

The hydrology of the Bois-des-Bel peatland restoration: hydrophysical properties limiting connectivity between regenerated *Sphagnum* and remnant vacuum harvested peat deposit

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ABSTRACT

The Bois-des-Bel peatland was restored in the winter of 1999; since then, an ~15–20 cm *Sphagnum* moss carpet has regenerated over the site, but it is currently unknown how the structure of the regenerated *Sphagnum* moss and cutover peat influences the hydrology 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 (UNR) site. The lowest field soil moisture in the *Sphagnum* moss at RES was $0.09 \text{ cm}^3 \text{ cm}^{-3}$, while $0.20 \text{ cm}^3 \text{ cm}^{-3}$ at NAT. These results were similar in both the monolith experiments and individual core hydraulic parameterization (i.e. soil water retention and unsaturated hydraulic conductivity). The low soil moisture and relatively abundant large pores ($>397 \mu\text{m}$) in the RES *Sphagnum* resulted in low unsaturated hydraulic conductivity (0.23 cm day^{-1} at $\psi = -35 \text{ cm}$) and high specific yield (0.45) compared with NAT *Sphagnum* (1.2 cm day^{-1} and 0.10, respectively). The abundance of large pores at RES resulted in hydrological conditions dissimilar to NAT and limited connectivity with the cutover peat, the latter being similar to UNR. To negate the implications of limited connectivity on water transfer from the cutover peat to the regenerated *Sphagnum*, the water table would need to fluctuate almost entirely within the regenerated *Sphagnum* layer. This will occur in time, as decomposition and compression cause a decrease in average pore size of the regenerated moss, thus detaining water and resulting in a higher water table. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS peatland restoration; harvested bog; *Sphagnum*; water retention; unsaturated hydraulic conductivity

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INTRODUCTION

In many bogs, *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 part of the catotelm (Lavoie *et al.*, 2003; Quilty and Rochefort, 2003), resulting in relatively 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) because of a greater degree of decomposition (Clymo, 1984; Clymo *et al.*, 1998). Unlike catotelm peat, the upper layer in many undisturbed bogs comprises undecomposed, poorly decomposed and living *Sphagnum* mosses (Rydin, 1985) with an abundance of large pores

(Hayward and Clymo, 1982; Quinton *et al.*, 2008). This results in high hydraulic conductivity (Baird, 1997; Quinton *et al.*, 2008) and low soil water retention (Hayward and Clymo, 1982; Carey *et al.*, 2007). Natural regeneration of bogs after harvesting is often limited to a sparse cover of vascular vegetation and non-peatland species (Girard *et al.*, 2002; Lavoie *et al.*, 2003; Poulin *et al.*, 2012). 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 pore size generates soil water pressures near the surface of the cutover peat, below the limit of *Sphagnum* regeneration of -100 cm (Price and Whitehead, 2001). Harvested sites typically require restoration measures to restore the necessary hydrological conditions (water table above -40 cm and soil water pressure above -100 cm) for successful *Sphagnum* revegetation and subsequent net carbon sequestration (Campeau and Rochefort, 1996; Waddington *et al.*, 2010). Although re-wetting, chiefly

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ditch blocking, increases the water table compared with drained sites, the water table fluctuations, storm response and mean water table depth are still divergent from adjacent undisturbed peatlands (Shantz and Price, 2006b; Holden *et al.*, 2011; McCarter and Price, 2013), indicating incomplete hydrological restoration.

Rocheffort *et al.* (2003) outlined restoration measures for North American bogs, in part based on measures implemented on the Bois-des-Bel (BdB) peatland in the autumn and winter of 1999. The restoration measures applied to BdB include ditch blocking, constructing bunds along elevation contour lines, reintroducing bog vegetation using the moss-transfer method (Rocheffort *et al.*, 2003) and applying straw mulch to create a suitable microclimate. Following the implementation of restoration measures (2000–2002), the average growing season water table and soil water pressures increased from -65.4 ± 6.9 and -63.6 ± 26.9 cm (1999) to -32.5 ± 11.4 and -13 ± 11.3 cm (2000–2002), respectively (Shantz and Price, 2006b; Shantz and Price, 2006a). This created conditions suitable for *Sphagnum* recolonization, which by 2002 covered 69% of the site (Rocheffort *et al.*, 2013). Growing season average volumetric soil moisture ($\text{cm}^3 \text{cm}^{-3}$, thus hereafter expressed without units) at the restored site (RES) increased by ~ 0.22 (0.51 ± 0.03 in 1999) and was typically ~ 0.40 above the unrestored site (UNR) (Petroni *et al.*, 2004; Shantz and Price, 2006b). This increase in volumetric soil moisture was due to the rise in water table along with the layer of straw mulch that was added during the restoration process to decrease evaporation (Price *et al.*, 1998). Although the hydrological conditions were suitable for revegetation, RES was still a net exporter of carbon in 2001 (Petroni *et al.*, 2003). The restoration measures were implemented over the existing catotelm peat (the post-harvested surface) (Rocheffort *et al.*, 2003) that is structurally unlike the acrotelm peat that *Sphagnum* moss naturally grows on (Price *et al.*, 2003). The abrupt interface between newly regenerated mosses and the old cutover peat affects the hydrological connectivity, whereby the moss moisture content is only sensitive to water table fluctuations when the water table is no less than 20 cm below the cutover surface (Ketcheson and Price, 2014).

Six years post-restoration (2006), a ~ 15 cm thick carpet of regenerated *Sphagnum* moss covered BdB (Lucchese *et al.*, 2010). By 2007, the moss at RES was reported to have lower bulk density, lower residual soil water content and higher specific yield compared with a natural site (NAT) (Waddington *et al.*, 2011). Furthermore, Waddington *et al.* (2011) found limited within-site variability in bulk density, porosity and residual soil water content at both RES and NAT. These results indicated that although there is a near complete cover of *Sphagnum* moss at RES, the structural (bulk density) and hydrological (water retention) properties remained dissimilar

to undisturbed *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 specific wetland species, resulting in a higher net biodiversity than NAT (Poulin *et al.*, 2012). In addition, the formation of a hummock-hollow topography has begun to appear at RES, but species assemblages on the hummocks are still dissimilar to hummocks at NAT (Pouliot *et al.*, 2012). Although a 15–20 cm carpet of *Sphagnum* had regenerated at RES, lower average *Sphagnum* soil moisture contents, evapotranspiration and water tables were observed compared with NAT (McCarter and Price, 2013). Thus, the hydrology of RES is still divergent from NAT, and RES in 2010 was a net exporter of carbon (Strack and Zuback, 2013). An ~ 5 – 10 cm rise in the mean annual water table has occurred since the initial assessment by Shantz and Price (2006b); however, by 2010, average near-surface (2.5 cm depth) growing season *Sphagnum* moisture contents observed at the RES (0.12) were much lower than at NAT (0.22) (McCarter and Price, 2013). 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, 2013). McCarter and Price (2013) concluded that the saturated hydrology (non-vadose zone) 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.

