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Peatland Water Repellency: Importance of Soil Water Content, Moss Species, and Burn Severity

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Abstract

Wildfire is the largest disturbance affecting peatlands, with northern peat reserves expected to become more vulnerable to wildfire as climate change enhances the length and severity of the fire season. Recent research suggests that high water table positions after wildfire are critical to limit atmospheric carbon losses and enable the re-establishment of keystone peatland mosses (*i.e. Sphagnum*). Post-fire recovery of the moss surface in *Sphagnum*-feathermoss peatlands, however, has been shown to be limited where moss type and burn severity interact to result in a water repellent surface. While in-situ measurements of moss water repellency in peatlands have been shown to be greater for feathermoss in both a burned and unburned state in comparison to *Sphagnum* moss, it is difficult to separate the effect of water content from species. Consequently, we carried out a laboratory based drying experiment where we compared the water repellency of two dominant peatland moss species, *Sphagnum* and feathermoss, for several burn severity classes including unburned samples. The results suggest that water repellency in moss is primarily controlled by water content, where a sharp threshold exists at gravimetric water contents (GWC) lower than ~1.4 g g^{-1}. While GWC is shown to be a strong predictor of water repellency, the effect is enhanced by burning. Based on soil water retention curves, we suggest that it is highly unlikely that *Sphagnum* will exhibit hydrophobic conditions under field conditions. Moreover, the superior water retention characteristics of *Sphagnum* compared to feathermoss or burned samples appears to be independent of bulk density.

1. Introduction

Peatlands are wetlands defined, in part, by thick accumulations of organic matter (>0.4m in Canada, National Wetlands Working Group, 1997). While representing less than 3% of global land area, northern peatlands comprise roughly one-third of global soil carbon storage (Yu et al., 2010). Fire-prone peatland-dominated regions exist over large areas of western boreal Canada and Siberia (de Groot et al., 2013), where relatively short fire return intervals play an important role for carbon storage and vegetation dynamics (Weber and Flannigan, 1997). Moreover, in western continental Canada, peatlands in a sub-humid climate exist at the limit of their climatic tolerance (Vitt et al., 2000). The contemporary carbon storage rate for peatlands in this region is estimated at 19.4 g C m^{-2} y^{-1} (Vitt et al., 2000), but fires have the potential to release a large amount of the long-term carbon stored in these ecosystems (Hokanson et al., 2016) and reduce carbon accumulation rates for years to decades (Turetsky et al., 2002). With an increase in large fires and total burned area for boreal peatlands (Kasischke and Turetsky, 2006; Turetsky et al., 2011), the carbon storage function of boreal peatlands may further be degraded. As such, there is concern that the predicted increase in climate change mediated disturbances, such as wildfire and/or drought, will negatively impact the contemporary carbon storage potential of these peatlands (Vitt et al., 2000; Flannigan et al., 2000; Flannigan et al., 2005).

However, peatlands which are not significantly affected by anthropogenic disturbance are considered resilient ecosystems, owing to a number of negative ecohydrological feedbacks (Waddington et al., 2015). Following wildfire, water repellency has recently been suggested to be a potentially important negative feedback acting to conserve water, and potentially aid in vegetation recovery (Kettridge et al., 2017), and is prevalent in post-fire Boreal Plains bogs (Kettridge et al., 2014; MacKinnon, 2016). Whilst well studied in mineral soils (*cf.* Doerr et al., 2000), few studies have examined water repellency in peatland ecosystems, where the soil surface is typically comprised of living mosses (*e.g.* O'Donnell et al., 2009b; Kettridge et al., 2014). Water repellency has been shown to affect capillary forces driving water movement in porous media (Shokri et al., 2009), limiting capillary flow to the evaporating surface from wetter and/or saturated soil layers (Diamantopoulos et al., 2013), thus potentially reducing surface evaporation (Shahidzadeh-Bonn et al., 2007). Therefore, water repellency may constitute an important ecohydrological feedback in peatlands, whereby evaporation is severely limited (Kettridge et al., 2017), amplifying the water table depth - moss resistance feedback (see Waddington et al., 2015), and thus conserving water.

While fire may induce or enhance soil water repellency (*cf*. DeBano, 2000), the degree of soil water repellency has also been linked to soil carbon (Karunarathna et al., 2010) and water content (Fishkis et al., 2015). In general, the soil characteristics, moisture content, and temperature of combustion in organic soil layers will all affect the production of hydrophobic compounds at depth (Doerr et al., 2000). In the case of peatlands which tend to have very high carbon content in near-surface soils (*e.g.* Yu, 2012) and where smouldering (*i.e.* low temperature) tends to dominate over flaming combustion on the peat surface during wildfire (*e.g.* Rein et al., 2008), there is likely a relatively high potential for the production of hydrophobic compounds as a result of wildfire (*e.g.* Neff et al., 2005).

Post-fire near-surface water repellency in peatlands can be created or exacerbated based on botanical origin and depth (O'Donnell et al., 2009b; Kettridge et al., 2014) and is persistent for several years (*e.g.* Kettridge et al., 2014; MacKinnon, 2016). As such, it is necessary to consider the importance of water repellency in relation to both peatland vadose zone hydrology and moss recovery post-fire. However, past studies on peatland water repellency persistence are somewhat contradictory. O'Donnell et al. (2009b) found minimal persistence of hydrophobicity 24 months post-fire at the peat surface for both *Sphagnum* and feathermoss species. In contrast, two studies undertaken in northern Alberta 15 months and 38 months post-fire showed significant and persistent near-surface water repellency for both feathermoss and *Sphagnum* species (Kettridge et al., 2014; MacKinnon, 2016). Both burned and unburned feathermoss species have been shown to exhibit relatively strong water repellency in the field; however, the degree of water repellency was shown to be greater for the burned feathermosses (Kettridge et al., 2014; MacKinnon, 2016). Comparatively, *Sphagnum* has been shown to exhibit only slight water repellency in burned locations and essentially none in unburned locations (Kettridge et al., 2014). It is possible that these observed differences of in-situ water repellency are due to differences in water content, given that water repellency in mineral soils has been previously linked to water content (Fishkis et al., 2015). Moreover, it has been suggested that desiccation of peat can exacerbate any water repellency that may be present (Valat et al., 1991); however, no study to our knowledge has examined the effect of water content on the water repellency of moss/peat soils. Examining the influence of water content on peat water repellency, especially in the post-fire environment, is essential not only to understand the temporal variability of water repellency but also water repellency persistence. While studies in mineral soils have found that post-fire water repellency can break down during wetting events (*e.g.* MacDonald and Huffman, 2004), it remains unknown if peatland wetting events (rainfall and/or an increase in water table position), lead to a decline in the spatial extent or severity of water repellency.

