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

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Abstract

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

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

Introduction

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

Peatlands cover around 4.4 million km^2 of the Earth's surface and store an estimated 612 Gt of carbon, equivalent to well over two thirds of the atmospheric store (Yu et al., 2010). Many major rivers flow from peatlands and the hydrological processes operating within peatland environments can have a major influence on the form of the river hydrograph and on river water quality (Armstrong et al., 2012; Holden and Burt, 2003; Holden et al., 2007). Blanket peat occurs on sloping terrain with poor underlying drainage in areas where there is a moisture surplus. Blanket peatlands are typically found in oceanic, high latitude environments but they also occur in high altitude environments in some low latitude regions (Charman, 2002; Evans and Warburton, 2007; Gallego-Sala and Prentice, 2012). Typically blanket peatlands form open (although sometimes there are trees), rolling landscapes, dominated by vascular plants and bryophytes such as Sphagnum.

Often peatlands are managed through prescribed burning (e.g. Buytaert et al., 2006; Buytaert et al., 2005; Holden et al., 2012) or can be subject to wildfires (Kuhry, 1994; Maltby et al., 1990; Thompson and Waddington, in press; Turetsky et al., 2002; Turetsky et al. 2011). However, there is relatively little known about the impact of surface burning on peatland hydrological processes (Glaves et al., 2005; Holden et al., 2007; Thompson and Waddington, in press; Tucker, 2003). Many blanket peatlands have historically been burned for management reasons, including for the reduction of wildfire risk and for habitat management. For example, in the UK, which hosts 8-10 % of the world's blanket peatland (Taylor, 1983), prescribed burning is mainly carried out to regenerate young heather shoots to support red grouse habitats as desired by the rural gun-sports industry and to regenerate palatable sedges and grasses for sheep and deer (Grant et al., 2012). Burn management, which typically consists of small patches (mainly 50-1000 m^2), burned on 5 to 25 year rotations, has become common-place over the past 150 years (Simmons, 2003) on many blanket peatlands in the UK producing a mosaic landscape of vegetation in different stages of recovery from fire. While there has been much research on the impacts of prescribed burning on peatland vegetation assemblages (e.g. Gilbert and Butt, 2010; Hobbs et al., 1984; Hobbs, 1984; Stewart et al., 2004) there has been very little work studying the impacts of burning on peatland hydrological processes and runoff production.

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

A number of studies have suggested that time since burning can influence stream water quality and that as peatland vegetation recovers in the years after a fire (be it a wildfire or be it prescribed burning at the patch scale) then water quality (in particular dissolved organic carbon flux) also recovers (e.g. Holden et al., 2012; Yallop and Clutterbuck, 2009). It may be the case that the dominance of particular hydrological processes differs depending on the time since fire. It is also possible that wildfire impacts on hydrological processes may be more severe than those resulting from prescribed burning. It is thought that many peatland wildfires burn at hotter temperatures and for longer than more ‘controlled’ prescribed burns which are typically only conducted during the winter months under high water tables and calm conditions (Tucker et al., 2003). However, temperature records during wildfires and prescribed burns are of limited availability and hence such differences cannot be verified.

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

The relationship between unsaturated hydraulic conductivity (K) and unsaturated pressure head is a key way of describing macropore functioning (Messing and Jarvis, 1993). Tension infiltrometers are widely used for in situ measurement of saturated and near-saturated soil hydraulic properties. The infiltrometer provides a source of water at a small negative porewater pressure at the surface. The negative pressure prevents the larger pores that fill at greater porewater pressures from wetting up and short-circuiting the flow. Hence, by subtraction, the hydrological role of larger pores during the infiltration process can be evaluated. Several studies have used tension infiltrometers on peat to investigate infiltration, hydraulic conductivity and macropore flow (Baird, 1997; Holden, 2009a; Holden, 2009b; Holden et al., 2001; Holden et al., 2006; Wallage and Holden, 2011). These have shown that drainage of peat, vegetation cover and topographic position can all be important controls on the proportion of infiltrating water moving through macropores in blanket peat. This study used tension infiltrometer measurements to investigate infiltration, saturated hydraulic conductivity and macropore flow under prescribed burning at three different time intervals since burning and at a wildfire site. It was hypothesised that the proportion of macropore flow and the saturated hydraulic conductivity would i) be greater under prescribed burning than where there has been no burning; ii) be affected significantly by time since prescribed burning and iii) be greater four months after wildfire than two to four years after prescribed burning.

