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Holden, J, Wearing, C, Palmer, S et al. (2014) Fire decreases near-surface hydraulic conductivity and macropore flow in blanket peat. *Hydrological Processes*, 28 (5). pp. 2868-2876. ISSN: 0885-6087

<https://doi.org/10.1002/hyp.9875>

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1 **Fire decreases near-surface hydraulic conductivity**
2 **and macropore flow in blanket peat**

3

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17 Date submitted to Hydrological Processes: 24 October 2012

18 Date submitted with corrections after review: 15 January 2013

19 Date submitted with final corrections after review: 22 April 2013

20

21 **Abstract**

22 Many peatlands have been subjected to wildfire or prescribed burning but it is not
23 known how these fires influence near-surface hydrological processes. Macropores are
24 important flowpaths in the upper layers of blanket peat and were investigated through
25 the use of tension disk infiltrometers, which also provide data on saturated hydraulic
26 conductivity. Measurements were performed on unburnt peat (U), where prescribed
27 burning had taken place 2 years (B2), four years (B4) and >15 (B15+) years prior to
28 sampling, and where a wildfire (W) had taken place four months prior to sampling.
29 Where there had been recent burning (B2, B4 and W), saturated hydraulic
30 conductivity was approximately three times lower than where there was no burning
31 (U) or where burning was last conducted > 15 years ago (B15+). Similarly, the
32 contribution of macropore flow to overall infiltration was significantly lower
33 (between 12 and 25 % less) in the recently burnt treatments compared to B15+ and U.
34 There were no significant differences in saturated hydraulic conductivity or
35 macropore flow between peat which had been subject to recent wildfire (W) and those
36 which had undergone recent prescribed burning (B2 and B4). The results suggest fire
37 influences the near-surface hydrological functioning of peatlands but that recovery in
38 terms of saturated hydraulic conductivity and macropore flow may be possible within
39 two decades if there are no further fires.

40

41 **Keywords:** Rotational heather burning, wildfire, peatland, tension infiltrometer,
42 hydraulic conductivity, grouse moor, soil hydrology.

43

44

45

46 **Introduction**

47 Fire is known to impact soil properties and surface conditions for runoff production.
48 Prescribed burning and wildfires have been shown to reduce hydraulic conductivity
49 and infiltration on forest soils (e.g. Campbell, 1977; Martin and Moody, 2001), and
50 rangelands (Soto et al., 1994), particularly where burning is more intense due to the
51 development of hydrophobic layers (Robichaud, 2000). This leads to enhanced
52 overland flow, higher streamflow peaks (Pierson et al., 2008) and, in combination
53 with a removed vegetation cover, can exacerbate surface erosion (e.g. Smith and
54 Dragovich, 2008). The effects can be spatially variable; for example Pierson *et al.*
55 (2001) indicated that rangeland wildfires could reduce infiltration by 28 % in the first
56 year, but only on areas under burnt shrubs, rather than across the wider landscape.
57 Nyman *et al.* (2010) suggested that in highly macroporous soils, infiltration would be
58 more variable after burning, perhaps because an increase in water repellency would
59 reduce infiltration in non-macropore zones. In contrast, where there are surface
60 macropores, infiltration rates will be enhanced due to additional ponded heads on the
61 surrounding soil forcing more water into the macropores. Redin *et al.* (2011),
62 however, suggested that fire may cause a decrease in the volume of macropores which
63 would contribute to reduced infiltration rates. At some sites fire has been associated
64 with an increase in infiltration rates across the landscape. For example, Neris *et al.* (in
65 press) found that infiltration was increased in a forest Andisol on the Canary Islands
66 due to the removal, by the fire, of a more water repellent forest floor layer. There
67 may, therefore, be different hydrological responses to fire depending on soil type,
68 vegetation type, macroporosity and fire severity.

69

70 Peatlands cover around 4.4 million km² of the Earth's surface and store an estimated
71 612 Gt of carbon, equivalent to well over two thirds of the atmospheric store (Yu et
72 al., 2010). Many major rivers flow from peatlands and the hydrological processes
73 operating within peatland environments can have a major influence on the form of the
74 river hydrograph and on river water quality (Armstrong et al., 2012; Holden and Burt,
75 2003; Holden et al., 2007). Blanket peat occurs on sloping terrain with poor
76 underlying drainage in areas where there is a moisture surplus. Blanket peatlands are
77 typically found in oceanic, high latitude environments but they also occur in high
78 altitude environments in some low latitude regions (Charman, 2002; Evans and
79 Warburton, 2007; Gallego-Sala and Prentice, 2012). Typically blanket peatlands form
80 open (although sometimes there are trees), rolling landscapes, dominated by vascular
81 plants and bryophytes such as *Sphagnum*.