To address this critical knowledge gap, we sought to determine: 1) whether there were significant interactive effects of water content with burn status and species on the degree of water repellency in peatland moss/soil samples; 2) whether prolonged saturation decreased the degree of water repellency of burned feathermoss peat; and 3) whether moisture retention characteristics of burned and unburned feathermoss and *Sphagnum* peat varied significantly and thus infer how differences in moisture retention might manifest under in-situ conditions. For the first objective, we hypothesized that the effect of low moisture content, feathermoss species, and burning on near-surface peat water repellency was additive and that this combination would exhibit the greatest degree of water repellency. For the second objective, we hypothesized that prolonged saturation would lead to a decrease in the severity of water repellency.

2. Methods

2.1 Study area and water repellency sampling

Sphagnum (*Sphagnum fuscum*) and feathermoss (*Pleurozium schreberi*) samples were collected in July of 2013 from a mature treed bog in the Utikuma Lake Research Study Area (56.107°N, 115.561°W) (Devito et al., 2012) that was partially burned in May of 2011. The burned and unburned portions are located ~100 m apart and are approximately 100 × 150 m and 90 × 150 m in size, respectively. Both portions of the bog are characterized by feathermoss (>95% *Pleurozium schreberi*) hollows, *S. fuscum* hummocks, vascular vegetation cover of *Rhododendron groenlandicum* and *Rubus chamaemorus*, and a dense black spruce (*Picea mariana*) tree canopy. For more details of the local hydrology, see Smerdon et al. (2005) and Lukenbach et al. (2017).

Small moss and peat blocks roughly 0.15 x 0.15 x 0.05 m were taken from both burned and unburned areas at three depths spanning 0-0.05 m, 0.03-0.08 m, and 0.06-0.11 m. Target depths of 0, 0.03, and 0.05 m were chosen to reflect changes in water repellency observed in the near-surface in other studies (*i.e.* Kettridge et al., 2014). A sample thickness of 0.05 m was chosen so that moss/peat structure could be maintained while having a thin sample which could dry in a relatively uniform manner. Treatments comprising both burn severity and species were defined similar to Lukenbach et al. (2015). There were five treatments consisting of burned and unburned *Sphagnum fuscum* (hereafter *B.Sph* and *Sph*, respectively), burned and unburned feathermoss (hereafter *B.FM* and *FM*, respectively), and burned hollows (*B.Hol*). *B.Hol* generally corresponds with higher burn severity where we were unable to determine the pre-fire moss cover. *B.Sph* corresponds with light burn severity where *Sphagnum* capitula are singed but have not been fully consumed by combustion. For our first research objective, ten samples were collected for each of the five treatments (n=50). For our second research objective, 50 samples of burned feathermoss were collected in order to test whether saturation (see section 2.2) had a significant effect on the persistence of water repellency. A larger sample size was chosen for the second objective because there has been no previous research that we are aware of on which to make an *a priori* assumption of effect size. We focused on feathermoss only for the second lab experiment because field-based measurements of Kettridge et al. (2014), as well as initial results from the first lab experiment had shown that water repellency in burned feathermoss was high, while that for burned *Sphagnum* was comparatively quite low.

2.2 Water drop penetration time

Water drop penetration time (WDPT) tests were undertaken on intact samples in the laboratory every 24 h. Distilled water was dispensed using a pipette held just above the peat sample surface and 10 equally sized water drops applied (Fig. 1). The WDPT was measured upon contact until the complete infiltration of the drop on the sample surface. WDPT was divided into five ranges, as defined by Bisdom et al. (1993) (see also Doerr,1998) as (number/name): 1/hydrophilic (WDPT <5 s); 2/slightly hydrophobic (WDPT 5-60 s); 3/strongly hydrophobic (WDPT 60-600 s); 4/severely hydrophobic (WDPT 600-3600 s); and 5/extremely hydrophobic (WDPT 3600+ s). Samples were transported from the field and allowed to air dry at constant temperature and humidity (20° C, RH=65%) until constant mass was reached. Prior to saturation, an initial air-dry WDPT test was carried out on all samples to provide a baseline water repellency value. Subsequently, all samples were saturated for 48 hours. Following saturation, samples were, again, air dried in a growth chamber at constant temperature and humidity (20° C, RH=65%). WDPT tests were undertaken every 24 hours until constant mass was reached for three consecutive daily measurements, after which samples were oven-dried for 48 h at 65° C. Sample dry weights were used to calculate gravimetric water content (GWC). A final WDPT test was undertaken following oven drying. Prior to each WDPT test, samples were weighed on a digital balance with 0.01 g precision.

2.3 Moisture retention

Moisture retention was measured for ten samples for each burn state and species. Samples consisted of the top 0.06 m of moss/peat, and were collected in 0.098 m diameter PVC pipe. A sharpened PVC tube was inserted into the moss surface, where scissors were used to cut around the periphery when necessary. Once inserted to a depth of 0.06 m, the moss/peat was undercut with scissors, with the bottom of the sample secured in place with cheesecloth. Samples were frozen for transport and storage. Prior to moisture retention measurements, samples were thawed and saturated in deionized water for 48 hr. Moisture retention was determined using a ceramic plate vacuum extractor, with an air entry tension of 1000 mbar. Tensions of 10, 30, 40, 50, 75, 100, 150, and 200 mbar were set using a vacuum regulator for at least 24 h, or until total water released from samples was 0.2 g hr^{-1} or less. The accuracy of the scale used was 0.2 g, and is therefore meant to represent no detectable change. Treatments (i.e. *B.Hol*, *B.FM*, *FM*, *B.Sph*, and *Sph*) were run separately, with each run constituting 10 replicate samples on a single extractor plate. The release of water from all samples (sample volume ~450 cm^3) in a given run was evaluated by weighing the water trap connected to the vacuum plate extractor. After each pressure step, samples were weighed on a digital balance (0.01 g precision). Samples were subsequently oven-dried at 65°C until constant mass was reached. Dry weights were used to calculate GWC, volumetric water content (VWC), and dry bulk density. Porosity was calculated based on an estimated peat particle density of 1470 kg m^{-3} (Redding and Devito, 2006), and subsequently used to calculate saturated GWC and VWC.

2.4 Statistics and curve fitting

We used classification analysis to determine what water content threshold best separated the data into two groups, one with relatively high water repellency, and the other with low water repellency. The optimal split point (GWC threshold) was determined based on the partitioned data which had the smallest total sum of squared residuals, where the respective group means of the partitioned data was used to evaluate residuals. A Monte Carlo approach was used to quantify the uncertainty in the GWC threshold value. The threshold identification procedure was repeated 500 times, where each iteration used a random sample consisting of ~66% of the original sample.

