquely derived calibrations for each peat type following the calibration method of Topp *et al.* (1980). Two pits per micrometeorological station (RES and NAT) were dug in the *Sphagnum* moss (the approximate cutover peat/Sphagnum interface was 20 cm below the surface at RES) and four TDR probes per pit were installed horizontally at depths below the *Sphagnum* surface of 2.5, 7.5, 17.5, and 27.5 cm. The pits were backfilled with peat and covered with the intact *Sphagnum* moss.

The differences in water table, soil water pressure and θ were assessed between sites and the differences in average water table and θ between this study (2010) and the initial assessment (2000-2002) were determined using One-way ANOVA.

2.5 Results

The spring and summer of 2010 were unusually dry with 201 mm of rainfall compared to the 30 year average of 366 mm; however, precipitation in 2010 was similar to the initial assessment in 2000-2002 (Table 2-1) which was also relatively dry. Most of the precipitation fell during large storm events >30 mm, with few smaller events in-between. ET was largest at NAT (329 mm) followed by UNR (290 mm) and lastly RES (242 mm). Runoff at RES was less than the UNR (Table 2-1 & Figure 2-2) as was also reported by Shantz and Price (2006a) for the early post-restoration period. θ in the cutover peat (i.e. 27.5 cm probe) at RES was not statistically different ($p > 0.05$) than the initial study (Table 2-1), while θ in the regenerated *Sphagnum* (i.e. probes 2.5, 7.5 and 17.5 cm) at RES were statistically lower ($p < 0.001$) than same probes at NAT (Table 2-1 & Figure 2-3). Ψ measured 10 and 20 cm below the level of the cutover peat were not statistically different ($p > 0.05$) at RES and UNR (Table 2-1). The water tables from the manual measurements (D 147 – 245) at NAT (-33.2 ± 9.0 cm) were higher than both RES (-42.3 ± 14.9 cm) and UNR (-42.3 ± 20.9 cm). Furthermore, both NAT and UNR had significantly different average water tables than RES ($p < 0.001$) during the study period. Note that the depth at RES is referenced to the new moss layer surface which is ~15 cm above the interface of the cutover peat. Thus, with respect to the old cutover peat surface the water table depths at RES and UNR were -27.3 ± 14.9 and -42.3 ± 20.9 cm, respectively. The water table at RES fluctuated almost entirely within the cutover peat and not within the regenerated moss layer (Figure 2-4).

The water table at all sites generally decreased throughout the summer with the final water table (D 245) at NAT (-50.3 cm) being the highest followed by RES (-60.9 cm) and lastly the UNR (-86.3 cm) (Figure 2-4). Generally, NAT had a higher water table than RES and UNR (Figure 2-4), and less variability (Figure 2-5). RES was most responsive to precipitation events (Figure 2-4).

ψ at both 10 and 20 cm below the cutover peat show similar distributions and were statistically not different at RES and UNR (Figure 2-6). There are no soil water pressure data for NAT, however, average θ within the moss layer at NAT was significantly higher ($p < 0.001$) than in the moss layer at RES at all depths (Figure 2-3). Only the probes within the cutover peat (27.5 cm) at RES retained a significant amount of moisture throughout the summer, yet were still statistically different ($p < 0.001$) than the same probe depth at NAT.

The regenerated *Sphagnum* moss (upper 12.5 cm) at RES had slightly lower average bulk densities than the mosses at NAT (Figure 2-7). Although similar ($p > 0.05$) capitula bulk density (NAT 0.027, RES 0.026 g/cm^3) were observed, the regenerated mosses underneath the capitula show statistically significant (except at 2.5 cm) lower bulk densities until 12.5 cm (Figure 2-7). Around 15-20 cm (depending on microtopography) was where the average cutover peat/*Sphagnum* interface resides and was apparent through the larger standard deviations in the 15 cm layer at RES. Within and below this region the bulk density of RES is statistically different than NAT ($p < 0.001$), while not statistically different than UNR ($p > 0.05$).

Table 2-1 Comparison of 2010 data to first three years post restoration. All measurements referenced to the interface between the new Sphagnum moss and cutover peat at the restored site, ~15 cm of moss growth has occurred on the cutover surface. Water table n= 476, 201, and 248 for RES, UNR, and NAT, respectively. Measurements were taken from D 147-245 (runoff D 181-245). RES $\Psi_{10\ cm}$ n=65, UNR $\Psi_{10\ cm}$ n=68, $\Psi_{20\ cm}$ n=66, UNR $\Psi_{20\ cm}$ n=67. * -42.3 cm from *Sphagnum* surface. . [e] Indicates significantly different than RES at p= 0.05. [f] Indicates significantly different than RES at p= 0.001. [a] Indicates data from Shantz and Price, 2006a,b

Year	2000[a]		2001[a]		2002[a]		2010		
Site	RES	UNR	RES	UNR	RES	UNR	RES	UNR	NAT
Precipitation (mm)	220		254		210		201		
ET (mm)	248	334	374	501	253	257	242	290	329
Runoff (mm)	15	18	13	43	2	17	7	37	-
Average $\Psi_{5\ cm}$ (mb)	-6.8 ± 8.3	-41.8 ± 17.3	-8.7 ± 9.7	-29.8 ± 19.7	-24.8 ± 15.9	-39.9 ± 16.8	-	-	-
Average $\Psi_{10\ cm}$ (mb)	-	-	-	-	-	-	-43.0 ± 12.2	-44.1 ± 13.1	-
Average $\Psi_{20\ cm}$ (mb)	-	-	-	-	-	-	-41.4 ± 13.0	-40.6 ± 10.5	-
Average Water Table (cm)	[e] -30.0 ± 9.5	-45.5 ± 6.0	[e] -30.4 ± 10.5	-40.4 ± 6.0	[f] -37.2 ± 14.3	-44.3 ± 6.6	-27.3 ±14.9*	[f] -42.3 ± 20.9	[f] -33.2 ± 9.0
Average Sphagnum $\theta_{5\ cm}$	-	-	-	-	-	-	0.12± 0.01	-	0.23± 0.01
Average Cutover Peat $\theta_{5\ cm}$	0.80 ± 0.03	0.41 ± 0.02	0.72 ± 0.03	0.37 ± 0.02	0.69 ± 0.09	0.41 ± 0.04	0.74 ± 0.04	-	-

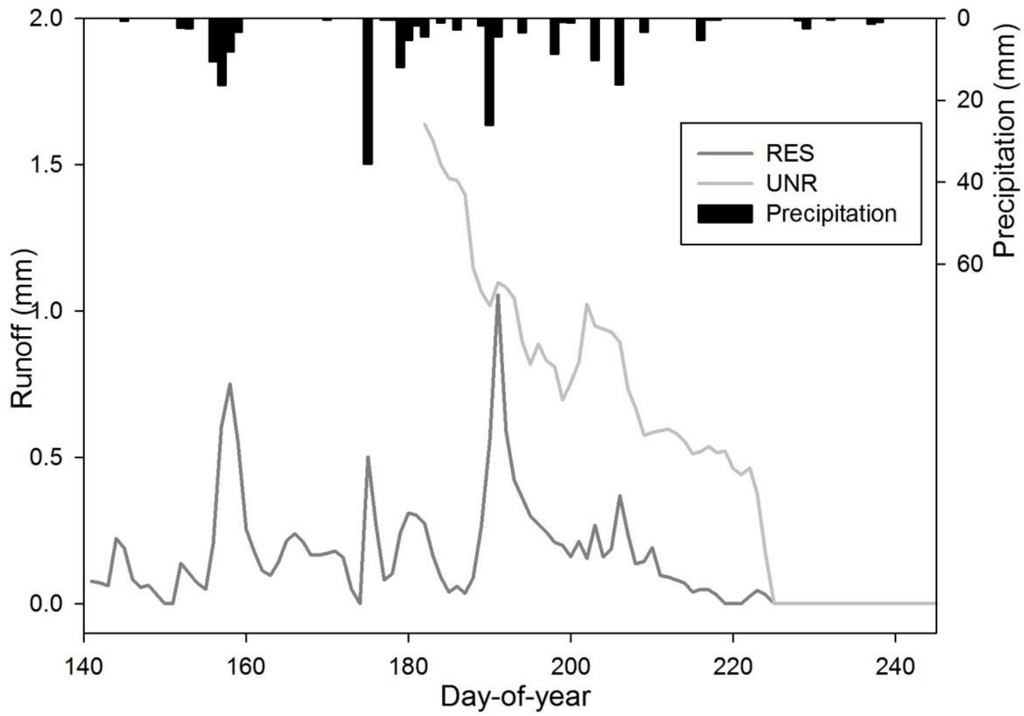

Figure 2-2 Runoff depth (mm) over time from RES and UNR from D 140 – 245. UNR started on D 182 due to the site outflow being blocked.

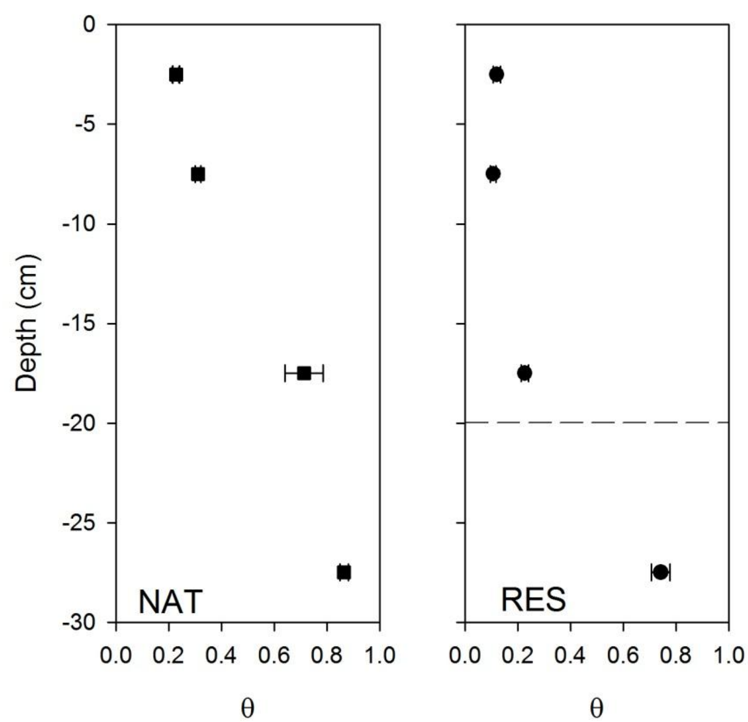

Figure 2-3 Average volumetric soil moisture contents of the *Sphagnum* and cutover peat at RES and NAT. Measurements centred at 2.5, 7.5, 17.5, and 27.5 cm below the *Sphagnum* surface. The dashed grey line represents the approximate interface between the regenerated *Sphagnum* moss and the cutover peat. Error bars indicate 1 standard deviation. All NAT measurements are significantly different than RES at p= 0.001.

