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Burned and unburned peat water repellency: Implications for peatland evaporation following wildfire

N. Kettridge [a,*], R.E. Humphrey [b], J.E. Smith [b], M.C. Lukenbach [b], K.J. Devito [c], R.M. Petrone [d], J.M. Waddington [b]

[a] *School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK*
[b] *School of Geography and Earth Sciences, McMaster University, Hamilton, ON L8S 4K1, Canada*
[c] *Department of Biological Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada*
[d] *Department of Geography & Environmental Management, University of Waterloo, Waterloo, ON N2L 3G1, Canada*

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SUMMARY

Water repellency alters soil hydrology after periods of wildfire, potentially modifying the ecosystem recovery to such disturbance. Despite this potential importance, the extent and severity of water repellency within burned peatlands and its importance in regulating peatland recovery to wildfire disturbance remains poorly understood. We characterised the water repellency of peat in a burned (one year post-fire) and unburned peatland in the Western Boreal Plain utilising the water drop penetration time and ethanol droplet molarity tests. Burned *Sphagnum* moss and feather moss sites had a more severe degree of water repellency than unburned sites, with differences being more pronounced between burned and unburned feather moss sites. Burned feather moss exhibited the most extreme water repellency, followed by unburned feather moss, and burned *Sphagnum*. The severity of water repellency varied with depth through the near surface of the moss/peat profile. This was most evident within the burned feathermoss where more extreme water repellency was observed at the near-surface compared to the surface, with the most extreme water repellency found at 1 and 5 cm depths. Unburned *Sphagnum* was completely hydrophilic at all depths. We suggest that the extreme water repellency in near-surface feather moss peat acts as a barrier that impedes the supply of water to the surface that replaces that lost via evaporation. This leads to drying of the near-surface vadose zone within feather moss areas and a concomitantly large decrease in peatland evaporation within feather moss dominated peatlands. This negative feedback mechanism likely enhances the resilience of such peatland to wildfire disturbance, maintaining a high water table position, thereby limiting peat decomposition. In comparison, such a feedback is not observed strongly within *Sphagnum*, leaving *Sphagnum* dominated peatlands potentially vulnerable to low water table positions post disturbance.

1. Introduction

Northern peatlands represent a globally significant carbon stock (Turunen et al., 2002) and contain approximately one-third of all global soil carbon. However, there is concern that this carbon stock may be vulnerable under future climatic conditions (Ise et al., 2008; Turetsky et al., 2011) as the severity and frequency of drought (Roulet et al., 1992; Petrone et al., 2005) and wildfire (Moritz et al., 2012; Flannigan et al., 2013) are both expected to increase. Evapotranspiration often provides the primary pathway for water loss from peatlands (Lafleur et al., 2005; Devito et al., 2005; Petrone et al., 2007; Brown et al., 2010). Therefore, negative feedbacks that regulate evapotranspiration (Kellner, 2001; Kettridge et al., 2013) are critical for maintaining the near saturated hydrological conditions that characterise peatlands (Ingram, 1978; Holden, 2005) and for providing ecosystems resilient to such disturbance, especially in the sub humid climates of the Western Boreal Plain (Devito et al., 2005; Petrone et al., 2007).

Peatland evapotranspiration can approximately equal potential evapotranspiration (Rouse, 1998; Lafleur et al., 2005) under near-saturated conditions, and in some cases can even exceed it where landscape configurations and high atmospheric demand can enhance the turbulent transfer of water vapour (Petrone et al., 2007). However, large surface temperature increases (up to 30 °C) have been observed on some burned peat (Kettridge et al.,

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* Corresponding author. Tel.: +44 121 4143575.
E-mail address: n.kettridge@bham.ac.uk (N. Kettridge).

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2012) that were attributed to a strong decrease in peatland evaporation (Kettridge and Waddington, 2013) owing to a drier vadose zone following wildfire (Thompson and Waddington, 2013). While more research is needed to quantify the prevalence of this change in evaporation, it represents a potentially strong negative feedback post-fire that retains moisture within the peat after a period of disturbance. This negative feedback likely maintains high water-table positions, limiting peat decomposition and enabling the re-establishment of moss species. The exact mechanism controlling this reduction in near-surface peat moisture content and the associated reduction in evaporation is unclear and requires further attention.