82
83 Often peatlands are managed through prescribed burning (e.g. Buytaert et al., 2006;
84 Buytaert et al., 2005; Holden et al., 2012) or can be subject to wildfires (Kuhry, 1994;
85 Maltby et al., 1990; Thompson and Waddington, in press; Turetsky et al., 2002;
86 Turetsky et al. 2011). However, there is relatively little known about the impact of
87 surface burning on peatland hydrological processes (Glaves et al., 2005; Holden et al.,
88 2007; Thompson and Waddington, in press; Tucker, 2003). Many blanket peatlands
89 have historically been burned for management reasons, including for the reduction of
90 wildfire risk and for habitat management. For example, in the UK, which hosts 8-10
91 % of the world's blanket peatland (Taylor, 1983), prescribed burning is mainly carried
92 out to regenerate young heather shoots to support red grouse habitats as desired by the
93 rural gun-sports industry and to regenerate palatable sedges and grasses for sheep and
94 deer (Grant et al., 2012). Burn management, which typically consists of small patches

95 (mainly 50-1000 m²), burned on 5 to 25 year rotations, has become common-place
96 over the past 150 years (Simmons, 2003) on many blanket peatlands in the UK
97 producing a mosaic landscape of vegetation in different stages of recovery from fire.
98 While there has been much research on the impacts of prescribed burning on peatland
99 vegetation assemblages (e.g. Gilbert and Butt, 2010; Hobbs et al., 1984; Hobbs, 1984;
100 Stewart et al., 2004) there has been very little work studying the impacts of burning
101 on peatland hydrological processes and runoff production.

102

103 Removal of vegetation cover through prescribed burning or wildfire can leave the peat
104 surface subject to desiccation. Peat can be susceptible to shrinkage and cracking when
105 it becomes exposed (Holden and Burt, 2002a; Holden and Burt, 2002b). Such a
106 change in soil structure may be important for hydrology, water quality and biota in
107 peatlands, if such changes result in changes to water flowpaths, by, for example,
108 creating connected macropore channels for water flow which may increase infiltration
109 rates and saturated hydraulic conductivity. On the other hand, desiccated peat is often
110 hydrophobic (Eggelsmann et al., 1993) and thus if a dry crust layer forms on the peat
111 (Evans and Warburton, 2007) this could impede infiltration. Wildfire has been shown
112 to result in the development of water-repellent compounds in surface peat (Clymo,
113 1983). However, there is a dearth of data on infiltration following fire in peatlands
114 but, as with forest and rangeland soils, contradictory reports of both increased
115 (Kinako, 1975) and decreased infiltration rates (Mallik et al., 1984) exist.

116

117 A number of studies have suggested that time since burning can influence stream
118 water quality and that as peatland vegetation recovers in the years after a fire (be it a
119 wildfire or be it prescribed burning at the patch scale) then water quality (in particular

120 dissolved organic carbon flux) also recovers (e.g. Holden et al., 2012; Yallop and
121 Clutterbuck, 2009). It may be the case that the dominance of particular hydrological
122 processes differs depending on the time since fire. It is also possible that wildfire
123 impacts on hydrological processes may be more severe than those resulting from
124 prescribed burning. It is thought that many peatland wildfires burn at hotter
125 temperatures and for longer than more 'controlled' prescribed burns which are
126 typically only conducted during the winter months under high water tables and calm
127 conditions (Tucker et al., 2003). However, temperature records during wildfires and
128 prescribed burns are of limited availability and hence such differences cannot be
129 verified.

130

131 Flow through the upper layers of blanket peat, like other forms of peat such as fens, is
132 known to be dominated by macropore flow. Baird (1997) reported that macropore
133 flow (pores > 1 mm diameter) contributed between 51% and 78% of the flow at the
134 peat surface in a fenland peat, while Holden (2009a) showed that 78% of the flow in
135 the upper 20 cm of a blanket peatland occurred in pores larger than 0.25 mm in
136 diameter. However, unlike fens, runoff production in blanket peatlands is dominated
137 by flow in the upper few centimetres of the peat profile (Holden and Burt, 2003;
138 Holden, 2005; Price, 1992) and therefore the role of near-surface macropores in
139 runoff generation and water quality may be very important.

140

141 The relationship between unsaturated hydraulic conductivity (K) and unsaturated
142 pressure head is a key way of describing macropore functioning (Messing and Jarvis,
143 1993). Tension infiltrometers are widely used for *in situ* measurement of saturated
144 and near-saturated soil hydraulic properties. The infiltrometer provides a source of

145 water at a small negative porewater pressure at the surface. The negative pressure
146 prevents the larger pores that fill at greater porewater pressures from wetting up and
147 short-circuiting the flow. Hence, by subtraction, the hydrological role of larger pores
148 during the infiltration process can be evaluated. Several studies have used tension
149 infiltrometers on peat to investigate infiltration, hydraulic conductivity and macropore
150 flow (Baird, 1997; Holden, 2009a; Holden, 2009b; Holden et al., 2001; Holden et al.,
151 2006; Wallage and Holden, 2011). These have shown that drainage of peat, vegetation
152 cover and topographic position can all be important controls on the proportion of
153 infiltrating water moving through macropores in blanket peat. This study used tension
154 infiltrometer measurements to investigate infiltration, saturated hydraulic conductivity
155 and macropore flow under prescribed burning at three different time intervals since
156 burning and at a wildfire site. It was hypothesised that the proportion of macropore
157 flow and the saturated hydraulic conductivity would i) be greater under prescribed
158 burning than where there has been no burning; ii) be affected significantly by time
159 since prescribed burning and iii) be greater four months after wildfire than two to
160 four years after prescribed burning.

