AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR016782

Impact of prescribed burning on blanket peat hydrology

Joseph Holden[1], Sheila M. Palmer[1], Kerrylyn Johnston[1,2,3], Catherine Wearing[1,4], Brian Irvine[1], and Lee E. Brown[1]

[1]Water@Leeds, School of Geography, University of Leeds, Leeds, UK, [2]School of Environmental Science, Murdoch University, Murdoch, Western Australia, Australia, [3]Marine and Freshwater Research Laboratory, Murdoch University, Murdoch, Western Australia, Australia, [4]Lancaster Environment Centre, Lancaster University, Lancaster, UK

Abstract Fire is known to impact soil properties and hydrological flow paths. However, the impact of prescribed vegetation burning on blanket peatland hydrology is poorly understood. We studied 10 blanket peat headwater catchments. Five were subject to prescribed burning, while five were unburnt controls. Within the burnt catchments, we studied plots where the last burn occurred $\sim$2 (B2), 4 (B4), 7 (B7), or greater than 10 years (B10+) prior to the start of measurements. These were compared with plots at similar topographic wetness index locations in the control catchments. Plots subject to prescribed vegetation burning had significantly deeper water tables (difference in means = 5.3 cm) and greater water table variability than unburnt plots. Water table depths were significantly different between burn age classes ($B2 > B4 > B7 > B10+$) while B10+ water tables were not significantly different to the unburnt controls. Overland flow was less common on burnt peat than on unburnt peat, recorded in 9% and 17% of all runoff trap visits, respectively. Storm lag times and hydrograph recession limb periods were significantly greater (by $\sim$1 and 13 h on average, respectively) in the burnt catchments overall, but for the largest 20% of storms sampled, there was no significant difference in storm lag times between burnt and unburnt catchments. For the largest 20% of storms, the hydrograph intensity of burnt catchments was significantly greater than those of unburnt catchments (means of 4.2×10^{-5} and $3.4 \times 10^{-5}\ \mathrm{s}^{-1}$, respectively), thereby indicating a nonlinear streamflow response to prescribed burning. Together, these results from plots to whole river catchments indicate that prescribed vegetation burning has important effects on blanket peatland hydrology at a range of spatial scales.

Key Points:
- Prescribed vegetation burning causes deeper water tables in blanket peat
- Time since burn is an important factor influencing water table dynamics
- Peatland river flow response to rainfall is affected by prescribed vegetation burning

Correspondence to:
J. Holden,
j.holden@leeds.ac.uk

Citation:
Holden, J., S. M. Palmer, K. Johnston, C. Wearing, B. Irvine, and L. E. Brown (2015), Impact of prescribed burning on blanket peat hydrology, *Water Resour. Res.*, *51*, 6472–6484, doi:10.1002/2014WR016782.

Received 6 DEC 2014
Accepted 16 JUL 2015
Accepted article online 21 JUL 2015
Published online 21 AUG 2015
Corrected 6 NOV 2015

The copyright line for this article was changed on 11 SEP 2015 after original online publication.
This article was corrected on 6 Nov 2015. See the end of the full text for details.

1. Introduction

Managed burning of vegetation is practiced in a range of environments around the world [*Cawson et al.*, 2012; *Freckleton*, 2004; *Verble and Yanoviak*, 2013; *Yibarbuk et al.*, 2001]. The purpose of such prescribed burning is most commonly either to mitigate wildfire effects, to promote changes in vegetation structure for food production, or to curtail processes of ecosystem succession. However, there have been few integrated studies examining how soils and river systems respond hydrologically to prescribed vegetation burning.

Fire can affect soil properties and surface conditions that may impact evapotranspiration, runoff production, and river flow response to precipitation. Enhanced overland flow production and exacerbated surface erosion have been reported from fire affected forest soils and rangelands, which have often been related to development of hydrophobic crusts [*Martin and Moody*, 2001; *Pierson et al.*, 2008; *Robichaud*, 2000; *Smith and Dragovich*, 2008]. However, *Neris et al.* [2013] found that infiltration capacity was increased in a forest Andisol on the Canary Islands due to the removal, by fire, of a more water-repellent forest floor layer. Decreased evapotranspiration has been reported after fire in many environments [e.g., *Bond-Lamberty et al.*, 2009]. However, effects on soil moisture may vary depending on how the soil structure and its drainage is affected by fire [*Cawson et al.*, 2012] and whether the removal of vegetation increases or decreases local albedo [*Thompson*, 2012]. Thus, there appear to be different hydrological responses to fire depending on soil type, local hydrological processes, and fire severity, necessitating multiscale, multilocation studies.