One possible mechanism controlling this observed reduction in surface evaporation in peatlands after wildfire is the development of water repellent peat. Slightly water repellent peat has been observed in post-wildfire organic soils in Alaska (O'Donnell et al., 2009) suggesting the development of a water repellent layer in near-surface peat post-fire (Beatty and Smith, 2013). High soil temperatures during wildfire induce bonding of organic substances to soil particles, leading to water repellency in previously hydrophilic soils (Doerr et al., 2000). During wildfire, volatized organic substances can move down the soil profile to cooler temperatures where they condense and coalesce onto soil particles creating water repellent layers deeper in the profile (Debano, 2000). Moreover, soils also become water repellent following drying (Doerr et al., 2000). Such drying may result from evaporation under the extreme temperatures of the wildfire event or the modified hydrological conditions post disturbance (Thompson et al., 2013). These water-repellent surfaces cause water droplets to bead on the surface rather than infiltrating into the soil profile (Dekker et al., 2000). As such, burned organic matter has complex and highly variable wettability at multiple spatial, as well as temporal scales. Water repellency has been shown to persist within soils for a period of months to years (Debano, 2000; Doerr et al., 2000). However, little is known about the longevity of soil water repellency and the different processes that control its breakdown over time (Doerr et al., 2000).

There is an immediate need to characterise the temporal and spatial variability in peat water repellency. The aim of this study is to undertake the first comprehensive characterisation of peat water repellency of recently burned and unburned *Sphagnum* and feather moss communities. We hypothesize that (1) burned peat would be more water repellent than unburned peat, and (2) that this water repellency will occur at depth. Moreover, based on the findings of O'Donnell et al. (2009) we also hypothesize that (3) burned peat of *Sphagnum* botanical origin will be more water repellent than burned peat of feather moss origin.

2. Methodology

2.1. Study area and research design

Measurements were conducted at two study sites within a wetland complex within the Utikuma Lake Region Study Area (URSA) in north-central Alberta (56.107°N 115.561°W). The two study sites represent two lobes (~200 m apart) on the edge of a larger wetland complex located on a coarse-textured outwash plain; see Smerdon et al. (2005) for details of the wider study area and its associated hydrology. Study site 1, referred to as 'burned' from this point forwards and represents a small lobe approximately 60 m by 150 m in size surrounded by aspen forestland (cf. Devito et al., 2012). Prior to the fire, the burned peatland was characterised by feather moss lawns, *Sphagnum fuscum* hummocks and a vascular vegetation cover of *Rhododendron groenlandicum* and *Rubus chamaemorus* (vegetation determined from the assessment of post-fire vegetation and similar adjacent unburned peatlands). A dense black spruce tree canopy with a stem density of approximately 7000 stems per hectare was evident across the study sites prior to fire. The peatland was burnt in May of 2011 as part of the ~90,000 ha Utikuma Complex forest fire (SWF-060). The fire resulted in the 100% mortality of the above ground biomass. Despite the high intensity of the crown fire there was no combustion to any significant depth of the *Sphagnum* moss communities within the majority of the central proportion of the peatland in which this study was conducted. Within *Sphagnum* areas, this was determined through the inspection of capitula at the moss surface; *Sphagnum* capitula and leaves remained intact. The precise depth of combustion within feather moss was more difficult to quantify with certainty due to the less defined structure of unburned species. Further, combustion of the feather moss was more severe, with the combustion of the feather moss leaves at the surface. However, a comparison of measurement locations to points of no combustion (adjacent to *Sphagnum* stems or black spruce trees without exposed adventitious roots), showed no reduction in the surface elevation as a result of wildfire. Study site 2 is referred to as 'unburned' from this point forward. The unburned peatland represent a second lobe of the larger wetland complex. Comparable to the burned peatland, the unburned peatland is characterised by feather moss lawns and *S. fuscum* hummocks and a canopy of black spruce and tamarack (5000 stems per ha). The unburned peatland (last burned ~140 years ago; M. Turetsky, personal communication, 2013) is considered to provide a good approximation of the pre fire vegetation communities within the burned study site.

