

Peatland Water Repellency:

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

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19 **KEY WORDS:** water repellency, moss, *Sphagnum*, feathermoss, wildfire, peatland

20

21 **Abstract**

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

40 **1. Introduction**

41 Peatlands are wetlands defined, in part, by thick accumulations of organic matter (>0.4m in
42 Canada, National Wetlands Working Group, 1997). While representing less than 3% of global
43 land area, northern peatlands comprise roughly one-third of global soil carbon storage (Yu et al.,
44 2010). Fire-prone peatland-dominated regions exist over large areas of western boreal Canada
45 and Siberia (de Groot et al., 2013), where relatively short fire return intervals play an important
46 role for carbon storage and vegetation dynamics (Weber and Flannigan, 1997). Moreover, in
47 western continental Canada, peatlands in a sub-humid climate exist at the limit of their climatic
48 tolerance (Vitt et al., 2000). The contemporary carbon storage rate for peatlands in this region is
49 estimated at $19.4 \text{ g C m}^{-2} \text{ y}^{-1}$ (Vitt et al., 2000), but fires have the potential to release a large
50 amount of the long-term carbon stored in these ecosystems (Hokanson et al., 2016) and reduce
51 carbon accumulation rates for years to decades (Turetsky et al., 2002). With an increase in large
52 fires and total burned area for boreal peatlands (Kasischke and Turetsky, 2006; Turetsky et al.,
53 2011), the carbon storage function of boreal peatlands may further be degraded. As such, there is
54 concern that the predicted increase in climate change mediated disturbances, such as wildfire
55 and/or drought, will negatively impact the contemporary carbon storage potential of these
56 peatlands (Vitt et al., 2000; Flannigan et al., 2000; Flannigan et al., 2005).

57 However, peatlands which are not significantly affected by anthropogenic disturbance are
58 considered resilient ecosystems, owing to a number of negative ecohydrological feedbacks
59 (Waddington et al., 2015). Following wildfire, water repellency has recently been suggested to
60 be a potentially important negative feedback acting to conserve water, and potentially aid in
61 vegetation recovery (Kettridge et al., 2017), and is prevalent in post-fire Boreal Plains bogs
62 (Kettridge et al., 2014; MacKinnon, 2016). Whilst well studied in mineral soils (*cf.* Doerr et al.,

63 2000), few studies have examined water repellency in peatland ecosystems, where the soil
64 surface is typically comprised of living mosses (*e.g.* O'Donnell et al., 2009b; Kettridge et al.,
65 2014). Water repellency has been shown to affect capillary forces driving water movement in
66 porous media (Shokri et al., 2009), limiting capillary flow to the evaporating surface from wetter
67 and/or saturated soil layers (Diamantopoulos et al., 2013), thus potentially reducing surface
68 evaporation (Shahidzadeh-Bonn et al., 2007). Therefore, water repellency may constitute an
69 important ecohydrological feedback in peatlands, whereby evaporation is severely limited
70 (Kettridge et al., 2017), amplifying the water table depth - moss resistance feedback (see
71 Waddington et al., 2015), and thus conserving water.

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

81

82 Post-fire near-surface water repellency in peatlands can be created or exacerbated based on
83 botanical origin and depth (O'Donnell et al., 2009b; Kettridge et al., 2014) and is persistent for
84 several years (*e.g.* Kettridge et al., 2014; MacKinnon, 2016). As such, it is necessary to consider
85 the importance of water repellency in relation to both peatland vadose zone hydrology and moss

86 recovery post-fire. However, past studies on peatland water repellency persistence are somewhat
87 contradictory. O'Donnell et al. (2009b) found minimal persistence of hydrophobicity 24 months
88 post-fire at the peat surface for both *Sphagnum* and feathermoss species. In contrast, two studies
89 undertaken in northern Alberta 15 months and 38 months post-fire showed significant and
90 persistent near-surface water repellency for both feathermoss and *Sphagnum* species (Kettridge
91 et al., 2014; MacKinnon, 2016). Both burned and unburned feathermoss species have been
92 shown to exhibit relatively strong water repellency in the field; however, the degree of water
93 repellency was shown to be greater for the burned feathermosses (Kettridge et al., 2014;
94 MacKinnon, 2016). Comparatively, *Sphagnum* has been shown to exhibit only slight water
95 repellency in burned locations and essentially none in unburned locations (Kettridge et al., 2014).
96 It is possible that these observed differences of in-situ water repellency are due to differences in
97 water content, given that water repellency in mineral soils has been previously linked to water
98 content (Fishkis et al., 2015). Moreover, it has been suggested that desiccation of peat can
99 exacerbate any water repellency that may be present (Valat et al., 1991); however, no study to
100 our knowledge has examined the effect of water content on the water repellency of moss/peat
101 soils. Examining the influence of water content on peat water repellency, especially in the post-
102 fire environment, is essential not only to understand the temporal variability of water repellency
103 but also water repellency persistence. While studies in mineral soils have found that post-fire
104 water repellency can break down during wetting events (*e.g.* MacDonald and Huffman, 2004), it
105 remains unknown if peatland wetting events (rainfall and/or an increase in water table position),
106 lead to a decline in the spatial extent or severity of water repellency.