161

162 **Methods**

163 The experiment was conducted on blanket peat in the Pennine hills of northern
164 England in July and August 2011. All sites had blanket peat > 1 m depth and were
165 subject to very light sheep grazing at < 0.5 sheep ha⁻¹ (with no sheep November –
166 February). The Bull Clough catchment (53.472°N, -1.716°E) is managed using
167 prescribed patch burning on a 20-25 year rotation. It is thought to be a relatively
168 typical peatland grouse moor. The vegetation cover at Bull Clough is dominated by
169 *Calluna* with very little moss cover but some *Eriophorum* spp. Here three treatments

170 were examined. Patches where burning took place just over two years prior to the
171 experiment (B2), patches with burning four years prior to the experiment (B4) and
172 patches which were burnt 15-25 years prior to the experiment (B15+). Patch age was
173 confirmed by the site manager who knew when burning had taken place across the
174 catchment. However, it was not possible to narrow down the age range of the patches
175 that were burnt at some point between 15 and 25 years prior to sampling, although it
176 is thought that most were last burnt around 20 years before our experiment. For B2
177 the ground cover was rather sparse with bare and burnt *Calluna* branches remaining
178 obvious but with some occasional rejuvenating shoots of new *Calluna* emerging from
179 the peat surface (Figure 1a). For B4 the vegetation cover was more widespread,
180 although there were still some small unvegetated zones (Figure 1b). *Calluna* was
181 dominant with some *Eriophorum* regrowth. For B15+ shrubby *Calluna* (~40 cm high)
182 dominated the plots with almost complete canopy cover but with some *Eriophorum*
183 and <3 % ground cover of *Sphagnum* on the peat surface (Figure 1c). Since burn
184 management is done to ensure widespread *Calluna* dominance, the *Calluna* cover and
185 scarcity of *Sphagnum* cover is typical of many grouse moor burning sites.

186

187 Prescribed burning occurs during winter months only in conditions when the peat is
188 saturated, the wind is calm and the peat surface is often frozen. The fire is controlled
189 to burn quickly across the vegetation cover without getting out of control or burning
190 hot into the peat layers. The regular and repeated nature of fire at the site combined
191 with the quick burn of vegetation means that the depth of char layers in the peat
192 cannot be used to differentiate fire severity between burn plots. However, it is thought
193 that fires from year to year on one site (i.e. B2, B4 and B15+) are of a similar severity
194 because the local management experience and techniques are passed on from year to

195 year. Fires are controlled by wardens who can fan the flames or put them out, so that
196 the fire quickly burns across the vegetation without getting out of control or burning
197 hot into the peat layers.

198

199 For comparative purposes, Moss Burn, an unburnt catchment (U) (54.690°N, -
200 2.386°E) was investigated, as was Oakner Clough (53.599°N, - 1.973°E) a catchment
201 where a wildfire had taken place 3-4 months prior to the experiment (W). At U the
202 vegetation cover was a mixture of *Calluna* (~ 40 cm high), *Eriophorum* spp. and
203 *Sphagnum* spp. (Figure 1d). Here *Sphagnum* cover is widespread (>40 % ground
204 cover) often smothering low-lying *Calluna* stems. The U site is protected and there
205 has been no prescribed burning on the catchment for at least 70 years, and probably
206 longer. At W the vegetation was approximately the same as for U except *Sphagnum*
207 cover provided ~ 30 % ground cover. The wildfire occurred on 9 April 2011, then
208 sampling took place 24 July – 1 August 2011. The ‘wildfire’ is thought to have started
209 via arson or accident and covered around 500 ha. The W site is not thought to have
210 experienced a severe fire as many of our instruments on the site, as part of a wider
211 peatland study, were undamaged from the fire which spread quickly, burning the
212 surface vegetation (Figure 1e) but not appearing to penetrate into the peat except at a
213 few localised ‘hot spots’. Table 1 provides background data on loss on ignition, bulk
214 density and Von Post classification for the near-surface peat for each treatment.

215

216 For each treatment (B2, B4, B15+, U and W) three patches of approximately 400 m²
217 were chosen. Patch locations were chosen with respect to the topographic index,
218 $\ln(\tan\beta/a)$ where β is the slope and a is drainage length per unit contour width. The
219 use of the topographic index allowed us to control for any possible slope position

220 effects which is important because Holden (2009b) showed that slope position can
221 control the proportion of flow through macropores in several soil types. Each
222 treatment had one patch in a low topographic index setting, one in a mid topographic
223 index setting and the other in a high topographic index setting. Effectively this was
224 equivalent to a top, mid and footslope position. The same topographic index values
225 were determined for patches chosen for each treatment so that slope position effects
226 were controlled and were equal between treatments. Across the three patches for each
227 treatment, 6 or 7 sampling points were randomly chosen so that each treatment had
228 twenty sampling points in total.

229

230 A tension disk infiltrometer similar to that designed by Ankeny et al. (1988) and
231 described further by Holden et al. (2001) was placed on the peat surface at each
232 sampling point. At each location, vegetation or the remains of burned heather stems
233 was carefully cut back to the peat surface. Fine moist sand was applied to the surface
234 to ensure good contact between the infiltrometer disk and the peat surface. The device
235 was lightweight and only required a small volume of water (135 mL) to operate and
236 hence compression of the peat surface was minimised making more accurate
237 infiltration measurements possible. The experiments were conducted at water tensions
238 of -0.1 and -4.1 cm. Infiltration measurements for each pressure head continued until
239 well after a steady state was achieved (e.g. Figure 2), which typically occurred within
240 20 minutes of the experiment, but was >30 minutes for around 10 % of cases. The
241 longest duration experiment was 2 hours. Low infiltration rates meant that many of
242 the experimental runs continued for several hours to ensure satisfactory volumetric
243 infiltration values had been achieved. Data from some of the sample runs were not
244 included in the analysis if there was a rapid rise in surrounding air temperature during

245 the experiment (e.g. when cloudy conditions were suddenly replaced with sunny ones)
246 or where there were other sampling problems. Thus n varied between 16 and 19 for
247 each treatment in the analysis.