To examine peat water repellency, five experimental plots were established within each of the four surface types: burned feather moss, burned *Sphagnum*, unburned feather moss, and unburned *Sphagnum*. The plots were established in mid August 2012, 15 months after the fire. This measurement time aimed to provide a snapshot of peatland water repellency at a time post fire when water repellency is predicted to endure based on research conducted within other environments. To examine peat water repellency within each plot, 10 replicate measurements of the water drop penetration test (WDPT) and molarity of an ethanol droplet (MED) test were made in situ at the peat surface and at a depth of 2 and 5 cm (near-surface). Details of the WDPT and MED tests are presented below. In addition, because of the more extreme water repellency observed within the burned feather moss plots, a more intensive study was undertaken at each of these plots. Ten replicates of WDPT and MED tests were performed in situ at 1 cm depth increments at each feather moss plot from the peat surface to a depth of 10 cm. These measurements provide a snap shot of the water repellency at a single point in time post fire.

2.2. Water drop penetration time test

The water drop penetration time (WDPT) test measures the persistence of water repellency of an exposed soil surface. Briefly, the WDPT test involves measuring the time taken for a water droplet placed on the surface to infiltrate completely. The longer the time taken for the water to infiltrate, the greater the persistence of soil water repellency. Water droplets were applied to the measurement surface with a pipette (average drop volume 0.056 ml ± 0.003 ml SE). The penetration time of each water drop was recorded to the nearest second. However, in order to maximise the number of measurements, water droplets were timed for a maximum of 12 min within this study. The impact of this maximum limit on the calculated mean water drop penetration times should be bourne in mind in the subsequent analysis. The water repellency was evaluated using the Dekker et al. (2000) WDPT water repellency classification scheme, classifying the soil as hydrophilic, slightly hydrophobic, strongly hydrophobic or severely hydrophobic based on the time taken for the droplet to infiltrate (Table 1).

2.3. Molarity of ethanol droplet test

The molarity of ethanol droplet (MED) test was used to indicate the initial severity of water repellency (Doerr, 1998). The MED test determines the minimum ethanol concentration that can penetrate the soil within 5 s (Letey, 2001). Increasing the ethanol solution concentration decreases the surface tension of the solution. Therefore, the higher the ethanol concentration required for absorption, the more water repellent the surface. Within the field measurements, ethanol concentrations of applied droplets were increased incrementally between 0%, 3%, 5%, 8%, 13%, 24% and 36%. Results were evaluated using the Doerr (1998) MED water repellency classification scheme (Table 2). Compared to the WDPT test, the MED test enabled the rapid quantification of a wider range of soil water repellency.

2.4. Statistical analyses

To test for significant differences in hydrophobicity between burn state, species, depth and their interactions, we employed a 3-way mixed-model ANOVA. WDPT and MED were treated as continuous response variables, and burn state (burnt, unburned), species (*Sphagnum*, feather moss), and depth (0, 2, 5 cm) were categorical predictors. Alternatively, the MED response can be treated as an ordinal variable with several classes. However, with many levels and a rather large spread of the levels, a continuous variable is justified (Johnson and Creech, 1983), and makes the analyses more powerful and easier to interpret. We included the plot as a random effect to account for the dependence among the three depth measurements within the same plot. Residual analyses indicated unequal variances between species and we therefore modelled different variances using the varIdent argument in the lme function in the R package *nlme* (Pinheiro et al., 2012). Final inspections of residual plots ensured that the models were adequately specified. *P* values were obtained by *F* tests. One of the five burned feather moss plots contained *Sphagnum* between 2 and 8 cm and was therefore removed in the analyses. To evaluate changes in hydrophobicity with depth at a more detailed level, the intensive WDPT and MED tests at the burned feather moss plots were analysed using a 2-way mixed-model ANOVA with depth as the only predictor (categorical with eleven levels) and plot as a random variable. Residual plots were used to check normality and homogeneity of variance.

3. Results

3.1. Water drop penetration time test

Water droplet penetration times differed significantly between burned and unburned plots ($p < 0.001$; Table 3), with burned plots exhibiting longer penetration times (Fig. 1). Penetration times were also significantly higher within feather moss plots ($p < 0.001$; Table 3; Fig. 1), indicating that feather moss is more water repellent than *Sphagnum*. Specifically, burned feather moss had the longest water drop penetration times followed by burned *Sphagnum* and unburned feather moss. Unburned *Sphagnum* exhibited the least water repellency. A 3-way interaction was observed in which penetration times differed significantly with depth, species and burn state ($p < 0.001$; Table 3).