Lucchese *et al.* (2010) projected that the system would have its 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 (Clymo *et al.*, 1998; Dimitrov *et al.*, 2011), high soil moisture contents (Lafleur *et al.*, 2005; Waddington *et al.*, 2010) and decay resistant plant material [e.g. *Sphagnum* (Clymo *et al.*, 1998; Belyea and Clymo, 2001)]. To achieve this, the regenerated *Sphagnum* needs to maintain suitable soil moisture contents (and soil water pressures) by accessing the stored water in the cutover peat and transferring it to the capitula. Regenerated *Sphagnum* has been shown to have lower bulk density (Waddington *et al.*, 2011; McCarter and Price, 2013) and soil water retention (Waddington *et al.*, 2011) than undisturbed *Sphagnum*, but it is unknown how the different hydrophysical parameters affect the regenerated *Sphagnum*'s ability to transmit water from the water table to the capitula. Furthermore, there was doubt that regenerated *Sphagnum* could access the water stored in the cutover peat because of differences in capillary strength of these two media (McCarter and Price, 2013). Therefore, the overall objective of this study is to characterize how the hydrophysical properties of a restored harvested bog

peatland evolve following restoration and what this means to the function of the system. The specific objectives are to (1) characterize the differences in the hydrophysical properties of UNR, RES and NAT sites at BdB peatland to identify the mechanisms that control water migration and soil moisture distribution in the evolving moss profile; (2) evaluate the limited connectivity theory proposed by McCarter and Price (2013), caused by the superposition of a poorly decomposed moss profile over cutover peat; and (3) suggest management prescriptions that could ameliorate constraints to better ecosystem function.

STUDY SITE

BdB is located 10 km northwest of Rivière-du-Loup, Quebec (47°57'47N, 69°26'23 W, 28 m a.s.l.) and contains three sites: UNR, RES and NAT. Since restoration measures were implemented in fall 1999, a complete ~15–20 cm layer of *Sphagnum* moss, chiefly *S. rubellum*, covered RES within 10 years. NAT is also dominated by *S. rubellum* (Poulin *et al.*, 2012; Pouliot *et al.*, 2012) 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). In contrast to NAT, where the dominant vascular vegetation are peatland specialist plants (e.g. *Chamaedaphne calyculata* and *Rhododendron groenlandicum*), RES's vascular species are a mix of peatland specialist and general wetland plants (e.g. *Typha latifolia*), but most prominently *Eriophorum vaginatum* (Poulin *et al.*, 2012). UNR is dominated by vascular plants (*Equisetum arvense* and *Vaccinium oxycoccos*) typically associated with forests (*Betula papyrifera*) or ruderal ecosystems (Poulin *et al.*, 2012) and bare (formerly) catotelm peat.

METHODS

Field methods. Volumetric soil moisture (θ) was recorded using Campbell Scientific CS615 Water Content Reflectometer probes (TDR) (accuracy $\pm 2.5\%$, precision 0.05%) every 60 min 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 RES and one location at NAT. Each probe measured an approximate depth of 5 cm centred at the above depths. No θ was recorded at UNR because of 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 comprises a mix of new poorly decomposed 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 RES, the probes were installed in *Sphagnum* hummocks in which *E. vaginatum* was also present because of its dominance at the site and the paucity of the typical ericaceous species. The probes installed at NAT were in a *Sphagnum* hummock at the same location as reported by McCarter and Price (2013) and utilized by Waddington *et al.* (2011) as their natural site comparison. The probes were calibrated following the method of Topp *et al.* (1980) for each soil type (i.e. natural *Sphagnum*, regenerated *Sphagnum* and cutover peat).

Solinst Levelogger Gold 3001 pressure transducers (error $\pm 0.05\%$ of measured value) were used to measure water tables every 30 min in locations near (<2 m away) the TDR sites. Care was taken to ensure the wells (100 cm slotted intake, 2.54 cm I.D. PVC pipe) were installed at locations with similar thicknesses of *Sphagnum* moss to determine the water table depth below the *Sphagnum* surface of the TDR profiles. The height of the regenerated *Sphagnum* at RES where the wells were installed was ~20 cm.

Field sampling. Three moss/peat monoliths were sampled in close proximity of the monitoring sites on DOY 291 and 292 per site (RES_m, NAT_m and UNR_m). The monoliths were ~35 cm deep (~25 cm at UNR because of high concentration of woody debris ~25 cm below surface) and 28 cm in diameter. The samples were taken using a circular guide of the same diameter and using a saw to cut around the guide to the appropriate depth. The monoliths were placed in 23 l water-filled buckets to prevent deformation or 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. Minimal vertical compression occurred during this process. 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 here (see further Section on Monolith Experiment).

Six additional cores 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 sample was then cut along the bottom of the PVC pipe and withdrawn to produce an undisturbed 5 cm core that remained in the section of pipe for shipment. The sample depths were centred 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. The cores were frozen for transport to University of Waterloo's Wetland Hydrology Laboratory where they were further sectioned into 2.5 cm high samples, for bulk density and porosity measurements.

Monolith experiment. Before the monoliths were placed in the buckets, the bottom was filled with ~2 cm of coarse sand to rapidly distribute water pressures evenly across the

bottom of the monolith. A 25 μm Nitex screen was placed over the sand and covered with a ~ 2 cm layer of 56–76 μm glass beads following a modified tension table method outlined by Paquet *et al.* (1993). This method allowed for a simulated water table 45 cm below the surface of the monolith. At the base of the buckets, an outlet spigot was attached to a Marriott system that supplied constant water supply and water table for the course of the experiment. A discharge valve was installed between the bucket and Mariotte 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 min, 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 because of the high compressibility of the upper 5 cm of the monoliths that 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 outlined by Strack and Price (2009) was used. Briefly, three (1 \times 2 cm) tabs made from calendared peatboard were placed equal distance apart along the centre of the monolith and left for 4 h to reach equilibrium with the surrounding capitula water content. The peatboard tabs were then weighed and calibrated following the method outlined by Strack and Price (2009) to convert the measured weight to θ . A known volume of the upper 3 cm of moss was sampled and dried at room temperature for approximately 2 weeks. Once per day, a peatboard tab was inserted into the sample and left to equilibrate. Once equilibrated, the peatboard tab and the moss sample were weighed. The volumetric moisture content of the moss was determined, and a linear regression between the moss volumetric moisture content and peatboard gravimetric moisture content was performed, resulting in an R^2 of 0.91 ($p < 0.001$) and 0.96 ($p < 0.001$) at NAT and RES, respectively.

After the monoliths were set up, they were filled from below with deionized water and left for 48 h to ensure complete saturation of the pores. 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 below the surface). 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 that was determined when θ was stable in a monolith for at least 24 h. A 6 h average of θ measurements was used to determine the final average θ at a given water table.

Monolith (hydraulic) parameterization. Hydraulic parameterization was restricted to a single monolith each of NAT,

RES and UNR; variability within and between site types is evaluated on the basis of replicate sampling of their physical properties (bulk density and porosity; $n=6$) as well a comparison of monolith response to water table ($n=3$ per site), field behaviour and the results of other studies at this site (Waddington *et al.*, 2011; McCarter and Price, 2013). The limited sample size precludes robust statistical analyses and universal applicability of the conclusions; however, we argue the validity of inter-site comparisons based on the significant differences in physical properties, the distinct hydraulic characteristics of each site and the hydrological behaviour they elicit. The monolith was frozen after the monolith experiment (to facilitate sectioning) and cut into 5 cm high (centred every 2.5 cm), 10 cm diameter pucks to a depth of 30 cm (25 cm for UNR_m), and when thawed, they were inserted into sections of PVC pipe of equivalent size. The capitula (uppermost 1 cm) of both RES and NAT were sampled by lightly spraying the tops of the monoliths with water while freezing to give the capitula the necessary rigidity to facilitate cutting from the sample. 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 $< 1 \text{ g day}^{-1}$) 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 tension 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 tension disk on to the top of the sample to ensure that 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 ψ of -25 cm on the hysteretic curve. The lower disk was connected to an Erlenmeyer flask with a constant head connected to an overflow where we 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 was 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} and then the samples were weighed so that θ could be determined.