248

249 K values were obtained from the steady-state infiltrometer data using the method
250 outlined by Reynolds and Elrick (1991). Detailed equations are described elsewhere
251 (Baird, 1997; Holden et al., 2001; Reynolds and Elrick, 1991) but in summary,
252 Wooding's solution for infiltration from a shallow pond (Wooding, 1968) was
253 combined with Gardner's (1958) unsaturated hydraulic conductivity function.
254 Reynolds and Elrick (1991) and Holden et al. (2001) showed for tension infiltrometer
255 experiments that errors using this technique associated with shallow water tables and
256 potential anisotropy, both of which could occur in blanket peat, would be minor,
257 particularly when compared to errors associated with other methods of measuring K in
258 peat. Nevertheless, to minimise errors the work was conducted during July to August
259 2011 when water tables would be at their deepest (e.g. Evans et al., 1999).

260

261 While definitions of macropores vary widely, and the choice of an effective size to
262 delimit macropores is necessarily arbitrary, several authors have used the value of -3
263 cm pressure head to distinguish between flow through macropores and smaller pores
264 (Baird, 1997; Luxmoore, 1981; Watson and Luxmoore, 1986). According to capillary
265 theory this defines that macropores are larger than 1 mm in diameter. We use this
266 definition here to aid comparison to earlier studies, particularly those on peatlands.
267 The proportion of saturated hydraulic conductivity (K_s) governed by macropores for
268 each run was calculated by subtracting K calculated for a pressure of -3 cm from K_s

269 (Baird, 1997). Results can therefore be presented as the rate of water moving through
270 macropores as a proportion (%) of K_s .

271

272 Effective macroporosity volumes were calculated using the procedure presented by
273 Watson and Luxmoore (1986) and Wilson and Luxmoore (1988), which is based on
274 Poiseuille's equation. Several assumptions are made in applying Poiseuille's equation
275 to the calculation of effective porosity and these include cylindrical pores and
276 minimum pore radius as the true pore radius. It may be that many of the capillaries in
277 peat are very short, non-uniform and not well-connected such that these assumptions
278 are not met. This should be borne in mind when interpreting effective macroporosity
279 volumes below.

280

281 It was necessary (to remove skewness and heterogeneous variation within groups) to
282 \log_{10} transform infiltration, K_s and effective macroporosity data before applying
283 parametric tests of difference. As macropore flow data was expressed as a percent of
284 overall flow, data were arcsine transformed before statistical analysis. Paired t-tests
285 were used to compare infiltration values at -0.1 and -4.1 cm tension within each of the
286 five treatments individually. The effect of both Treatment and Slope (three categories
287 of low, medium and high topographic index) on infiltration, K_s , macropore flow and
288 effective macroporosity were investigated using a nested ANOVA (Minitab 15.1.20)
289 with Treatment nested within Slope. In all cases Slope was not a significant factor
290 within the nested ANOVA at $p < 0.05$. Therefore, to compare between treatments,
291 slope position was discounted as a factor in the results presented and a straightforward
292 one-way ANOVA was used followed by Tukey's multiple comparison tests to
293 examine which individual mean values differed significantly from others.

294

295 **Results**

296 Typical infiltration runs are shown in Figure 2. For all sample points steady-state
297 infiltration rates were greater at -0.1 cm than at -4.1 cm water tension. This difference
298 was significant for the dataset as a whole ($t = -20.24$ $p < 0.001$) and for each treatment.
299 At -0.1 cm tension, infiltration rates were significantly different between treatments
300 ($F = 20.9$, $p < 0.001$) with Tukey's post-hoc differences between all treatment pairs
301 being significant ($p < 0.05$) except for pairs B2 and B4, B2 and W and B15+ and U
302 (Figure 3). At -4.1 cm tension, steady-state infiltration rates were significantly
303 different between treatments ($F = 9.1$, $p < 0.001$) with Tukey's post-hoc tests showing
304 significant differences ($p < 0.05$) between B2 and B4, and for W and B4, W and B15+,
305 and W and U.

306

307 K_s varied by around three orders of magnitude across the samples ranging from 0.6 to
308 $25.3 \times 10^{-8} \text{ m s}^{-1}$ with a mean of $7.2 \times 10^{-8} \text{ m s}^{-1}$. Treatment was a significant factor in
309 controlling K_s ($F = 20.4$, $p < 0.001$). Where there had been recent burning (B2, B4 and
310 W) K_s was significantly lower for all pairs (Tukey's post hoc tests, $p < 0.05$) than
311 where there was no burning or where burning was last conducted > 15 years ago
312 (Figure 4). K_s was around three times smaller where there had been recent burning
313 compared to B15+ and U. There were no significant differences in K_s between the
314 recent burn treatments (W, B2 or B4) and there was no significant difference between
315 K_s for U or B15+.