107

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

118

119 **2. Methods**

120 *2.1 Study area and water repellency sampling*

121 *Sphagnum* (*Sphagnum fuscum*) and feathermoss (*Pleurozium schreberi*) samples were collected
122 in July of 2013 from a mature treed bog in the Utikuma Lake Research Study Area (56.107°N,
123 115.561°W) (Devito et al., 2012) that was partially burned in May of 2011. The burned and
124 unburned portions are located ~100 m apart and are approximately 100 × 150 m and 90 × 150 m
125 in size, respectively. Both portions of the bog are characterized by feathermoss (>95%
126 *Pleurozium schreberi*) hollows, *S. fuscum* hummocks, vascular vegetation cover of
127 *Rhododendron groenlandicum* and *Rubus chamaemorus*, and a dense black spruce (*Picea*
128 *mariana*) tree canopy. For more details of the local hydrology, see Smerdon et al. (2005) and
129 Lukenbach et al. (2017).

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

150 2.2 Water drop penetration time

151 Water drop penetration time (WDPT) tests were undertaken on intact samples in the laboratory
152 every 24 h. Distilled water was dispensed using a pipette held just above the peat sample surface

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

168 *2.3 Moisture retention*

169 Moisture retention was measured for ten samples for each burn state and species. Samples
170 consisted of the top 0.06 m of moss/peat, and were collected in 0.098 m diameter PVC pipe. A
171 sharpened PVC tube was inserted into the moss surface, where scissors were used to cut around
172 the periphery when necessary. Once inserted to a depth of 0.06 m, the moss/peat was undercut
173 with scissors, with the bottom of the sample secured in place with cheesecloth. Samples were
174 frozen for transport and storage. Prior to moisture retention measurements, samples were thawed
175 and saturated in deionized water for 48 hr. Moisture retention was determined using a ceramic

176 plate vacuum extractor, with an air entry tension of 1000 mbar. Tensions of 10, 30, 40, 50, 75,
177 100, 150, and 200 mbar were set using a vacuum regulator for at least 24 h, or until total water
178 released from samples was 0.2 g hr⁻¹ or less. The accuracy of the scale used was 0.2 g, and is
179 therefore meant to represent no detectable change. Treatments (i.e. *B.Hol*, *B.FM*, *FM*, *B.Sph*, and
180 *Sph*) were run separately, with each run constituting 10 replicate samples on a single extractor
181 plate. The release of water from all samples (sample volume ~450 cm³) in a given run was
182 evaluated by weighing the water trap connected to the vacuum plate extractor. After each
183 pressure step, samples were weighed on a digital balance (0.01 g precision). Samples were
184 subsequently oven-dried at 65°C until constant mass was reached. Dry weights were used to
185 calculate GWC, volumetric water content (VWC), and dry bulk density. Porosity was calculated
186 based on an estimated peat particle density of 1470 kg m⁻³ (Redding and Devito, 2006), and
187 subsequently used to calculate saturated GWC and VWC.

188 *2.4 Statistics and curve fitting*

189 We used classification analysis to determine what water content threshold best separated the data
190 into two groups, one with relatively high water repellency, and the other with low water
191 repellency. The optimal split point (GWC threshold) was determined based on the partitioned
192 data which had the smallest total sum of squared residuals, where the respective group means of
193 the partitioned data was used to evaluate residuals. A Monte Carlo approach was used to quantify
194 the uncertainty in the GWC threshold value. The threshold identification procedure was repeated
195 500 times, where each iteration used a random sample consisting of ~66% of the original sample.