Methods

The experiment was conducted on blanket peat in the Pennine hills of northern England in July and August 2011. All sites had blanket peat > 1 m depth and were subject to very light sheep grazing at < 0.5 sheep ha^{-1} (with no sheep November – February). The Bull Clough catchment (53.472ºN, -1.716ºE) is managed using prescribed patch burning on a 20-25 year rotation. It is thought to be a relatively typical peatland grouse moor. The vegetation cover at Bull Clough is dominated by Calluna with very little moss cover but some Eriophorum spp. Here three treatments were examined. Patches where burning took place just over two years prior to the experiment (B2), patches with burning four years prior to the experiment (B4) and patches which were burnt 15-25 years prior to the experiment (B15+). Patch age was confirmed by the site manager who knew when burning had taken place across the catchment. However, it was not possible to narrow down the age range of the patches that were burnt at some point between 15 and 25 years prior to sampling, although it is thought that most were last burnt around 20 years before our experiment. For B2 the ground cover was rather sparse with bare and burnt Calluna branches remaining obvious but with some occasional rejuvenating shoots of new Calluna emerging from the peat surface (Figure 1a). For B4 the vegetation cover was more widespread, although there were still some small unvegetated zones (Figure 1b). Calluna was dominant with some Eriophorum regrowth. For B15+ shrubby Calluna (~40 cm high) dominated the plots with almost complete canopy cover but with some Eriophorum and <3 % ground cover of Sphagnum on the peat surface (Figure 1c). Since burn management is done to ensure widespread Calluna dominance, the Calluna cover and scarcity of Sphagnum cover is typical of many grouse moor burning sites.

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

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

For each treatment (B2, B4, B15+, U and W) three patches of approximately 400 m^2 were chosen. Patch locations were chosen with respect to the topographic index, $\ln(\tan\beta/a)$ where β is the slope and a is drainage length per unit contour width. The use of the topographic index allowed us to control for any possible slope position effects which is important because Holden (2009b) showed that slope position can control the proportion of flow through macropores in several soil types. Each treatment had one patch in a low topographic index setting, one in a mid topographic index setting and the other in a high topographic index setting. Effectively this was equivalent to a top, mid and footslope position. The same topographic index values were determined for patches chosen for each treatment so that slope position effects were controlled and were equal between treatments. Across the three patches for each treatment, 6 or 7 sampling points were randomly chosen so that each treatment had twenty sampling points in total.

A tension disk infiltrometer similar to that designed by Ankeny et al. (1988) and described further by Holden et al. (2001) was placed on the peat surface at each sampling point. At each location, vegetation or the remains of burned heather stems was carefully cut back to the peat surface. Fine moist sand was applied to the surface to ensure good contact between the infiltrometer disk and the peat surface. The device was lightweight and only required a small volume of water (135 mL) to operate and hence compression of the peat surface was minimised making more accurate infiltration measurements possible. The experiments were conducted at water tensions of -0.1 and -4.1 cm. Infiltration measurements for each pressure head continued until well after a steady state was achieved (e.g. Figure 2), which typically occurred within 20 minutes of the experiment, but was >30 minutes for around 10 % of cases. The longest duration experiment was 2 hours. Low infiltration rates meant that many of the experimental runs continued for several hours to ensure satisfactory volumetric infiltration values had been achieved. Data from some of the sample runs were not included in the analysis if there was a rapid rise in surrounding air temperature during the experiment (e.g. when cloudy conditions were suddenly replaced with sunny ones) or where there were other sampling problems. Thus n varied between 16 and 19 for each treatment in the analysis.

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

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

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

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

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

Results

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

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

The proportion of flow moving through macropores ranged from 13 % to 96 % (mean =76 %; SD= 18%; Figure 5). Burn treatment exerted a significant control on the proportion of macropore flow (arcsin % data, $F = 8.0$, $p<0.001$) with U and B15+ both having a significantly greater proportion of flow (Tukey's post hoc tests, $p<0.05$) occurring within macropores than the recently burnt treatments. The mean proportion of macropore flow to overall flow in the recently burnt treatments was between 12 and 25 % less than for U or B15+ where 88 and 86 % of flow moved through macropores respectively. Tukey's post hoc tests on transformed data showed there were no significant differences in proportion of macropore flow between the recent burn treatments (W, B2 or B4), nor was there a significant difference between between U and B15+.

