Low evapotranspiration enhances the resilience of peatland carbon stocks to fire

Kettridge, Nicholas; Lukenbach, Maxwell Curtis; Hokanson, Kelly Jean; Hopkinson, Chris; Devito, Kevin J.; Petrone, Richard Michael; Mendoza, Carl; Waddington, James Michael

DOI:
[10.1002/2017GL074186](https://doi.org/10.1002/2017GL074186)

License:
None: All rights reserved

Document Version
Peer reviewed version

Citation for published version (Harvard):
Kettridge, N, Lukenbach, MC, Hokanson, KJ, Hopkinson, C, Devito, KJ, Petrone, RM, Mendoza, C & Waddington, JM 2017, 'Low evapotranspiration enhances the resilience of peatland carbon stocks to fire', *Geophysical Research Letters*, vol. 44, no. 18, pp. 9341-9349. <https://doi.org/10.1002/2017GL074186>

[Link to publication on Research at Birmingham portal](#)

General rights

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Low evapotranspiration enhances the resilience of peatland carbon stocks to fire

N. Kettridge^{1*}, M.C. Lukenbach^{2,3}, K.J. Hokanson^{2,4}, C. Hopkinson⁵, K.J. Devito⁴, R.M. Petrone⁶, C.A.
Mendoza³, J.M. Waddington²

¹School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston,
Birmingham, B15 2TT, UK.

²School of Geography and Earth Sciences, McMaster University, Hamilton, ON, Canada, L8S 4K1.

³Department of Earth and Atmospheric Science, University of Alberta, Edmonton, AB, Canada, T6G 2E3.

⁴Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada, T6G 2E9.

⁵Department of Geography, University of Lethbridge, Lethbridge, AB, Canada, T1K 3M4.

⁶Department of Geography and Environmental Management, University of Waterloo, Waterloo, Canada,
ON, N2L 3C5.

*Corresponding author: N. Kettridge, School of Geography, Earth and Environmental Sciences, University of
Birmingham, Birmingham, UK, B15 2TT

Phone: +44 121 4143575 Email: n.kettridge@bham.ac.uk

A paper for submission to *Geophysical Research Letters*

Key words: peatland, wildfire, evapotranspiration, resilience, temperature, water repellency, hydrophobicity

Highlights:

1. Low evapotranspiration from feather moss peatlands following wildfire.
2. Low evapotranspiration observable at landscape scale through concomitant high surface temperature.
3. Water repellency may act as an important, previously unidentified, control on peatland water loss via evaporation.

25 **Abstract**

26 Boreal peatlands may be vulnerable to projected changes in the wildfire regime under future climates.
27 Extreme drying during the sensitive post-fire period may exceed peatland ecohydrological resilience,
28 triggering long-term degradation of these globally significant carbon stocks. Despite these concerns, we
29 show low peatland evapotranspiration at both the plot and landscape scale post-fire, in water-limited
30 peatlands dominated by feather moss that are ubiquitous across continental western Canada. Low post-fire
31 evapotranspiration enhances the resilience of carbon stocks in such peatlands to wildfire disturbance and
32 reinforces their function as a regional source of water. Near-surface water repellency may provide an
33 important, previously unexplored, regulator of peatland evapotranspiration that can induce low
34 evapotranspiration in the initial post-fire years by restricting the supply of water to the peat surface.

35

36 **1. Introduction**

37 Peatlands represent a global climate regulator and a regionally important water resource, containing one-
38 third of the global soil carbon pool [Turunen *et al.*, 2002] and accounting for 10% of global surface fresh
39 water [Holden, 2005]. Wildfire represents the largest disturbance to boreal peatlands, burning almost 1500
40 km² yr⁻¹ and releasing 6,300 Gg C yr⁻¹ within Western Canada alone [Turetsky *et al.*, 2002]. However,
41 peatland carbon stocks are generally resilient to wildfire [Weider *et al.*, 2009]. Despite acting as a net carbon
42 source in the initial years after fire, peatlands return to a net carbon sink and begin to offset the carbon lost
43 during wildfires within ~20 years of the disturbance [Weider *et al.*, 2009]. This resilience over multiple fire
44 cycles arises from a complex array of negative ecohydrological feedback mechanisms that secure peatland
45 carbon stocks under waterlogged conditions and promote the establishment and growth of keystone moss
46 species [Waddington *et al.*, 2015; Johnston *et al.*, 2010]. However, changing climatic conditions are
47 projected to induce drying across the Boreal [Walker *et al.*, 2015], increasing the severity [Turetsky *et al.*,
48 2011], extent and frequency [Flannigan *et al.*, 2005] of wildfires. Such an alteration to the boreal fire regime
49 may exceed peatland ecohydrological resilience of carbon stocks [Kettridge *et al.*, 2015b], resulting in their

50 long-term degradation, and providing a critical positive feedback to changing climatic conditions. As a
51 result, there is an urgent need to identify and understand the key negative feedback mechanisms that regulate
52 the resilience of peatland carbon stocks to wildfire, which have enabled these ecosystems to persist for
53 millennia.

54

55 Evapotranspiration (ET) is the dominant water loss mechanism from boreal peatlands [Lafleur *et al.*, 2005;
56 Petrone *et al.*, 2007; Brown *et al.*, 2010]. The change in ET as a result of wildfire therefore provides the
57 primary control on the ecosystem's capability to maintain the near-saturated conditions necessary to promote
58 recovery [Schouwenaars, 1988]. Following wildfire, transpiration is substantially reduced due to the loss of
59 vascular vegetation [Amiro, 2001]. Model simulations suggest that these reductions across the Canadian
60 boreal are largely offset by increased sub-canopy evaporation [Bond-Lamberty *et al.*, 2009]. Further, within
61 *Sphagnum* dominated boreal peatlands, post-fire ET can exceed pre-fire ET [Thompson *et al.*, 2014]. Canopy
62 removal increases both the energy availability [Kettridge *et al.*, 2012; Thompson *et al.*, 2015] and the
63 potential ET within the sub-canopy [Plach *et al.*, 2016]. Within *Sphagnum* dominated peatlands the sub
64 canopy can account for up to 80% of pre-fire ET [Gabrielli, 2016; Lafleur and Schreader, 1994]. This may
65 enhance peatland drying in the initial years following wildfire [Thompson *et al.*, 2014] when ecosystems are
66 sensitive to perturbation [Kroel-Dulay *et al.*, 2015]. However, continental boreal regions are dominated by
67 water limited peatlands dominated by feather moss [Natural Regions Committee, 2006]. Whilst ET from
68 peatlands dominated by feather moss are comparable to *Sphagnum* systems [Kettridge *et al.*, 2012], their
69 post-fire ET are unknown.