316

317 The proportion of flow moving through macropores ranged from 13 % to 96 % (mean
318 = 76 %; SD = 18%; Figure 5). Burn treatment exerted a significant control on the

319 proportion of macropore flow (arcsin % data, $F = 8.0$, $p < 0.001$) with U and B15+
320 both having a significantly greater proportion of flow (Tukey's post hoc tests, $p < 0.05$)
321 occurring within macropores than the recently burnt treatments. The mean proportion
322 of macropore flow to overall flow in the recently burnt treatments was between 12
323 and 25 % less than for U or B15+ where 88 and 86 % of flow moved through
324 macropores respectively. Tukey's post hoc tests on transformed data showed there
325 were no significant differences in proportion of macropore flow between the recent
326 burn treatments (W, B2 or B4), nor was there a significant difference between
327 between U and B15+.

328

329 The effective macroporosity ranged from 0.06 to 15.5 cm³ m⁻³ and was significantly
330 different between treatments ($F = 16.4$, $p < 0.001$). Tukey's post hoc tests showed that
331 effective macroporosity was significantly greater in B15+ and U than for the recently
332 burnt sampling points. A large proportion of flow was calculated to move through
333 only a small volume of the near-surface peat (Table 2). For B2, for example, a mean
334 of 69 % of the flow moved through only 0.0002 % of the peat volume.

335

336 For infiltration at -0.1 cm tension, for K_s , and for effective macroporosity, the
337 interquartile range and standard deviation was greater for both U and B15+ treatments
338 than the recently burnt cases. Conversely, the interquartile range and standard
339 deviation for the proportion of flow moving through macropores was greater for the
340 recently burnt cases than for either U or B15+.

341

342 **Discussion and conclusions**

343 Infiltration was greater in all pairs of samples at -0.1 cm tension compared to -4.1 cm
344 demonstrating that under saturated conditions macropores must be important
345 pathways for water movement in near-surface blanket peat. The values of K_s , the
346 proportion of macropore flow and the effective macroporosity are in line with
347 previously reported values for peatlands (e.g. Baird, 1997; Holden, 2009a; Holden,
348 2009b; Holden et al., 2001).

349

350 Contrary to our first hypothesis, this study has provided evidence that burning reduces
351 (rather than increases) the role of macropores in water flow in the upper peat layers.
352 Wallage and Holden (2011) compared drained and undisturbed blanket peat
353 treatments and similarly found the proportion of macropore flow was reduced with
354 disturbance compared to the undisturbed state. However, unlike in our present
355 burning impact study, they did not find that saturated hydraulic conductivity was
356 significantly lower in the disturbed treatment compared to the undisturbed treatment.

357

358 The impact of fire on macropore flow may be related to collapse of pores due to
359 consolidation of bare peat subject to drying (Eggelsmann, 1975; Silins and Rothwell,
360 1988). The bulk density of the peat in the upper 5 cm for U was smaller than for the
361 burnt treatments. The mean near-surface bulk density was greater for B2 than for B4
362 which in turn was greater than for B15+ suggesting that consolidation of the peat
363 related to recent burning could be factor in reducing macropore flow and saturated
364 hydraulic conductivity under recent burn treatments. It may be the case that over time
365 since burning the upper peat might have a reduced bulk density as new vegetation
366 establishes.

367

368 The reduction of macropore flow may also be related to fine sediment and ash which
369 is mobilised during and after fire and blocks up macropore entrances thereby reducing
370 flow. Onda *et al.* (2008) found reduced infiltration on sandy forest soil plots after
371 wildfire due to sealing of macropores by ash and fine sediment. Holden (2009a) found
372 that effective porosity decreased by two orders of magnitude over the upper 20 cm of
373 the peat profile in blanket peatlands, suggesting that pores > 0.25 mm, which flow had
374 been measured through, did not extend vertically into the peat by more than a few
375 centimetres. Thus, surface clogging of macropores is likely to be an important factor
376 controlling the overall effective macroporosity in blanket peat. Holden (2009b) has
377 previously shown, for a number of soil types, that clogging of macropores by
378 sediment from overland flow is potentially an important driver of spatial patterns in
379 macropore flow across hillslopes. Blanket peat tends to be dominated by overland
380 flow processes and hence sediment movement across unvegetated surfaces after
381 burning is likely to be high. The importance of this potential mechanism could be
382 established by a further disk infiltrometer experiment conducted before and after ash
383 addition on unburnt peat. Saturated hydraulic conductivity also appears to be reduced
384 by recent burning in comparison to sites where burning has not taken place or where it
385 took place > 15 years ago. This may reflect the development of a hydrophobic layer or
386 be a function of clogging of pore spaces with mobile sediment, which reduces pore
387 connectivity at, and close to, the peat surface. Over time, removal and breakdown of
388 this sediment could enable macropore networks to open up once more. The
389 establishment of a vegetation cover, new root formation and active peat growth could
390 also increase near-surface saturated hydraulic conductivity in the years after burning.
391

392 Samples from B15+ plots (burnt 15-25 years prior to measurement) produced
393 significantly greater macropore flow and had significantly greater saturated hydraulic
394 conductivity than those from the more recently burnt peat, which confirmed our
395 second hypothesis that time since fire is an important control on peatland hydrological
396 function. These values were not statistically different to those from unburnt peat
397 indicating recovery of the peat system from fire. These data also suggest at least in
398 the case of K_s and macropore flow, that there is a hydrological recovery lag time
399 which is > 4 years (since values from B2 and B4 were not significantly different), but
400 < 15 years (B15+).