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

$$197 \quad GWC = \frac{a}{\psi^b}$$

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

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

209 *2.5 Methodological limitations*

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

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

226 **3. Results**

227 *3.1 Water drop penetration time and gravimetric water content*

228 The degree of water repellency was affected by species, burn status, water content, and their
229 interactions. Following saturation and free drainage, no degree of water repellency was observed
230 in any sample for at least 48 hr of drying (Fig.2). Of the five treatments, only *FM*, *B.FM*, and
231 surface *B.Hol* exhibited appreciable severe or extreme water repellency during the drying
232 process. *B.Sph*, *Sph*, and non-surface *B.Hol* samples were largely hydrophilic, or only slightly
233 hydrophobic, throughout the drying process. For feathermoss, the burned treatment had a greater
234 proportion of higher water repellency compared to the unburned treatment (Fig. 2), where
235 average WDPT category for *B.FM* and *FM* were 2.52 and 2.25, respectively. The difference was
236 greatest for the 3 cm samples, where average WDPT for *B.FM* and *FM* were 2.74 and 2.08,
237 respectively (Fig. 3). Meanwhile, *Sphagnum* samples had lower average WDPT for burned
238 (1.24) and unburned (1.39) samples compared to feathermoss. In the case of severe burning (*i.e.*
239 *B.Hol*), while water repellency was not particularly strong, water repellency appeared to decrease
240 noticeably with depth (average WDPT at: 0 cm = 1.45; 3 cm = 1.12; 6 cm = 1.04). This
241 contrasted with the other burned treatments which had slightly higher water repellency with
242 depth (Fig. 3).

243 The increased water repellency over the drying experiment (Fig. 2) was in part related to water
244 content (Fig. 4 and 5). Upon initiation of drying, all treatments had a relatively high average
245 GWC, on the order of 10 g g^{-1} (Fig. 3). On average, GWC of both burned and unburned
246 feathermoss samples decreased more rapidly with time compared to other treatments. For
247 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,
248 and 14 days of drying for *B.Sph*, *B.Hol*, and *Sph*, respectively. Across all treatments, with the
249 exception of two sample out of 50, there was no observed water repellency for samples with a
250 GWC greater than 5 g g^{-1} (Fig.5). Below 5 g g^{-1} , there is a general increase in water repellency
251 with reduced moisture contents for all species and burn states. Based on classification analysis,
252 the estimated threshold GWC for water repellency of all samples lumped together is $1.4 \pm 0.2 \text{ g g}^{-1}$
253 ¹. Individually, threshold estimates for *B.Hol*, *B.FM*, *FM*, *B.Sph*, and *Sph* pooled across depths
254 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
255 compare several different linear mixed effects models to elucidate the significance of GWC, burn
256 state - species, and depth on average WDPT. Table 1 shows that all three fixed factors have a
257 significant effect on WDPT. The fixed-factor coefficients of the linear model show that burn
258 state – species has a greater influence on WDPT than depth (Table 2). While the coefficient for
259 GWC is of a similar magnitude to the depth factor, GWC is a continuous rather than categorical
260 variable. Consequently, GWC has an effect size that is an order of magnitude larger than depth
261 (*i.e.* GWC ranges from $\sim 0\text{-}10 \text{ g g}^{-1}$), and is thus comparable to the effect size of burn state –
262 species. Despite the smaller influence of depth on WDPT compared to the other two fixed
263 factors, the interaction of depth and burn state – species is significant (Table 1), where direction
264 of change in WDPT with depth is variable and large in some cases (Table 2).

265 3.2 Effect of saturation on water repellency of burned moss

266 Overall, saturation had a small, diminishing effect on the degree of water repellency. Based on
267 the large sample size of the second lab run, pre-saturation air-dry samples of *B.FM* were wetter,
268 with roughly twice the GWC compared to post-saturation air-dry samples (Fig. 6). If water
269 content was the only controlling factor on water repellency, pre-saturation air-dry samples
270 should have been less water repellent compared to air-dry post-saturation *B.FM* samples.
271 However, the results show the opposite, where the mean pre-saturation air-dry water repellency
272 classification was 4.4 with a mean GWC of 0.016 g g⁻¹ compared to a mean post-saturation air-
273 dry water repellency classification of 3.3 and a mean GWC of 0.008 g g⁻¹. Figure 6b shows that
274 the difference in air-dry GWC pre- and post-saturation follows a strong (R²=0.87) linear relation
275 with a slope significantly different than one (t₄₉ = -20.35, p < 2E-16). In fact, the pre-saturation
276 air-dry mean water repellency classification was roughly equal to the mean value after oven
277 drying, post-saturation (Fig. 6a).