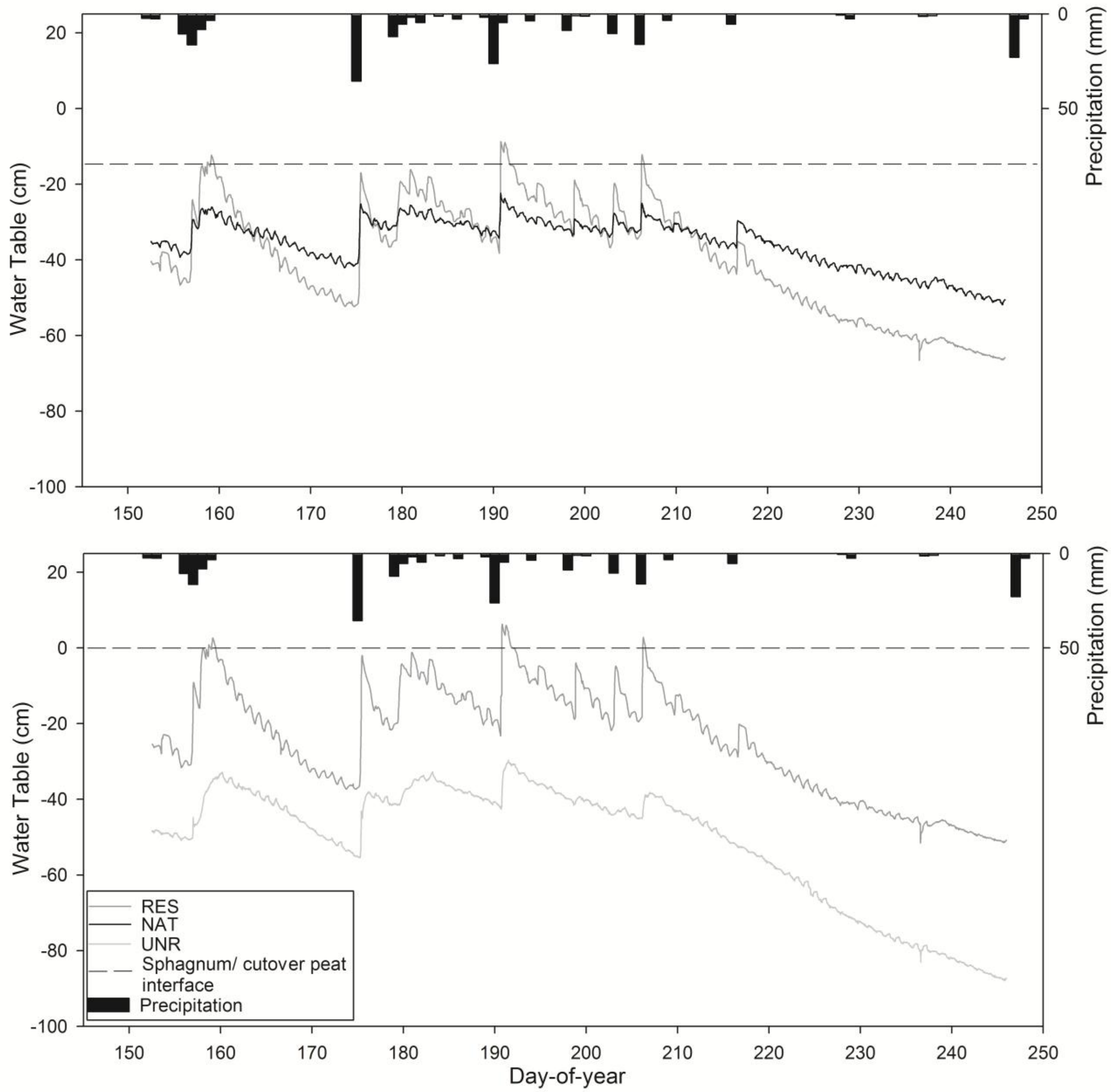

Figure 2-4 Water tables over time (D 145-245) generated from the continuous water table data. RES and NAT's datum are referenced to the top of the Sphagnum moss. RES and UNR's datum are referenced to the top of the cutover peat, ~15 cm below the regenerated *Sphagnum* moss at RES.

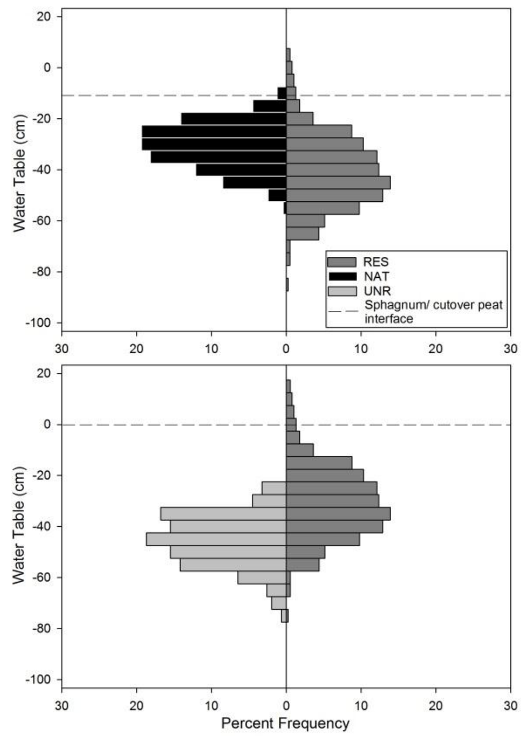

Figure 2-5 Histograms of the manual measurement water tables. NAT (-33.2 ± 9.0 cm) had the highest and least variable average water table, followed by RES (-27.3 ± 14.9 cm) and UNR (-42.3 ± 20.9 cm). RES and NAT's datum are referenced to the top of the *Sphagnum* moss. The RES and UNR's datum are referenced to the top of the cutover peat, ~15 cm below the regenerated *Sphagnum* moss at RES.

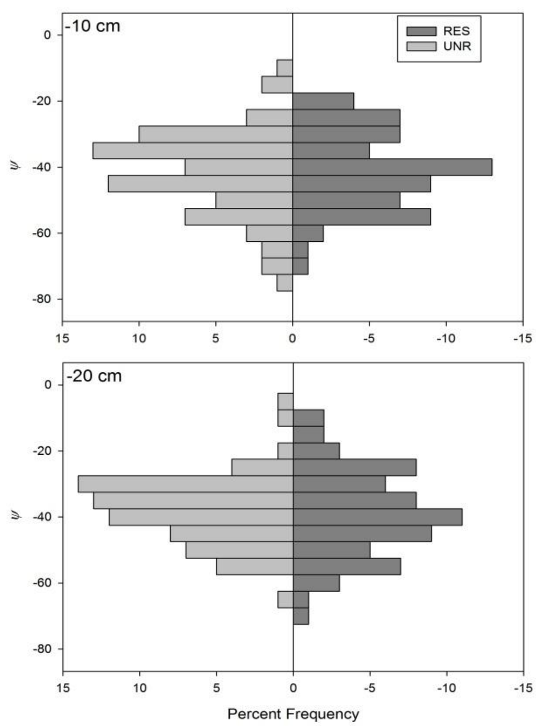

Figure 2-6 Histograms of soil water pressures at 10 and 20 cm below the cutover peat surface (~30 and 40 cm below the regenerated *Sphagnum* surface). RES and UNR had similar average soil water pressures at both depths. The cutover peat/*Sphagnum* interface was at ~ 20 cm below the surface.

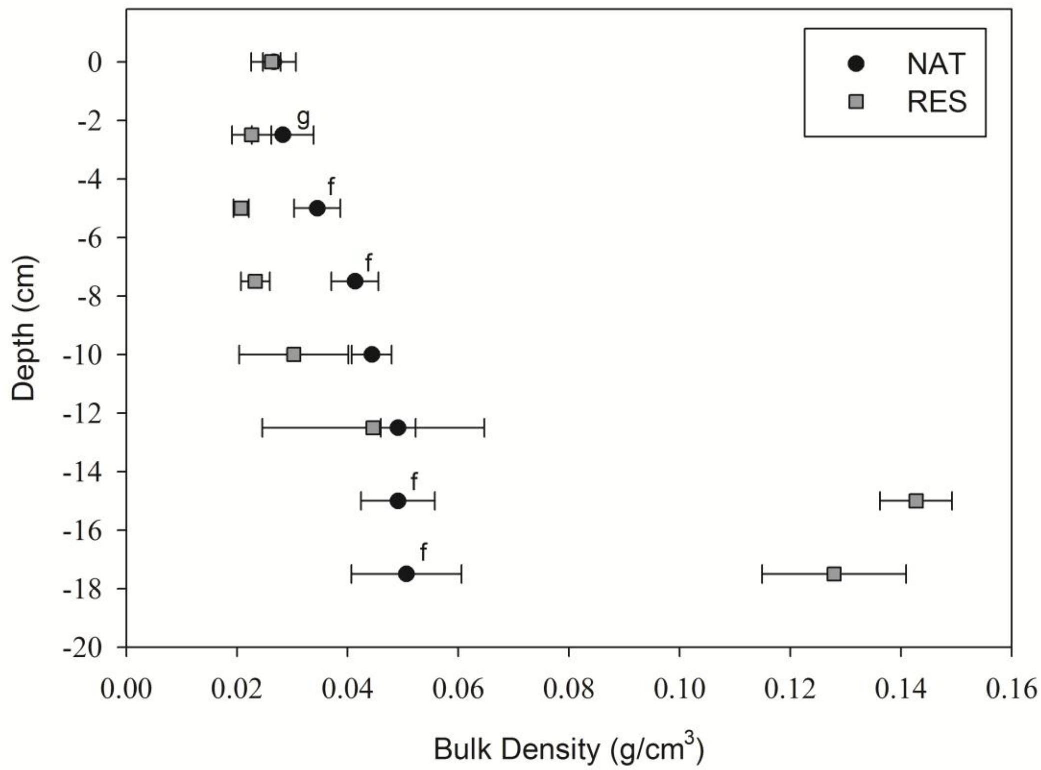

Figure 2-7 Bulk density of the *Sphagnum* moss in 2.5 cm increments of RES and NAT. The capitula (upper 1 cm) are represented by the 0 depth sample. The average cutover peat/*Sphagnum* interface was at ~ 20 cm below the surface. The average cutover peat/*Sphagnum* interface is ~ -15 cm and is apparent through the larger standard deviations in the 15 cm samples at RES. [e] Indicates significantly different than RES at p= 0.05. [f] Indicates significantly different than RES at p= 0.001. [g] Indicates significantly different than RES at p= 0.01. n = 4

2.6 Discussion

Although being a drier than normal spring and summer, rainfall and ET were not distinct from the first 3 years post-restoration (Table 2-1), which were also relatively dry. However, these data show that ET from RES (242 mm) is 87 mm lower than from NAT (329 mm) and 48 mm lower than from UNR (290 mm). The difference in ET between RES and NAT occurred despite both sites having a dominant vegetation cover of *S. rubellum*. The lower average θ in the upper 5 cm of *Sphagnum* at RES (0.12 ± 0.01) compared to NAT (0.23 ± 0.01) (Figure 2-3) was probably limiting ET compared to NAT. Given the relative close proximity of the sites (~ 2 km) the incoming radiation, temperature and relative humidity were similar between sites (data not shown) thus differences in ground heat flux and outgoing radiation would cause the differences in ET between sites (Kellner, 2001). The low moisture contents observed at RES decreased the water available for ET, thus lower ET was observed compared to NAT. The low ET and θ at RES signifies a limited connectivity between the wetter cutover peat (0.74 ± 0.04) and *Sphagnum* capitula (evaporating surface). Given the lower bulk density of moss at RES compared to NAT (Figure 2-7), the former likely had much poorer capillarity, hence limited ability to retain and deliver water to the surface.