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

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

Discussion and conclusions

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

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

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

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

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

Contrary to our third hypothesis the values of saturated hydraulic conductivity, macropore flow or effective macroporosity obtained from the wildfire site four months after the fire were not significantly different to those from the prescribed burning treatments two or four years after burning. This suggests that the wildfire impacts were no more severe than those from prescribed burning at a patch scale. However, it may be that the response to the wildfire over longer time periods (say one to five years) may be greater than for prescribed burning, as there may be a lag time which is longer than 4 months at which the hydrological impacts of the fire are at their greatest. To establish such an effect would require repeated measurements of macropore flow and K_s at frequent time intervals following fire over a period of many years. We do not know whether the wildfire was hotter at the peat surface than the prescribed burning but it may be the case that both the wildfire and prescribed burning treatments we investigated were similar (indeed the Von Post data suggest that this is indeed the case). There is a spectrum of fire types (cooler to hotter, quick to long lasting) which may have different impacts on hydrological function and the ability of the hydrology of the peat to recover toward those conditions equivalent to an unburnt treatment. Of course, the overall effect of the wildfire will be greater because it covers a large and continuous area rather than being confined to small patches.

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

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

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

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

Site	Burn age	LOI, %	Bulk density, g cm^{-3}	Von Post
Moss Burn (U)	n/a	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)

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

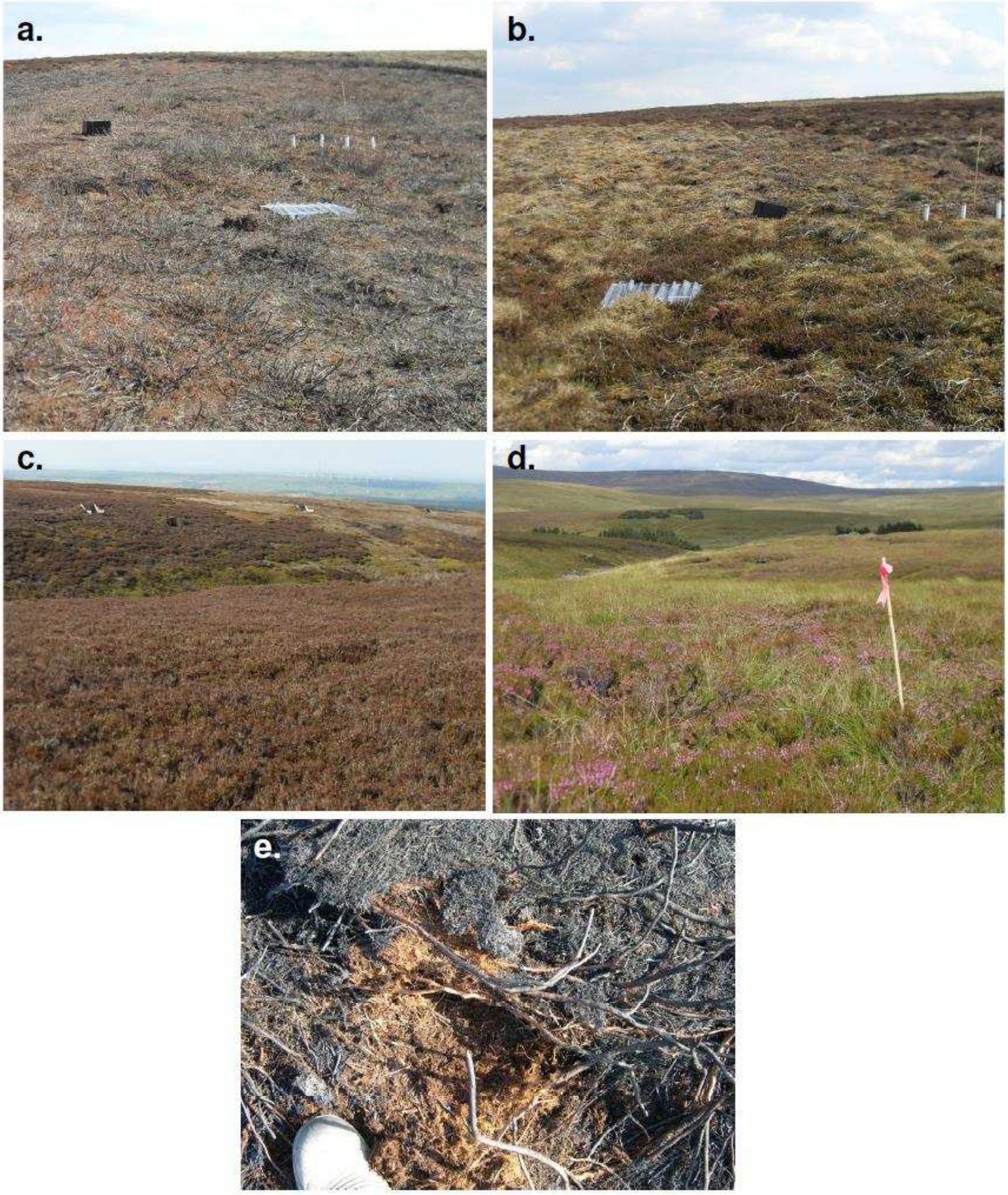
Figure 1. Photographs showing examples of conditions at a) B2, b) B4, c) B15+ (foreground), d) U and e) W.