278 3.3 Water retention of burned and unburned moss

279 Figure 7 shows that, on a gravimetric basis, there is an apparent distinction between the water
280 retention of *Sphagnum* and feathermoss, where differences between species are larger than
281 differences based on burn state. A simple power function fit (see Methods) provided a good fit to
282 GWC- ψ curves (R² of 0.92 to 0.99). Based on the fitted curves, the tension at which *B.FM* was
283 estimated to reach a GWC of 1.4 g g⁻¹ was 300±54 mbar (95% confidence interval). For all other
284 treatments, estimated tensions were >>1000 mbar, with confidence intervals of roughly equal
285 magnitude. Figure 7b shows the same water retention data, but on a volumetric basis. On
286 average, bulk density of the *B.Hol* samples was greatest (84 ± 16 kg m⁻³), followed by *B.FM* (51
287 ± 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

288 the relatively large difference in bulk density between treatments, *B.Hol* retains more water on a
289 volumetric basis compared to the other treatments. Meanwhile, *Sphagnum* retained more water
290 on a volumetric basis compared to feathermoss, where differences between species were still
291 greater compared to between burn state. In order to compare VWC across samples, Figure 8
292 shows the relation between bulk density and VWC at a tension of 150 mb. While VWC_{150mb} of
293 all treatments have a significant positive correlation (R^2 of 0.67 to 0.92, and p of 2E-08 to 0.03)
294 to bulk density, an ANCOVA suggests that the slopes of the relation are significantly different
295 ($F_4=40.7$, $p < 0.01$). While not all pair-wise comparisons are significant, the slope of the relation
296 between VWC_{100mb} and bulk density decreases according to $Sph > B.Sph > B.Hol > FM > B.FM$.

297 **4. Discussion**

298 *4.1 Water content threshold to water repellency in moss and peat*

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

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

314 *4.2 Fire and depth dependence of water repellency*

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

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

333 4.3 Peatland water repellency following wildfire

334 Different studies have reported a range of water contents (GWC of 1.10 to 2.95 g g⁻¹) below
335 which ignition and combustion may occur in peatlands (Frandsen, 1987; Huang and Rein, 2015;
336 Rein et al., 2008; Benscoter et al., 2011). Since the threshold for peat and moss ignition lies in
337 the upper range of GWC where water repellency is observed, field-based attribution of water
338 repellency to fire may be conflated with antecedent dry conditions necessary for smouldering to
339 occur. This suggests that measuring the degree of water repellency post-fire in the field may be
340 more indicative of antecedent weather conditions, relative water table position, and/or inherent
341 differences in moss/peat water retention. For example, Figure 4 shows that the time necessary to
342 reach the average threshold GWC of 1.4 g g⁻¹ differed by up to a factor of 3 between treatments.
343 In the context of field moisture retention, Figure 7 would suggest that water repellent conditions
344 are linked to conditions where water table is deep and/or evaporative potential exceeds capillary
345 rise. Furthermore, given that surface evaporative demand is greater in burned peatlands due to
346 the loss of the canopy (Thompson et al., 2015) and that feathermosses preferentially occupy
347 shaded areas in unburned peatlands (Bisbee et al., 2001), in-situ moisture contents likely differ
348 appreciably between burned and unburned areas, especially for feathermosses. These factors
349 likely explain the contradictory results between O'Donnell et al. (2009b) and Kettridge et al.
350 (2014) in which moisture content was not considered. Given the variation in peatland surface
351 moisture contents observed in the field, ranging from ~0.02 m³ m⁻³ in *B. FM* sites to ~0.75 m³ m⁻³
352 ³ in *B.Hol* (Lukenbach et al., 2015), in-situ water repellency is likely to be highly variable
353 spatially. Nevertheless, our results support the general findings from other studies where
354 observed differences of in-situ water repellency are primarily due to differences in water content
355 (e.g. Fishkis et al., 2015; Valat et al., 1991). Our results also support the findings of Kettridge et