Peatlands cover around 4.4 million km^2, holding 612 Gt of carbon, equivalent to more than two-thirds of the atmospheric store [*Yu et al.*, 2010]. Hydrological processes operating within peatland environments can have a major influence on the form of the river hydrograph and on river water quality [*Acreman and Holden*, 2013; *Holden and Burt*, 2003c; *Holden et al*., 2007, 2014; *Price*, 1992]. Blanket peat occurs on sloping terrain with poor underlying drainage in wet, cool, typically oceanic areas [*Evans and Warburton*, 2007]. Blanket peatlands often form open, rolling landscapes, dominated by vascular plants and bryophytes such as *Sphagnum* which can sometimes form an understory for shrubs. Normally dominated by saturation-excess overland flow or near-surface throughflow, blanket peatlands have low-saturated hydraulic conductivity throughout most of their depth [*Holden and Burt*, 2003a,b; *Ingram*, 1983; *Price*, 1992]. Shallow water tables that maintain the peat in anoxic conditions suitable for organic matter preservation, coupled with active peat formation in the uppermost layers, mean that infiltration-excess overland flow is far less common than saturation-excess overland flow in undisturbed blanket peatlands [*Holden*, 2009; *Holden and Burt*, 2002].

While it is known that dryness of peat increases the impact of fire [*Benscoter et al*., 2011; *Turetsky et al*., 2011], relatively little is known about fire impacts on peatland hydrology. Wildfire has been shown to result in the development of water-repellent compounds in surface peat [*Clymo*, 1983]. *Thompson and Waddington* [2013] showed, for an ombrotropic forested peatland in northern Alberta, that water table response to rainfall was significantly more variable after wildfire. Specifically, there was a larger fluctuation in unsaturated zone thickness, particularly to smaller rain events. Enhanced surface drying combined with increased bulk density and associated water retention in the near-surface peat made conditions less conducive for *Sphagnum* colonization after the fire. Pore water tensions that place moss under stress were reached more quickly after fire.

Blanket peatlands in the UK uplands are often subject to managed fires which seek to quickly burn the surface vegetation without burning or removing any underlying peat [*Holden et al*., 2012; *Yallop et al*., 2006]. Prescribed fires are performed under calm winter conditions when personnel are present to keep the fire under control. Such managed fires, which try to avoid consumption of the underlying peat, are therefore quite different to wildfires which often burn away the surface peat layers and can smoulder for long periods [*Davies et al*., 2013; *Lukenbach et al*., 2015]. As such the impacts of prescribed vegetation burning on the hydrology of blanket peat is largely unknown and it is not possible to rely on previous fire studies in other types of ecosystem to determine how the hydrological system will respond to such management practices.

Prescribed burning in the UK uplands is mainly carried out to provide a mosaic of young heather shoots and older shrubs, designed to optimize habitat for red grouse (*Lagopus lagopus scotica*) as desired by the rural gun-sports industry. Burning is also used in some areas to regenerate palatable sedges and grasses for sheep and deer, and to aid the prevention of wildfire [*Holden et al*., 2007]. While often thought of as a long-term traditional activity, prescribed patch burning has been practiced in the UK in this way for around 150 years [*Blundell and Holden*, 2014; *Simmons*, 2003]. The burning occurs across the landscape in patches typically of around 20–30 m length and width, with each patch burned once every 8–25 years depending on the shrub vegetation productivity and local custom or agreements with government bodies. Where such rotations occur there will typically be prescribed burning each year across parts of the catchment to maintain a mosaic of newly burnt patches, rejuvenating patches and older, mature vegetation patches. If the burning cycle is 20 years, then it would be expected that approximately 5% of the land cover is burnt each year within the catchment. Unlike wildfires which may occur at larger intervals, repeated peatland vegetation burning on individual patches, at intervals of only a few years, may make it difficult to separate out the impacts of a single fire on the peat [e.g., *Blundell and Holden*, 2014].