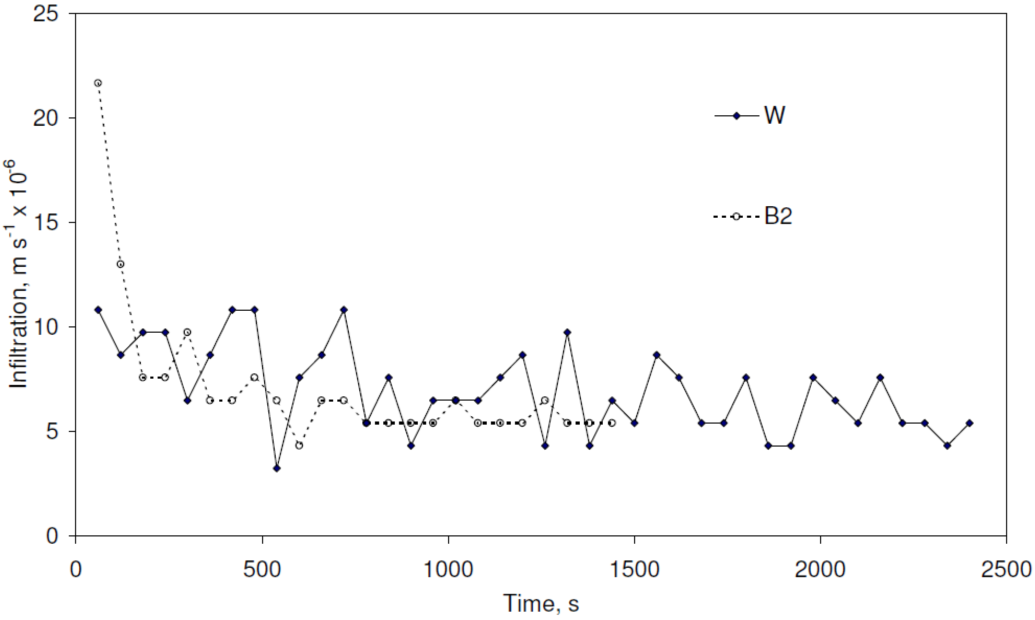
Figure 2. Example infiltration measurements over time for -4.1 cm tension at sample point 6 for B2 and W.