A power function was used to estimate the relation between GWC and tension:

$$GWC = \frac{a}{\psi^b}$$

where *a* and *b* are fitted parameters, and ψ is tension. Parameter estimates were derived using the *nlinfit* function in Matlab (The Mathworks), which uses the Levenberg-Marquardt algorithm for nonlinear least squares regression.

A two-way ANOVA was used to test for significant effects of burn state – species groupings and GWC on WDPT, where GWC was treated as a continuous variable. The ANOVA was run using rank-transformed WDPT. Tukey's honestly significant difference criteria was used for multiple comparisons. An ANCOVA was used to test for a significant difference in the slope of the relation between VWC and bulk density. The relation was evaluated at the VWC corresponding to a tension of 100 mbar, which is considered an ecohydrologically important value for *Sphagnum* (Thompson and Waddington, 2008). Unless otherwise stated, averages are reported along with standard deviation.

2.5 Methodological limitations

While the general response of water repellency in *Sphagnum* and feathermoss to drying and the relative magnitude of water repellency would very likely hold under different experimental conditions, we recognize that GWC thresholds identified within this study may be specific to the drying rate used in the experiment. Assuming a homogenous sample, during the drying process it is not possible for the water content to be uniform with depth unless the pore-water tension is in equilibrium with the humidity inside of the growth chamber. Even under steady-state conditions, a small pressure gradient would exist within the sample, proportional to the thickness of the sample. Our drying experiment used a single, fixed relative humidity and we measured both weight and water repellency through time even though the water content profile was not in steady state. To try and minimize the effects of non steady-state conditions, our samples were exposed at both ends to allow evaporation from both the top and bottom of the sample.

Moreover, we chose a relatively thin sample size of 0.05 m to limit water content gradients within the sample, while simultaneously keeping the moss/peat structure intact. While a high relative humidity would further ensure relatively small water content gradients within the sample, the maximum sustainable relative humidity we were able to maintain given our experimental setup was 70%.

3. Results

3.1 Water drop penetration time and gravimetric water content

The degree of water repellency was affected by species, burn status, water content, and their interactions. Following saturation and free drainage, no degree of water repellency was observed in any sample for at least 48 hr of drying (Fig.2). Of the five treatments, only *FM*, *B.FM*, and surface *B.Hol* exhibited appreciable severe or extreme water repellency during the drying process. *B.Sph*, *Sph*, and non-surface *B.Hol* samples were largely hydrophyllic, or only slightly hydrophobic, throughout the drying process. For feathermoss, the burned treatment had a greater proportion of higher water repellency compared to the unburned treatment (Fig. 2), where average WDPT category for *B.FM* and *FM* were 2.52 and 2.25, respectively. The difference was greatest for the 3 cm samples, where average WDPT for *B.FM* and *FM* were 2.74 and 2.08, respectively (Fig. 3). Meanwhile, *Sphagnum* samples had lower average WDPT for burned (1.24) and unburned (1.39) samples compared to feathermoss. In the case of severe burning (*i.e. B.Hol*), while water repellency was not particularly strong, water repellency appeared to decrease noticeably with depth (average WDPT at: 0 cm = 1.45; 3 cm = 1.12; 6 cm = 1.04). This contrasted with the other burned treatments which had slightly higher water repellency with depth (Fig. 3).

The increased water repellency over the drying experiment (Fig. 2) was in part related to water content (Fig. 4 and 5). Upon initiation of drying, all treatments had a relatively high average GWC, on the order of 10 g g^{-1} (Fig. 3). On average, GWC of both burned and unburned feathermoss samples decreased more rapidly with time compared to other treatments. For example, it took only 5 days for *FM* and *B.FM* to reach a GWC of 1 g g^{-1}, while it took 9, 11, and 14 days of drying for *B.Sph*, *B.Hol*, and *Sph*, respectively. Across all treatments, with the exception of two sample out of 50, there was no observed water repellency for samples with a GWC greater than 5 g g^{-1} (Fig.5). Below 5 g g^{-1}, there is a general increase in water repellency with reduced moisture contents for all species and burn states. Based on classification analysis, the estimated threshold GWC for water repellency of all samples lumped together is 1.4±0.2 g g^{-1}. Individually, threshold estimates for *B.Hol*, *B.FM*, *FM*, *B.Sph*, and *Sph* pooled across depths are 1.0±0.3, 1.0±0.5, 1.8±0.9, 0.9±0.4, and 3.0±0.6, respectively. An ANOVA was used to compare several different linear mixed effects models to elucidate the significance of GWC, burn state - species, and depth on average WDPT. Table 1 shows that all three fixed factors have a significant effect on WDPT. The fixed-factor coefficients of the linear model show that burn state – species has a greater influence on WDPT than depth (Table 2). While the coefficient for GWC is of a similar magnitude to the depth factor, GWC is a continuous rather than categorical variable. Consequently, GWC has an effect size that is an order of magnitude larger than depth (*i.e.* GWC ranges from ~0-10 g g^{-1}), and is thus comparable to the effect size of burn state – species. Despite the smaller influence of depth on WDPT compared to the other two fixed factors, the interaction of depth and burn state – species is significant (Table 1), where direction of change in WDPT with depth is variable and large in some cases (Table 2).

3.2 Effect of saturation on water repellency of burned moss

Overall, saturation had a small, diminishing effect on the degree of water repellency. Based on the large sample size of the second lab run, pre-saturation air-dry samples of *B.FM* were wetter, with roughly twice the GWC compared to post-saturation air-dry samples (Fig. 6). If water content was the only controlling factor on water repellency, pre-saturation air-dry samples should have been less water repellent compared to air-dry post-saturation *B.FM* samples. However, the results show the opposite, where the mean pre-saturation air-dry water repellency classification was 4.4 with a mean GWC of 0.016 g g^{-1} compared to a mean post-saturation air-dry water repellency classification of 3.3 and a mean GWC of 0.008 g g^{-1}. Figure 6b shows that the difference in air-dry GWC pre- and post-saturation follows a strong (R^2=0.87) linear relation with a slope significantly different than one (t_{49} = -20.35, p < 2E-16). In fact, the pre-saturation air-dry mean water repellency classification was roughly equal to the mean value after oven drying, post-saturation (Fig. 6a).