The impact of prescribed patch fires on blanket peatland hydrology is poorly understood. A limited amount of work to date has focused on some small experimental plots at Moor House in the English North Pennines that were set up in 1954 and burned on 10 and 20 year cycles [*Rawes and Williams*, 1973]. These investigations suggest that burning (and more regular burning) is associated with shallower water tables than for plots without burning [*Clay et al*., 2009; *Worrall et al*., 2007]. However, these plots may not be typical of managed burns elsewhere given their extremely controlled nature [*Lindsay*, 2010] and the studies, based on monthly spot samples, have been unable to investigate finer temporal-scale water table dynamics. Other studies on burn patches created by land managers in the Peak District of England have compared burning and cutting effects of blanket peat vegetation on water tables. Both management techniques were observed to reduce the mean depth to water table, reduce its variability, and increase overland flow occurrence in comparison with control plots [*Worrall et al*., 2013]. These findings are therefore in direct contrast to the wildfire study from forested northern Alberta peatlands described above which found deeper and more variable water tables after fire [*Thompson*, 2012; *Thompson and Waddington*, 2013]. Using disk infiltrometers, *Holden et al*. [2014] showed that prescribed burning reduced both hydraulic conductivity and macropore flow in prescribed burning plots compared to controls. The effects were stronger for more recently burnt plots (1–4 years after burning) than for plots that had last been burnt 15–25 years earlier. However, further work is required over multiple sites with many more replicate sampling points to convincingly determine whether prescribed vegetation burning does have a very different impact on water table dynamics and flow production compared to the wildfire studies above. For blanket peat that has undergone prescribed burning, there are no studies that have examined both short-term water table responses to rainfall events and longer-term seasonal effects. Such an investigation would be useful to establish whether some of the wildfire water table responses reported by *Thompson and Waddington* [2013] are also applicable to prescribed burning in blanket peatlands.

If there are shallower water tables and there is greater overland flow associated with prescribed burning then it could be hypothesized that river flows in burnt catchments should have a flashier response to rainfall (e.g., shorter lag times to peak flow, greater storm peaks per unit rainfall and larger area-weighted total stormflow) than for unburnt catchments. *Holden et al*. [2008] also showed that flows could be an order of magnitude faster across the peat mass when there was a lack of vegetation cover, potentially contributing to river flow flashiness. However, if there are deeper water tables and consequently less saturation-excess overland flow in burnt catchments, it could be expected that river flows would be less flashy in blanket peatlands subject to prescribed vegetation burning. Thus, it is not clear how river flow response to rainfall should vary between blanket peat catchments that have undergone prescribed vegetation burning and those which have not. There are no previous studies that examine catchment-scale impacts of prescribed vegetation burning on peatland river hydrology. Catchments which have undergone prescribed vegetation burning are only partly burnt in any given year and have patches which are a range of ages since the last burn. Therefore, in order to understand how the system is hydrologically functioning, it is necessary to undertake multiscale, multisite studies. This paper seeks to test three hypotheses, based largely on the implications of the somewhat piecemeal small-scale research on prescribed vegetation burning to date, as described above. If confirmed then these hypotheses would suggest rather different hydrological responses to fire compared with those reported in the peatland wildfire studies described above. However, it is equally plausible that we find responses that are in line with wildfire responses reported for bog peatlands in North America and as such our hypotheses are entirely tentative. The hypotheses are: (i) water table depths are shallower with a smaller variability, while overland flow occurrence is greater, in catchments with prescribed burning than for catchments with unburnt blanket peat; (ii) overland flow occurrence and water table depths and fluctuations are significantly different depending on time since the last burn, and tend toward those of unburnt peat the longer it has been since burning; (iii) river flow in those blanket peat catchments which have prescribed patch vegetation burning is more responsive to rainfall events, with flashier river regimes compared to unburnt catchments.

2. Methods

Ten catchments were selected for study (Table 1), five with prescribed burning and five unburnt controls. None of the 10 catchments had other major management interventions such as artificial ditch drainage or forestry, but all were subject to very light sheep grazing ($<$0.5 sheep ha^{-1}, often with no sheep in winter months). The unburnt catchments had no history of wildfire or prescribed burning for at least 30 years and generally longer (e.g., $>$70 years for Trout Beck). The burnt catchments were subject to prescribed patch vegetation burning and therefore we would not expect significant consumption of the peat by fire. Such fires tend to only last for a few minutes on each patch. It is not possible, therefore, to determine differences in the historical fire intensity for each burn that has occurred on each patch over the last few decades.