The flashy water table at RES (Figure 2-4) indicates it responds to precipitation events more quickly and to a larger magnitude than both NAT and UNR due to wetter antecedent conditions of the cutover peat. The rapid response and the persistently drained state of the regenerated *Sphagnum* signify most of the precipitation was not retained in the loosely structured moss, but infiltrated and saturated the cutover peat or potentially flowed along the cutover peat/*Sphagnum* interface to generate runoff (Figure 2-2). The new moss had little water retention capacity (Figure 2-3) and imparts a low hydraulic resistance, which explains the persistence of flashy runoff hydrographs for RES (Figure 2-2) as was also noted by Shantz and Price (2006b). We note, however, that the ratio of runoff between RES and UNR in 2010 was 1:5.2, compared to 1:2.6 before the moss layer developed, signifying some water detention caused by the moss layer. The water table at RES was statistically higher than at UNR, and since the initial assessments increased by a further ~5-10 cm (Table 2-1). This may in part be explained by this detention of runoff. Despite the higher water table, there was no evidence that ET increased in 2010 compared to 2000 – 2002 (Table 2-1), as the wetter cutover peat still had limited connectivity with the regenerated *Sphagnum*.

The inability of the regenerated *Sphagnum* moss to retain water compared to NAT signifies that the water table and runoff dynamics are still controlled by the cutover peat and not the regenerated *Sphagnum* moss layer. Until the regenerated moss layer develops greater water retention (i.e. through decay, collapse at the base, and lateral branch infilling (Waddington *et al.*, 2011)), it is unlikely that the water table will behave similarly to a natural peat forming system. This includes its carbon sequestration function; although measurements for the dry 2010 season were inconclusive since both RES and NAT experienced a net carbon loss (Strack, unpublished data). Lucchese *et al.* (2010) postulated that a 19 cm thick regenerated *Sphagnum* layer would be needed at BdB to provide sufficient water storage to maintain the water table above the old cutover peat, requiring 17 years based on their measured moss accumulation rates.

The vertical growth of *S. rubellum* (~15 cm) was greater than the rise in water table (~5-10 cm) since restoration leading to the current low average water tables of -42.3 cm. Although *S. rubellum* is a hummock species it may not be as well suited to the low water tables observed at RES as other hummock *Sphagnum* species (Rydin and McDonald, 1985). For example, *S.*

fuscum can thrive with average water tables similar to those observed at RES (-42.3 cm), due to its` greater transport ability (Rydin, 1985; Clymo, 1987; Rydin, 1993), while *S. rubellum* is most productive with higher water tables, typically between 10-20 cm below the capitula (Clymo, 1987). This indicates that the water table at RES still needs to rise by ~20 cm for the regenerated *S. rubellum* to be in its optimal growth habitat. However, this assumes that the moss structure (i.e. bulk density, water retention capacity, capillary conductivity etc.) is similar. Over time, we anticipate that the base of the new moss layer will become partially decomposed and collapse to result in a medium with a smaller pore-size distribution and better water retention properties. Once the water table has risen further (i.e. primarily fluctuating within the regenerated *Sphagnum* moss), it seems likely that it should be able to retain enough moisture to promote a carbon accumulating system.

2.7 Conclusion

Although the restoration measures implemented in 1999 had a large and immediate effect on the site hydrology of BdB (Shantz and Price, 2006a), after ten years of post-restoration development the system is still primarily controlled by water relations in the cutover peat beneath the regenerated *Sphagnum* moss. Although there is a 15-20 cm layer of regenerated *Sphagnum* moss at BdB, its properties are still distinct from a natural system and must evolve further for the hydrological variables to converge. The average water table depth is still outside the optimal range for *S. rubellum*, which covers the site. As the system evolved and the moss layer developed, the vertical growth outpaced the rise in water table, resulting in less favorable conditions for *S. rubellum*, and may result in a shift to *S. fuscum*. The low water tables and hydraulic properties of the moss has led to poor hydraulic connection with the (generally wetter) cutover peat, hence the regenerated *Sphagnum* being ~50% drier than the same species at NAT. The inability for the regenerated *Sphagnum* to transmit water from the wetter cutover peat to the top of the *Sphagnum* is potentially limiting the available moisture for the *Sphagnum* itself, thus possibly retarding the progress of the restoration (and net carbon sequestration). Assuming the mosses can adapt or tolerate this in the short term, more favourable conditions will develop in time as the water retention capacity of the mosses, particularly at the base of the profile, increases with decomposition and compaction or a shift in species from *S. rubellum* to *S. fuscum*. Only then will the water table fluctuate primarily within the regenerated *Sphagnum* moss layer and be more effectively transmitted up the profile to the capitula to facilitate net carbon sequestration.

3.0 The hydrology of the Bois-des-Bel peatland restoration: Hydrophysical properties retarding restoration

3.1 Overview

The Bois-des-Bel peatland was restored in the winter of 1999; since then a ~ 15-20 cm *Sphagnum* moss carpet has regenerated over the site but it is currently unknown how the hydrophysical properties of the regenerated *Sphagnum* moss and cutover over peat influence the restoration of Bois-des-Bel. This study evaluates the hydrophysical properties of Bois-des-Bel, based on a combination of field and monolith experiments, at a Restored (RES), Natural (NAT) and Unrestored site (UNR). The lowest field soil moisture at RES was 0.09 in the *Sphagnum* moss, while 0.20 at NAT. These results were similar in both the monolith experiments and monolith parameterization. The low soil moisture and relatively large abundance of pores > 397 μm in the RES *Sphagnum* resulted in low unsaturated hydraulic conductivity (0.23 cm day^{-1} at ψ = -35 cm), which limits the connectivity between the cutover peat and regenerated *Sphagnum* moss, and high specific yield (0.45), which fails to retain precipitation, compared to NAT *Sphagnum* (1.2 cm day^{-1} and 0.10, respectively). Lateral infilling of the leaves and branches and further basal decomposition is needed to create a larger abundance of small pores (< 397) to increase soil water retention and generate stronger capillary forces to better store and transmit water. To negate the difference in hydrophysical properties between the cutover peat and regenerated *Sphagnum*, the water table might need to fluctuate almost entirely within the *Sphagnum* and combined with a decrease in average pore size and growth of ericaceous shrubs would create conditions suitable for net carbon sequestration.

3.2 Introduction

In bog peatlands, *Sphagnum* moss is the keystone and dominant genus (Rochefort, 2000) and is the primary peat forming plant (Clymo *et al.*, 1998). Peatland harvesting removes the living *Sphagnum* in addition to the acrotelm and much of catotelm (Lavoie *et al.*, 2003; Quinty and Rochefort, 2003), resulting in dense decomposed peat at the surface (Price, 2003). Catotelm peat typically has a relatively small pore size (Carey *et al.*, 2007), low hydraulic conductivity (Boelter, 1965; Price *et al.*, 2003) and high soil water retention (Clymo, 1984; Schouwenaars and Vink, 1992) due to a greater degree of decomposition (Clymo, 1984; Clymo *et al.*, 1998).

Natural regeneration of bog peatlands after harvesting is often limited to vascular vegetation and non-peatland species (Girard *et al.*, 2002; Lavoie *et al.*, 2003; Poulin *et al.*, *in press*). Rochefort *et al.* (2003) proposed restoration measures for North American bog peatlands, which were implemented on the Bois-des-Bel peatland (BdB) in the autumn and winter of 1999. Ten years after restoration it is unknown what hydrological conditions present in the vadose zone of BdB are and how they impact the restoration.

In natural bog peatlands, the surficial peat comprises undecomposed and living *Sphagnum* moss (Rydin, 1985) with an abundance of large pores (Hayward and Clymo, 1982; Quinton *et al.*, 2008), that gives it a high hydraulic conductivity (Baird, 1997; Quinton *et al.*, 2008) and low soil water retention (Hayward and Clymo, 1982; Carey *et al.*, 2007). Furthermore, peat harvesting typically results in water tables far below that of an undisturbed bog (Clymo, 1984; LaRose *et al.*, 1997; Price *et al.*, 2003; Ketcheson and Price, 2011). The combination of low water tables (below -40 cm) (Price and Whitehead, 2001; Ketcheson and Price, 2011) and decreased pores size generates soil water pressures below the limit of *Sphagnum* regeneration of -100 mb (Price and Whitehead, 2001). Harvested sites typically require restoration measures to restored the necessary hydrological conditions (water table above -40 cm and soil water pressure above -100 mb) for successful *Sphagnum* vegetation and the net subsequent carbon sequestration (Campeau and Rochefort, 1996; Waddington *et al.*, 2010).

The restoration measures applied to BdB include ditch blocking, constructing bunds along elevation contour lines, milling to refresh the surface (it had been abandoned for ~20 years) and reintroducing bog peatland vegetation (Rochefort *et al.*, 2003). Restoration measures raised both the water table (> -40 cm) and soil water pressures (> -100 mb) creating conditions suitable for *Sphagnum* recolonization (Shantz and Price, 2006a). The restoration measures were implemented over the existing catotelm peat (the post-harvested surface) (Rochefort *et al.*, 2003) that is structurally unlike the acrotelm peat which *Sphagnum* moss naturally grows on (Price, 2003); however, few long-term studies on the hydrological effect of restoring *Sphagnum* moss on catotelm peat and its effect on the outcome of restoration have been completed.

The restoration measures applied to BdB created hydrological conditions (Shantz and Price, 2006a) suitable for the reintroduction bog peatland vegetation. Lucchese *et al.* (2010) projected that the system would have its net carbon accumulation function restored within 17 years of the initial restoration measures, based on rate of organic matter accumulation, net primary productivity and decomposition rates. Carbon accumulation in peatlands requires relatively high water tables (Strack and Price, 2009; Dimitrov *et al.*, 2010), high soil moisture contents (Lafleur *et al.*, 2005; Waddington *et al.*, 2010) and decay resistant plant material (i.e. *Sphagnum* (Clymo *et al.*, 1998; Belyea and Clymo, 2001). Once these ecohydrological conditions are met the restored peatland will be suitable for net carbon sequestration.

In the three years following the implementation of restoration measures (2000-2002) at the restored section at BdB the water table increased by ~ 30 cm to an average of 32.5 cm below the surface (Shantz and Price, 2006a); well above the threshold for successful *Sphagnum* regeneration (> -40 cm) proposed by Price and Whitehead (2001) at the nearby Cacouna peatland. This led to an increase in soil water pressure 5 cm below the surface by ~ 55 mb to ~ 13 mb compared to pre-restoration (1999) and ~ 24 mb compared to an adjacent Unrestored site (UNR) (Shantz and Price, 2006a). This soil-water pressure is well above the -100 mb limit suggested by Price and Whitehead (2001). Volumetric soil moisture at RES increased by ~ 0.22 (0.51 in 1999) and was typically ~ 0.40 above UNR (Petrone *et al.*, 2004b; Shantz and Price, 2006a). This increase was due to the rise in water table along with the layer of straw mulch that was added during the restoration process (Price *et al.*, 1998). Although the hydrological conditions were suitable for revegetation, the Restored site (RES) was still a net exporter of carbon in 2001 (Petrone *et al.*, 2003).

Six years post restoration (2006) a ~ 15 cm thick carpet of regenerated *Sphagnum* moss covered BdB (Lucchese *et al.*, 2010) and by 2007 Waddington *et al.* (2011) reported lower bulk density, residual soil water content and higher specific yield at RES compared to a Natural site (NAT) within the BdB peatland. These results indicated that although there is a near complete cover of *Sphagnum* moss at the restored site, the structural (bulk density) and hydrological (water retention) properties were dissimilar to natural *Sphagnum* (Waddington *et al.*, 2011), and the restoration could not yet be deemed complete.