Table 1
Water drop penetration time (WDPT) test water repellency classification categories (after Dekker et al., 2000).

Classification	Time
Hydrophilic	<5 s
Slightly hydrophobic	5–60 s
Strongly hydrophobic	60–600 s
Severely hydrophobic	600+

Table 2
Molarity of ethanol droplet (MED) test water repellency classification categories (after Doerr, 1998). Classification based on minimum percentage of ethanol required to infiltrate in less than 5 s.

Classification	% Ethanol
Very hydrophilic	0
Hydrophilic	3
Slightly hydrophobic	5
Moderately hydrophobic	8
Strongly hydrophobic	13
Very strongly hydrophobic	24
Extremely hydrophobic	36

Table 3
Results of 3-way mixed-model ANOVA of WDPT results with burn state, species, and depth (nested in plot) as varying factors affecting penetration time.

Factor	numDF	denDF	*F*-value	*P*-value
Burn state	1	15	11.14	0.005
Species	1	15	87.74	<0.001
Depth	2	30	0.5145	0.603
Burn state, species	1	15	48.46	<0.001
Burn state, depth	2	30	0.6063	0.552
Species, depth	2	30	18.35	<0.001
Burn state, species, depth	2	30	9.942	<0.001

Approximately 70% of the burned feather moss samples at the near-surface (depth 2–5 cm) were severely hydrophobic (Fig. 2a). This includes the burned feather moss plot that was composed of *Sphagnum* at depth (indicated previously). The exclusion of these *Sphagnum* profiles increased the percentage of near-surface severely hydrophobic soils to 90%, with only two samples being classified as either hydrophilic or slightly hydrophilic. The persistence of water repellency was lower at the surface of the burned feather moss lawns (Fig. 2a). 35% of the burned feather moss surface measurements were hydrophilic and no samples were classified as severely hydrophobic. In comparison, unburned feather moss was principally hydrophilic (Fig. 2b). At the surface, 78% of measurements were hydrophilic whilst the remainder were classified as either slightly or strongly hydrophobic. In the near-surface, the hydrophobic persistence increased; however the moss remained largely hydrophilic. Within the unburned feather moss sites, only 8% and 12% of measurements were classified as severely hydrophobic at a depth of 2 and 5 cm, respectively. Water drop penetration times differed significantly between feather moss and *Sphagnum* ($p < 0.001$; Table 2; Fig. 1). Burned *Sphagnum* was slightly hydrophobic at the surface (82% of measurements; Fig. 2c). Water repellency was lower within the near-surface, with >60% of measurements classified as hydrophilic. Within the unburned *Sphagnum*, 100% of measurements were classified as hydrophilic at all depths (Fig. 2d).

3.2. Molarity of an ethanol droplet test

Results of MED tests correspond closely to the outcomes of the WDPT tests. The minimum ethanol concentration that penetrated the soil within 5 s was significantly higher within the burned peat than the unburned peat ($p = 0.002$) and higher within feather moss than *Sphagnum* peat ($p < 0.001$; Fig. 3; Table 4). Similar to

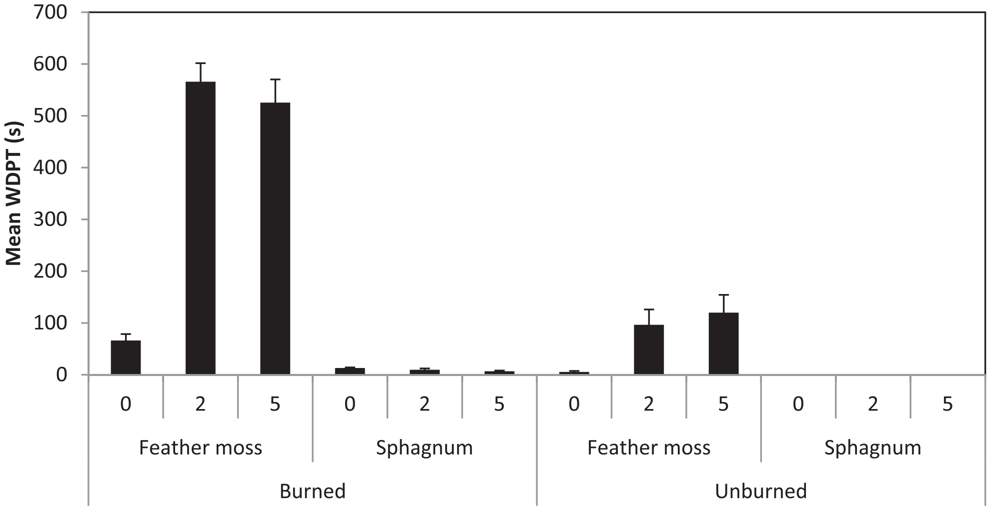

Fig. 1. Mean water drop penetration times for each burn state, species, and depth. Bars indicate standard errors.