401

402 Contrary to our third hypothesis the values of saturated hydraulic conductivity,
403 macropore flow or effective macroporosity obtained from the wildfire site four
404 months after the fire were not significantly different to those from the prescribed
405 burning treatments two or four years after burning. This suggests that the wildfire
406 impacts were no more severe than those from prescribed burning at a patch scale.
407 However, it may be that the response to the wildfire over longer time periods (say one
408 to five years) may be greater than for prescribed burning, as there may be a lag time
409 which is longer than 4 months at which the hydrological impacts of the fire are at their
410 greatest. To establish such an effect would require repeated measurements of
411 macropore flow and K_s at frequent time intervals following fire over a period of many
412 years. We do not know whether the wildfire was hotter at the peat surface than the
413 prescribed burning but it may be the case that both the wildfire and prescribed burning
414 treatments we investigated were similar (indeed the Von Post data suggest that this is
415 indeed the case). There is a spectrum of fire types (cooler to hotter, quick to long
416 lasting) which may have different impacts on hydrological function and the ability of

417 the hydrology of the peat to recover toward those conditions equivalent to an unburnt
418 treatment. Of course, the overall effect of the wildfire will be greater because it covers
419 a large and continuous area rather than being confined to small patches.

420

421 Infiltration, K_s and effective macroporosity were spatially more variable for U and
422 B15+ than for any of the recently burnt treatments. Recent burning may therefore
423 reduce the spatial variability of overall infiltration and near-surface flow rates creating
424 a hydrologically more homogeneous near-surface peat. However, while overall
425 macropore flow rates and spatial variability in these rates were smaller for recently
426 burnt treatments, the relative proportion of flow moving through macropores at each
427 sampling point was spatially more variable compared to U and B15+.

428

429 We recognise that three nearby sites were used for this study and that there are likely
430 to be between-site differences that may not be the result of fire effects. The potential
431 between-site effects should be borne in mind when interpreting the results. The U site
432 had smaller bulk density values in the near-surface zone and higher loss on ignition
433 (Table 1) than any of the burnt sites. However, we think that this is, in itself, evidence
434 of an effect of fire but further work is required to examine the impact of prescribed
435 fire on peat physical and chemical properties. However, the evidence for fire effects is
436 strong within the Bull Clough catchment alone. Here there were significant
437 differences for all hydrological variables studied between recently burned patches and
438 patches burned more than 15 years before the study. It is also interesting to note that
439 there were no significant differences between U and B15+ for the variables tested
440 which adds weight to results in this study.

441

442 In summary, this paper has provided evidence that fire leads to changes in the
443 movement of water in the upper layers of blanket peat. It reduces the role of
444 macropores and therefore increases the role of micropores in the infiltration and
445 percolation process. In doing so, this may increase the potential for leaching of
446 dissolved organic carbon from the peat system because there would increased contact
447 time between infiltrating water and the peat matrix (Clark et al., 2010). Several
448 studies have suggested dissolved organic carbon leaching may increase following
449 prescribed burning and then decrease over the initial few years after the burn as the
450 vegetation canopy becomes more established and bryophytes re-appear (Holden et al.,
451 2012). However, further work is required to fully understand the role of different pore
452 sizes and their connectivity in stream water quality and carbon cycling in peatlands.

453

454 **Acknowledgements**

455 The research was conducted as part of the EMBER project funded by the UK's
456 Natural Environment Research Council (grant NE/G00224X/1). We thank the
457 landowners and gamekeepers, Natural England and The National Trust for granting
458 permission to access the field sites.

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- 629
630

631 Table 1. Summary of soil physical properties at 0-5 cm depth at Moss Burn (intact,
 632 n=12), Bull Clough (burned, n=3 per burn age) and Oakner (wildfire, n=12) at 0-5 cm
 633 depth. Data are means and standard errors except for Von Post humification index
 634 (median, min-max.).
 635

Site	Burn age	LOI, %	Bulk density, g cm ⁻³	Von Post
Moss Burn (U)	<i>n/a</i>	96.4 (0.4)	0.110 (0.008)	6.5 (4 – 8)
Bull Clough (B)	2 (B2)	90.7 (1.3)	0.249 (0.013)	7 (6 – 9)
	3-4 (B4)	90.5 (0.4)	0.166 (0.008)	6 (2 – 7)
	15-25 (B15+)	90.9 (1.0)	0.136 (0.047)	3 (2 – 5)
Oakner (W)	< 1 (W)	89.8 (2.0)	0.201 (0.013)	6 (4 – 8)