Ten years post restoration (2010) RES was dominated by peatland species with some non-peatland wetland species, resulting in a higher net biodiversity than NAT (Poulin *et al., in press*). In addition at RES a 15-20 cm carpet of *Sphagnum* had regenerated, but the hydrology was different from NAT with lower water tables, *Sphagnum* soil moisture contents and evapotranspiration at RES (McCarter and Price, *in review*) and is still a net exporter of carbon

(Strack, unpublished data). A ~ 5-10 cm water table rise has occurred since the initial assessment by Shantz and Price (2006a), however, by 2010 average near-surface (2.5 cm depth) *Sphagnum* moisture contents observed at the Restored site (0.12) were much lower than at NAT (0.22) (McCarter and Price, *in review*). This trend was exaggerated at 17.5 cm (just above the regenerated *Sphagnum*/cutover peat interface at RES) with average water contents of 0.22 and 0.71 at the RES and NAT, respectively (McCarter and Price, *in review*). McCarter and Price (*in review*) concluded that the hydrology of BdB is still controlled by the cutover peat and inferred through soil moisture data that there was limited connectivity between the regenerated *Sphagnum* and cutover peat.

For restoration to be successful (i.e. net carbon sequestering) the regenerated *Sphagnum* needs to maintain suitable soil moisture contents by accessing the stored water in the cutover peat and transfer it to the capitula. Currently it is unknown what hydrophysical processes are the limiting the restoration at BdB and how the system needs to evolve in order to become net carbon sequestering. Therefore the overall objective of this study is to determine why the hydrology of RES does not function similarly to NAT through a combination of field measurements and *Sphagnum*/peat monolith laboratory experiments; while the specific objectives are 1) characterization the hydrophysical properties of RES, UNR and NAT and 2) evaluating the limited connectivity theory proposed by McCarter and Price (*in review*).

3.3 Study Site

BdB is located 10 km northwest of Riviére-du-Loup, Quebec (47°57’47 N, 69°26’23 W, 28 masl) and contains three sites: UNR, RES and NAT. Since restoration measures were implemented in fall 1999 a complete ~15-20 cm of *Sphagnum* moss, chiefly *S. rubellum*, has covered RES within 10 years. NAT is also dominated by *S. rubellum* (Poulin *et al.*, *in press*) with an average peat depth of ~ 2.2 m (Lavoie *et al.*, 2001). The harvested section of BdB (RES and UNR) has a residual peat depth of 1.8 m (Lavoie *et al.*, 2001). The interface between the regenerated *Sphagnum* and the cutover peat is variable over the site with small hummocks being ~ 20 cm, while other areas are ~ 15 cm below the surface of the *Sphagnum* moss as of 2010. In contrast to NAT, where the dominant vascular vegetation are specific peatland plants (e.g. *Chamaedaphne calyculata*, *Rhododendron groenlandicum*, etc.), RES’s vascular species are a mix of peatland and wetland plants, but most prominently *Eriophorum vaginatum* (Poulin *et al.*, *in press*). UNR is dominated by vascular plants typically associated with forests or ruderal ecosystems (Poulin *et al.*, *in press*) and bare (formerly) catotelm peat.

3.4 Methods

3.4.1 Field Methods

Volumetric soil moisture (θ) was recorded every 60 minutes from day-of-year (DOY) 145-290 at 2.5, 7.5, 17.5 and 27.5 cm below the *Sphagnum* surface at two locations in NAT and RES. No θ was recorded at UNR due to equipment malfunction. At RES the 27.5 cm probe was completely in the cutover peat, while the 17.5 cm probe was at the interface region (15-20 cm below *Sphagnum* surface). This region is comprised of a mix of new yet decomposing moss and old cutover peat. Both the 2.5 and 7.5 cm probes were completely in the *Sphagnum* moss at RES. The probes were installed where the *Sphagnum* mosses presented a flat surface to ensure accurate depth placement. At NAT probes were installed in both a *Sphagnum* hummock with no vascular vegetation and a hummock with ericaceous vegetation (*C. calyculata & R. groenlandicum)* in close proximity to each other (< 3 m) and at the same elevation above the water table, thus limiting the potential for dramatically different moss structures. At RES the probes were installed in *Sphagnum* hummocks with only *E. vaginatum* due to its dominance at the site and the paucity of the typical ericaceous species. The probes were calibrated following the method of Topp *et al.* (1980) for each soil type (i.e. natural *Sphagnum*, regenerated *Sphagnum*, cutover peat).

Pressure transducers were used to measure water tabled every 30 min in locations near the TDR sites. Care was taken to ensure the wells were installed in similar depths of *Sphagnum* moss to determine the water table depth below the *Sphagnum* surface. The height of the regenerated *Sphagnum* at RES where the wells were installed was ~ 20 cm.

Field Sampling – Three moss/peat monoliths were sampled on DOY 291 & 292 per site (RES_m, NAT_m and UNR_m). The monoliths were ~35 cm deep (~25 cm at UNR due to high concentration of woody debris ~ 25 cm below surface) and 28 cm in diameter. The samples were taken using a circular guide the same diameter, using a saw to cut around the guide to the appropriate depth. The monoliths were placed in 23 *l* water filled buckets to prevent compression of the sample during transport to the University of Waterloo's Wetland Hydrology Laboratory for further analysis. The monoliths were drained and frozen upon arrival at the laboratory. Once frozen, the bottoms of the samples were cut to produce a monolith of the appropriate height (35 cm) and to ensure a flat bottom contact surface, and placed back in a 23 l bucket modified as described below.

Three additional profiles at each site were taken in 5 cm depth increments by cutting, with scissors, and gently sliding a 5 cm long section of 10 cm diameter PVC pipe into the moss. The sampling follows a modified method outlined by McCarter and Price (*in press*). The sample depths were centered at 2.5, 7.5, 12.5, 17.5, 22.5 and 27.5 cm at RES and NAT and to 22.5 cm at UNR. When the 5 cm long tube was flush with the exposed moss the sample was cut along the bottom of the PVC pipe and withdrawn to produce an undisturbed 5 cm core section. The cores were frozen for transport to University of Waterloo's Wetland Hydrology Laboratory where they were cut in half making 2.5 cm high samples for bulk density and porosity measurements. One-way ANOVA was performed between the RES and NAT/UNR.

3.4.2 Monolith Experiment

Before the monoliths were placed in the buckets, the bottom was filled with ~2 cm of course sand to distribute water pressures evenly across the bottom of the monolith. A 25 μm Nytex screen was placed over the sand and covered with a ~2 cm of 56-76 μm glass layer of beads following a modified tension table method outlined by Paquet *et al.* (1993). This allowed us to mimic a water table 10 cm below the base of the monolith (20 cm for UNR_m). At the base of the buckets an outlet spigot was installed and attached to a Marriott system that supplied a constant water supply and water table for the course of the experiment. A discharge valve was installed between the bucket and Marriott system to allow collection and measurements of the water drained from the sample when the water table was dropped. Once the monoliths were in place, TDR probes were installed 7.5, 15.0 and 27.5 cm below the surface to measure θ, in two monoliths per site. The TDR probes recorded every 20 minutes and individual calibrations for each soil type were derived following the method of Topp *et al.* (1980). A 2.5 cm probe was planned (to complement field measurements) but was not installed due to the high compressibility of the upper 5 cm of the monoliths which would have torn the moss layer as it dried. To estimate θ in capitula at the top of the sample (0 – 1 cm) the peatboard method outline by Strack and Price (2009) was used. Briefly, three (1 x 2 cm) tabs made from calendared peat board were placed equal distance apart along the centre of the monolith and left for 4 hours to reach equilibrium with the surrounding capitula water content. The tabs were then weighed and calibrated using the method of Strack and Price (2009) to convert the measured weight to θ.

After the monoliths were set up they were filled from below with deionized water for 48 hours to saturate them. The water table was then progressively lowered (15, 20, 30, 35 and 45 cm below the surface) and raised in reverse in stages (45, 35, 30, 20 and 15 cm). The specific yield was determined for a given water table drop by collecting the discharge from the monoliths during each water table change. The monoliths were left to equilibrate (typically 2-4 days) at each water table which was determined when θ was stable in a monolith for at least 24 hours. An average of 6 hours of θ measurements were used to determine the final average θ at a given water table.

3.4.3 Monolith Parameterization

Based on the limited variability of the monolith θ data, only one monolith was chosen for parameterization. The monolith was frozen after the monolith experiment (to facilitate sectioning) and cut into 5 cm high (centered every 2.5 cm), 10 cm diameter pucks to a depth of 30 cm (25 cm for UNR_m) and when thawed, inserted into sections of PVC pipe of equivalent size. Each sample was placed on a tension disk (Price *et al.*, 2008) connected to an Erlenmeyer flask whose position was used to control the soil water pressure (ψ), which was set at -5, -10, -15, -25 and -35 cm (then reversed to measure hysteresis), centred at the midpoint of each sample. This ensured the average ψ across the samples was consistent with the pressure tested. The samples were covered to minimize water loss from evaporation and left to equilibrate (a net weight loss of < 1 g d^{-1}) for ~ 7 days.

Once ψ was equilibrated, K_{unsat} was determined based on the method of Price *et al.* (2008), with ψ of -5, -10, -15, -25 and -35 cm. Two disks with 25 µm screens, one above and one below the sample were used. The Erlenmeyer flask was lowered by half the sample height before placing the upper disk on to thus ensuring the entire core was at the desired tension. Before testing the ψ of -35 cm, 15 µm screens were placed on the tension disks as the air entry pressure of the 25 µm screens is greater than 35 cm of pressure. The screens were again replaced with 25 µm screens once the sample was back at -25 cm on the hysteretic curve. The lower disk was connected to an Erlenmeyer flask with a constant head connected to an overflow measured discharge (Q), while the upper disk was connected to a constant head reservoir to ensure a constant supply of water. This disk arrangement allowed for the sample to have an equally distributed pressure across the sample for testing. The samples were run for at least an hour before measurement of Q began. Once Q was at a constant rate it recorded every 5 min for a minimum of 30 min to determine an average value. Q was used in Darcy's law to estimate K_{unsat}, then the samples were weighed so that θ could be determined.

Saturated hydraulic conductivity (K_{sat}) was measured using a Darcy parmeameter under steady state flow conditions. Due to the porous nature of *Sphagnum* a modified wax method (Hoag and Price, 1997) was used. Each sample was wrapped in two layers of plaster of paris to prevent the melted wax from entering the porous sample. Once the plaster paris was dry, a coat of paraffin wax was brushed on the plaster of paris to ensure a water-tight seal. This was then installed in a Darcy parmeameter and sealed with a layer of paraffin wax to ensure no leakage between the sample and the permeameter wall.

The theoretical pore size distribution (pore opening radius, r) was determined with the capillary rise equation (Bear, 1972) based on a given pressure head (h), as

$$r = \frac{2\gamma \cos\beta}{\rho g h} \quad , \qquad \textbf{Eq. 3-1}$$

where γ is the surface tension of water , β is the contact angle (40° for moderately hydrophobic soils (Carey *et al.*, 2007)), ρ is the density of water, and g is gravitational acceleration. The calculated pore opening radius is the largest pore filled with water for a given pressure head. The total fraction of water filled pores (ϕ_{vw}) was determined by

$$\phi_{vw} = \frac{\theta_\psi}{\phi} \quad , \qquad \textbf{Eq. 3-2}$$

where ϕ is the porosity and θ_ψ is the volumetric soil moisture content for a given ψ. Higher fractions of water filled pores indicate more water is contained within the sample for a given pressure head (ψ) (McCarter and Price, *in press*). The relationship between the pore diameter and fraction of water filled pores illustrates both the pore size distribution and the relative abundance of smaller pores. Although based on the $\theta(\psi)$ relationship, this analysis gives good insight into the structure and distribution of the pores within the samples.

The cores were cut in half (2.5 cm high cores) and then the bulk density and porosity of the samples was determined, for comparison with their respective field samples, using a one-way ANOVA and added to the field samples to determine the site averages.