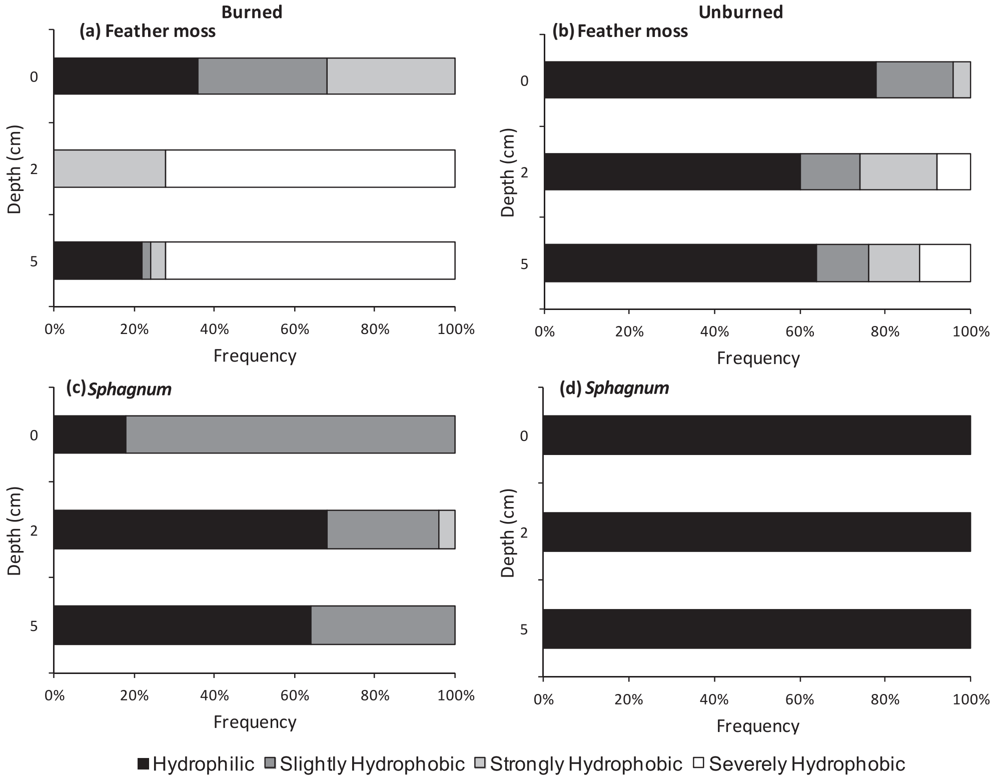

Fig. 2. Relative frequency of water drop penetration times for all samples ($n = 50$ at each depth).

the WDPT results, a 3-way interaction was observed in which ethanol concentration differed significantly with depth, species and burn state ($p = 0.01$; Table 3). Burned feather moss was the most water repellent, exhibiting extremely hydrophobic soils within the near-surface (Fig. 3a). Similar to the WDPT results, the near-surface unburned feather moss peat showed lower water repellency, varying from very hydrophilic to extremely hydrophobic. At the surface and at a depth of 2 cm, *Sphagnum* demonstrated some slight water repellency in the burned plots (Fig. 3c). In comparison, no water repellency was observed in the unburned plots (Fig. 3d).