70

71 Substantial reductions in peatland evaporation due to drying have been observed under laboratory conditions
72 [Kettridge and Waddington, 2014] and are incorporated in peatland hydrological simulations [McCarter and
73 Price, 2012; Kettridge *et al.*, 2015a]. Reductions in evaporation are triggered by low near-surface hydraulic
74 conductivities that limit upward capillary flow under periods of drying [Aluwihare and Watanabe, 2003;

75 *McCarter and Price*, 2012]. Water repellency may also reduce evaporation, as evidenced by laboratory-
76 based sand column experiments [*Shokri et al.*, 2009], because it causes a hydraulic disconnect and/or a
77 reduction in the capillary driving force between the soil water store and surface [*Shokri et al.*, 2008]. Given
78 that water repellency is observed in burned organic soils and peat [*O'Donnell et al.*, 2009; *Beatty and Smith*,
79 2013], notably within feather moss peat [*Kettridge et al.*, 2014], it may counteract enhanced post-fire drying,
80 providing an important restriction on peatland ET.

81

82 Post-fire sub canopy ET (ET_{sc}) has not been observed within feather moss peatlands, despite their
83 dominance across continental boreal regions and their functional role as global carbon stock and boreal head
84 water sources [*Devito et al.*, 2017]. For this reason, we directly measure post-fire ET_{sc} at the plot scale
85 within a feather moss dominated peatland that may be vulnerable to post-fire drying. Furthermore, we
86 expand this examination of ET_{sc} to the landscape scale, across multiple peatlands. We couple remote sensing
87 with the dependence of high peat surface temperature on low ET_{sc} [*Kettridge et al.*, 2012], recognizing that
88 if ET_{sc} is low because the water supply to the surface is impeded then evaporative cooling of the surface is
89 reduced, resulting in high surface temperatures. We determine how ET_{sc} responds to the high evaporative
90 demand post disturbance and consider: i) the ecological and hydrological controls that regulate this primary
91 water loss mechanism and ii) the implications of this response to the ecohydrological resilience of these
92 carbon rich landscapes.

93

94 **2. Methods**

95 **2.1 Study site**

96 Field measurements were conducted within a peatland located on a coarse-textured outwash plain [*Smerdon*
97 *et al.*, 2005; *Lukenbach et al.*, 2015, 2016] within the Utikuma Region Study Area (URSA), north-central
98 Alberta (56.107°N 115.561°W). Prior to fire, the study site had a dense black spruce tree canopy (stem
99 density of approximately 7,000 stems per hectare). The peatland burned in May 2011 during the ~90,000 ha

100 Utikuma complex forest fire. The fire resulted in complete mortality of above ground biomass. We classified
101 the central portion of the peatland into two dominant surface covers based on the vegetation communities
102 [Lukenbach *et al.*, 2015]. The first microhabitat was dominated by feather moss (*Pleurozium schreberi*; 73%
103 coverage [Lukenbach *et al.*, 2015]). Combustion of the feather moss microhabitat occurred to a depth of 0.02
104 ± 0.01 m [Lukenbach *et al.*, 2016]. The second microhabitat was dominated by *Sphagnum* (*Sphagnum*
105 *fuscum*; 19 % coverage [Lukenbach *et al.*, 2015]), which remained largely intact following the wildfire, with
106 only slight observable combustion (singeing) of the peat surface (*Sphagnum capitula* intact) [Lukenbach *et*
107 *al.*, 2016].

108

109 2.2 Plot scale sub-canopy evapotranspiration measurement

110 ET_{sc} was measured at three representative locations within each microhabitat every hour between May and
111 August 2012, one year after the fire, using Perspex® chambers (surface area, 0.2 m^2 ; volume $\sim 0.05\text{ m}^3$).
112 Each chamber closed for two minutes each hour, during which the air within the chamber was continuously
113 mixed by a fan. ET_{sc} at each measurement time was calculated from the rate of increase in humidity within
114 the closed chamber (ACS-DC; Licor LI-840) [cf Kettridge and Waddington, 2014; McLeod *et al.* 2004]. The
115 controls of the different microhabitats on daily ET_{sc} were analyzed using a general linear model [R Core
116 Team, 2016] with the zone as a fixed effect and the chamber as a random effect to account for the lack of
117 independence among collar measurements. Surface temperature was measured every hour within each
118 chamber using a type-T thermocouple inserted just below the moss/peat surface. Leaf area index (LAI) was
119 determined for each chamber throughout the growing season from the classification of digital images of the
120 chambers [Kettridge and Baird, 2008], and at the end of the growing season (August 2012) using the leaf
121 count approach [Strack *et al.*, 2004]. Stomatal conductance of three leaves on three plants of each species
122 within each chamber was measured where available using an AT4 Delta-T porometer. In combination with
123 measured LAI, the stomatal conductance was used to calculate the proportion of ET_{sc} lost via evaporation
124 (see S.1).