3.5 Results

3.5.1 Field Measurements

Soil moisture and water table – RES had an average water table depth of 53.7 ± 17.8 cm, while at NAT was 31.9 ± 8.3 cm (below the *Sphagnum* surface near the TDR probes). The regenerated *Sphagnum* at RES remained much drier than NAT *Sphagnum* (Figure 3-1). θ in the *Sphagnum* at both NAT (except with ericaceous) and RES remained relatively consistent throughout most of the study period, only varying substantially after DOY 270 (Figure 3-1). In contrast, θ under the ericaceous vegetation was higher and more variable during the study period (Figure 3-1). $\theta_{2.5\ cm}$ and $\theta_{7.5\ cm}$ in the regenerated *Sphagnum* at RES were nearly identical (~0.15), while at NAT $\theta_{7.5\ cm}$ was about 0.10 higher than $\theta_{2.5\ cm}$ (Figure 3-1). Furthermore, $\theta_{17.5\ cm}$ at RES was far drier than at the equivalent depth at NAT. Only brief increases in $\theta_{17.5\ cm}$ were observed (DOY 273 & 281) at RES and quickly decreased as precipitation ceased. In comparison, at NAT the moss retained water rather than shedding it once precipitation ceased (Figure 3-1). NAT $\theta_{17.5}$ ericaceous was completely saturated during the entire study period, unlike that at the NAT site without ericaceous (Figure 3-1). Additionally, both $\theta_{2.5\ cm}$ and $\theta_{7.5\ cm}$ ericaceous were ~ 0.20 higher than their counterparts under only *Sphagnum* at NAT, and showed greater response to precipitation events (especially after DOY 270) (Figure 3-1).

Bulk Density and Porosity – Bulk density increased with depth at NAT and was relatively uniform with depth in the regenerated *Sphagnum* at RES (Figure 3-2). Only the 5.0, 7.5 and 10.0 cm depths were significantly different than RES ($p < 0.01$, 0.001 and 0.001, respectively). However, 15 cm below *Sphagnum* surface at RES the bulk density increased substantially in two samples (the average of the two denoted by [b]), and to a lesser extent in two samples (the average of the two denoted by [a]) (Figure 3-2). Between the dashed grey lines in Figure 3-2 is the transition zone between regenerated *Sphagnum* and cutover peat, where the bulk densities became more similar to UNR (~0.15 g/cm^3) ($p > 0.05$) than NAT (~ 0.053 g/cm^3) ($p < 0.001$). All NAT samples at or below 17.5 cm had much lower bulk density than both RES and UNR (Figure 3-2).

The porosity data exhibited the same general trends between the sites and depths (not shown). From 0-12.5 cm below the surface, RES (0.97 ± 0.01) had slightly higher porosity than NAT (0.94 ± 0.02), although only significantly different at 7.5, 10.0 and 12.5 cm ($p< 0.01$, 0.05 and 0.05, respectively). NAT porosity linearly decreased to 0.91 at 27.5 cm, while at RES porosity sharply declined 15 cm below the surface (0.87) near the transition zone, and decreased further to 0.82 at 27.5 cm (average 15-27.5 cm 0.85 ± 0.03). All UNR samples were similar ($p > 0.05$) and showed no trend in porosity, maintaining an average of 0.83 ± 0.05.

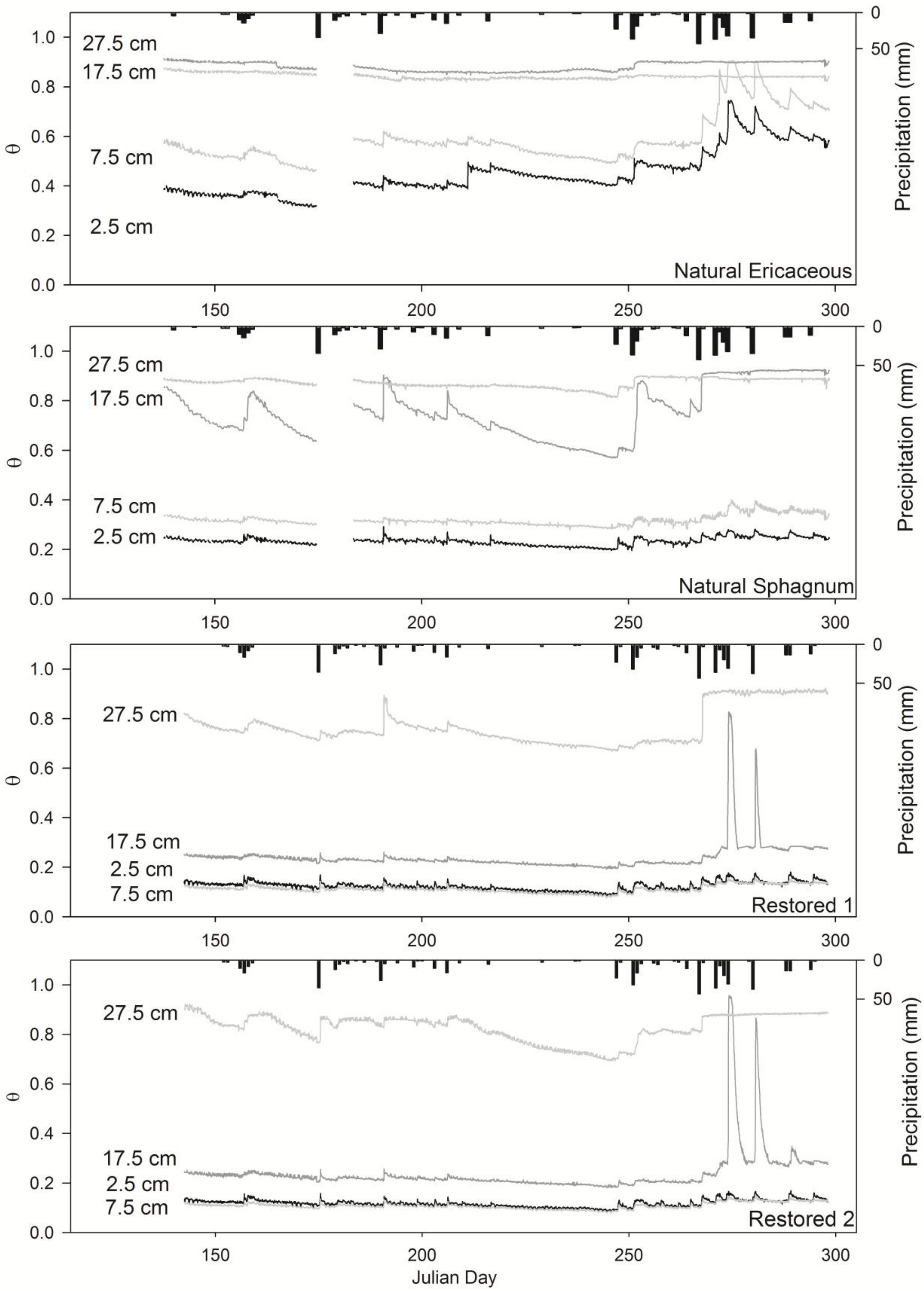

Figure 3-1 Time-series θ from in-situ measurements at 4 sites (2 RES and 2 NAT) from DOY 145-290. RES (bottom) show limited variability between the 2.5 and 7.5 cm probes and overall low θ above the cutover peat/*Sphagnum* interface. NAT probes were placed under a pure *Sphagnum* hummock and an ericaceous covered hummock and show large differences in the θ of the upper 3 probes.

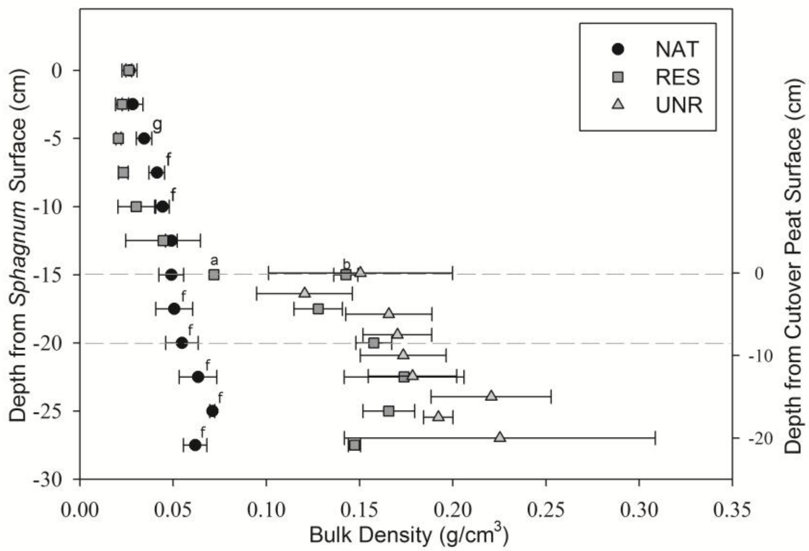

Figure 3-2 Bulk density by samples depth centered at 2.5 cm for all three sites. Between the dashed grey lines represent the interface region between the cutover peat and *Sphagnum* moss at RES. The 15 cm RES samples were split into two groups of 2 (denoted by [a] or [b]) based the dominant material type (*Sphagnum* or cutover peat). n=4 per site

3.5.2 Monolith Experiment

Water retention – The θ-*wt* data from the monolith experiment (Figure 3-3) was consistent with the field observations with respect to θ (Figure 1), where RES_m retained less water than NAT_m in the *Sphagnum* ($\theta_{7.5\ cm}$ and $\theta_{15.0\ cm}$), while remaining similar to UNR in the cutover peat ($\theta_{27.5\ cm}$). Additionally, $\theta_{capitula}$ showed little difference in water retention (Figure 3-3) between NAT_m and RES_m, this trend was also apparent in the bulk density and porosity measurements. Regardless of the water table position, $\theta_{7.5\ cm}$ at RES_m remained very dry (≤ 0.20) and showed limited hysteresis, unlike NAT_m. Although near saturation with a water table of 15 cm, $\theta_{15.0\ cm}$ was below saturation (most likely due to small errors (± 1 cm) in placement of the probes); however, $\theta_{15\ cm}$ experienced a substantial drop (from 0.64 to 0.29) between the "zero" and 20 cm water table position, and decreased to 0.16 at lower water tables. Hysteresis is apparent in all retention tests (Figure 3-3). NAT_m retained far more water through the range of water table decline at both $\theta_{7.5\ cm}$ (0.47 – 0.30) and $\theta_{15\ cm}$ (0.88 – 0.48) compared to RES_m (0.20 – 0.11, and 0.65 – 0.16, respectively) (Figure 3-3). UNR_m typically retained more water than both NAT_m and RES_m (excluding 27.5 cm) but showed less hysteresis than NAT_m (Figure 3-3). At 27.5 cm RES_m had a similar water retention and hysteresis curve than at equivalent depths at UNR_m, although retaining slightly less water at each water table position (~0.10). NAT_m had the strongest hysteresis effects at 27.5 cm.

Specific yield – The monolith specific yield further illustrated the inability of the regenerated *Sphagnum* at RES_m to retain water. Large specific yields (0.44) were observed in the RES_m monolith when the water table was dropped from 15 to 20 cm compared to NAT_m and UNR_m (Figure 3-4). Once below the *Sphagnum*/cutover peat interface the specific yield of RES_m decreased and was more similar to UNR_m than NAT_m (Figure 3-4). Both NAT_m and UNR_m show relativity consistent specific yield regardless of the water table drop (0.1 ± .03 and 0.05 ± 0.03, respectively) (Figure 3-4).