Saturated hydraulic conductivity (K_{sat}) was measured using a Darcy permeameter under steady state flow conditions with a hydraulic gradient of 2 cm cm^{-1} . Once a constant volumetric discharge was observed over 20 min, eight separate discharge measurements were taken per sample and averaged to determine the final discharge value. Because of 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 cloth to prevent the melted wax from entering the porous sample. Once the plaster of Paris was dry, a coat of paraffin wax was brushed on to ensure a water-tight seal. This was then installed in a Darcy permeameter 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 (ψ), as

$$r = \frac{2\gamma \cos \beta}{\rho g \psi} \quad (1)$$

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 fraction of water in the sample (ϕ_{vw}) was determined by

$$\phi_{\text{vw}} = \frac{\theta_\psi}{\phi} \quad (2)$$

where ϕ is the porosity and θ_ψ is the volumetric soil moisture content for a given ψ . Higher ϕ_{vw} indicates that more water is contained within the sample for a given pressure head (ψ) (Carey *et al.*, 2007; McCarter and Price, 2014). The relationship between the pore diameter and ϕ_{vw} 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.

Once hydraulic parameterization was completed, the 5 cm cores were sectioned into 2.5 cm high lengths and their bulk density and porosity were determined, for comparison with their respective field samples.

RESULTS

Field soil moisture and water table. RES had an average water table depth of -53.7 cm , while at NAT was -31.9 cm (below the *Sphagnum* surface near the TDR probes). The regenerated *Sphagnum* at RES remained much drier than NAT *Sphagnum* (Figure 1). θ in the upper 10 cm of *Sphagnum* at NAT and RES remained relatively consistent throughout most of the study period, only varied

substantially after DOY 270 (Figure 1). $\theta_{2.5 \text{ cm}}$ and $\theta_{7.5 \text{ cm}}$ in the regenerated *Sphagnum* at RES were nearly identical (~ 0.15), while at NAT $\theta_{7.5 \text{ cm}}$ was about 0.10 higher than $\theta_{2.5 \text{ cm}}$ (Figure 1). Furthermore, $\theta_{17.5 \text{ cm}}$ at RES was far drier than at the equivalent depth at NAT. Only brief increases in θ were observed (DOY 273 and 281) at 17.5 cm at RES and quickly decreased as precipitation ceased. In comparison, at NAT, the moss typically retained water once precipitation ceased, as shown by the more gradual decrease in θ (Figure 1).

Bulk density and porosity. The bulk density and porosity values of the monolith parameterization ($n = 1$) cores all fell within 1 standard deviation of the field samples ($n = 6$) at their respective depths. Bulk density increased with depth at NAT and was relatively uniform with depth in the regenerated *Sphagnum* at RES (Figure 2). However, 15 cm below the *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 other samples (the average of the two denoted by ^a) (Figure 2). Between the dashed grey lines in Figure 2 is the transition zone between regenerated *Sphagnum* and cutover peat, where the bulk densities became more similar to UNR ($\sim 0.15 \text{ g cm}^{-3}$) than NAT ($\sim 0.05 \text{ g cm}^{-3}$). All NAT samples at or below 17.5 cm had much lower bulk density than both RES and UNR (Figure 2).

The porosity data exhibited the same general trends between the sites and depths (not shown). From 0 to 12.5 cm below the surface, RES (0.97 ± 0.01) had slightly higher porosity than NAT (0.94 ± 0.02). 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 and showed no trend in porosity, maintaining an average of 0.83 ± 0.05 .

Monolith experiment

Water retention. The θ -wt data from the monolith experiment (Figure 3) were consistent with the field observations with respect to θ (Figure 1), where RES_m retained less water at a given water table than NAT_m in the *Sphagnum* ($\theta_{7.5 \text{ cm}}$ and $\theta_{15.0 \text{ cm}}$) and was similar to UNR in the cutover peat ($\theta_{27.5 \text{ cm}}$). Additionally, θ_{capitula} showed little difference in water retention (Figure 3) between NAT_m and RES_m at all water tables tested; this apparent lack of difference was also observed in the bulk density and porosity measurements. Regardless of the water table position, $\theta_{7.5 \text{ cm}}$ at RES_m remained very dry (≤ 0.20) and showed limited hysteresis, unlike NAT_m (Figure 3). Because of inaccuracies ($\pm 1 \text{ cm}$) in the placement of moisture sensors at the 15 cm depth, $\theta_{15.0 \text{ cm}}$ recorded

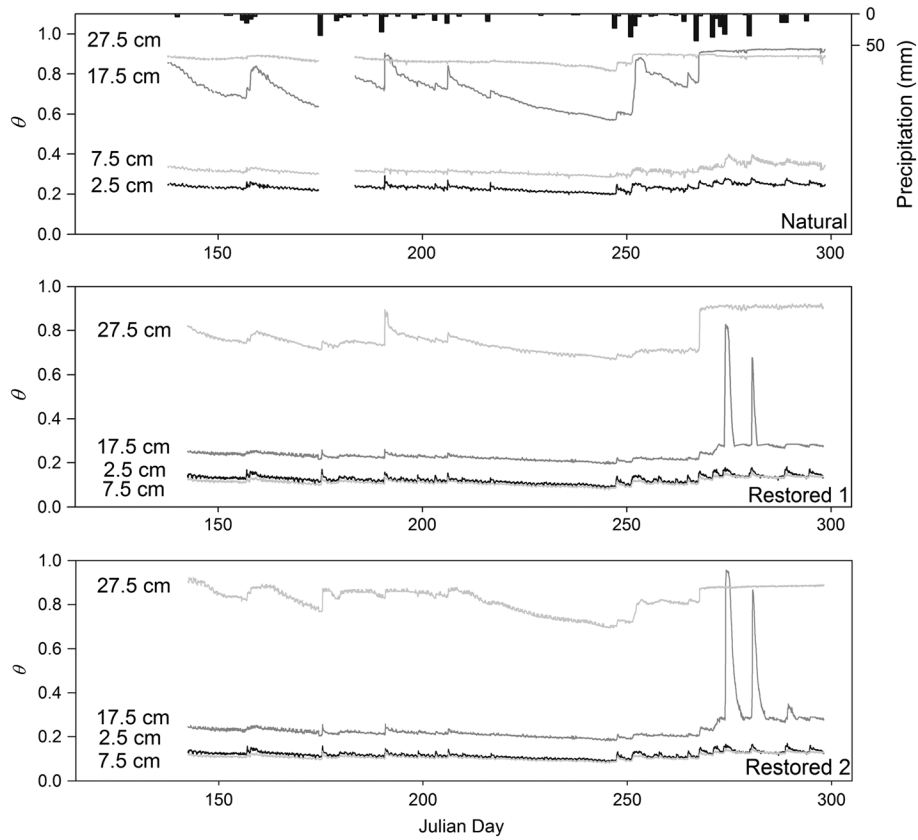


Figure 1. Time series θ from *in-situ* measurements at three sites (2 RES and 1 NAT) and daily precipitation from DOY 145–290. RES (bottom) show limited variability between the 2.5 and 7.5 cm probes and overall low θ above the cutover peat/*Sphagnum* interface. At RES the upper three probes (2.5, 7.5 and 17.5 cm) were installed in regenerated *Sphagnum*, while the 27.5 cm probe was installed in the cutover peat. NAT probes were placed under a pure *Sphagnum* hummock.