3.3 Water retention of burned and unburned moss

Figure 7 shows that, on a gravimetric basis, there is an apparent distinction between the water retention of *Sphagnum* and feathermoss, where differences between species are larger than differences based on burn state. A simple power function fit (see Methods) provided a good fit to GWC-ψ curves (R^2 of 0.92 to 0.99). Based on the fitted curves, the tension at which *B.FM* was estimated to reach a GWC of 1.4 g g^{-1} was 300±54 mbar (95% confidence interval). For all other treatments, estimated tensions were >>1000 mbar, with confidence intervals of roughly equal magnitude. Figure 7b shows the same water retention data, but on a volumetric basis. On average, bulk density of the *B.Hol* samples was greatest (84 ± 16 kg m^{-3}), followed by *B.FM* (51 ± 19 kg m^{-3}), *FM* (32 ± 8 kg m^{-3}), *B.Sph* (27 ± 11 kg m^{-3}), and *Sph* (20 ± 4 kg m^{-3}). Because of the relatively large difference in bulk density between treatments, *B.Hol* retains more water on a volumetric basis compared to the other treatments. Meanwhile, *Sphagnum* retained more water on a volumetric basis compared to feathermoss, where differences between species were still greater compared to between burn state. In order to compare VWC across samples, Figure 8 shows the relation between bulk density and VWC at a tension of 150 mb. While VWC_{150mb} of all treatments have a significant positive correlation (R^2 of 0.67 to 0.92, and p of 2E-08 to 0.03) to bulk density, an ANCOVA suggests that the slopes of the relation are significantly different (F_4=40.7, $p<<0.01$). While not all pair-wise comparisons are significant, the slope of the relation between VWC_{100mb} and bulk density decreases according to *Sph* > *B.Sph* > *B.Hol* > *FM* > *B.FM*.

4. Discussion

4.1 Water content threshold to water repellency in moss and peat

We show that water content is a controlling factor on water repellency in moss and peat and that there was a threshold-like response of water repellency to GWC, where both *Sphagnum* and feathermoss samples in either a burned or unburned state became water repellent at a GWC less than 1 – 3 g g^{-1}. While all treatments exhibited some degree of water repellency, the magnitude was much smaller for *Sphagnum*, similar to Kettridge et al. (2014). However, for horticultural/agricultural soil, *Sphagnum* peat has been shown to have stronger water repellency upon drying, where degree of water repellency increases with level of decomposition (Michel et al., 2001). Similar to our study, Michel et al. (2001) showed that there is a good relation between water repellency and GWC (therein reported as hydration energy and water ratio, respectively). Similarly, in a fen with agricultural peat, a threshold of water repellency was observed when VWC decreased below 25-30% (Berglund and Persson, 1996). Based on their reported bulk densities, this would correspond to a GWC of between roughly 0.4-1 g g^{-1}. The data presented by

Berglun and Persson (1996), however, are from samples which are much denser than those measured herein, and are heavily decomposed due to cultivation, rather than constituting living moss at the surface.

4.2 Fire and depth dependence of water repellency

During a wildfire, the interface between heated and cooled substrates tends to be only a few centimeters below the surface, and is the location where volatilized organic compounds could condense (Debano, 2000; Certini, 2005). In organic soils, Neff et al. (2005) suggest that the relative abundance of hydrophobic compounds (*i.e.* lignins and lipids) may increase relative to hydrophilic compounds (*i.e.* polysaccharides) in the top few centimeters of soil due to wildfire. Herein, feathermoss lawns exhibit an increase in WDPT at depth (Fig. 3). Feathermoss does not possess the same moisture holding properties as *Sphagnum* mosses and, as such, would not have high surface moisture (Fig. 7-8). Since the thermal properties of peat are largely driven by water content rather than botanical origin or degree of decomposition (O'Donnell et al., 2009a), characteristic differences in water retention might lead to systematic differences in where volatilized compounds condense within the peat profile.

Given that water repellency in mineral soils has been linked to the presence of hydrophobic organic compounds (Ma'shum and Farmer, 1985) or high organic content (de Jonge et al., 2007; Fishkis et al., 2015), perhaps it is not surprising that peatland soils, comprised almost entirely of organic matter (*cf.* Kuhry 1994; Turunen et al., 2002), also exhibit water repellency. However, large differences in water repellency, after accounting for water content effects (Table 1 and 2), between peatland moss species is striking, especially when considered in conjunction with the contrasting water retention properties of these mosses (Fig. 7).

4.3 Peatland water repellency following wildfire

Different studies have reported a range of water contents (GWC of 1.10 to 2.95 g g^{-1}) below which ignition and combustion may occur in peatlands (Frandsen, 1987; Huang and Rein, 2015; Rein et al., 2008; Benscoter et al., 2011). Since the threshold for peat and moss ignition lies in the upper range of GWC where water repellency is observed, field-based attribution of water repellency to fire may be conflated with antecedent dry conditions necessary for smouldering to occur. This suggests that measuring the degree of water repellency post-fire in the field may be more indicative of antecedent weather conditions, relative water table position, and/or inherent differences in moss/peat water retention. For example, Figure 4 shows that the time necessary to reach the average threshold GWC of 1.4 g g^{-1} differed by up to a factor of 3 between treatments. In the context of field moisture retention, Figure 7 would suggest that water repellent conditions are linked to conditions where water table is deep and/or evaporative potential exceeds capillary rise. Furthermore, given that surface evaporative demand is greater in burned peatlands due to the loss of the canopy (Thompson et al., 2015) and that feathermosses preferentially occupy shaded areas in unburned peatlands (Bisbee et al., 2001), in-situ moisture contents likely differ appreciably between burned and unburned areas, especially for feathermosses. These factors likely explain the contradictory results between O'Donnell et al. (2009b) and Kettridge et al. (2014) in which moisture content was not considered. Given the variation in peatland surface moisture contents observed in the field, ranging from ~0.02 m^3 m^{-3} in *B. FM* sites to ~0.75 m^3 m^{-3} in *B.Hol* (Lukenbach et al., 2015), in-situ water repellency is likely to be highly variable spatially. Nevertheless, our results support the general findings from other studies where observed differences of in-situ water repellency are primarily due to differences in water content (e.g. Fishkis et al., 2015; Valat et al., 1991). Our results also support the findings of Kettridge et al. (2014), where, once dry, water repellency in feathermoss is greater than *Sphagnum fuscum*, and feathermoss is more water repellent in a burned compared to an unburned state. Although not directly comparable to our results (Fig. 3), Kettridge et al. (2014) found that the field-based average water repellency of burned *Sphagnum* was greater than unburned *Sphagnum*, albeit the absolute difference between burned and unburned *Sphagnum* was small in both their and our study. Field measurement results from other studies could be explained by differences in water content. For a given tension our results (Fig. 7) indicate that unburned *Sphagnum* has a greater GWC than burned samples (see also Thompson and Waddington, 2013) as well as other treatments, and is therefore less likely to be water repellent, all else being equal. Others have shown that there are significant spatio-temporal differences in near-surface water content associated with burn state – species (Lukenbach et al., 2016). While such differences can easily be measured, accounting for within-site differences in bulk density which tends to be small and not highly variable in the near-surface (*e.g.* Hokanson et al., 2016) would be more challenging.