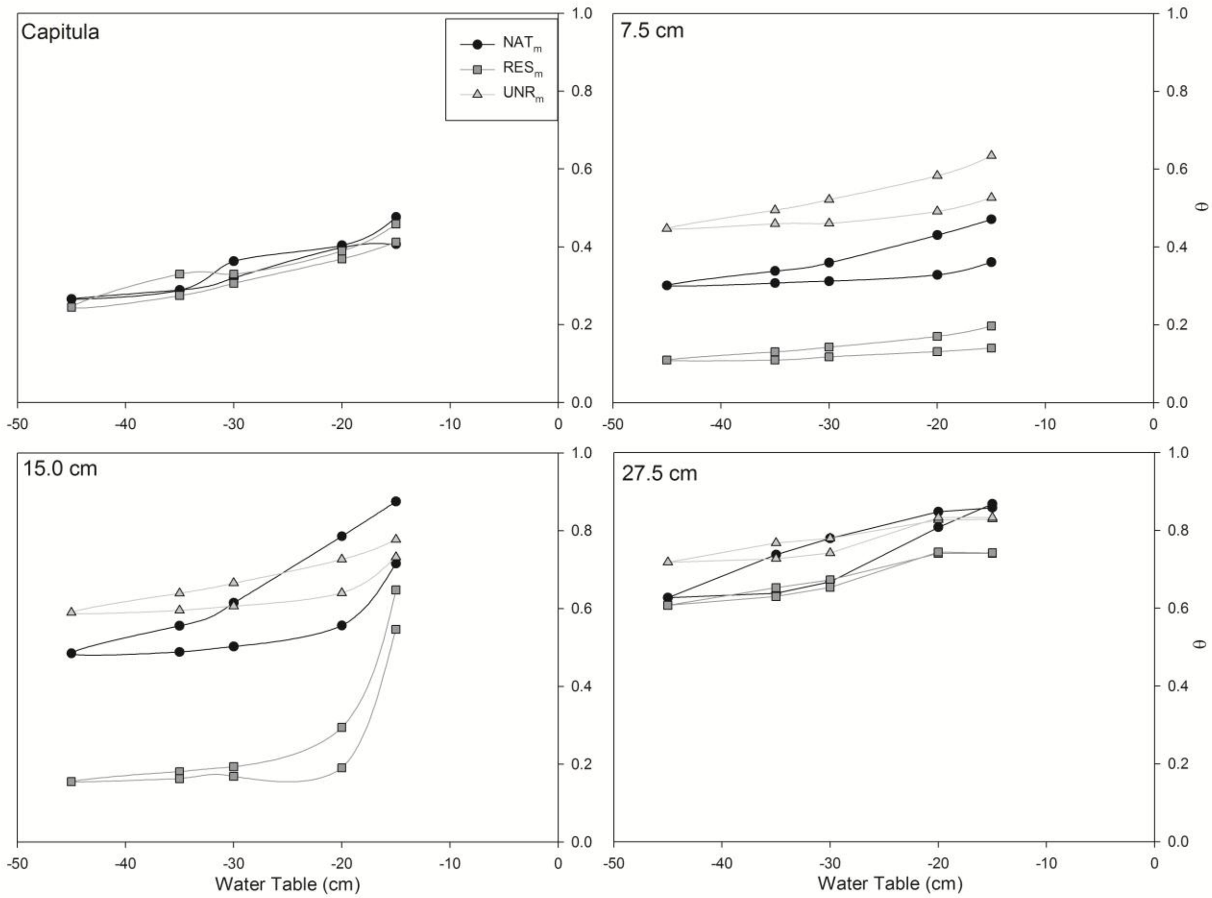

Figure 3-3 Average θ results from the monolith experiments for each probe (n=2) and the capitula peatboard (n=9). The capitula, 7.5 and 15.0 cm measurements are within the *Sphagnum* at RES and the 27.5 cm measurements is within the cutover peat at RES.

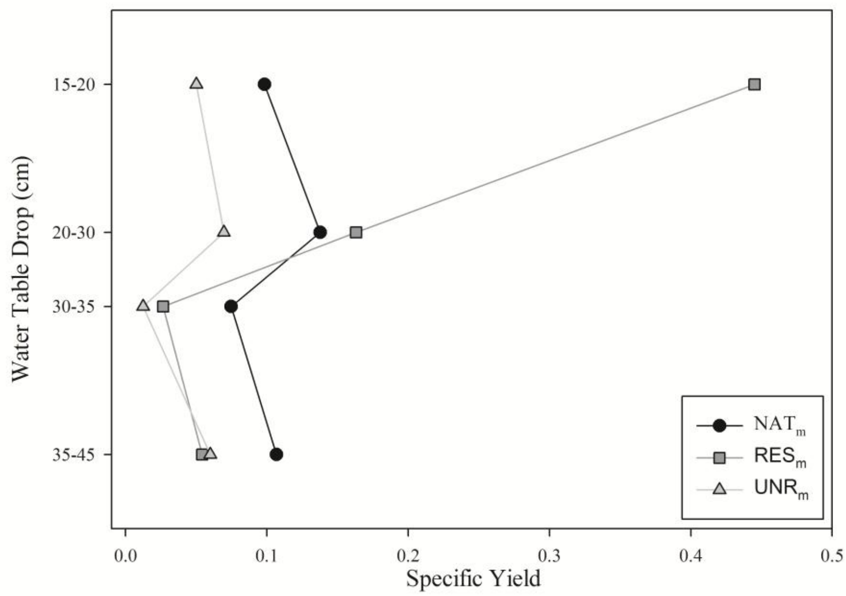

Figure 3-4 Monolith specific yield per water table drop (cm). n=3 per site.

3.5.3 Monolith Parameterization

Water retention – The monolith parameterization cores' bulk density and porosity were not statistically different ($p < 0.001$) from the additional field samples and were thus used to determine the site averages. Soil water retention and hysteresis curves showed similar trends between the monolith experiments (i.e. θ vs *wt*) and water retention of the monolith samples (i.e. θ vs ψ). Water retention was low in the regenerated *Sphagnum* at 2.5, 7.5 and 12.5 cm, typically around 0.2 (Figure 3-5), which was similar to the reported field values (Figure 3-1) and the monolith experiment at water tables below 15 cm (Figure 3-3). Higher θ of the 17.5 cm sample was observed (more similar to the 22.5 and 27.5 cm samples) at RES, however, the sample still desaturated quickly and showed limited hysteresis (similar to the 2.5. 17.5 and 12.5 cm samples) (Figure 3-5). RES 22.5 and 27.5 cm samples were more similar to UNR than NAT. RES θ of the capitula sample had lower water retention compared to NAT θ of the capitula sample and showed less hysteresis (Figure 3-5).

Hydraulic conductivity – The regenerated *Sphagnum* (excluding the capitula) at RES had higher K_{sat} values (6681 cm d^{-1}) than NAT (4495 cm d^{-1}) but (once tension was applied) K_{unsat} at RES decreased more quickly than at NAT, ultimately leading to lower K_{unsat} (typically nearly an order of magnitude) at a given ψ, although still higher than UNR possibly due to the majority of water filled pores not contributing significantly to flow in UNR samples (Figure 3-6).

Pore size and porosity - The fraction of water-filled pores in the capitula, ϕ_{vw} , was similar although slightly higher in NAT than RES (~0.4) indicating a similar number of same size pores. For pore sizes < 198 μm there was a larger proportion of water-filled pores in the capitula of NAT, suggesting the pores were typically smaller than at RES (Figure 3-7). The regenerated *Sphagnum* moss at all depths (excluding the capitula) at RES had similar theoretical pore size distributions (Figure 3-7), showed a relatively low proportion of water-filled pores (~0.2), and changed little over the range of pore diameters tested (Figure 3-7). The 17.5 cm sample (the transition zone between cutover peat and *Sphagnum*) showed an overall increase in ϕ_{vw} (0.69) but a similar limited decrease in ϕ_{vw} over the pressures tested. NAT had constantly higher ϕ_{vw} as depth increased (excluding the capitula). While NAT's ϕ_{vw} increased with depth, the slopes of the lines were similar between 2.5, 7.5 and 12.5 cm samples and between the 17.5, 22.5 and 27.5 cm samples (similar slopes indicate pores of a similar size are draining). UNR's upper two samples (2.5 and 7.5 cm) differed in the actual ϕ_{vw}, but had a consistent decrease in ϕ_{vw} of ~ 0.2 over the pressures tested (Figure 3-7). The bottom 3 UNR samples (12.5, 17.5 and 22.5 cm) all showed the same decrease (~0.1) in ϕ_{vw}. Cutover peat from RES mimics UNR (i.e. 22.5 cm) (Figure 3-7).

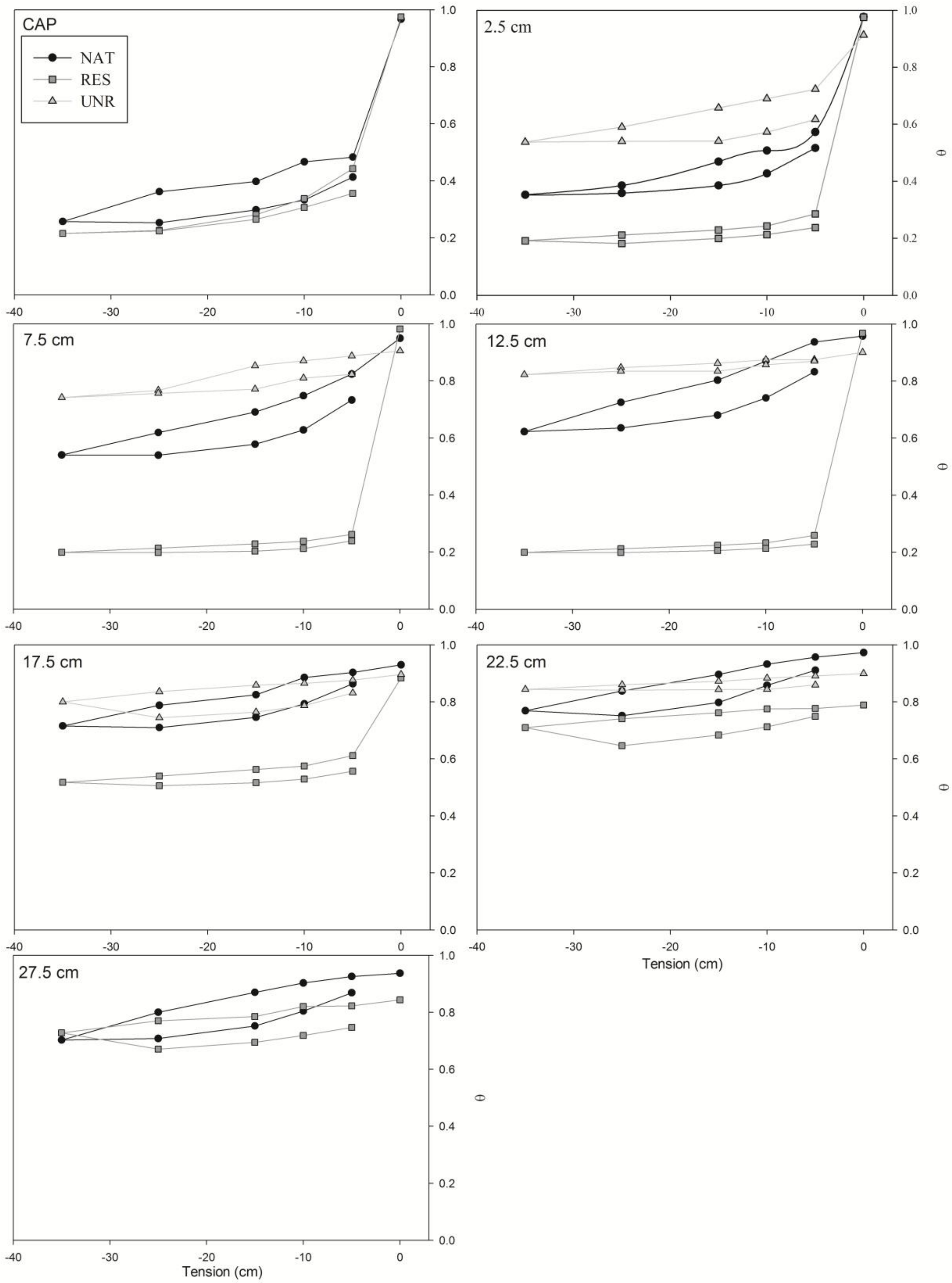

Figure 3-5 Soil water retention and hysteresis curves from the monolith parameterization for each sample depth. RES 22.5 and 27.5 cm are within the cutover peat and the 17.5 cm sample is within the transition zone between cutover peat and *Sphagnum* moss.