125
126
127
128
129
130
131
132
133
134
135
136
137
138
139
140
141
142
143
144
145
146
147
148
149

In early June 2013, two years after fire, ET_{sc} was measured at a further 37 locations (18 feather moss, 19 *Sphagnum*) across the full extent of the peatland during a period of high potential evaporation: humidity = $25.8 \pm 6.0\%$ (average $\pm$ standard deviation); air temperature = 29.8 ± 2.7 °C. ET_{sc} was measured using a mobile chamber system equivalent to the automatic system described above (PP systems EGM-4 infrared gas analyzer, chamber dimensions: diameter 0.3 m, height 0.5 m). Following ET_{sc} measurement, water repellency was measured at each location at a depth of 0.02 m (i.e., the zone within the moss/peat profile of extreme water repellency [Kettridge *et al.*, 2014]) using the water drop penetration test (WDPT). This approach is used widely to characterize and compare the persistence of soil water repellency [Doerr, 1998; Dekker *et al.*, 2000; Letey, 2001] and involves measuring the time taken for a water droplet placed on the surface to infiltrate completely. Water repellency was determined from the classification of five water drops applied at separate positions within each chamber area. Each water drop location was classified as hydrophilic (<5 s), slightly hydrophobic (5-60 s), strongly hydrophobic (60-600 s) or severely hydrophobic (>600 s) [Dekker *et al.*, 2000]. The water drop penetration time of each plot was taken as the average of the five discrete water droplet classes applied.

2.3 Thermal remote sensing and landscape classification

Remotely observed surface temperatures have been used widely to derive ET [Fisher *et al.*, 2017]. However, direct calculation of ET can be difficult [Zhang *et al.*, 2016]. Small variations in surface temperatures (<1°C) result from numerous controls that vary in response to fire [Rocha and Shaver, 2011]. Detailed simulations of adjacent burned and unburned peatlands (<40 km from the study site) examined the magnitude of different controls on peat surface temperatures; notably, differences in microclimate, moisture content, vegetation cover, albedo, surface roughness and potential difference in ET_{sc} were the primary controls [Kettridge *et al.*, 2012]. The impact on peat surface temperatures of these above differences were limited; the compound impact of these variations increased maximum surface temperature by only 2.3 °C [Kettridge *et*

150 *al.*, 2012]. In comparison, reducing ET_{sc} to zero increased simulated surface temperature by $>6^{\circ}C$ more than
151 a freely evaporating peat surface. Therefore, only low/near-zero ET_{sc} can induce substantial increases in peat
152 surface temperatures. Surface temperature of peat can thus be used to differentiate between regions in which
153 ET is occurring freely and areas in which ET is severely restricted. This capability maps directly onto i) the
154 bimodal nature of laboratory measures of peat evaporation (peat cores demonstrate rapid transitions in
155 evaporation when threshold drying is exceeded [Kettridge and Waddington, 2014]), ii) the bimodal ET
156 applied in peatland modelling studies [Kettridge *et al.*, 2015a; McCarter and Price, 2012] and iii) the
157 characteristic transitions between stage I and stage II evaporation for soils more generally [Or *et al.*, 2013].
158

159 To classify landscape-scale peatland ET, Airborne LiDAR (Light Detection and Ranging) and forward-
160 looking thermal FLIR digital imagery (FLIR Inc. S60, Boston, MA, USA) were captured from an aircraft
161 between 16:00 and 16:30 on August 12, 2011, approximately three months after the wildfire. Measurements
162 were taken during clear conditions (Figure S.1), with an air temperature of $25^{\circ}C$, relative humidity of 34%
163 and average wind speed of 2.0 m s^{-1} (recorded at an adjacent unburned peatland) [*cf. Thompson et al.*, 2014].
164 Four adjacent and overlapping flight lines of approximately 800 m width were flown for FLIR imagery,
165 covering 40 km^2 across the region, with measurements obtained at a ground sample spacing of $\sim 1.3\text{ m}$ along
166 and across track. Of this region, 8.7 km^2 was burned as part of the Utikuma Complex forest fire. The thermal
167 imaging used the infrared range of the electromagnetic spectrum, quantifying skin (surface) temperatures
168 from the amount of radiation emitted from the surface in accordance with Stephan-Boltzman Law.
169 Measurements assumed a black body with emissivity equal to 0.95, which is the emissivity of wet soil
170 [Weast, 1986]. Thermal imagery was linearly ramped from 10 to $50^{\circ}C$ and manually georegistered to the
171 corresponding LiDAR imagery and resampled to $1\text{ m} \times 1\text{ m}$ pixel resolution following methods first
172 described in Hopkinson *et al.* [2010]. Wetland and forestland areas were classified by Chasmer *et al.* [2016]
173 from LiDAR images obtained prior to the fire.
174

175 **3. Results**

176 ET_{sc} of burned feather moss ($0.63 \pm 0.27 \text{ mm day}^{-1}$) was significantly lower than that of burned *Sphagnum*
177 ($3.03 \pm 0.13 \text{ mm day}^{-1}$) (Figure 1a; $df = 4$, $t = -22.32$, $p < 0.001$). The lower ET_{sc} of feather moss throughout
178 the day (Figure 1b) was associated with daily maximum surface temperatures more than 20°C greater than
179 the surface temperature of *Sphagnum* (Figure 1c). The LAI was low within *Sphagnum* chambers (*Ledum*
180 *groenlandicum* and *Vaccinium oxycoccus*), increasing from an average of 0.22 to 0.45 over the measurement
181 period (May to August). Given these values, evaporation accounted for between 55% and 78% of ET_{sc} in the
182 *Sphagnum* chambers through the growing season (see S.1). Within the feather moss chambers, there was no
183 leaf cover. Therefore, ET_{sc} was entirely attributable to evaporation.