3.3. Extended burned feather moss study

Within the detailed investigation of feather moss plots, water drop penetration times were significantly depth dependent ($p = 0.023$, $F = 2.43$, numDF = 10, denDF = 40). The least water repellent surface layer observed within the WDPT tests was $\leqslant 1$ cm in depth. WDPT increases significantly within the top 1 cm of the profile and was significantly higher than the surface at depths from 1 to 6 cm and 9 to 10 cm ($p < 0.05$; Fig. 4). Water repellency at depths of 7 and 8 cm was not significantly greater than at the peat surface ($p > 0.05$). The zone of most severe water

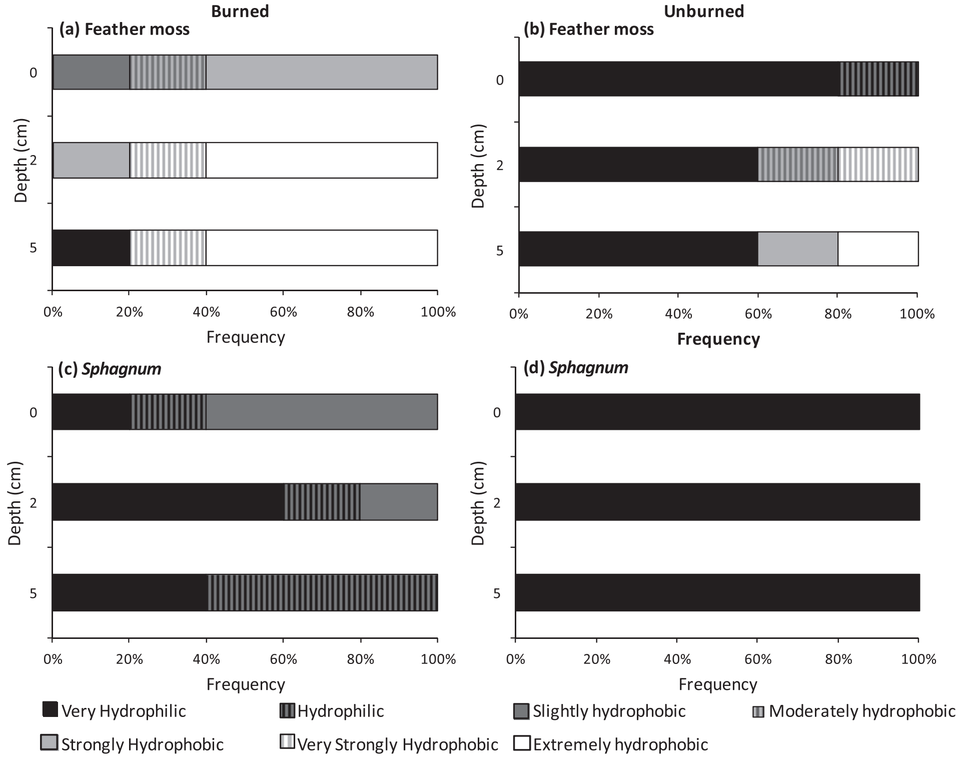

Fig. 3. Relative frequency of MED results of all samples ($n = 50$ at each depth).

Table 4
Results of 3-way mixed-model ANOVA of MED results with burn state, species, and depth (nested in plot) as varying factors affecting penetration time.

Factor	numDF	denDF	*F*-value	*P*-value
Burn state	1	15	14.97	0.002
Species	1	15	31.76	<0.001
Depth	2	30	1.031	0.370
Burn state, species	1	15	13.28	0.002
Burn state, depth	2	30	1.83	0.178
Species, depth	2	30	15.55	<0.001
Burn state, species, depth	2	30	5.387	0.015

repellency occurred between a depth of 1 and 3 cm where 86% of measurements were classified as severely hydrophobic and decreased to a minimum at a depth of 7 cm where only 38% of measurements were classified as hydrophobic (Fig. 4a). None of the WDPT measurements were classified as hydrophilic at depths of 1 to 3 cm.

Our MED test results once again showed strong agreement with WDPT tests. Extremely hydrophobic soil was observed in 20–80% of MED measurements between a depth of 1 and 10 cm. The peat surface was the only measurement depth where either very strongly or extremely hydrophobic soil was not observed. The strongest water repellency was again observed at a depth of 1–3 cm, where 100% of measurements were classified as strongly hydrophobic or above. The water repellent nature of the peat declined to a minimum at a depth of 7 cm.

4. Discussion

4.1. Wildfire and water repellency

Our analyses using multiple methods (WDPT, MED) to characterise peat water repellency 15 months after a wildfire demonstrate that burned peat was much more water repellent than unburned peat. This confirms our first hypothesis and implies that wildfire likely caused water repellency at this peatland, either through the production of volatised organics during burning or as a result of a modified hydrology. Within feather moss plots, water repellency was found to persist at depth (1–5 cm), confirming hypothesis two. Such water repellency was not however observed below the surface within the *Sphagnum* plots.