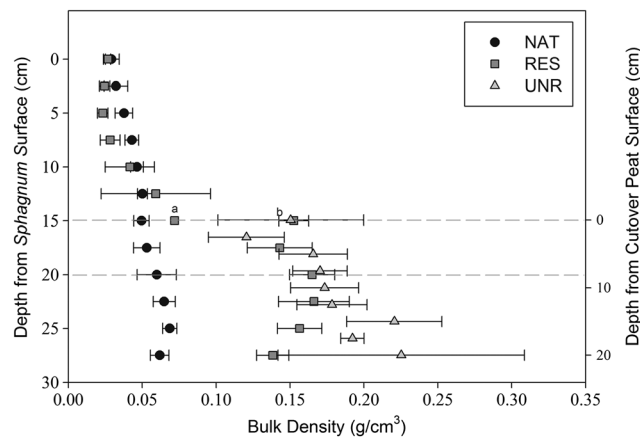


Figure 2. Average bulk density (\pm standard deviation) by sample depth centred at 2.5 cm for all three sites. Between the dashed grey lines represent the interface region between the cutover peat and *Sphagnum* moss at RES. The 15 cm RES samples were split into two groups of 2 (denoted by ^a or ^b) based the dominant material type (*Sphagnum* or cutover peat). $n=4$ per site.

values were below saturation at a water table of -15 cm. Notwithstanding these small deviations in probe placement, the $RES_m \theta_{15\text{ cm}}$ dropped substantially between the -15 and -20 cm water table position and decreased further at lower water tables and approached its residual water

content at a -40 cm water table. The abrupt decrease in $RES_m \theta_{15\text{ cm}}$ was not observed in $NAT_m \theta_{15\text{ cm}}$, which showed a gradual decrease over the same water table drop (Figure 3). Hysteresis was apparent in all retention tests except for the capitula samples (Figure 3). NAT_m retained

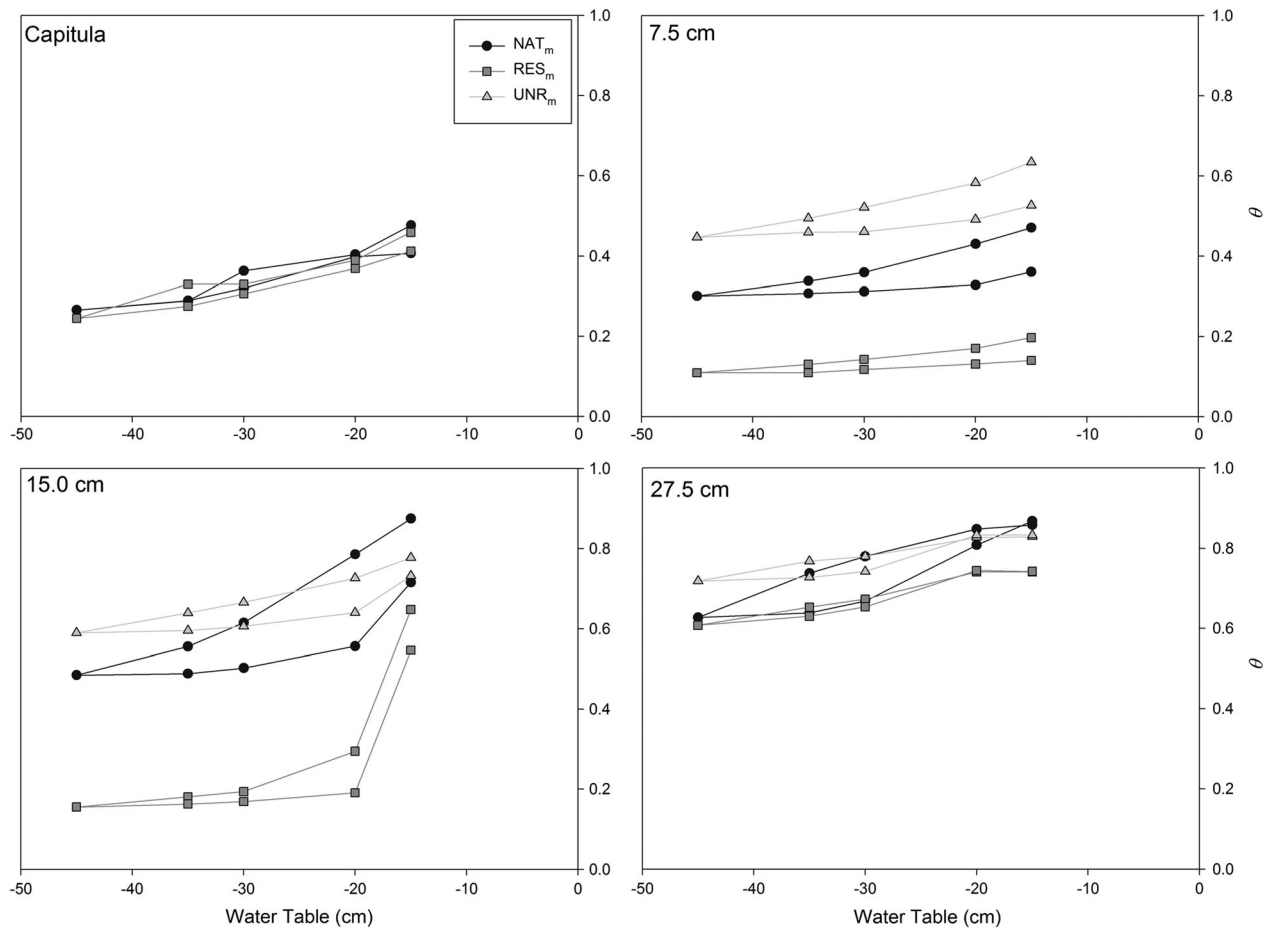


Figure 3. Average θ -wt results from the monolith experiments. Each probe (7.5, 15.0 and 27.5 cm) ($n=2$) and the capitula peatboard ($n=9$). The capitula, 7.5 and 15.0 cm measurements are within the *Sphagnum* at RES, and the 27.5 cm measurements is within the cutover peat at RES.

far more water through the range of water table decline at both $\theta_{7.5\text{cm}}$ and $\theta_{15\text{cm}}$ compared with RES_m at the same depths (Figure 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). At 27.5 cm, RES_m had similar water retention and hysteresis curves than at equivalent depth at UNR_m, although it retained slightly less water at each water table position. 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 RES_m when the water table was dropped within the regenerated *Sphagnum* from -15 to -20 cm compared with NAT_m and UNR_m (Table I). Once below the *Sphagnum*/cutover peat interface, the specific yield of RES_m decreased and was more similar to UNR_m than NAT_m (Table I). Both NAT_m and UNR_m show relatively consistent specific yield regardless of the water table drop (0.1 ± 0.03 and 0.05 ± 0.03 , respectively) (Table I).

Monolith (hydraulic) parameterization

Water retention. Soil water retention curves (i.e. θ vs ψ) of the monolith samples displayed a similar pattern to the water table lowering experiments in the monoliths (i.e. θ vs wt). Water retention was low in the regenerated *Sphagnum* (RES) at 2.5, 7.5 and 12.5 cm, typically around 0.2 (Figure 4), which was similar to the reported field values (Figure 1) and the monolith experiment at water tables below -15 cm (Figure 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 4). RES θ of the capitula sample had lower water retention compared with NAT θ of the capitula sample and showed less hysteresis (Figure 4). At RES, the *Sphagnum* (0–15 cm) reached its residual water content at a ψ of -35 cm, while at NAT, the soil water retention curves still sloped considerably at the same ψ , indicating they had not yet reached the residual soil water content (Figure 4).