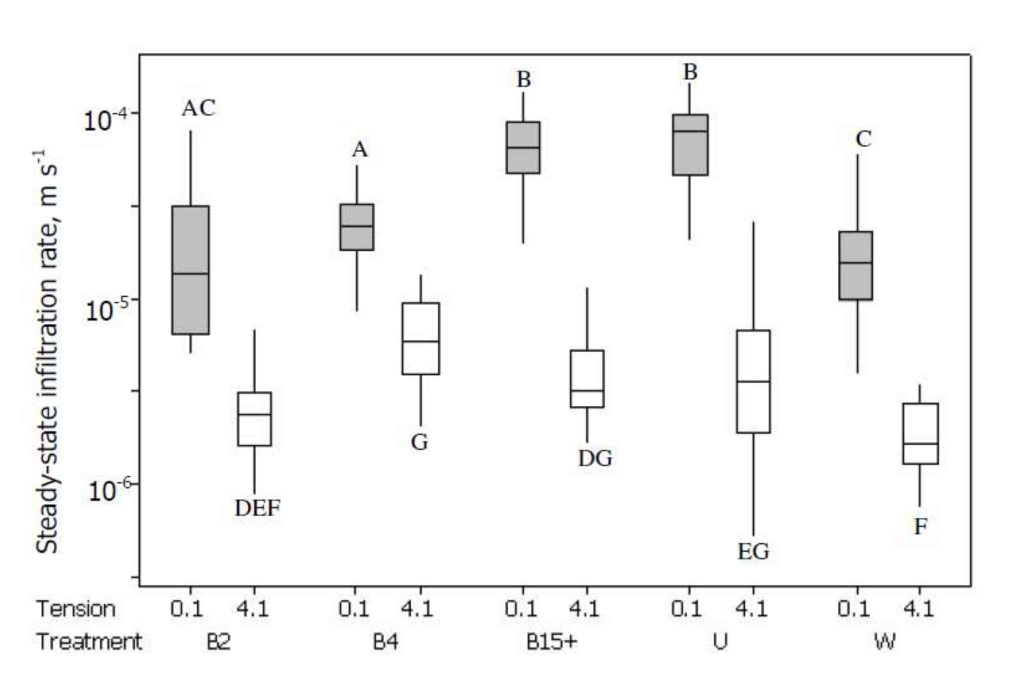
Figure 3. Box and whisker plots showing steady-state infiltration rate for each burn condition and tension. The upper end point of the whiskers indicates Q3 + (1.5 × (Q3-Q1)). The lower end point of the whiskers indicates Q1 – (1.5 × (Q3-Q1)). n for each treatment is given in Table 2. Means with different letters are significantly different.

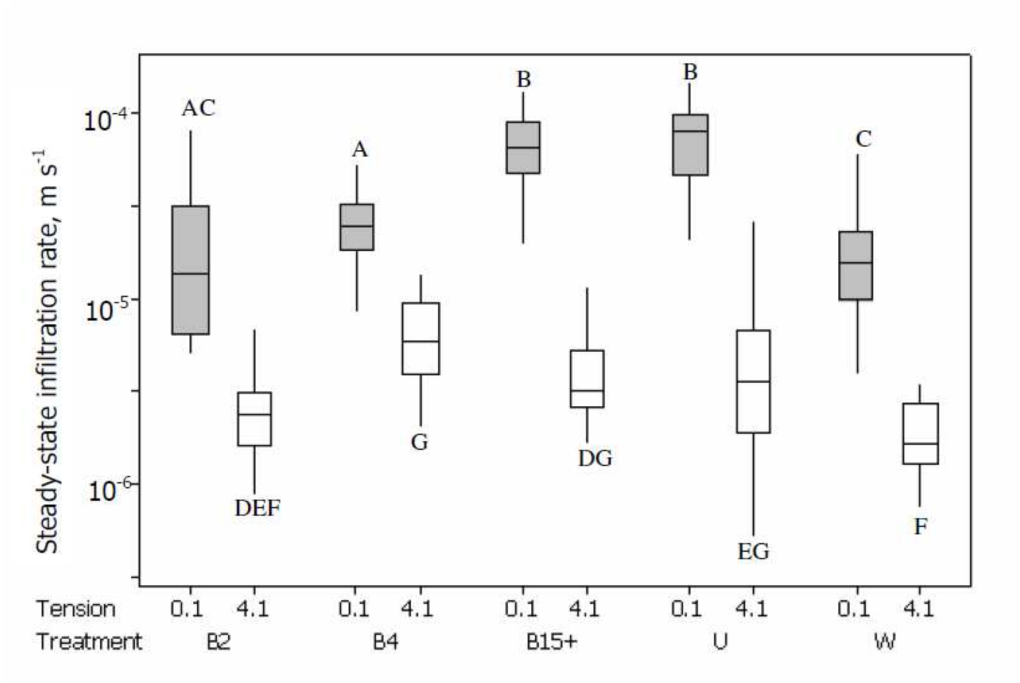
Figure 4. Box and whisker plots showing saturated hydraulic conductivity (K_s) for each burn condition. The upper end point of the whiskers indicates Q3 + (1.5 × (Q3-Q1)). The lower end point of the whiskers indicates Q1 – (1.5 × (Q3-Q1)). n for each treatment is given in Table 2. Means with different letters are significantly different.