184
185 Across the peatland, between 11:00 and 16:00 on a day of high evaporative demand, ET_{sc} varied
186 between -0.008 (dewfall) and 0.17 mm hr^{-1} ($\mu = 0.038 \text{ mm hr}^{-1}$, standard error = $0.0058 \text{ mm hr}^{-1}$, $n = 41$).
187 During this period (i) ET_{sc} ($p < 0.0001$, $Z = -4.892$, $n = 37$), (ii) surface temperature ($p < 0.001$, $F = 5.202$, n
188 $= 37$) and (iii) mean water drop penetration time at a depth of 0.02 m ($p < 0.0001$, $Z = -5.318$, $n = 37$), all
189 differed significantly between burned *Sphagnum* and feather moss microhabitats. All *Sphagnum*
190 microhabitats were hydrophilic. Feather moss plots were predominantly strongly hydrophobic (78%), with a
191 small proportion classified as severely hydrophobic (17%) and slightly hydrophobic (6%).

192
193 Average surface temperatures of the previously treed and non-treed peatland areas within the fire perimeter
194 were 11°C higher than outside the fire perimeter (Figure 2). Outside the burn, mean surface temperature
195 within the treed and non-treed peatland area averaged $23 \pm 4^\circ\text{C}$ ($\pm$ standard deviation). Within the perimeter,
196 treed and non-treed peatland surface temperatures averaged $34 \pm 10^\circ\text{C}$. These high surface temperatures
197 within the burned region strongly suggest that the low post-fire ET_{sc} observed over time within the auto
198 chambers and across the peatland from the roving chamber measurements, are evident at the landscape scale
199 across multiple peatlands within the burn scar. It is not currently feasible to confidently classify the

200 subsurface micro habitats from post fire remote sensing imagery and thus to directly compare temperatures
201 between feather moss and *Sphagnum* micro habitats at the landscape scale.

202

203 **4. Discussion**

204 4.1 Cross-scale post-fire sub-canopy evapotranspiration

205 Differences in post-fire ET_{sc} between feather moss and *Sphagnum* microhabitats are stark and are far in
206 excess of differences observed previously within unburned peatlands (Figure 3a; [Heijmans *et al.*, 2004;
207 Brown *et al.*, 2010; Kettridge *et al.*, 2013]). Average post-fire *Sphagnum* ET_{sc} is similar in magnitude to
208 previous studies. Concurrently, ET_{sc} from feather moss microhabitats is lower than any previous peatland
209 study, including those in which the vascular vegetation cover is removed reducing transpiration to zero
210 [Heijmans *et al.*, 2004]. As a result, the ratio between *Sphagnum* and feather moss ET_{sc} was equal to 5.0,
211 three times that of the unburned sites (Figure 3b). Further, this ratio was even higher (8.1) under a period of
212 extreme evaporative demand during the spatial survey. The response of the peatland sub-canopy thus
213 appears to show a diverging pattern in response to fire, with post-fire ET_{sc} from *Sphagnum* microhabitats
214 being largely maintained, and ET_{sc} from feather moss microhabitats reducing to rates equivalent to black
215 spruce boreal forests above a mineral soil [Heijmans *et al.*, 2004].

216

217 Post-fire ET can exceed pre-fire losses in *Sphagnum* dominated-boreal peatlands (Figure 4) [Thompson *et*
218 *al.*, 2014]. Pre-fire, feather moss peatland ET is similar to *Sphagnum* dominated ecosystems [Kettridge *et al.*,
219 2012]. However, ET within these ecosystems is reduced substantially post-fire due to the loss of tree
220 transpiration and the inability of the burned feather moss sub canopy to respond to the increased evaporation
221 potential (Figure 4). Elevated surface temperatures in the burnt peatland areas of the remotely surveyed
222 region highlight the wide spatial extent of this low post-fire ET at the landscape scale. Whilst complex
223 feedback mechanisms regulate near-surface soil temperatures [Kellner *et al.*, 2001; Kettridge and Baird,
224 2010], only near-zero ET can induce the high surface temperatures observed [Kettridge *et al.*, 2012]. Where

the remote sensing was undertaken, wetlands accounted for 47% and 60% of the land surface area within the till moraine and clay plain hydrogeological settings, respectively [Chasmer *et al.*, 2016]. Therefore, low post-fire ET within feather moss peatlands not only influences the ecohydrological function the individual wetlands, but also has the potential to result in large-scale transitions in water conservation within the western boreal plain; with such peatlands acting as regional scale head water sources in the sub-humid climate of the Boreal Plains [Devito *et al.*, 2017].

The dominance of peatland communities varies widely among peatlands driven by differences in climate, hydrogeology [Devito *et al.*, 2005], age [Benscoter and Vitt, 2008], disturbance regime [Turetsky *et al.*, 2012] and recovery period [Benscoter and Vitt, 2008; Lukenbach *et al.*, 2016]. *Sphagnum* dominated systems, where increased evaporation may exceed small reductions in tree transpiration post-fire (Figure 4) [Thompson *et al.*, 2014], tend to be wetter and deeper peatlands with larger water and carbon stocks available to endure discrete disturbances. In comparison, feather moss dominated peatlands are associated with low available light, shallow peat depths and deeper water table positions [Bisbee *et al.*, 2001]. Importantly, these drier peatland systems with higher pre-fire tree transpiration and limited carbon stocks will likely show a strong negative feedback response to fire, with both reduced ET_{sc} and tree transpiration post-disturbance (Figure 4).

4.2 Controls on post-fire sub-canopy evapotranspiration

The extreme contrast in post-fire ET_{sc} between *Sphagnum* and feather moss microhabitats results, in part, from the lack of recovery of vascular vegetation within the feather moss microhabitats and thus the low sub-canopy transpiration. Despite that, ET_{sc} remains lower than in manipulation experiments in which the vascular vegetation is removed [Heijmans *et al.*, 2004] (Figure 3), with the exposed moss unable to meet the high post-disturbance potential evaporative demand [Kettridge and Waddington, 2014; McCarter and Price, 2014]. Even under high post-fire evaporative demand, *Sphagnum* profiles maintain connectivity with

250 subsurface water stores. In comparison, within the study site, a severe disconnect occurs between the burned
251 feather moss surface and saturated water stores just 0.33 m below [Lukenbach *et al.*, 2016]. This results from
252 the nature peat moss structure which unlike *Sphagnum* does not have an effective external wicking system
253 along the moss surfaces [Callaghan *et al.*, 1978] and the low moisture content observed at the study site
254 within the near-surface of the peat [Lukenbach *et al.*, 2016]. Lower water contents reduce the unsaturated
255 hydraulic conductivity, which limits the supply of water to the peat surface, leading to further drying of the
256 near-surface [Waddington *et al.*, 2015; McCarter and Price, 2014]. Here, we hypothesize that this feedback
257 response is further enhanced by the water repellent nature of the feather moss profile, induced by drying and
258 enhanced by fire [Kettridge *et al.*, 2014].