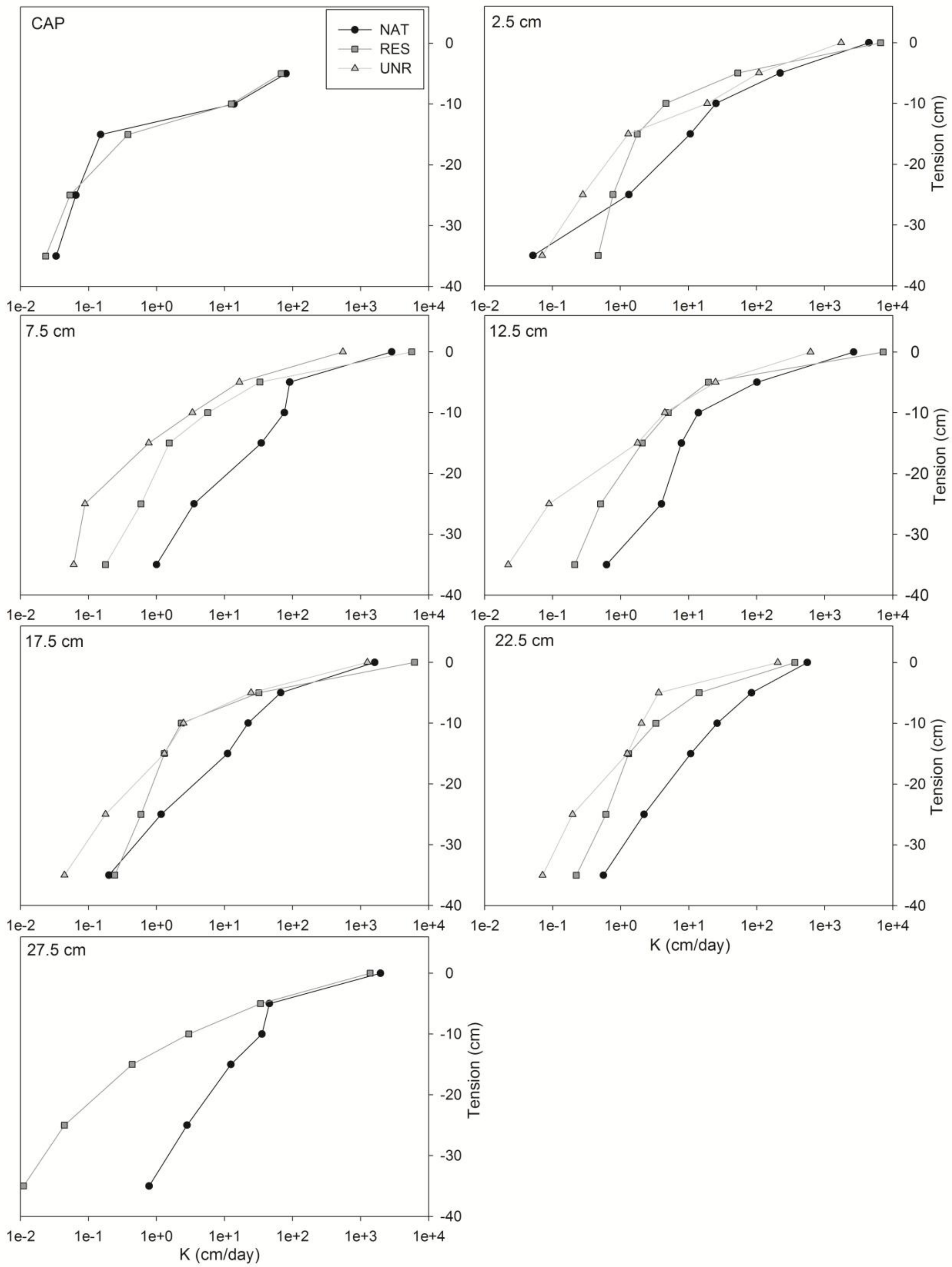

Figure 3-6 Hydraulic conductivity and ψ from the monolith parameterization for each sample depth. RES 22.5 and 27.5 cm are within the cutover peat and the 17.5 cm sample is within the transition zone between cutover peat and *Sphagnum* moss. The hysteretic curves were removed for clarity but follow the same general trends as the soil water retention hysteretic curves.

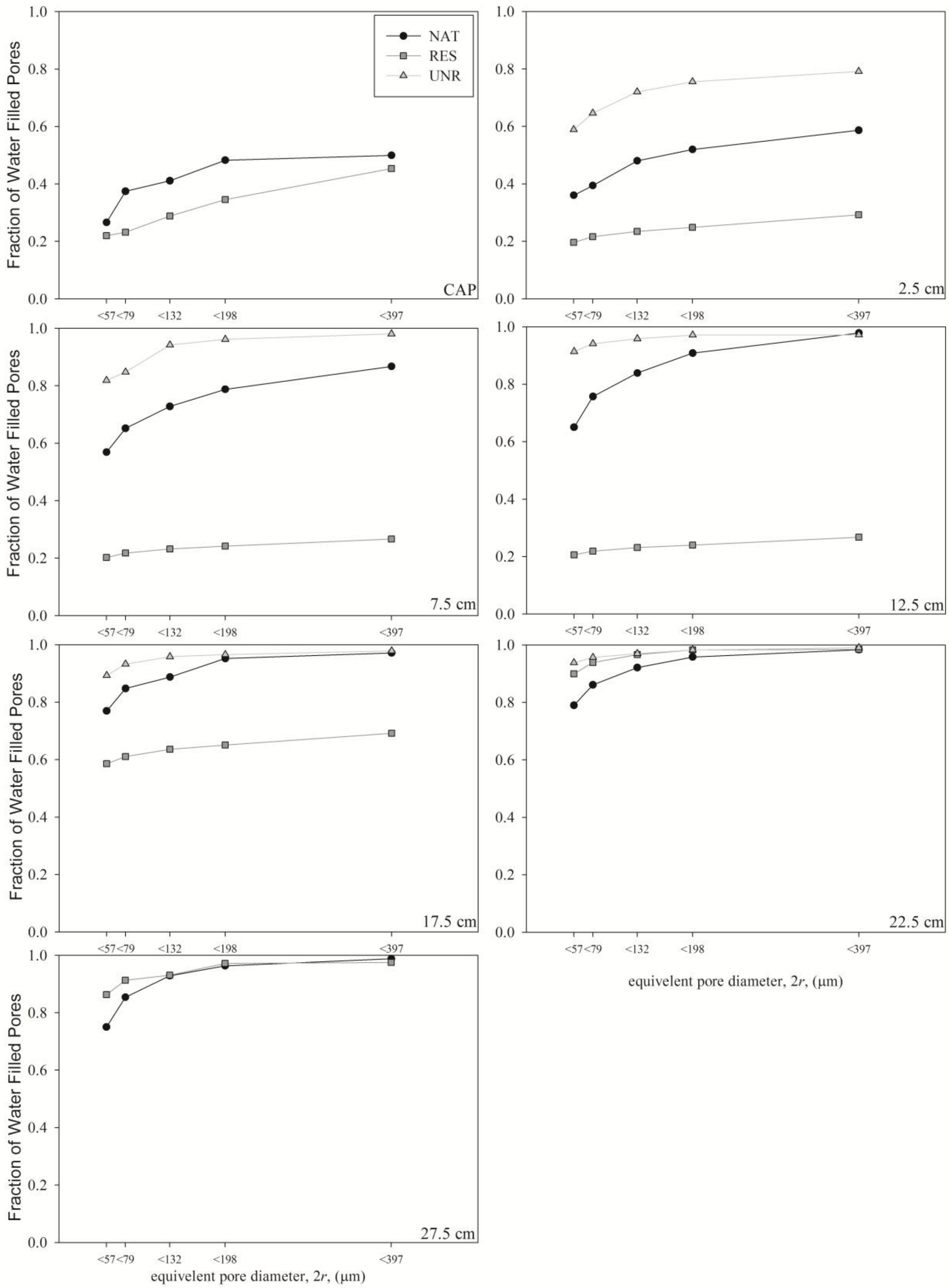

Figure 3-7 Theoretical pore size distribution and ϕ_{vw} curves from the monolith parameterization for each sample depth. The theoretical pore size represents the largest diameter pore that is filled with water. Higher plotted ϕ_{vw} indicate more smaller pores than lower plotted ϕ_{vw}. Higher slopes of the line represent a less even pore size distribution over the pore sizes tested. RES 22.5 and 27.5 cm are within the cutover peat and the 17.5 cm sample is within the transition zone between cutover peat and *Sphagnum* moss.

3.6 Discussion

The lower values of θ measured in the field at NAT *Sphagnum* compared to NAT ericaceous (Figure 3-1) are likely due to greater shading provided by the ericaceous shrubs (Farrick and Price, 2009), subsequently reduced the evapotranspiration losses (McNeil and Waddington, 2003). At RES there is also very limited ericaceous coverage and the dominant vascular plant cover was *Eriophorum vaginatum* (Poulin *et al*., in press), a sedge species predominantly located in hollows and not hummocks (Rydin and McDonald, 1985) in undisturbed bogs. The limited canopy cover at RES would increase the incoming radiation on the surface of the regenerated *Sphagnum*, further increasing evapotranspiration if moisture was not limiting; however, θ was limiting at RES which resulted in lower evapotranspiration than NAT (McCarter and Price, *in review*). This partially explains the low θ of the regenerated *Sphagnum* at RES, although we attribute a greater share of the difference to the structure of the mosses, as described below.

RES and NAT capitula typically had higher θ than the lower layers of unsaturated moss (Figure 3-3) primarily due to their higher bulk density (Figure 3-2) and smaller proportion of large pores (< 397 μm) (Figure 3-7). This trend was most apparent at RES where the capitula θ under tension was higher in both the monolith *wt* experiment (Figure 3-3) and the monolith parameterization of $\theta(\psi)$ (Figure 3-5), than it was in the underlying moss. Since the capitula is the growing part of the plant, its higher θ may allow the plant to remain photosynthetically active for longer than it otherwise could, potentially explaining the success of RES *Sphagnum* regeneration.