Figure 5. Box and whisker plots showing the proportion of flow moving through macropores for each burn condition. The upper end point of the whiskers indicates Q3 + (1.5 × (Q3-Q1)). The lower end point of the whiskers indicates Q1 – (1.5 × (Q3-Q1)). Raw data were used to generate the figure, although data were analysed using an arcsin transformation. n for each treatment is given in Table 2. Means with different letters are significantly different.

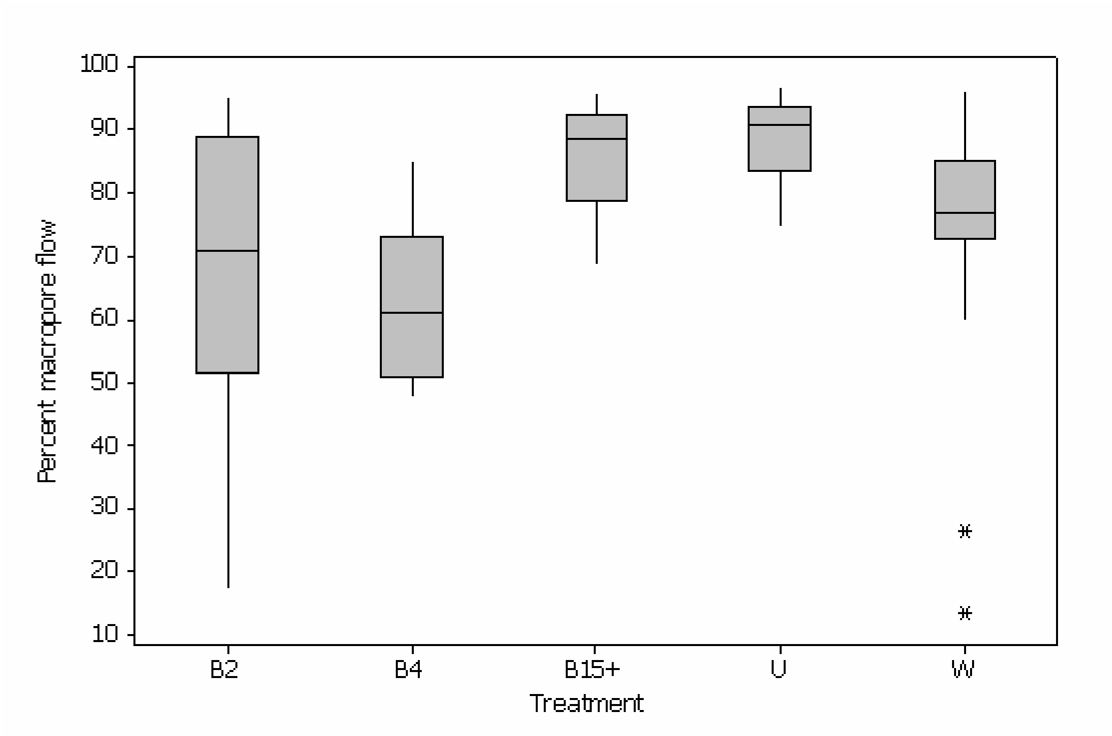

a.
b.
c.
d.
e.


W
B2
Infiltration, m s-1 x 10-6
Time, s
0
5
10
15
20
25
0
500
1000
1500
2000
2500


Steady-state infiltration rate, m s-1
10-4
10-5
10-6
AC
A
B
B
C
DEF
G
DG
EG
F
Tension 0.1 4.1 0.1 4.1 0.1 4.1 0.1 4.1 0.1 4.1
Treatment B2 B4 B15+ U W


Steady-state infiltration rate, m s-1
10-4
10-5
10-6
AC
A
B
B
C
DEF
G
DG
EG
F
Tension 0.1 4.1 0.1 4.1 0.1 4.1 0.1 4.1 0.1 4.1
Treatment B2 B4 B15+ U W

674


Percent macropore flow
100
90
80
70
60
50
40
30
20
10
B2
B4
B15+
U
W
Treatment