259
260 Water repellency is more severe under dry conditions and can arise from bonding of organic substances to
261 soil particles because of the temperatures experienced during the wildfire [Doerr *et al.*, 2000]. Thus, the low
262 moisture content in the near-surface of the burned feather moss induces water repellent conditions. A
263 severely hydrophobic layer is observed at a depth of 0.02 m, and extends between a depth of 0.01 and 0.07
264 m with a slightly hydrophobic layer above and a hydrophilic layer below [Kettridge *et al.*, 2014]. The direct
265 control of this water repellent layer on water transport through the peat profile is not certain. Further, the
266 codependence of evaporation, water repellency, hydraulic conductivity and moisture content prevents the
267 direct control of water repellency on evaporation being defined here. This may be examined within future
268 research in which the water repellent nature of moss species is altered by without impacting the soil
269 structure. Within laboratory-based sand columns experiments such an approach has shown water repellency
270 to substantially reduce evaporation, causing a hydrological disconnect and/or reduction in the capillary
271 driving force between the soil-water store and the evaporation surface [Bachmann *et al.*, 2001; Shokri *et al.*,
272 2008]. The water repellent layer may accordingly act as a figurative one-way valve, permitting rainfall to
273 percolate down through preferential flow pathways to the water table beneath because of the high porosity of
274 the peat and the abundance of macro pores [Holden, 2009], but restricting its loss via evaporation at local

and regional scales [Rye and Smettem, 2017]. Such a feedback response would limit peatland evaporation during periods of high solar radiation resulting from the burning of the shrub and canopy cover [Thompson *et al.*, 2015]. Whilst water repellency in the studied peatland persisted for at least two years, depending upon site conditions, water repellency can remain for of several years [Doerr *et al.*, 2000]. Water repellency therefore has the potential to conserve water during this period, protecting the peatland until a shrubs and canopy cover increases shading and reduce evaporative demand.

5. Conclusion

Sub canopy evapotranspiration (ET_{sc}) is a critical determinant of peatland carbon stock vulnerability to wildfire and has the potential to influence landscape-scale transitions in water availability. Despite increased energy availability due to the open post-fire canopy and increased turbulent exchange from the sub-canopy post-fire, feather moss ET_{sc} was extremely low, equivalent to rates observed within a black spruce boreal forests above a mineral soil. Thus, rather than counteracting post-disturbance reductions in tree transpiration from the canopy, ET_{sc} enhances such reductions in systems dominated by feather moss (Figure 4). Reduced ET_{sc} results from the poor recovery of the sub-canopy vascular vegetation cover and the hydraulic disconnect of the surface from the saturated peat just decimeters below. The latter is likely due to the low hydraulic conductivity of the dry near-surface peat and the severely hydrophobic nature of the post-disturbance feather moss peat. Moreover, low post-fire ET was evident at the landscape scale. Thus, shallow water tables and associated near-saturated conditions will be maintained across the burned regions, protecting boreal peat by reducing decomposition rates [Waddington *et al.*, 2015] and increasing the resilience of their carbon stocks to disturbance over multiple fire cycles. Further it will enable peatlands to act as important post-fire water sources within boreal landscape.

Acknowledgements

We are grateful to Reed Parsons for the georegistration of the FLIR images. Financial support was provided

300 by: Syncrude Canada Ltd and Canadian Natural Resources Ltd (SCL4600100599 to KJD, RMP, CAM, NK
301 and JMW); Natural Sciences and Engineering Research Council (NSERC-CRD CRDPJ477235-14 to KJD,
302 RMP, CAM and JMW); Canadian Foundation for Innovation funding to CH for the lidar and thermal
303 imaging hardware; Campus Alberta Innovates Program (CAIP) laboratory operating funding to CH. We are
304 extremely grateful to the Editor M. Prof. Bayani Cardenas, Dr Petter Nyman and four anonymous reviewers
305 whose comments helped improve an earlier version of this manuscript. Data used for this analysis area
306 available at <https://beardatashare.bham.ac.uk/dl/fiV9zmh1TPLrZQhQf2P4MwWv/GRL2017.zip>.

307

308 **References**

309 Aluwihare, S., and K. Watanabe (2003), Measurement of evaporation on bare soil and estimating surface
310 resistance, *J Environ Eng*, 129, 1157-1168.

311 Amiro, B. D. (2001), Paired-tower measurements of carbon and energy fluxes following disturbance in the
312 boreal forest, *Glob Change Biol*, 7, 253-268.

313 Bachmann, J., R . Horton, and R. R. van der Ploeg (2001), Isothermal and nonisothermal evaporation from
314 four sandy soils of different water repellency, *Soil Sci. Soc. Am. J.*, 65, 1599 – 1607.

315 Beatty, S. M., and J. E. Smith (2013), Dynamic soil water repellency and infiltration in post-wildfire soils,
316 *Geoderma*, 192, 160-172, doi:10.1016/j.geoderma.2012.08.012.

317 Benscoter, B. W., and D. H. Vitt (2008), Spatial patterns and temporal trajectories in bog ground layer
318 composition along a post-fire chronosequence, *Ecosystems*. 11, 1054-1064.

319 Bisbee, K. E., S. T. Gower, J. M. Norman and E. V. Nordheim (2001), Environmental controls on ground
320 cover species composition and productivity in a boreal black spruce forest. *Oecologia*, 129, 261-270.