Following saturation (*i.e.* high water content), all treatments initially were not water repellent, but *FM* and *B.FM* treatments quickly developed water repellency compared to other treatments. Contrary to some mineral soils (*e.g.* MacDonald and Huffman, 2004), prolonged saturation did not permanently decrease the degree of water repellency by a substantial amount. This suggests that even if a water table were to rise to the peat surface it would not appreciably affect the persistence of water repellency in feathermoss peat. Moreover, water repellency was readily re-established to its pre-saturation state following oven drying. Given that surface temperatures can exceed 50°C in burned peatlands following wildfire (Kettridge et al., 2017), the degree of water repellency may remain elevated until a substantial shrub and/or tree canopy establishes. Future research should examine under what conditions, or if at all, water repellency diminishes over time in peatlands following wildfire, especially peat of feathermoss origin.

4.4 Implications for recovery and resiliency

Sphagnum is a keystone species in peatlands, and is the primary species responsible for peatland carbon storage (Yu, 2012). Following wildfire, the ecological succession of groundcover in continental bogs and poor fens is characterized by early pioneer species less than five years post-fire, *Sphagnum* dominance between roughly 20-30 years post-fire, and feathermoss dominance at roughly 70 years post-fire (Benscoter and Vitt, 2008). In continental boreal bogs and poor fens, a sustained crown fire is a function of canopy fine-fuel load (Van Wagner, 1977) and is more likely to occur in mature black spruce canopies (Krawchuk et al., 2006) which tend to be underlain by feathermoss groundcover (Bisbee et al, 2001; Benscoter and Vitt, 2008). Consequently, an extensive post-fire surface cover of lightly burned feather mosses exhibiting significant water repellency can be present. This would imply that a large portion of peatlands post-fire will be strongly water repellent, and is supported by findings of MacKinnon (2016).

Relatively low soil water tensions, typically less than 100 mbar, are necessary for *Sphagnum* recolonization (Price, 1997; Thompson and Waddington, 2008). Post-fire, Lukenbach et al. (2016) demonstrate that near-surface tensions frequently exceed this threshold, particularly for *B.FM* (therein LB-F). Our results indicate that high post-fire surface tensions may be exacerbated by near-surface water repellency, where imbibition is shown to be suppressed in water repellent soil (Diamantopoulos et al., 2013). A reduction in capillary flow, which has been shown to occur in hydrophobic porous media (Shahidzadeh-Bonn et al., 2007), would likely leave much of the peatland surface unsuitable to germinating moss spores, as they require high moisture contents and humidity at the surface to be successful (Sundberg and Rydin, 2002;

Smolders et al., 2003; Koyama and Tsuyuzaki, 2010). Given that high water contents are necessary to decrease the degree of water repellency in feathermosses, this suggests that high water availability (*e.g.* a shallow WT or ponding) is likely necessary for *Sphagnum* recolonization on *B.FM* surfaces in peatlands. This is especially relevant for 'over-mature' peatlands (*i.e.* significantly older than a typical fire cycle), where the groundcover is very likely to be heavily dominated by feathermoss (Benscoter and Vitt, 2008). Given that the average depth to *Sphagnum* in *B.FM* classified areas at a nearby study site was ~0.2 m (MacKinnon, 2016), and that *Sphagnum* peat tends to dominate western boreal peat profiles (Kuhry, 1994), high burn severity (large depth of burn) increases the likelihood of exposing *Sphagnum* peat at the surface. While it was not possible to determine the original surface moss species at *B.Hol* locations, our high burn severity *B.Hol* samples showed low water repellency. Nevertheless, a dense tree canopy and lower moisture retention of feathermoss is likely to lead to greater average depth of burn compared to sites where *Sphagnum* mosses are present (Thompson et al., 2015). While severe burning would serve to enhance potential recovery post-fire, this would represent a substantial loss of carbon. Conversely, for moderate to light smouldering of feathermoss, persistent strong water repellency would act to limit moss recovery, particularly for *Sphagnum* mosses, which are thought to be a keystone species for maintaining long-term peatland resilience.

While near-surface water repellency may limit post-fire vegetation recovery, it may be beneficial in restricting peatland-scale water losses due to net water retention (Kettridge et al., 2014). In post-fire peatland sites with a significant portion of burned feathermoss surfaces, such as reported by Lukenbach et al. (2015), ubiquitous water repellency could represent an important feedback for water conservation following wildfire. In the absence of vascular vegetation immediately post-fire, high surface resistance/tension, particularly in burned feathermoss, represents a negative feedback to water loss. Under water-limiting conditions, where the magnitude of near-surface tension is greater than the height above water table, Kettridge and Waddington (2014) showed that surface resistance rapidly increased with tension for burned moss surfaces, which would thereby shutdown surface evaporation. In the short term, the dynamic of water conservation by water repellent surfaces, such as burned feathermoss, combined with the potential for greater water table rise with rainfall may act to increase water availability to low-lying areas within a peatland, thus facilitating recovery in areas that were in a low microtopographic position pre-fire or burned deeply.

5. Conclusion

Water content is a key determinant of water repellency in peatlands, where the degree of water repellency exhibits a threshold-like increase at gravimetric water contents less than 1.4 g g^{-1} in both *Sphagnum* and feathermoss peat. The prevalence of such water contents under field conditions is likely to be closely associated with the water retention functions of different moss species (*i.e. Sphagnum* vs. feathermosses). In particular, our results suggest that water repellency in peatlands would directly coincide with the presence of feathermosses, regardless of burn status, because 1) feathermoss-derived peat characteristically has a high degree water repellency and 2) feathermosses exhibit poor water retention, resulting in low water contents under field conditions and thus a high degree of water repellency. In contrast, *Sphagnum* mosses and peat intrinsically exhibit a low degree of water repellency and are more effective at retaining water on a gravimetric basis, decreasing the likelihood of water repellency under field conditions.

Wildfire, while playing a smaller role than water content and moss species in determining water repellency, enhances peatland water repellency. This results from: 1) decreasing the ability of mosses to retain water (Fig. 6); and 2) the likely alteration of organic compounds present in peat (*cf.* Doerr et al, 2000). The latter appears to be related to heating, based on an enhancement in water repellency following oven drying, but an understanding of this mechanism requires further research. Perhaps the largest influence wildfire has on peatland water repellency, however, is the combustion of centimeters to decimeters of water repellent feathermoss, which can expose underlying *Sphagnum* peat that is rarely water repellent under field conditions (*e.g.* Kettridge et al., 2014). Elevated water contents and the absence of water repellency in these locations likely supports post-fire moss recovery. However, if the deep combustion of feathermosses is widespread in a peatland, peatland-scale water losses may be higher following wildfire due to an increase in evaporation. Comparatively, if burned and water repellent feathermosses are still a ubiquitous part of the post-fire surface following wildfire, the amount of water available at the surface is likely low, simultaneously limiting post-fire moss recovery and evaporation. This highlights an important trade-off between recovery and water conservation in the post-fire peatland environment. How these interact at larger scales to influence overall peatland ecosystem hydrology and function requires further research.