Table I. Average (\pm standard deviation) monolith specific yield per water table drop (cm).

Final water table depth (cm)	Decrease in water table (cm)	Sy		
		NAT _m	RES _m	UNR _m
20	5	0.09 \pm 0.02	0.41 \pm 0.04	0.05 \pm 0.03
30	10	0.13 \pm 0.10	0.15 \pm 0.02	0.07 \pm 0.02
35	5	0.07 \pm 0.04	0.03 \pm 0.01	0.01 \pm 0.01
45	10	0.10 \pm 0.08	0.05 \pm 0.01	0.06 \pm 0.01

$n=3$ per site.

Hydraulic conductivity. The regenerated *Sphagnum* (excluding the capitula) at RES had higher K_{sat} values (6681 cm day⁻¹) than NAT (4495 cm day⁻¹), but (once tension was applied) K_{unsat} at RES decreased more quickly than at NAT (Figure 5). This ultimately led to lower K_{unsat} (typically near an order of magnitude lower) at a given ψ (Figure 5); however, RES K_{unsat} was typically higher than UNR (Figure 5).

Theoretical pore size distribution. For all depths, ϕ_{vw} held in pores less than or equal to a given size is greater in NAT than in RES (Figure 6). In other words, NAT was more dominated by smaller pore sizes, which were more capable of holding water at a given pressure. At the capitula layer, the difference was not large, especially at a pressure of -5 cm in which pores $\leq 397 \mu\text{m}$ hold 45–50% of the water. The greatest distinction can be seen in the 2.5 to 12.5 cm layers (Figure 6) in which pores $\leq 198 \mu\text{m}$ (when the pressure is -10 cm) can be seen to hold only ~25% of the water at RES, 50–85% of the water at NAT and ~95% of the water at UNR. The regenerated moss at RES clearly had fewer small pores that can hold water. At a depth of 22.5 cm, the pore size distribution is similar between all sites – this being the cutover peat in RES and UNR, and relatively decomposed peat at NAT.

DISCUSSION

The mute θ response to precipitation of the upper layers of regenerated *Sphagnum* at RES (Figure 1), except for the sharp rise and then fall in $\theta_{17.5 \text{ cm}}$ after heavy precipitation events on DOY 273 and 281, demonstrated RES's regenerated *Sphagnum* did not have high enough soil water retention (Figure 4) to retain much precipitation. Furthermore, $\theta_{2.5 \text{ cm}}$, $\theta_{7.5 \text{ cm}}$ and $\theta_{17.5 \text{ cm}}$ remained relatively steady over most of the summer, while evapotranspiration averaged 2.4 mm day⁻¹ (McCarter and Price, 2013), indicating that water must be rising from the cutover peat to maintain the soil moisture in the regenerated moss layer unless (more likely) transpiration from vascular vegetation rooted in the cutover peat was the dominant water loss and evaporation from the moss surface was negligible compared

with transpiration. Instantaneous evapotranspiration, determined from chamber humidity and temperature data provided by Strack (unpublished) using methods described by Mcleod *et al.* (2004) and Brown *et al.* (2010), was compared with vascular plant cover (Strack and Zuback, 2013). There was a moderate ($R^2=0.37$, $n=9$) positive linear correlation between percent vascular cover and instantaneous evapotranspiration at RES ($n=9$). At NAT, there was weak negative relationship ($R^2=0.11$; $n=5$) except when an outlying point (a much higher percent vascular cover than typically observed) was included, which strengthened the negative relationship ($R^2=0.37$; $n=6$). Given the low θ and K_{unsat} in the upper moss profile at RES (Figures 1 and 5), it was unlikely that capillary rise could meet the evaporative demand, so evapotranspiration was dominated by transpiration, as suggested earlier. In contrast, the hydraulic properties of *Sphagnum* at NAT enabled more effective upward water delivery to the moss surface, thus providing more water for evaporation and offsetting the influence of vascular plant transpiration.

Unlike the upper three probes, RES $\theta_{27.5 \text{ cm}}$ experienced protracted declines during dry periods (Figure 1), meaning water loss from drainage and/or transpiration. At NAT, $\theta_{17.5 \text{ cm}}$ was substantially higher than at RES and showed larger peaks (evidence of water storage) and longer recession limbs (evidence of sustained water loss) following precipitation events (Figure 1). These longer recession limbs suggest the moss above this layer, which sustained relatively steady θ , readily obtained water from the deeper moss (soil) matrix to supply the evaporative demand. There appeared to be some similarity between the $\theta_{17.5 \text{ cm}}$ at NAT and $\theta_{27.5 \text{ cm}}$ at RES, in terms of their role in supplying water. However, K_{unsat} was typically an order of magnitude higher at NAT (Figure 5); thus, it was better able to supply water to meet atmospheric demand. Evapotranspiration from NAT and RES averaged 3.3 and 2.4 mm, respectively, between DOY 147 and 245 (McCarter and Price, 2013). For most of the study period, the field $\theta_{2.5 \text{ cm}}$ and $\theta_{7.5 \text{ cm}}$ in the regenerated *Sphagnum* at RES (Figure 1) were close to or below the residual water contents (Figures 3 and 4), indicating partial desiccation by evaporative loss. These low water contents suggest that the