321 Bond-Lamberty, B., S. D. Peckham, S. T. Gower, and B. E. Ewers (2009), Effects of fire on regional
322 evapotranspiration in the central Canadian boreal forest, *Glob Change Biol*, 15, 1242-1254.

323 Brown, S. M., R. M. Petrone, C. Mendoza, and K. J. Devito (2010), Surface vegetation controls on
324 evapotranspiration from a sub-humid Western Boreal Plain wetland, *Hydrol. Proc.*, 24, 1072-1085,
325 doi: 10.1002/hyp.7569.

356 Callaghan, T. V., N. J. Collins, and C. H. Callaghan (1978) Photosynthesis, growth and reproduction of
357 *Hylocomium splendens* and *Polytrichum commune* in Swedish Lapland, *Oikos*, 31, 73-88.

358 Chasmer, L., C. Hopkinson, J. Montgomery, and R. Petrone (2016), A Physically-based Terrain Morphology
359 and Vegetation Structural Classification for Wetlands of the Boreal Plains, Alberta, Canada. *Can. J.*
360 *of Remote Sens*, 42, 521-540.

361 Dekker, L. W., C. J. Ritsema, and K. Oostindie (2000), Extent and significance of water repellency in dunes
362 along the Dutch coast, *J. Hydrol.*, 231, 112-125, doi: 10.1016/S0022-1694(00)00188-8.

363 Devito, K., I. Creed, T. Gan, C. Mendoza, R. Petrone, U. Silins, and B. Smerdon (2005), A framework for
364 broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last
365 thing to consider?, *Hydrol. Proc.*, 19, 1705-1714, doi: 10.1002/hyp.5881.

366 Devito, K. J., K. J. Hokanson, P. Moore, N. Kettridge, A. Anderson, L. Chasmer, C. Hopkinson, M. C.
367 Lukenbach, C. A. Mendoza, J. Morissette, D. L. Peters, R. Petrone, U. Silins, B. Smerdon, J. M.
368 Waddington (in press), Landscape controls on long-term runoff in sub-humid heterogeneous Boreal
369 Plain catchments, *Hydrol. Proc.*, doi: 10.1002/hyp.11213.

370 Doerr, S. H., and A. D. Thomas (2000), The role of soil moisture in controlling water repellency: new
371 evidence from forest soils in Portugal, *J. Hydrol.*, 231, 134-147, doi: 10.1016/S0022-1694(00)00190-
372 6.

373 Doerr, S. H. (1998), On standardizing the ‘water drop penetration time’ and the ‘molarity of an ethanol
374 droplet’ techniques to classify soil hydrophobicity: a case study using medium textured soils, *Earth*
375 *Surf. Proc. Land.*, 23, 663-668, doi: 10.1002/(SICI)1096-9837.

376 Fisher, J. B., F. Melton, E. Middleton, C. Hain, M. Anderson, R. Allen, M. McCabe, S. Hook, D. Baldocchi,
377 P. A. Townsend, A. Kilic, K. Tu, D. Miralles, J. Perret, J. P. Lagouarde, D. Waliser, A. J. Purdy, A.

French, D. Schimel, J. S. Famiglietti, G. Stephens, and E. F. Wood (2017), The Future of
 Evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks,
 agricultural management, and water resources, *Water Resour. Res.* doi:10.1002/2016WR020175.

Flannigan, M. D., K. A. Logan, B. D. Amiro, W. R. Skinner, and B. J. Stocks (2005), Future area burned in
 Canada, *Climatic Change*, 71, 1-16, doi: 10.1007/s10584-005-5935-y.

Gabrielli, E. C. (2016) Partitioning Evapotranspiration in Forested Peatlands within the Western Boreal
 Plain, Fort McMurray, Alberta, Canada, *Theses and Dissertations (Comprehensive)*, University of
 Waterloo, Paper 1820.

Heijmans, M. M., W. J. Arp, and F. S. Chapin (2004), Controls on moss evaporation in a boreal black spruce
 forest, *Global Biogeochem Cy*, 18(2), GB2004.

Holden, J. (2005), Peatland hydrology and carbon cycling: why small-scale process matters, *Philos. T. R.
 Soc.*, A 363, 2891-2913, doi: 10.1098/rsta.2005.1671.

Holden, J. (2009), Flow through macropores of different size classes in blanket peat, *J. Hydrol*, 364, 342-34,
 doi: 10.1016/j.jhydrol.2008.11.010.

Hopkinson, C., Barlow, J., Demuth, M., Pomeroy, J. 2010. Mapping changing temperature patterns over a
 glacial moraine using oblique thermal imagery and lidar, *Can. J. Remote Sensing*, 36, 257-265

Johnstone, J. F., F. S. Chapin, T. N. Hollingsworth, M. C. Mack, V. Romanovsky, and M. R. Turetsky
 (2010), Fire, climate change and forest resilience in interior Alaska, *Can. J. Forest Res.*, 40, 1302-
 1312, doi: 10.1139/X10-061.

Kellner, E. (2001), Surface energy fluxes and control of evapotranspiration from a Swedish Sphagnum
 mire, *Agricultural and Forest Meteorology*, 110, 101-123.

Kettridge, N., and A. J. Baird (2008), Modelling soil temperatures in northern peatlands. *Eur. J. Soil
 Science*, 59, 327-338, 10.1111/j.1365-2389.2007.01000.x.

Kettridge, N., and A. J. Baird (2010), Simulating the thermal behavior of northern peatlands with a 3-D
 microtopography, *J. Geophys. Res-Bioge*, 115, G3, doi: 10.1029/2009JG001068.

403 Kettridge, N., and J. M. Waddington (2014), Towards quantifying the negative feedback regulation of
404 peatland evaporation to drought, *Hydrol. Process.*, 28, 3728-3740, doi: 10.1002/hyp.9898.

405 Kettridge, N., D. K. Thompson, and J. M. Waddington (2012), Impact of wildfire on the thermal behavior of
406 northern peatlands: Observations and model simulations, *J. Geophys. Res-Biogeophys.*, 117, G2, doi:
407 10.1029/2011JG001910.