Finally, we suggest that future studies may be able to obtain a more direct measure of surface water content by using multispectral imaging, as suggested by Fishkis et al. (2015). Placing results from this study in context of peatland water repellency, we suggest that future studies would benefit from quantifying the persistence of moss water repellency with time since fire while accounting for water content through destructive sample for quantifying GWC.

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Table(s)

Table 1: Linear mixed effects models for sample average water drop penetration time (WDPT) as a function of different combinations of fixed effect (gravimetric water content (GWC); burn state-species (BrnSp); and depth), as indicated by the model formula, and sample as a random effect. Model formula is based on R conventions.

	WDPT~GWC+BrnSp+Dpth+(1|Sample)		
Model:	χ^2	d.f	p
WDPT~GWC+BrnSp+(1|Sample)	11.94	2	0.0025
WDPT~GWC+Depth+(1|Sample)	127.9	4	<<0.001
WDPT~BrnSp+Depth+(1|Sample)	1142	1	<<0.001
WDPT~GWC+BrnSp*Dpth+(1|Sample)	250.7	8	<<0.001
WDPT~GWC*BrnSp+Dpth+(1|Sample)	987.2	4	<<0.001

Table 2: Summary of fixed effects for linear mixed effects model of sample average water drop penetration time (WDPT) as a function of gravimetric water content (GWC); burn state-species, and depth, and sample as a random effect. Two model variants are presented, one with and without an interaction term between [depth] and [burn state - species]. Results are presented for rank transformed WDPT, where lower rank indicates higher average WDPT.

		Interaction	Estimate (no interaction)	Std. Err	Estimate (/w interaction)	Std. Err
Intercept		---	2072	36	2083	44
GWC		---	-79	2	-80	2
Burn state - species	*B.FM*	---	0	---	0	---
	FM	---	-72	47	72	62
	Sph	---	-536	48	-433	62
	B.Sph	---	-740	48	-743	62
	B.Hol	---	-930	47	-1212	62
Depth	0 cm	---	-73	23	-189	48
		FM	---	---	-70	69
		Sph	---	---	-161	69
		B.Sph	---	---	70	69
		B.Hol	---	---	737	69
	3 cm	---	-11	23	75	48
		FM	---	---	-363	69
		Sph	---	---	-132	69
		B.Sph	---	---	-47	69
		B.Hol	---	---	115	69
	6 cm	---	0	---	0	---

Figure List

Figure 1: Simple experimental setup of water drop penetration time (WDPT) test using a pipette to apply water drops from a consistent minimal height above moss/peat surface (a). WDPT test was applied to surface samples of both feathermoss (b) and *Sphagnum* (c), as well as underlying peat soil (d). Images are of unburned samples.

Figure 2: Summary of water drop penetration time (WDPT) tests for air drying of unburned and burned *Sphagnum* (Sph and B.Sph), unburned and burned feathermoss (FM and B.FM), and burned hollow (B.Hol) samples at three depths. Results are for up to 26 days of drying, and also include results from pre-saturation air-dry (Pre), and oven-dry (Ovn) state. Colour-coded bars represent the percent of water drops (10 drops per sample × 10 samples) that infiltrated the sample surface in: <5 s (1 - hydrophilic); 5-60 s (2 – slightly hydrophobic); 61-600 s (3 – strongly hydrophobic); 601-3600 s (4 – severely hydrophobic); >3600 s (5 – extremely hydrophobic).

Figure 3: Boxplots of average water repellency category for all three depths (0, 3, and 6 cm). Bars represent the inter-quartile range, notches are the 95% confidence interval on the median, and open circles beyond whiskers are considered extreme values.

Figure 4: Average gravimetric water content (GWC) of unburned (open) and burned (filled) *Sphagnum* (blue square symbols; Sph and B.Sph), unburned and burned feathermoss (red circle symbols; FM and B.FM), and burned hollow (black triangle symbol; B.Hol) samples throughout the drying experiment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure 5: Average water repellency category for each sample (based on 10 water drops per sample) over the course of air-drying under constant temperature and humidity. Results are shown for 0 cm (a), 3cm (b), and 6 cm (c) samples. Gravimetric water content (GWC) is displayed on a log scale to provide better visualisation of data points at low water contents.

Figure 6: Comparison of water repellency for large sample (n=70) of burned feathermoss between pre-saturation air-dry state (Pre), post-saturation air-dry state (Post) and oven-dry state (Oven). Colour-coded bars represent the percent of water drops (10 drops per sample × 10 samples) that infiltrated the sample surface in: <5 s (1 - hydrophilic); 5-60 s (2 – slightly hydrophobic); 61-600 s (3 – strongly hydrophobic); 601-3600 s (4 – severely hydrophobic); >3600 s (5 – extremely hydrophobic). The lower panel shows the relationship between gravimetric water content (GWC) of sample in a pre- and post-saturation air-dry state.

Figure 7: Gravimetric (GWC) (a) and volumetric (b) water content of unburned (white-filled circles) and burned (black-filled circles) *Sphagnum* (Sph and B.Sph – blue lines), unburned and burned feathermoss (FM and B.FM – red lines), and burned hollow (B.Hol – black line). Error bars represent the standard error based on ten replicate samples. Estimated saturation GWC values are arbitrarily plotted along the left y-axis since tension of 0 mbar cannot be plotted in log-log space. Tension values in panel (b) have been jittered to improved data visibility.

Figure 8: Volumetric water content at a tension of 100 mbar as a function of dry bulk density for unburned (white-filled circles) and burned (black-filled circles) *Sphagnum* (Sph and B.Sph – blue), unburned and burned feathermoss (FM and B.FM – red), and burned hollow (B.Hol – black line). Linear least-squares regression forced through zero are shown.