356 al. (2014), where, once dry, water repellency in feathermoss is greater than *Sphagnum fuscum*,
357 and feathermoss is more water repellent in a burned compared to an unburned state. Although
358 not directly comparable to our results (Fig. 3), Kettridge et al. (2014) found that the field-based
359 average water repellency of burned *Sphagnum* was greater than unburned *Sphagnum*, albeit the
360 absolute difference between burned and unburned *Sphagnum* was small in both their and our
361 study. Field measurement results from other studies could be explained by differences in water
362 content. For a given tension our results (Fig. 7) indicate that unburned *Sphagnum* has a greater
363 GWC than burned samples (see also Thompson and Waddington, 2013) as well as other
364 treatments, and is therefore less likely to be water repellent, all else being equal. Others have
365 shown that there are significant spatio-temporal differences in near-surface water content
366 associated with burn state – species (Lukenbach et al., 2016). While such differences can easily
367 be measured, accounting for within-site differences in bulk density which tends to be small and
368 not highly variable in the near-surface (e.g. Hokanson et al., 2016) would be more challenging.

369

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

379 research should examine under what conditions, or if at all, water repellency diminishes over
380 time in peatlands following wildfire, especially peat of feathermoss origin.

381 *4.4 Implications for recovery and resiliency*

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

393 Relatively low soil water tensions, typically less than 100 mbar, are necessary for *Sphagnum*
394 recolonization (Price, 1997; Thompson and Waddington, 2008). Post-fire, Lukenbach et al.
395 (2016) demonstrate that near-surface tensions frequently exceed this threshold, particularly for
396 *B.FM* (therein LB-F). Our results indicate that high post-fire surface tensions may be
397 exacerbated by near-surface water repellency, where imbibition is shown to be suppressed in
398 water repellent soil (Diamantopoulos et al., 2013). A reduction in capillary flow, which has been
399 shown to occur in hydrophobic porous media (Shahidzadeh-Bonn et al., 2007), would likely
400 leave much of the peatland surface unsuitable to germinating moss spores, as they require high
401 moisture contents and humidity at the surface to be successful (Sundberg and Rydin, 2002;

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

420 While near-surface water repellency may limit post-fire vegetation recovery, it may be beneficial
421 in restricting peatland-scale water losses due to net water retention (Kettridge et al., 2014). In
422 post-fire peatland sites with a significant portion of burned feathermoss surfaces, such as
423 reported by Lukenbach et al. (2015), ubiquitous water repellency could represent an important
424 feedback for water conservation following wildfire. In the absence of vascular vegetation

425 immediately post-fire, high surface resistance/tension, particularly in burned feathermoss,
426 represents a negative feedback to water loss. Under water-limiting conditions, where the
427 magnitude of near-surface tension is greater than the height above water table, Kettridge and
428 Waddington (2014) showed that surface resistance rapidly increased with tension for burned
429 moss surfaces, which would thereby shutdown surface evaporation. In the short term, the
430 dynamic of water conservation by water repellent surfaces, such as burned feathermoss,
431 combined with the potential for greater water table rise with rainfall may act to increase water
432 availability to low-lying areas within a peatland, thus facilitating recovery in areas that were in a
433 low microtopographic position pre-fire or burned deeply.

434 **5. Conclusion**

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

446 Wildfire, while playing a smaller role than water content and moss species in determining water
447 repellency, enhances peatland water repellency. This results from: 1) decreasing the ability of

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

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

468

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475

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650

651 **Table(s)**

652 *Table 1: Linear mixed effects models for sample average water drop penetration time (WDPT)*
 653 *as a function of different combinations of fixed effect (gravimetric water content (GWC); burn*
 654 *state-species (BrnSp); and depth), as indicated by the model formula, and sample as a random*
 655 *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

656

657

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

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

663

664

665 **Figure List**

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

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

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

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

686

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

691 Figure 6: Comparison of water repellency for large sample (n=70) of burned feathermoss
692 between pre-saturation air-dry state (Pre), post-saturation air-dry state (Post) and oven-dry state
693 (Oven). Colour-coded bars represent the percent of water drops (10 drops per sample \times 10
694 samples) that infiltrated the sample surface in: <5 s (1 - hydrophilic); 5-60 s (2 – slightly
695 hydrophobic); 61-600 s (3 – strongly hydrophobic); 601-3600 s (4 – severely hydrophobic);
696 >3600 s (5 – extremely hydrophobic). The lower panel shows the relationship between
697 gravimetric water content (GWC) of sample in a pre- and post-saturation air-dry state.