408 Kettridge, N., D. K. Thompson, L. Bombonato, M. R. Turetsky, B. W. Benscoter, and J. M. Waddington
409 (2013), The ecohydrology of forested peatlands: Simulating the effects of tree shading on moss
410 evaporation and species composition, *J Geophys Res: Bio*, 118, 422-435.

411 Kettridge, N., R. E. Humphrey, J. E. Smith, M. C. Lukenbach, K. J. Devito, R. M. Petrone, and J. M.
412 Waddington (2014), Burned and unburned peat water repellency: implications for peatland
413 evaporation following wildfire, *J. of Hydrol.*, 513, 335-341, doi: 10.1016/j.jhydrol.2014.03.019.

414 Kettridge, N., A. S. Tilak, K. J. Devito, R. M. Petrone, C. A. Mendoza, and J. M. Waddington (2015a), Moss
415 and peat hydraulic properties are optimized to maximize peatland water use
416 efficiency, *Ecohydrology*, 9, 1039–1051.

417 Kettridge, N., M. R Turetsky, J. H. Sherwood, D. K. Thompson, C. A. Miller, B. W. Benscoter, M. D.
418 Flannigan, B. M. Wotton, and J. M. Waddington (2015b), Moderate drop in water table increases
419 peatland vulnerability to post-fire regime shift, *Scientific Reports*, 5, 8063, doi:
420 doi:10.1038/srep08063.

421 Kröel-Dulay, G., J. Ransijn, I. K. Schmidt, C. Beier, P. De Angelis, G. De Dato, J. S. Dukes, B. Emmett, M.
422 Estiarte, J. Garadnai, and J. Kongstad (2015), Increased sensitivity to climate change in disturbed
423 ecosystems, *Nature communications*, 6, 6682.

424 Lafleur, P.M., and C. P. Schreder (1994), Water loss from the floor of a subarctic forest, *Arctic and Alpine*
425 *Research*, 152-158.

426 Lafleur, P. M., R. A. Hember, S. W. Admiral, and N. T. Roulet (2005), Annual and seasonal variability in
427 evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada, *Hydrol.*
428 *Process.*, 1918, 3533-3550, doi: 10.1002/hyp.5842.

429 Letey, J. (2001), Causes and consequences of fire-induced soil water repellency, *Hydrol. Process.*, 15, 2867-
430 2875, doi: 10.1002/hyp.378.

431 Lukenbach, M. C., K. J. Hokanson, P. A. Moore, K. J. Devito, N. Kettridge, D. K. Thompson, B. M.
432 Wotton, R. M. Petrone, and J. M. Waddington (2015), Hydrological controls on deep burning in a
433 northern forested peatland, *Hydrol. Process.*, 29, 4114-4124.

434 Lukenbach, M. C., Devito, K.J., Kettridge, N., Petrone, R.M. and Waddington, J.M., 2016. Burn severity
435 alters peatland moss water availability: Implications for post-fire recovery. *Ecohydrology*, 9(2),
436 pp.341-353.

437 Lukenbach, M. C., K. J. Hokanson, K. J. Devito, N. Kettridge, R. M. Petrone, C. A. Mendoza, G. Granath,
438 and J. M. Waddington (2017), Post-Fire Ecohydrological Conditions At Peatland Margins In
439 Different Hydrogeological Settings Of The Boreal Plain, *J. of Hydrol.*

440 McCarter, C. P. and J. S. Price (2014), Ecohydrology of Sphagnum moss hummocks: mechanisms of
441 capitula water supply and simulated effects of evaporation, *Ecohydrology*, 7, 33-44.

442 McLeod, M. K., D. H., Faulkner, and R. Murison (2004), Evaluation of an enclosed portable chamber to
443 measure crop and pasture actual evapotranspiration at small scale. *Agr. Water. Mange.*, 67, 15–34.

444 Natural Regions Committee (2006), Natural Regions and Subregions of Alberta. Compiled by D.J. Downing
445 and W.W. Pettapiece. Government of Alberta. Pub. No. T/852.

446 O'donnell, J. A., M. R. Turetsky, J. W. Harden, K. L. Manies, L. E. Pruett, G. Shetler, and J. C. Neff
447 (2009), Interactive effects of fire, soil climate, and moss on CO₂ fluxes in black spruce ecosystems of
448 interior Alaska, *Ecosystems*, 12, 57-72.

449 Or, D., P. Lehmann, E. Shahraeeni, and N. Shokri (2013), Advances in soil evaporation physics - A review,
450 *Vadose Zone Journal*, 12, 4.

451 Petrone, R. M., U. Silins, and K. J. Devito (2007), Dynamics of evapotranspiration from a riparian pond
452 complex in the Western Boreal Forest, Alberta, Canada, *Hydrol. Process*, 21,1391-1401.

453 Plach, J. M., R. M. Petrone, J. M. Waddington, N. Kettridge, and K. J. Devito (2016), Hydroclimatic
454 influences on peatland CO₂ exchange following upland forest harvesting on the Boreal
455 Plains, *Ecohydrology*, 9,1590-1603.

456 R Core Team (2016), R: A language and environment for statistical computing. R Foundation for Statistical
457 Computing, Vienna, Austria. URL <https://www.R-project.org/>.

458 Rocha, A.V. and Shaver, G.R., 2011. Postfire energy exchange in arctic tundra: the importance and climatic
459 implications of burn severity. *Global Change Biology*, 17(9), pp.2831-2841.

460 Rye, C.F. and Smettem, K.R.J., 2017. The effect of water repellent soil surface layers on preferential
461 flow and bare soil evaporation. *Geoderma*, 289, 142-149.

462 Schouwenaaars, J. M. (1988), The impact of water management upon groundwater fluctuations in a
463 disturbed bog relict, *Agric. Water Manage.*, 14, 439–449, doi: 10.1016/0378-3774(88)90096-0.