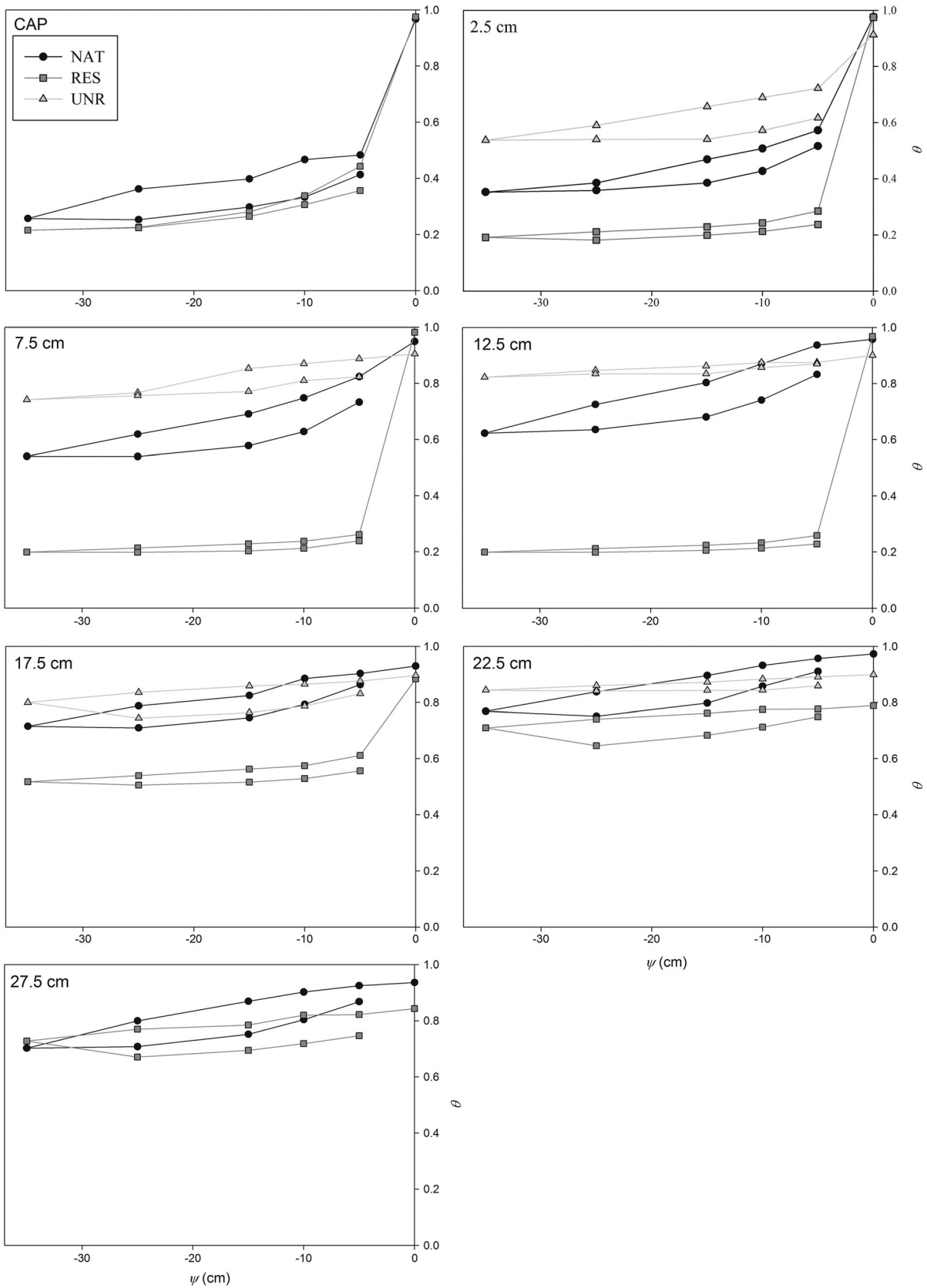


Figure 4. Soil water retention and hysteresis curves from the monolith parameterization for each sample depth. RES 22.5 and 27.5 cm are within the cutover peat, and the 17.5 cm sample is within the transition zone between cutover peat and *Sphagnum* moss. $n = 1$.

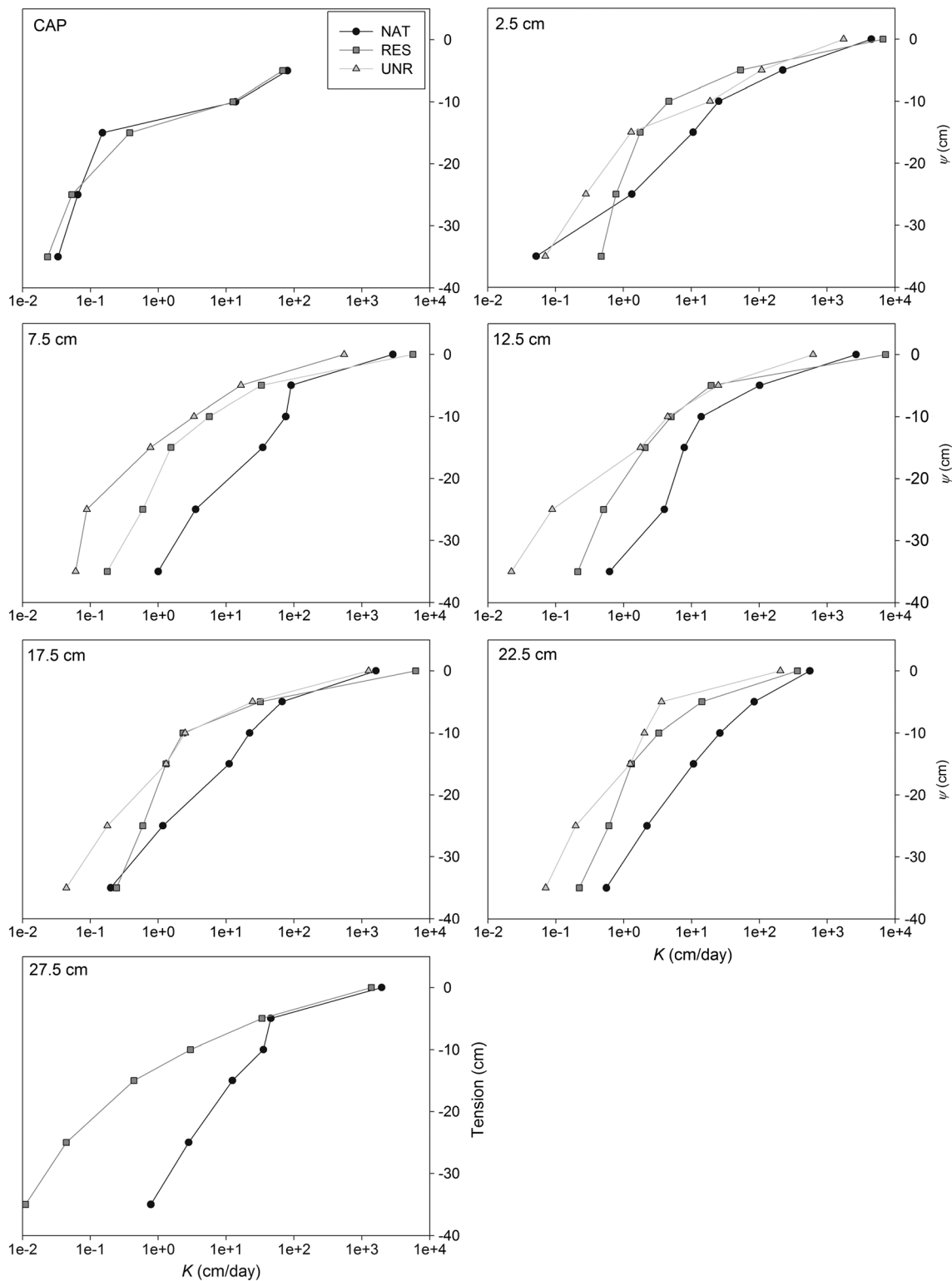


Figure 5. Hydraulic conductivity and ψ from the monolith parameterization for each sample depth. RES 22.5 and 27.5 cm are within the cutover peat, and the 17.5 cm sample is within the transition zone between cutover peat and *Sphagnum* moss. The drying hysteretic curves were removed for clarity but follow the same general trends as the soil water retention hysteretic curves. $n = 1$.