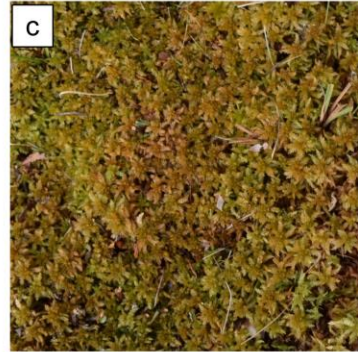
698 Figure 7: Gravimetric (GWC) (a) and volumetric (b) water content of unburned (white-filled
699 circles) and burned (black-filled circles) *Sphagnum* (Sph and B.Sph – blue lines), unburned and
700 burned feathermoss (FM and B.FM – red lines), and burned hollow (B.Hol – black line). Error
701 bars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

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

708

709 **Figures**

710 *Figure 1*

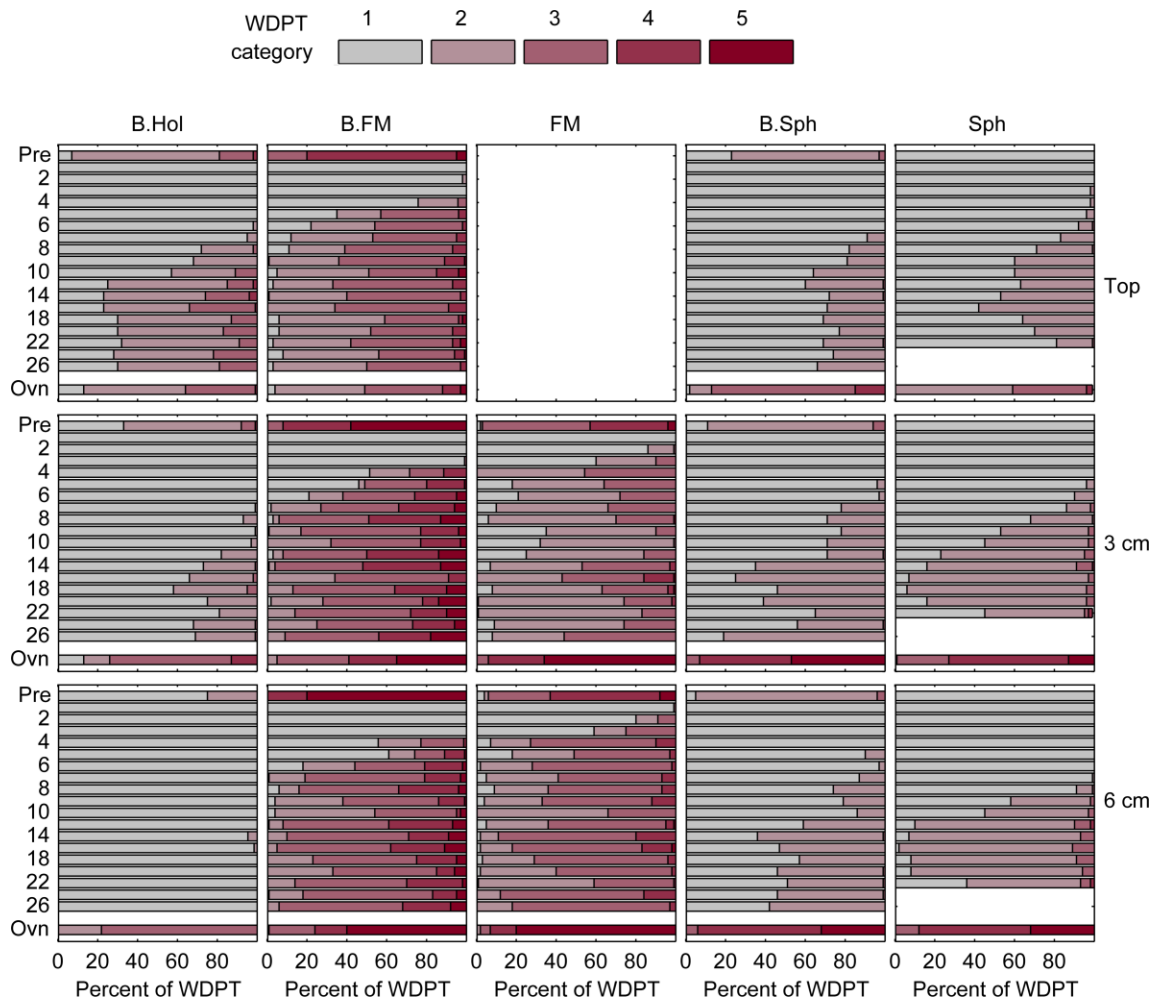


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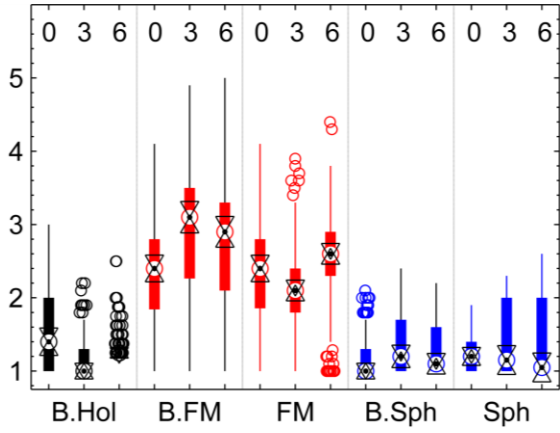
714 *Figure 2*



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717 *Figure 3*

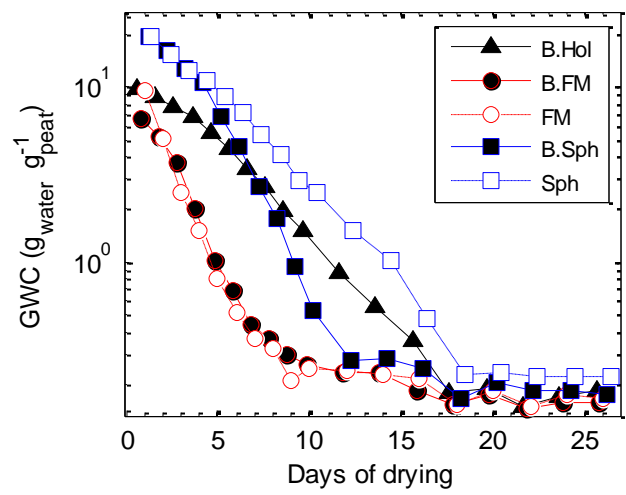


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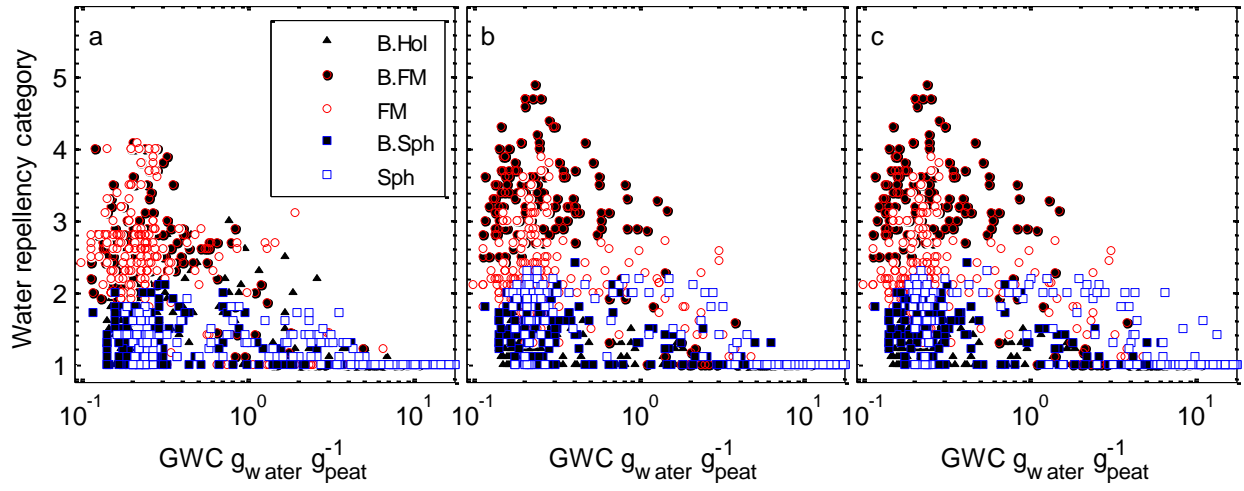
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721 Figure 4