464 Shokri, N., P. Lehmann, P. Vontobel, and D. Or (2008) Drying front and water content dynamics during
465 evaporation from sand delineated by neutron radiography, *Water Resou Res*, 44, W06418.

466 Shokri, N., P. Lehmann, and D. Or (2009), Characteristics of evaporation from partially wettable porous
467 media, *Water Resou Res*, 45, W02415.

468 Smerdon B. D., K. J. Devito, and C. A. Mendoza (2005), Interaction of groundwater and shallow lakes on
469 outwash sediments in the subhumid Boreal Plains of Canada, *J. Hydrol*, 314, 246-262, doi:
470 10.1016/j.jhydrol.2005.04.001.

471 Strack, M., J. M. Waddington, and E. S. Tuittila (2004), Effect of water table drawdown on northern
472 peatland methane dynamics: Implications for climate change, *Global Biogeochem. Cy.*, 18, GB4003,
473 doi: 10.1029/2003GB002209.

474 Thompson, D. K., B. W. Benscoter, and J. M. Waddington (2014), Water balance of a burned and unburned
475 forested boreal peatland, *Hydrol. Process*, 28, 5954-5964, doi: 0.1002/hyp.10074.

Thompson, D. K., A. S. Baisley, and J. M. Waddington (2015), Seasonal variation in albedo and radiation exchange between a burned and unburned forested peatland: implications for peatland evaporation, *Hydrol. Process*, 29, 3227-3235.

Turetsky, M., K. Wieder, L. Halsey, and D. Vitt (2002), Current disturbance and the diminishing peatland carbon sink. *Geophys. Res. Lett.*, 29, 1526, doi: 10.1029/2001GL014000.

Turetsky, M. R., W. F. Donahue, and B. W. Benscoter (2011), Experimental drying intensifies burning and carbon losses in a northern peatland, *Nat. Comm.*, 2, 514, doi: 10.1038/ncomms1523.

Turetsky, M. R., B. Bond-Lamberty, E. Euskirchen, J. Talbot, S. Frolking, A. D. McGuire, and E. S. Tuittila (2012), The resilience and functional role of moss in boreal and arctic ecosystems, *New Phytologist*, 196, 49-67.

Turunen J, E. Tomppo, K. Tolonen, and A. Reinikainen (2002), Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions, *Holocene*, 12, 69–80, doi: 10.1191/0959683602hl522rp.

Waddington, J. M., P. J. Morris, N. Kettridge, G. Granath, D. K. Thompson, and P. A. Moore (2015), Hydrological feedbacks in northern peatlands, *Ecohydrology*, 8, 113-127, doi: 10.1002/eco.1493.

Walker, X. J., M. C. Mack, and J. F. Johnstone (2015), Stable carbon isotope analysis reveals widespread drought stress in boreal black spruce forests, *Global Change Biol.*, 21, 3102-3113, doi: 10.1111/gcb.12893.

Weast, R. C. (1986), *CRC Handbook of Chemistry and Physics*. Boca Raton, FL, CRC Press.

Wieder, R. K., K. D. Scott, K. Kamminga, M. A. Vile, D. H. Vitt, T. Bone, B. I. N. Xu, B. W. Benscoter, and J. S. Bhatti (2009), Postfire carbon balance in boreal bogs of Alberta, Canada. *Glob. Change Biology*, 15, 63-81, doi: 10.1111/j.1365-2486.2008.01756.x.

Zhang, K., J. S. Kimball, and S. W. Running (2016), A review of remote sensing based actual evapotranspiration estimation, *Wiley Interdisciplinary Reviews: Water*, 3, 834-853.

501

502

504
505 Figure 1: a) Distribution of median (total) daily sub canopy evapotranspiration measured in six auto
506 chambers within burned feather moss and *Sphagnum* microhabitats for the entire measurement period.
507 Diurnal fluctuation in b) hourly sub-canopy evapotranspiration and c) hourly surface temperature across two
508 representative days for the six auto chambers.

Figure 2: (a) Landcover classification (after *Chasmer et al.* [2016]) and (b) thermal image of remote sensing area. Burned area is within the solid black lines in lower half of images.

Figure 3: a) Sub-canopy evapotranspiration (ET_{sc}) from *Sphagnum* and feather moss microhabitats in the current study, and from the studies of *Heijmans et al.* [2004], *Brown et al.* [2010] and *Kettridge et al.* [2013]. b) Ratio of *Sphagnum* and feather moss ET_{sc} presented within a). *Sphagnum* communities consist of *S. fuscum* only in the current study and the study of *Kettridge et al.* [2013]. *S. fuscum* dominates *Sphagnum* microhabitats in *Heijmans et al.* [2004] and *Brown et al.*, [2010]. However, *S. capillifolium* is also present in microhabitats of *Brown et al.*, [2010] and *S. capillifolium* and *S. magellanicum* are present in micro habitats of *Heijmans et al.* [2004]. ET_{sc} is measured diurnally within the current study and in *Heijmans et al.* [2004]. Within *Brown et al.* [2004] and *Kettridge et al.*, [2013], ET_{sc} is measured between 10:00 and 16:00. Daily totals presented are calculated assuming the ratios with the current study are maintained over the entire diurnal cycle.

Figure 4: Evapotranspiration (ET) from burned and unburned *Sphagnum* and feather moss dominated peatlands and their associated components relative to ET from a *Sphagnum* dominated peatland. *Sphagnum* evapotranspiration fluxes were derived from Thompson *et al.* [2014]. Unburned feather moss ET equal to unburned *Sphagnum* peatland [cf. Kettridge *et al.*, 2013]. Unburned feather moss sub-canopy evapotranspiration from Heijmans *et al.* [2004], Brown *et al.* [2004] and Kettridge *et al.*, [2013], with sub-canopy transpiration component assumed equivalent to the unburned *Sphagnum* peatland (Figure 3). Burned feather moss ET derived within this study.