RES's regenerated *Sphagnum* did not have high enough soil water retention (Figure 3-5) to retain precipitation (Figure 3-1, DOY 273 & 281) and must rely on water transported from the relatively wet cutover peat (Figure 3-1) and water table. However, the high θ of the cutover peat and the low θ of the regenerated *Sphagnum* (particularly at 17.5 cm just above the cutover peat) indicated limited transfer between the two layers (McCarter and Price, *in review*). The cutover peat at RES was similar to the peat at UNR in bulk density (Figure 3-2), pore size distribution (Figure 3-7), water retention (Figure 3-3 & Figure 3-5) and specific yield (Figure 3-4). During restoration the surface of RES was altered through removal of spontaneously regenerated vegetation, tilling, grading, bund construction, mulch application and compaction from heavy machinery; however, the results indicated that the hydrophysical properties (excluding K_{sat} and

K_{unsat} which increased post restoration) remain unchanged through the restoration process. The restoration measures created a growth surface that has sufficiently high soil water pressures (> -100 mb) for *Sphagnum* recolonization but generated strong capillary forces due to a high abundance of small pores, as illustrated by high ϕ_{vw} with a pore diameter < 57 μm. This two layer capillary system (i.e. low capillarity strength of *Sphagnum* and high capillarity strength of cutover peat) created a capillary barrier between the regenerated *Sphagnum* and cutover peat, which potentially retards restoration.

For most of the study period, the field $\theta_{2.5\ \mathrm{cm}}$ and $\theta_{7.5\ \mathrm{cm}}$ depths of the regenerated *Sphagnum* at RES (Figure 3-1) are close to the residual water contents (θ_r) reported by Waddington et al. (2011) (0.10 - 0.14). These water contents indicate that the mosses at the restored site are potentially under moisture stress compared to the same mosses in a natural peatland, whose field $\theta_{2.5\ cm}$ and $\theta_{7.5\ cm}$ (Figure 3-1) did not reach their residual water contents. Regenerated *Sphagnum*'*s* low bulk density (Figure 3-2) and poor soil water retention (Figure 3-5) were almost identical between sample depths (2.5, 7.5 and 12.5 cm), indicating a similar number of large pores (Figure 3-7) throughout all of the regenerated *Sphagnum*; in other words its loose structure provided it with poor retention capabilities. Unlike other moss genera, *Sphagnum* will devote resources to either sustained fast growth or structural growth (Turetsky *et al.*, 2008). Waddington *et al.* (2011) postulated that the limited retention and low θ_r observed at RES was a result of the mosses devoting resources to sustain fast growth (vertical) over structural growth. The similarity of the regenerated moss' physical properties is consistent with a sustained growth pattern. In comparison, NAT illustrates structural development as the theoretical pores size is smaller, due to a combination of greater interlinking of branches and leaves (Turetsky *et al.*, 2008) within the living *Sphagnum* and partial decomposition and collapse of older underlying layers. For RES to have conditions suitable for net carbon sequestration, the regenerated *Sphagnum* must devote more resources to structural growth as opposed to sustained fast growth, and more time for decomposition and collapse of the layer, which would result in higher θ. At RES's 17.5 cm layer there were some indications that decomposition had changed the pore structure and thus water retention characteristics of the layer. The ϕ_{vw} is greater (0.69-0.55) (Figure 3-7) at 17.5 cm than the above regenerated *Sphagnum* layer including the capitula. The greater abundance of smaller pore (< 397 μm) imparted increased soil water retention (Figure 3-1, Figure 3-3 & Figure 3-5) at 17.5 cm but did not generate enough capillary force to access the tightly held water in the cutover peat as seen by low field θ in the regenerated *Sphagnum*. Further decomposition of the basal layers (i.e. directly above the cutover peat) could create pores small enough to generate the necessary capillary forces to access the water stored in the cutover peat.

Another limitation to the upward transfer of water through the moss to the capitula was due to relatively low K_{unsat} of the regenerated *Sphagnum* (Figure 3-6). When the soil water retention and hydraulic conductivity curves were extrapolated to $\theta = 0.15$ (the approximate $\theta_{2.5\ cm}$ of RES's regenerated *Sphagnum* seen in Figure 1), $K_{unsat} \approx 0.002$ cm d^{-1}. Given the average evaporation (flux) reported by McCarter and Price (*in review*) at BdB (~ 0.5 cm d^{-1}), this would require a large pressure gradient ($dh/dl \approx 250$) and a resulting surface pressure head of -4375 cm to supply a steady-state flux (no change in water storage in the moss layer). Although surface pressure head has been numerically simulated (c.f. McCarter and Price (*in press*)), no methods exist to directly measure the surface pressure head in *Sphagnum* moss. In contrast at NAT, whose $\theta_{2.5cm}$ $K_{unsat} = 0.20$ (the lowest field θ values recorded under only *Sphagnum*) is 0.48 cm d^{-1}, could potentially supply the average evaporation at BdB under unit hydraulic gradient. Since water cannot be readily transmitted from the cutover peat, and the soil water retention of the capitula is limited, the regenerated *Sphagnum* could receive water from dew or distillation to prevent desiccation (Carleton and Dunham, 2003). Consequently, further structural development of the regenerated *Sphagnum* is required to increase its soil water retention and K_{unsat}. However, even with this, the system could still be limited by the restricted water supply from the cutover peat because of the capillary barrier effect and potentially restricted by K_{unsat}, which here dropped to 0.22 cm d^{-1}, under the pressure range tested. These results confirm the conclusions of Waddington et al., (2011) that further lateral infilling and basal decomposition (McCarter and Price, *in review*) of the regenerated *Sphagnum* is required before BdB will have suitable hydrological conditions for net carbon sequestration.

3.7 Conclusions

Although providing suitable habitat for *Sphagnum* recolonization and subsequent growth, the North American bog peatland restoration approach depends on undirected succession after restoration. Essentially the species best suited for the habitat, in BdB's case *S. rubellum* and *E. vaginatum*, would thrive while other species in the donor seed pool would be outcompeted, such as *S. fuscum* and ericaceous species. Although *S. rubellum* and *E. vaginatum* were able to successfully recolonize the site and form a substantial *Sphagnum* carpet, the specific combination of the limited shading effects provided by *E. vaginatum* and the sustained vertical growth of *S. rubellum* severely limits the ability of the restored peatland to remain adequately wet for net carbon sequestration due to the loose structure (low bulk-density and relatively large pores) these two conditions create. While this restoration approach relies on natural succession, it might be prudent to plant ericaceous species once a suitable *Sphagnum* carpet has developed which would increase the near surface moisture content and potentially allow the *Sphagnum* to allocate more resources into structural growth. In turn this could result in increased water retention and hydraulic conductivity of the *Sphagnum,* thus facilitate upward transfer of moisture if the low hydraulic conductivity of the cutover peat are not limiting. To negate the dramatically different hydrophysical properties between the cutover peat and *Sphagnum* moss the water table would need to fluctuate almost entirely within the regenerated *Sphagnum* moss and not the cutover peat. A combination of all three processes will probably be required for BdB to become net carbon sequestering. Given its trajectory it seems likely that the system will self-regulate and make the necessary structural changes over time; however, it is plausible that under severe drought stress the regenerated *Sphagnum* will not survive, which would be catastrophic for the restoration goal.

4.0 Conclusions and Implications

Notwithstanding successful reintroduction of bog peatland vegetation and positive hydrological changes at BdB, ten years posts restoration the cutover peat is still the primary control on the hydrology. The regenerated *S. rubellum* does not have the hydrophysical properties (i.e. water retention, hydraulic conductivity, pore geometry, porosity and bulk density) needed to support conditions suitable for net carbon sequestration after ten years. These hydrophysical parameters are reflected in the lack of change of the runoff dynamics and evapotranspiration since the initial assessments. Despite a modest further water table rise of 5-10 cm since the initial hydrological assessment of Shantz and Price (2006a), the regenerated *Sphagnum* cannot adequately access water in the cutover peat due to the weak capillary forces generated by the abundance of larger pores, resulting in relatively dry *Sphagnum* directly above the wet cutover peat. Effectively, a capillary barrier is formed between the cutover peat and the regenerated *Sphagnum* moss due to the large difference in average pore-diameter. Further compounding this, the regenerated *Sphagnum* is still unable to retain precipitation, and the majority of precipitation becomes soil water in the cutover peat or generates runoff. Additionally, the constantly dry conditions caused by the relative abundance of large pores of the regenerated *Sphagnum* results in low unsaturated hydraulic conductivities, further retarding water transfer from the cutover peat. The inability to obtain moisture from the cutover peat and the incapacity to retain moisture from precipitation combined with the low unsaturated hydraulic conductivity results in *Sphagnum* at the Restored site being ~ 50% drier than the same species at the Natural site and creates conditions unsuitable to sequester carbon.

The poor connectivity between the regenerated *Sphagnum* and cutover peat is primarily due to physiological and ecological processes rather than hydrological. The high abundance of large pores at the Restored site was primarily caused by sustained vertical growth of the *Sphagnum* following restoration, as opposed to structural growth, which results in a higher density of leaves and branches; thus smaller pores. Increased abundance of smaller pores will retain and transmit water more efficiently than larger pores. For *S. rubellum* to create net carbon sequestering conditions, structural growth must occur to better retain and transmit water. Although *S. rubellum* is the dominant *Sphagnum* species at BdB, other *Sphagnum* species, such as *S. fuscum*, are better suited to the low water tables observed and it is possible that *S. fuscum* will begin to dominate the site in the years to come. *S. fuscum* has slightly higher pore connectivity than *S. rubellum* and this shift in species could potentially result in conditions suitable for net carbon sequestering at BdB. Moreover, higher near surface *Sphagnum* moisture contents are observed under ericaceous shrubs compared to pure *Sphagnum* lawns, which are more typical of the Restored site. Increasing the coverage of ericaceous shrubs at BdB could increase the near surface moisture contents due to decreased evapotranspiration from the capitula. It is possible that in the next few years ericaceous species might become more dominant at the site, thus reducing moisture loss. However, it is also possible that the original seed bank used during restoration is no long viable and planting will be required to return the ericaceous species.

North American peatland restoration relies on restoring the necessary hydrological conditions for the vegetation to re-establish itself with no further intervention. Given the current state of BdB it might be prudent to intervene in future restorations to accelerate the return of net carbon sequestering functionality to peatlands. Planting ericaceous shrubs to increase the shading on the regenerated *Sphagnum* could decrease water loss from evaporation and potentially produce healthier *Sphagnum*. Furthermore, targeting *Sphagnum* species in donor material collection that include more drought avoidant species (i.e. *S. fuscum*) could increase the ability of regenerated *Sphagnum* to access and transmit water from the cutover peat to the capitula. However, it is unknown why the regenerated *Sphagnum* allocates more resources to vertical growth rather than structural growth when grown on cutover peat and further research into the mechanisms controlling growth dynamics of *Sphagnum* are needed.

Although after ten years this approach is partially successful (i.e. returned vegetation but not hydrology nor net carbon sequestration), it is still unknown whether this approach will be completely successful. There have been several estimated predictions to achieve complete restoration but they have been made with partial information (i.e. just ecological succession or decomposition rates). To fully grasp the complexities of peatland restoration a more holistic approach is needed when attempting to predict how long restoration will take. Through incorporating the hydrological, ecological and biogeochemical processes a better understanding of peatland growth, development and function will arise and likely aid in restoration.

Through assessing the large scale (water table, evapotranspiration, runoff, etc.) in conjunction with the small scale (soil water retention, hydraulic conductivity, pore size distribution, etc.) a complete ecohydrological snap-shot of Bois-des-Bel ten years post restoration is observed and it is clear BdB is a site of two scales. The limited connectivity between the cutover peat and the regenerated *Sphagnum* moss coupled with the cutover peat still controlling much of the large scale hydrology results in a system that is partially restored; yet is still on course for complete restoration. This research identifies how it is the structure of the regenerated *Sphagnum* moss that inhibits the development of conditions suitable for net carbon sequestration and gives some insight on how to improve upon the restoration techniques. Despite the emphasis on the hydrology of BdB, this research has far reaching implications on both the ecology and biogeochemistry of restored peatlands in North America.

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