Figures

Figure 1

Figure 2

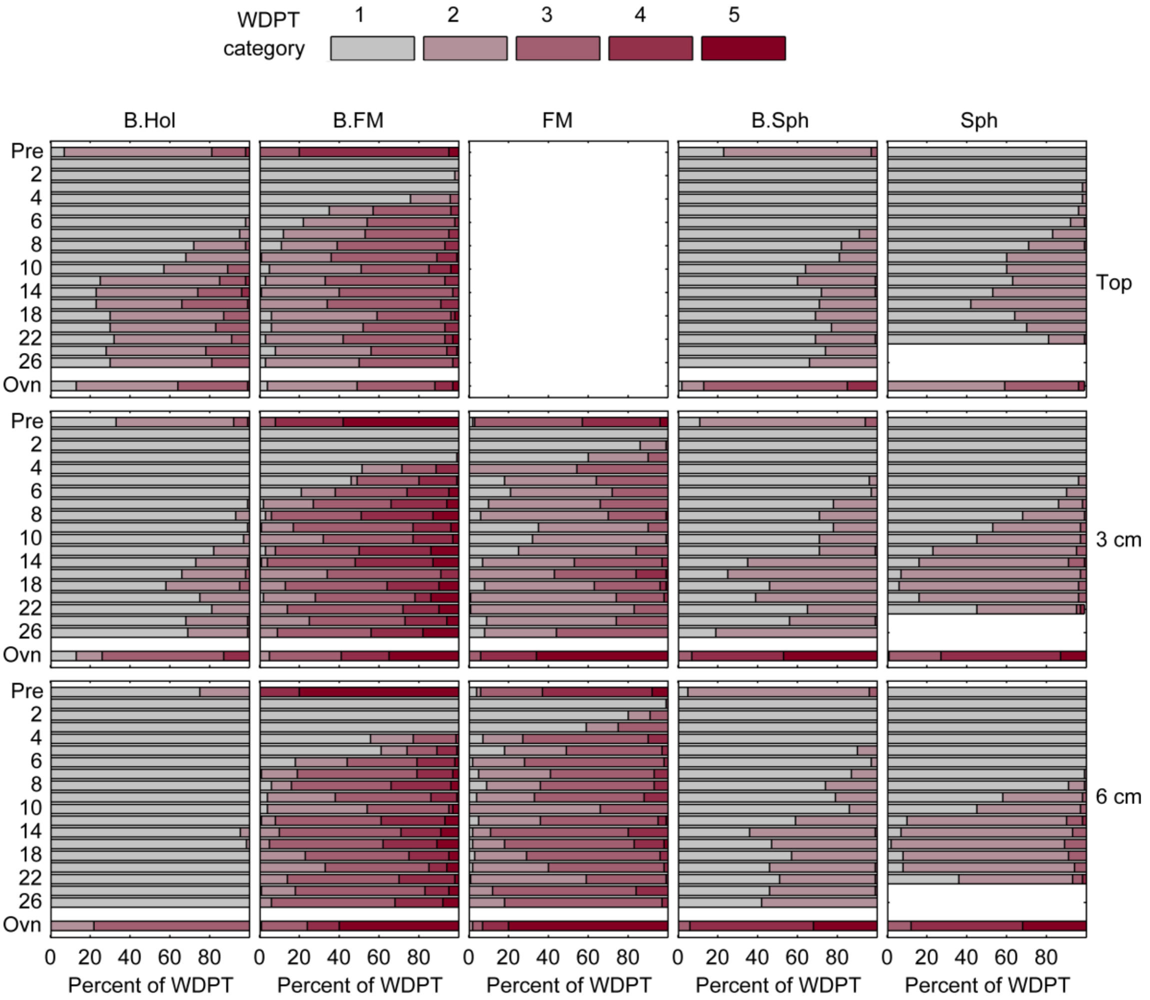

WDPT category
1
2
3
4
5
B.Hol
B.FM
FM
B.Sph
Sph
Top
3 cm
6 cm
Pre
2
4
6
8
10
14
18
22
26
Ovn
0
20
40
60
80
Percent of WDPT

Figure 3

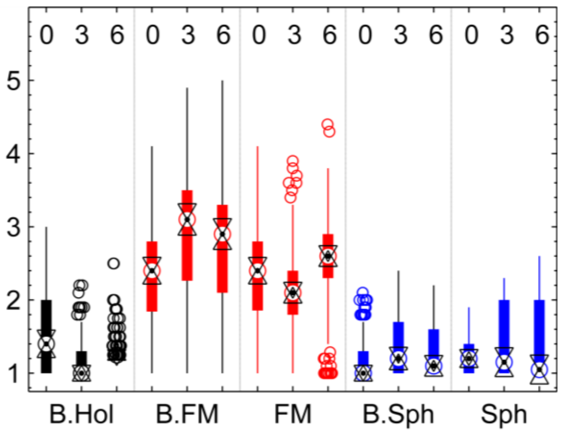
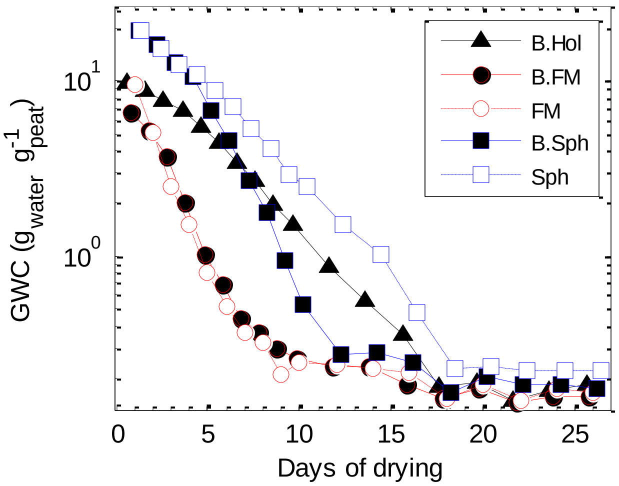


Figure 4



GWC (g_{water} g_{peat}^{-1})
10^1
10^0
0
5
10
15
20
25
Days of drying
▲ B.Hol
● B.FM
○ FM
■ B.Sph
□ Sph

Figure 5

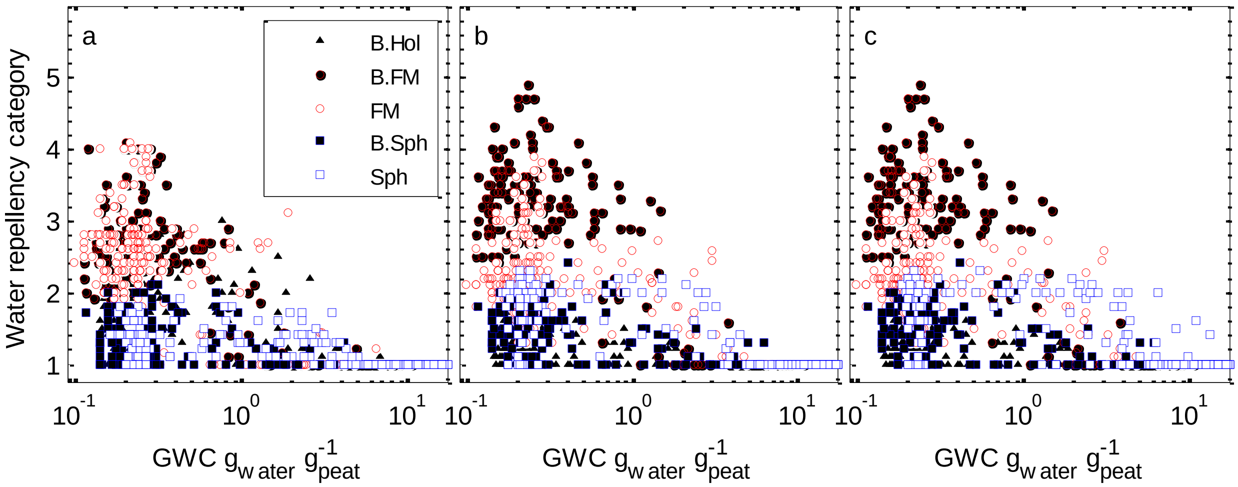

a
b
c
B.Hol
B.FM
FM
B.Sph
Sph
Water repellency category
1
2
3
4
5
10^{-1}
10^{0}
10^{1}
GWC $g_{water}\ g^{-1}_{peat}$