636

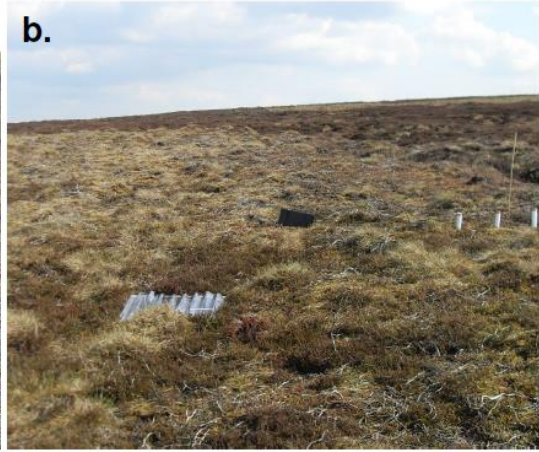
637

638 Table 2.. Effective macroporosity for each burn condition (untransformed data).

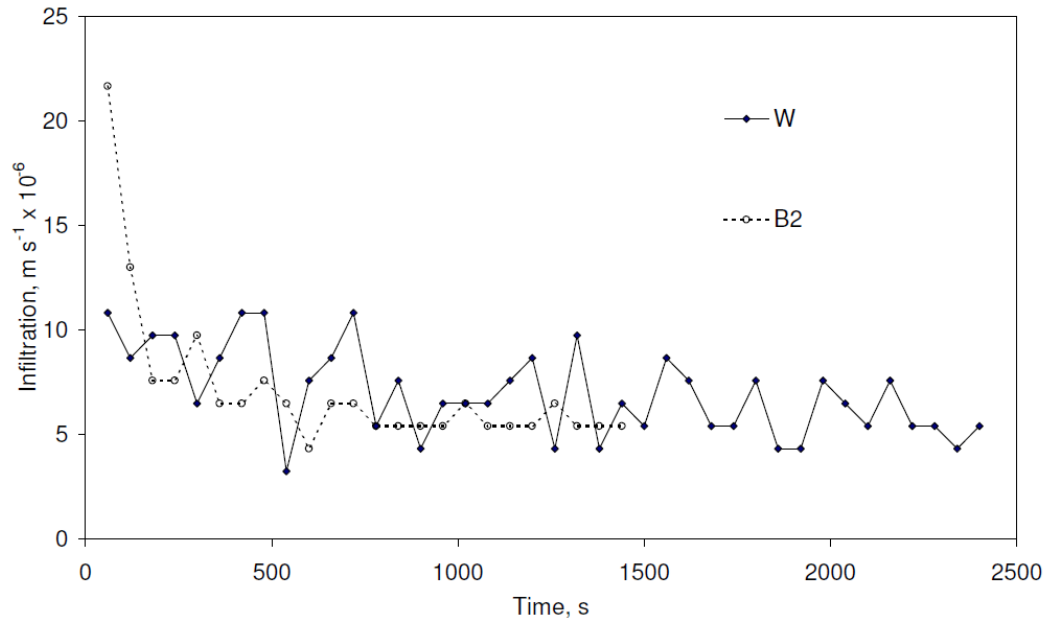
Burn condition	n	Effective macroporosity cm ³ m ⁻³	
		Mean	Standard error
B2	19	2.0	0.5
B4	16	2.2	0.5
B15+	18	7.0	0.9
U	16	8.3	1.0
W	18	1.6	0.4

639

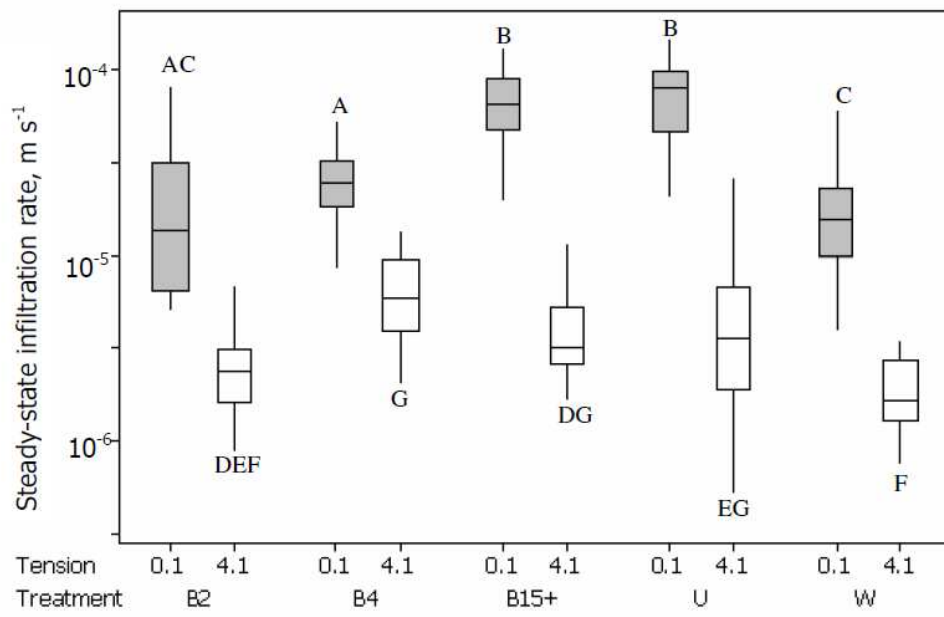
640 Figure 1. Photographs showing examples of conditions at a) B2, b) B4, c) B15+
641 (foreground), d) U and e) W.
642
643 Figure 2. Example infiltration measurements over time for -4.1 cm tension at sample
644 point 6 for B2 and W.
645
646 Figure 3. Box and whisker plots showing steady-state infiltration rate for each burn
647 condition and tension. The upper end point of the whiskers indicates $Q3 + (1.5 \times (Q3-$
648 $Q1))$. The lower end point of the whiskers indicates $Q1 - (1.5 \times (Q3-Q1))$. n for each
649 treatment is given in Table 2. Means with different letters are significantly different.
650
651
652 Figure 4. Box and whisker plots showing saturated hydraulic conductivity (K_s) for
653 each burn condition. The upper end point of the whiskers indicates $Q3 + (1.5 \times (Q3-$
654 $Q1))$. The lower end point of the whiskers indicates $Q1 - (1.5 \times (Q3-Q1))$. n for each
655 treatment is given in Table 2. Means with different letters are significantly different.
656
657
658 Figure 5. Box and whisker plots showing the proportion of flow moving through
659 macropores for each burn condition. The upper end point of the whiskers indicates $Q3$
660 $+ (1.5 \times (Q3-Q1))$. The lower end point of the whiskers indicates $Q1 - (1.5 \times (Q3-$
661 $Q1))$. Raw data were used to generate the figure, although data were analysed using
662 an arcsin transformation. n for each treatment is given in Table 2. Means with
663 different letters are significantly different.
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665