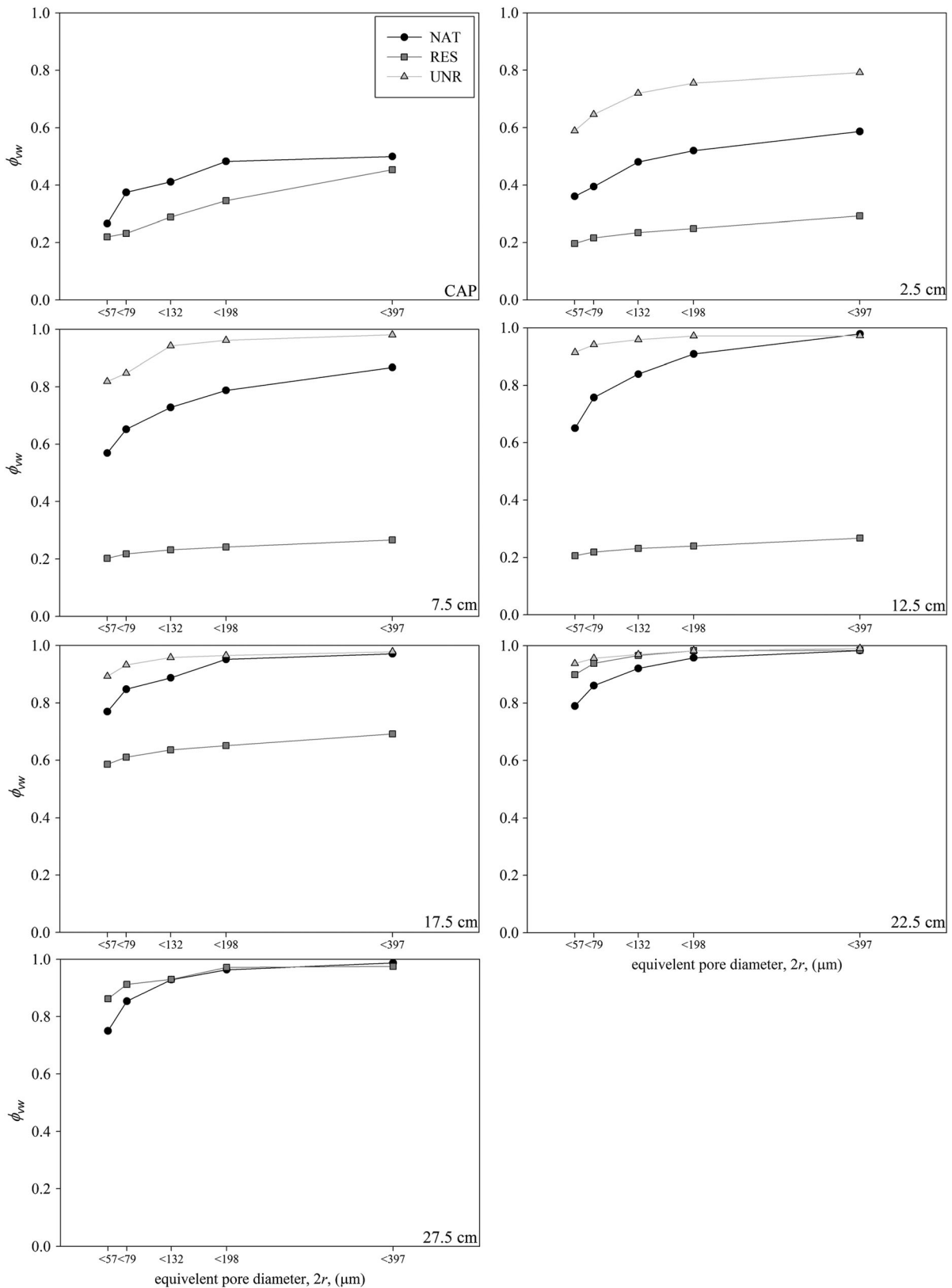


Figure 6. Theoretical pore size distribution and ϕ_{vw} curves from the monolith parameterization for each sample depth. The theoretical pore size represents the largest diameter pore that is filled with water. Higher plotted ϕ_{vw} indicate smaller pores than lower plotted ϕ_{vw} . Higher slopes of 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. $n = 1$.

mosses at RES were under greater moisture stress than those at NAT, whose $\theta_{2.5\text{ cm}}$ and $\theta_{7.5\text{ cm}}$ (Figure 1) did not reach their residual water contents (Figure 4). Although water content can indicate the potential for water stress, the soil water pressure will determine whether the *Sphagnum* can access the soil water (Hayward and Clymo, 1982). If there was a more severe atmospheric demand such that water supply from below could not keep pace, the pressure in the moss would far exceed -100 cm and hyaline water (water stored in dead cells unconnected to the active pore network) would be released causing an abrupt drop in soil moisture (Hayward and Clymo 1982). At this point, the mosses would desiccate and turn whitish (Ingram, 1983), and vapour flow would likely exceed capillary flow in the moss, contrary to the normal situation (Price *et al.*, 2009). We note that the mosses at NAT did not desiccate in the field, while periodic desiccation of the mosses at RES occurred, typically associated with topographic highs (hummocks). Given the limited desiccation observed in the field, the mosses typically remained above the threshold pressure for hyaline cell drainage, which would limit photosynthesis (Silvola and Aaltonen, 1984; Schipperges and Rydin, 1998). Because the mosses rarely desiccated, it seems likely that the regenerated *Sphagnum* received some water from dew or distillation (condensation of internally generated vapour at the colder *Sphagnum* surface) to prevent desiccation (Carleton and Dunham, 2003). Alternatively, evidence of hydraulic lift was observed at RES and NAT because of diurnal fluctuations in water table (McCarter and Price, 2013) and θ (Figure 1). Water from the rooting zone could be transported upward in the vascular vegetation and released into the surrounding soil once the daily evapotranspiration demand ceased and the soil water pressure within the root was greater than that of the surrounding soil (Dawson, 1993). This mechanism could have provided water from the remnant cutover peat to the *Sphagnum* moss at RES without relying on capillary rise, effectively short-circuiting the system and preventing desiccation of the *Sphagnum*.

The restoration measures and outcomes (higher soil water pressures) created a growth surface (cutover peat) that had sufficiently high soil water pressures (greater than -100 cm) for *Sphagnum* recolonization but relatively strong capillary retention due to a high abundance of small pores in the cutover peat. The two layer capillary system (i.e. low capillarity strength of *Sphagnum* and high capillarity strength of cutover peat) created a system where hydrological connectivity was limited between the relatively wet cutover peat and the drier regenerated *Sphagnum* moss. This would not be an issue if the water table fluctuated within the regenerated *Sphagnum*, but this occurred only briefly in 2010 (McCarter and Price, 2013). Furthermore, water flows were still limited by the low effective hydraulic conductivity of the regenerated

Sphagnum moss (Figure 5), which resulted in less water flow to the capitula at RES than at NAT (recall evapotranspiration was less at RES). Both RES and NAT capitula typically had higher θ than in the layer below it (2.5 cm layer) (Figure 3) primarily because of the capitulum's higher bulk density (Figure 2) and larger proportion of small pores ($<397\text{ }\mu\text{m}$) (Figure 6). Because the capitulum are the growing part of the plant (Clymo, 1973), its higher θ may have allowed the plant to remain photosynthetically active for longer than it otherwise could, potentially explaining the abundant growth of the regenerated *Sphagnum* at RES.