Figure 6

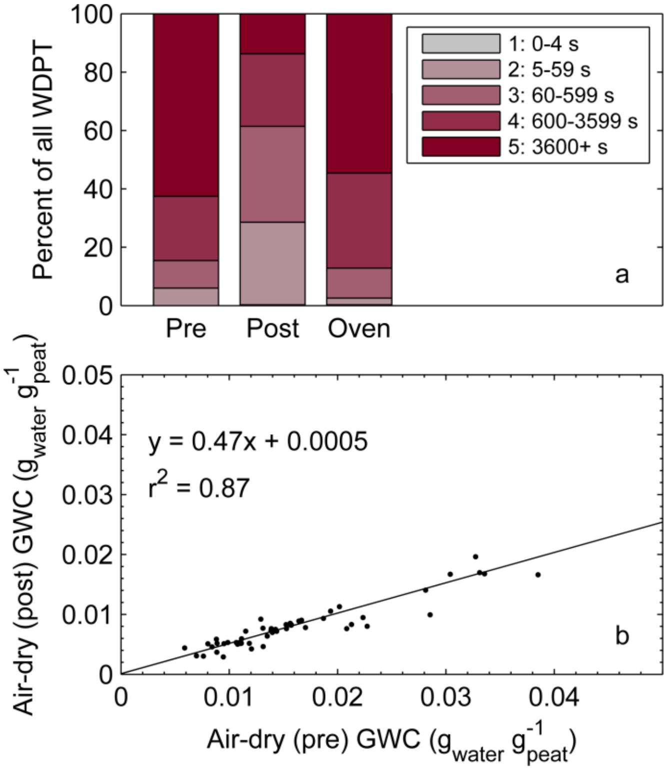

100
80
60
40
20
0
Percent of all WDPT
1: 0-4 s
2: 5-59 s
3: 60-599 s
4: 600-3599 s
5: 3600+ s
a
Pre
Post
Oven
0.05
0.04
0.03
0.02
0.01
0
Air-dry (post) GWC (g_{water} g_{peat}^{-1})
y = 0.47x + 0.0005
r^2 = 0.87
b
0
0.01
0.02
0.03
0.04
Air-dry (pre) GWC (g_{water} g_{peat}^{-1})

Figure 7

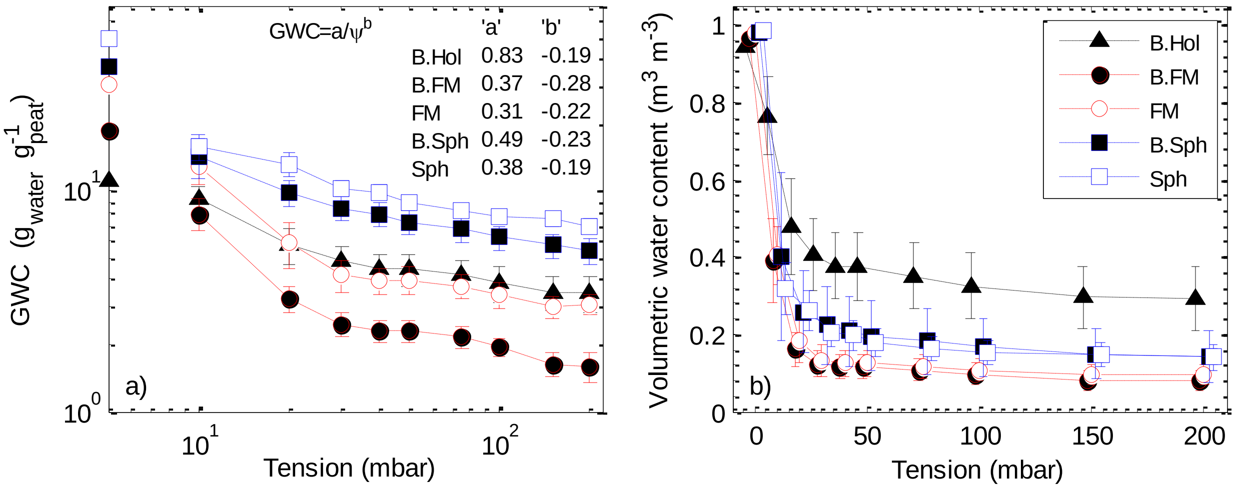
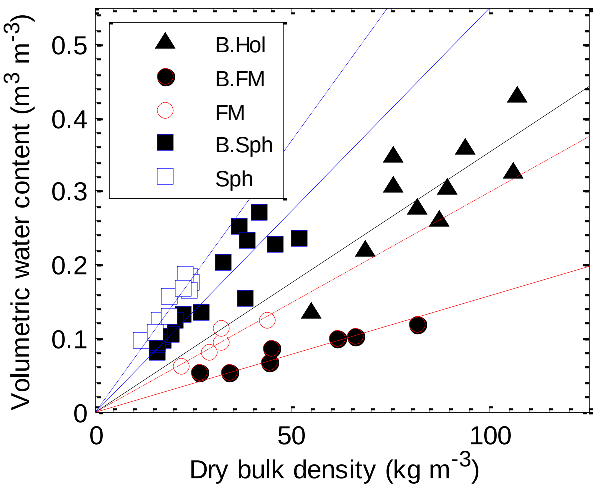

GWC=a/ψ^b
'a' 'b'
B.Hol 0.83 -0.19
B.FM 0.37 -0.28
FM 0.31 -0.22
B.Sph 0.49 -0.23
Sph 0.38 -0.19
GWC (g_water g_peat^-1)
10^1
10^0
10^1
10^2
Tension (mbar)
a)
Volumetric water content (m^3 m^-3)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
Tension (mbar)
b)
B.Hol
B.FM
FM
B.Sph
Sph

Figure 8


B.Hol
B.FM
FM
B.Sph
Sph
Volumetric water content (m^3 m^{-3})
0.5
0.4
0.3
0.2
0.1
0
0
50
100
Dry bulk density (kg m^{-3})