The cause of the observed spatial variations in peat water repellency and its persistence over time cannot be confirmed through this research. However, based on the current understanding of water repellency within soil environments, a number of processes can by hypothesised that should provide the foundation for future research. Water repellency below the surface within feather moss could have resulted from high temperatures being observed at depth during fire. Water repellency has been linked with burn severity and fire temperature (Doerr et al., 2000). Peat temperatures could have been within the appropriate range to induce water repellency in the near-surface (1–5 cm) and been too low to induce water repellency beyond a depth of 5 cm, where water repellency becomes less pronounced. However, dry peat can act as an excellent insulator (Kettridge and Baird, 2007), restricting the propagation of high temperatures to the depths at which water repellency was observed within this study. Alternatively, the persistence with depth could have resulted from the propagation of burned hydrophobic compounds deeper into the cooler near-surface where they bonded with the peat through the profile. Further, it could also result from water being removed via evaporation at depth either during or after the wildfire event, substantially reducing soil moisture contents. Determining the cause of the observed increase in hydrophobicity within the burned peatland and its variation with depth is critical to determine the response of peatlands to varying wildfire events and should be the focus of future research. Further, this research provides a snapshot of the water repellency of peatlands at a single time after wildfire. The

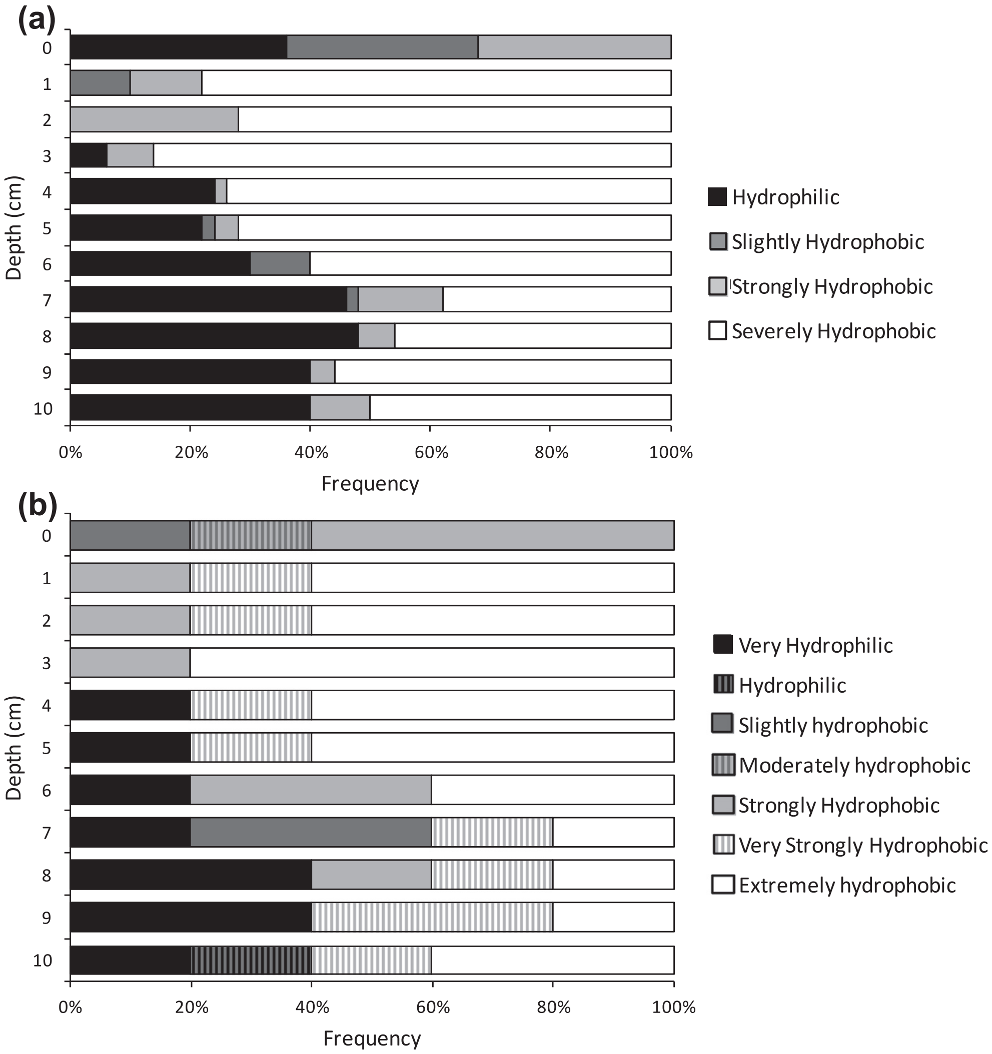

Fig. 4. Distribution of (a) WDPT and (b) MED at 1 cm increments through the burned feather profiles. Classifications of soil water repellency from (a) Table 1 and (b) Table 2 respectively.

magnitude of the water repellency in the first year after fire and its persistence in time may provide a critical control on peatland recovery post disturbance and should also be the focus of future research.

4.2. Moss species water repellency

Contrary to hypothesis three, burned peat of *Sphagnum* botanical origin did not become more water repellent than the burned peat of feather moss origin. Mean WDPTs for the burned *Sphagnum* surface and unburned feather moss surface (13 and 5 s) were comparable to those of O'Donnell et al. (2009), with mean times of 13.2 and 2 s, respectively. However, contrary to the findings of O'Donnell et al. (2009), where the mean WDPT for *Sphagnum* was equal to 14.2 s, our results had no samples with a mean WDPT greater than 1 s (i.e., essentially instantaneous). Further, burned feather moss within this study (mean WDPT of 66 s) was also substantially more water repellent than observed by O'Donnell et al. (2009) (mean of 8.4 s). As a result, burned feather moss was more water repellent than burned *Sphagnum* moss. The cause of this variation between studies, and more specifically the difference in water repellency of unburnt *Sphagnum* and burned feather moss between studies, is unclear and should be the focus of future research. Such differences have potentially important implications to the recovery and resilience of different peatlands to wildfire disturbance which are now examined.