Unlike other moss genera, *Sphagnum* will devote resources to either sustained fast growth or structural growth (Turetsky *et al.*, 2008). Sustained rapid vertical growth results in low bulk density, high porosity and high specific yield compared with the lateral growth pattern (Turetsky *et al.*, 2008; Waddington *et al.*, 2011). Waddington *et al.* (2011) postulated that the limited retention and low residual water content observed at RES (and by this study) were a result of the mosses devoting resources to sustain fast growth (vertical) over structural growth. These vertical growth characteristics (low bulk density, high porosity, higher specific yield and limited soil water retention) were all still present at RES, thus indicating sustained vertical growth over the past 10 years at the expense of lateral growth. In comparison, NAT illustrated a different structural development, as there is higher soil water retention and bulk density (observed in both this study and Waddington *et al.* (2011)), and the theoretical pore sizes were smaller within the *Sphagnum* (Figure 6). These properties are likely due to a combination of a greater density of interlinking branches and leaves (Turetsky *et al.*, 2008) within the living *Sphagnum* and partial decomposition and subsequent collapse of older 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 is required for the decomposition and collapse of the dead *Sphagnum* moss. These changes in the physical structure of the *Sphagnum* and the resulting changes in pore distribution would result in higher θ and more favourable conditions for net carbon sequestration. There are some indications that decomposition has changed the pore structure and thus water retention characteristics of the 17.5 cm layer at RES. The ϕ_{vw} is greater (0.69–0.55) (Figure 6) at 17.5 cm than the above regenerated *Sphagnum* layer including the capitula, indicating more small pores. The greater abundance of smaller pores ($<397\text{ }\mu\text{m}$) imparts increased soil water retention (Figures 1, 3 and 4) at 17.5 cm and is likely a critical transition from the tightly held water in the cutover peat to the loose moss characterized by large pores (Figure 6) that would form a strong capillary barrier if situated directly on the cutover peat. Nevertheless, the relatively sharp transition in pore

size distribution between cutover and newly generated mosses was limiting the water transfer, as evidenced by the lower water contents and lower evaporation losses from RES. Further decomposition of the basal layers (i.e. directly above the cutover peat) will create more small pores and enhance the capillary flow from water stored in the cutover peat. Consequently, further structural development of the regenerated *Sphagnum* is required to increase its soil water retention and K_{unsat} . These results confirm the conclusions of Waddington *et al.* (2011) that further lateral infilling and basal decomposition of the regenerated *Sphagnum* is required before BdB, which was a net carbon exporter (Strack and Zuback, 2013), will have more suitable hydrological conditions for net carbon sequestration.

Our findings have shown newly regenerated mosses at RES, compared with equivalent depths in NAT, had substantially lower bulk density (Figure 2), water retention (Figures 3 and 4) and unsaturated hydraulic conductivity (Figure 5), and higher specific yield (Table I) and theoretical pore size (Figure 6). These results mimic those observed by Waddington *et al.* (2011) where RES had lower bulk density (0.019 g cm^{-3}) and soil water retention, while having higher porosity (0.98) in the upper 4 cm of the *Sphagnum* moss compared with NAT. Furthermore, the soil water retention curves ($n=7$) of the lower 4 cm (8–12 cm) observed by Waddington *et al.* (2011) closely paralleled the observed soil water retention curves at similar depths in this study. The measured properties had a distinct and readily explainable impact on the hydrological behaviour of the different sites, as already noted. However, given the small sample size, it is imperative to consider the limitations regarding the broad applicability of these findings.

Firstly, we acknowledge that the very nature of this experiment involves simple pseudoreplication (Hurlbert, 1984) given that there is only the one experimental unit (BdB) for our treatments. This is the first field-scale restoration of a bog peatland using the methods described by Rochefort *et al.* (2003) and thus only one of this age and with this level of moss regeneration. Consequently, we make no claims about the broad applicability of the results to other sites. However, other studies have noted the clear distinction in the physical and hydraulic properties of newly regenerated moss compared with the cutover peat substrate, although on spontaneously regenerated moss cushions on abandoned cutover peatlands (e.g. Ketcheson and Price (2014); Price and Whitehead (2001)). The higher level of detail in monitoring the hydrological behaviour and its relation to the parameterization in the current study provides insight into spontaneously regenerated mosses, as well as other (younger) restoration attempts, notwithstanding the simple pseudoreplication.

Secondly, the laborious task of full hydraulic parameterization of multiple profiles of moss and peat at the three

sites (treatments) at BdB resulted in a relatively small sample size, insufficient to robustly test within-site differences with inferential statistics. On the basis of what we measured, and based on the extensive work carried out by others at this site (i.e. Andersen *et al.* (2010); McCarter and Price (2013); Pouliot *et al.* (2012); Rochefort *et al.* (2013); Waddington *et al.* (2011)), we are confident that we have captured the essence of the variability that exists between treatments (UNR, RES and NAT). Considering physical parameters, Waddington *et al.* (2011) measured bulk density at this site 3 years prior to our study. Based on their 0–4 cm sample depth at NAT ($n=5$) and RES ($n=14$), their measured bulk density was not significantly different than ours ($n=6$) ($p > 0.01$). In both studies, the coefficient of variation was relatively small at RES and NAT (0.16 and 0.16, and 0.21 and 0.13, in this study and Waddington *et al.* (2011), respectively), suggesting low within-site variability. Furthermore, Waddington *et al.* (2011) also measured water retention. They found significantly higher θ at $\psi_{-35 \text{ cm}}$ in NAT versus RES, consistent with our results. In the current study, θ at $\psi_{-35 \text{ cm}}$ fell within 1 standard deviation of their values in both the upper and lower samples. We recognize that our measurements from the same site occurred after 3 years' more moss development; the comparison is intended to show that we have captured the essence of the distinction between RES and NAT, and that we can confidently generalize about observed differences in hydrological behaviour at and between these sites, and make recommendations regarding future restoration (below).

Peatland restoration relies on restoring the necessary hydrological conditions for the vegetation to re-establish itself with no further intervention. Given the current state (as of 2010) of BdB, it might be prudent to intervene in future restorations to accelerate the return of net carbon sequestering functionality to peatlands. From a management perspective, there is merit in ensuring ditch-dams, and bunds are maintained to retain water on site (higher water tables) and perhaps compressing the moss layer (e.g. rolling while frozen). This would decrease the abundance of large pores and increase the capillary retention of the moss, therefore retaining more precipitation and potentially better-accessing the water in the cutover peat. Furthermore, the vascular vegetation may provide additional water through hydraulic lift that would be unable to transmit from the cutover peat to the *Sphagnum* moss because of low effective hydraulic conductivities. Lastly, hummock forming *Sphagnum* species were targeted during the restoration process, and the resulting mixture of species was 50/50 between *S. rubellum* and *S. fuscum* (Poulin *et al.*, 2012). Although both planted species are hummock forming, *Sphagnum fuscum* is able to more efficiently transmit water from the water table to the capitula and avoid desiccation than *S. rubellum* (McCarter and Price, 2014). By targeting desiccation avoidant *Sphagnum* species

in donor material collection, such as *S. fuscum*, the ability of regenerated *Sphagnum* to access and transmit water from the cutover peat to the capitula could be increased. A combination of decreasing average pore size and planting ericaceous shrubs potentially increases the water available for *Sphagnum* mosses.

CONCLUSIONS

The restoration at BdB has favoured the dominance of *S. rubellum* and *E. vaginatum*, but the sustained vertical growth of *S. rubellum* and limited time for basal decomposition have created a loose structure resulting in an abundance of large pores. These large pores restrict the capillary transfer of water from the old cutover peat to the new moss layer. It appears as if there is a thin but critical layer at the base of the moss layer whose intermediate hydraulic properties partially bridge the capillary barrier otherwise formed by the juxtaposition of mosses with large pores against cutover peat with relatively small pores. It is likely that in time, the average pore size at the base of the moss layer will further decrease because of decomposition, consolidation and structural growth, thus increasing water retention and hydraulic conductivity of the *Sphagnum*. These changes to pore structure will facilitate the upward transfer of water if the low hydraulic conductivity of the cutover peat is not limiting. A higher water table, at or above the interface between the moss and cutover peat, would negate the impacts of the dramatically different hydrophysical properties between the cutover peat and *Sphagnum* moss. A combination of all three measures (structural growth, decomposition and consolidation, and a higher water table) will probably be required for BdB to become a net carbon sequestering system. Given its trajectory, it seems likely that the system will self-regulate and make the necessary structural changes over time.

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