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723 *Figure 5*



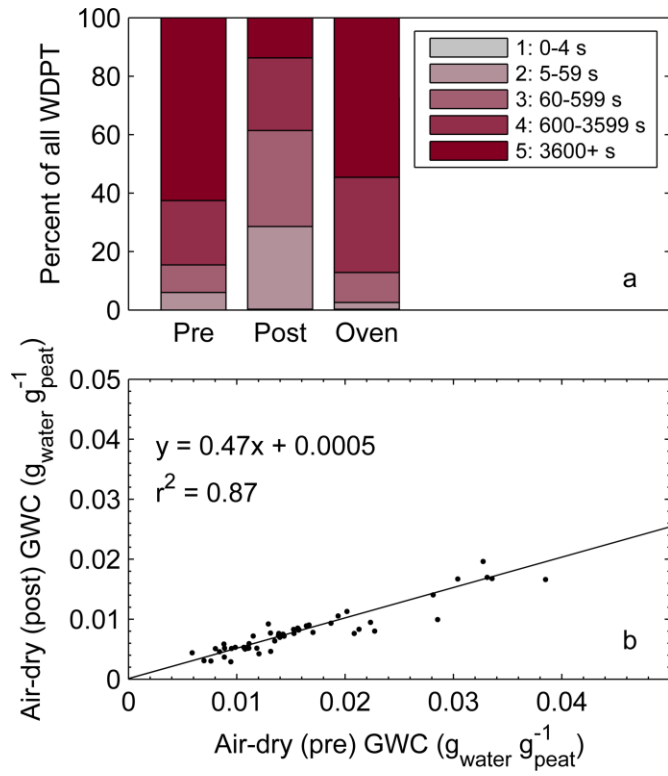
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727 Figure 6

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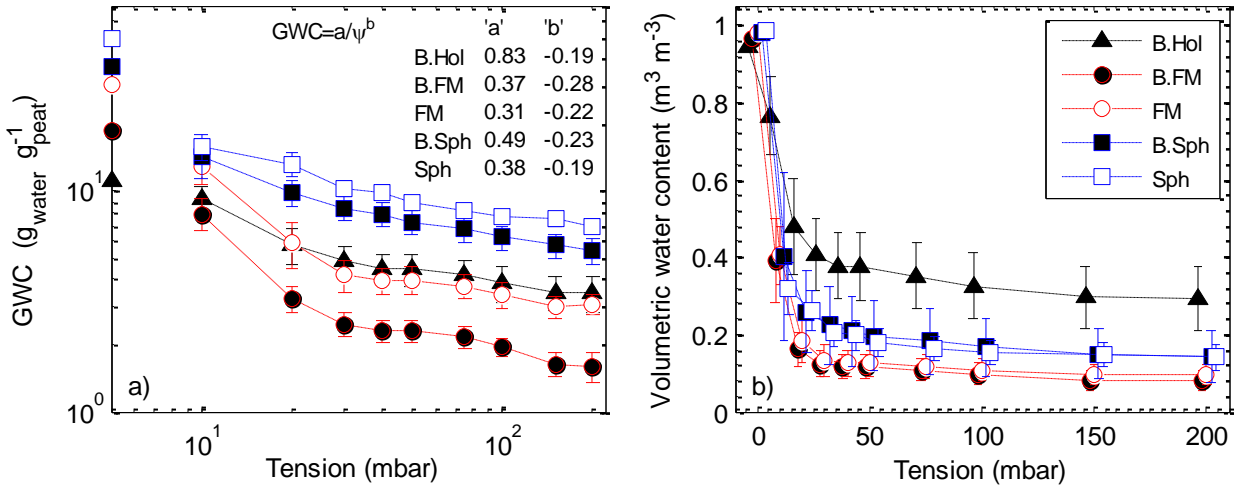


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732 Figure 7

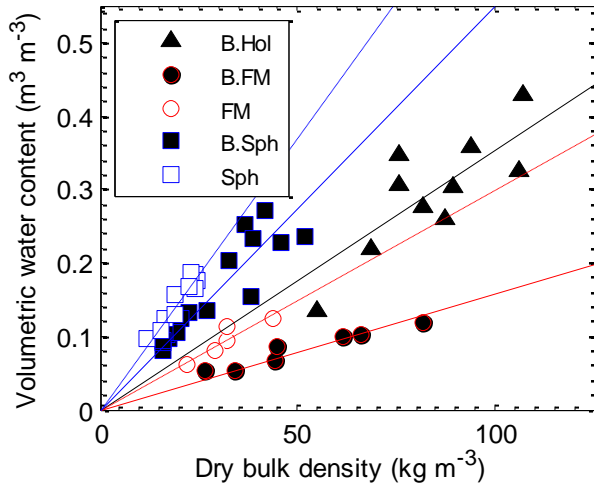


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736 Figure 8



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