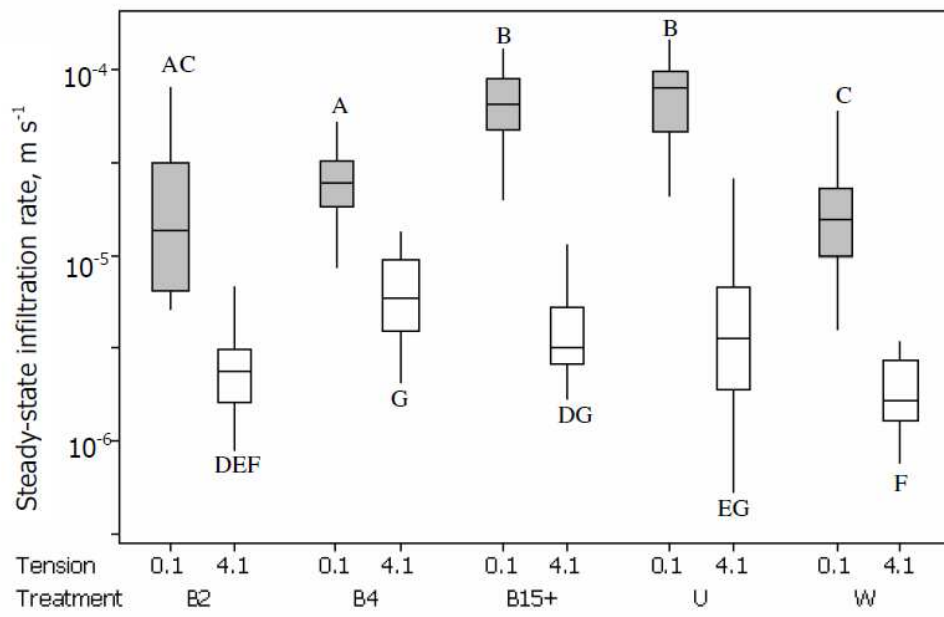
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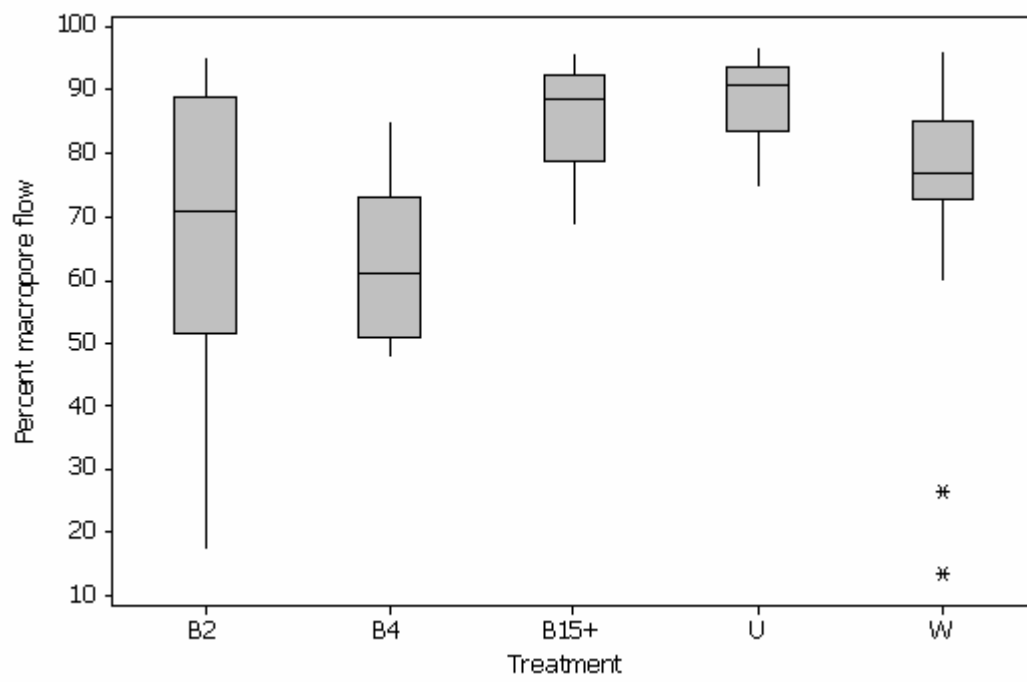
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