4.3. Implications for peatland evaporation

Peat water repellency may provide an important negative feedback that maintains high water table positions in some peatlands after wildfire. Kettridge et al. (2012) observed high temperatures (low evaporation) and very dry conditions in the near-surface of a peatland several years following wildfire. Additionally, deeper in the soil profile, conditions cooler and wetter than one would expect post-fire were observed (Thompson and Waddington, 2013; Kettridge et al., 2012) due to a hydrological disconnection in the near-surface, which we hypothesize to be due to water repellency. Water repellency will act as a physical barrier to the capillary rise of water from the water table to the peat surface. In addition, rather than being absorbed within the water repellent peat, rainfall will infiltrate through preferential flow pathways (despite their reduction post fire; Holden et al., 2013) or hydrophilic (*Sphagnum*) areas within the heterogeneous surface. As a result, we may expect rates of evaporation above these water repellent layers to be very low because of the restricted water supply (Kettridge and Waddington, 2013; McCarter and Price, 2012). This reduction in evaporation will help to maintain a higher water table and associated near-saturated conditions, protecting the peat from decomposition. However, as demonstrated here, the strength of this negative feedback varies considerably with the vegetation species and the disturbance as a result of wildfire. In feather moss dominated systems, we suggest that these processes could avoid a regime shift and the release of carbon into the atmosphere post-wildfire. We encourage future research to examine and quantify the interaction of peat water repellency, peat moisture dynamics and evaporation and the specific longevity over which this feedback occurs. Whilst the longevity of water repellency in the studied peatland was at least 1.25 years, durations of a few months to several years have been observed within the literature depending upon site conditions (Doerr et al., 2000).

5. Conclusion

Water repellency was found to be significantly higher within a burned peatland 15 months following wildfire compared to an unburned peatland. Water repellency was much more pronounced in the near-surface compared to the surface, and much more pronounced on feather moss than *Sphagnum*. These water repellent layers could create a disconnect between the water table and atmosphere, effectively shutting down evaporation. Here we have provided evidence for an underlying negative feedback between wildfire and evaporation whereby increased water repellency following wildfire has the potential to increase peatland resilience. A quantitative examination of the evaporative nature of the location is required to examine this phenomenon. We argue that it is essential to understand the associated feedback mechanisms between wildfire and peatlands to effectively manage and predict changes to these ecosystems in a changing climate and in order to develop effective landscape reclamation plans in response to large scale disturbances.

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