The catchments were all dominated by deep blanket peat, typically over 1 m in depth. At all 10 catchments, 12 soil plots were selected of approximately 400 m^2. In the burned sites, plots with different ages since burning were identified following discussions with local land managers. The burn ages spanned the normal cycle for each site and were $<$2 years since burning (B2), approximately 4 years since burning (B4), approximately 7 years since burning (B7), and $>$10 years since burning (B10+). Three replicates of each age class were chosen, with one each located in top, middle, and foot slope positions. The plots were chosen based

Table 1. Details of the 10 Study Catchments

Name	Unburnt/ Burnt	WGS84 Lat/Long	Altitude (m)	Area (km^2)	National Vegetation Classification Code [*Rodwell*, 1991] and Main Vegetation Cover
Oakner Clough	Unburnt	53°36′11.1″N; 1°58′03.4″W	240–451	1.2	M20b *Eriophorum* spp., *Molinia*
Trout Beck	Unburnt	54°40′59.6″N; 2°24′46.0″W	595–794	2.8	M19b *Calluna, Eriophorum vaginatum, Hypnum jutlandicum, Plagiothecium undulatum, Pleurozium schreberi, Rhytidiadelphus loreus*
Green Burn	Unburnt	54°40′40.0″N; 2°21′43.9″W	548–734	0.7	M19b *Empetrum nigrum, Eriophorum vaginatum, Hypnum jutlandicum, Plagiothecium undulatum, Pleurozium schreberi, Rhytidiadelphus loreus, Sphagnum capilifolium*
Moss Burn	Unburnt	54°41′19.7″N; 2°23′01.7″W	560–768	1.4	M19b *Calluna, Empetrum nigrum, Eriophorum vaginatum, Hypnum jutlandicum, Pleurozium schreberi, Sphagnum capillifolium*
Crowden Little Brook	Unburnt	53°30′51.7″N; 1°53′29.7″W	355–582	3.1	M20b *Vaccinium myrtillus, Empetrum nigrum, Eriophorum spp.,* Deschampsia flexuosa,
Bull Clough	Burnt	53°28′24.8″N; 1°42′46.2″W	455–541	0.7	H9b *Calluna, Eriophorum* spp., *Rubus chamaemorus, Vaccinium myrtillus*
Rising Clough	Burnt	53°23′38.4″N; 1°40′25.0″W	344–487	1.8	H9b *Calluna, Eriophorum* spp., Campylopus introflexus
Great Eggleshope Beck	Burnt	54°40′59.6″N; 2°04′11.9″W	480–653	1.6	M19a *Calluna, Eriophorum spp., Campylopus, Hypnum jutlandicum, Vaccinium myrtillus, Sphagnum capillifolium*
Lodgegill Sike	Burnt	54°40′35.5″N; 2°04′04.1″W	515–608	1.2	M19a *Calluna, Hypnum jutlandicum, Polytrichum commune*
Woo Gill	Burnt	54°12′06.1″N; 1°53′26.3″W	430–546	1.0	M19a *Calluna, Eriophorum* spp., *Campylopus, Hypnum jutlandicum, Vaccinium myrtillus*

on an analysis of the topographic wetness index [*Beven and Kirkby*, 1979] with approximately the same topographic index value chosen for each slope position category across the 10 catchments. At unburned sites (U), 12 patches were selected randomly with four replicates per slope position (with reference to the topographic index).

The vegetation cover in each plot was surveyed using quadrats. Sedges and grasses provided less cover on burnt plots than unburnt controls. Conversely, dwarf shrubs provided greater cover on burnt plots and had significantly greater cover on B7 plots than for other burn ages or the controls. *Sphagnum capillifolium* was greater in total percentage cover at unburnt sites than burnt ones while other *Sphagnum* species occurred in less than 15% of plots and at low abundance.

Each soil plot ($n = 10 \times 12$) had a dipwell installed at approximately its center for measurements of water table depth at approximately 3 weekly intervals. In one burned catchment (Bull Clough) and one unburned catchment (Oakner Clough), all of the plots were instrumented with a dipwell containing a Trafag DL/N 70 pressure transducer (Trafag (UK) Ltd, Basildon, Essex) providing automatic water table depth recordings logged at 15 min intervals. Unfortunately, four of the 24 loggers failed at some point during the study and those records were excluded from analysis (two footslope plots at Oakner Clough, the B7 topslope logger, and the B2 midslope logger at Bull Clough). However, these points were still sampled for water table depth as part of the manual 3 weekly assessments and included in that analysis.

Overland flow occurrence was measured at Oakner Clough and Bull Clough using 10 crest-stage tubes (as described in *Holden and Burt* [2003c]) per plot arranged in a 2×5 grid, 1 m apart ($n = 240$). These were sampled on each visit to assess whether overland flow had occurred or not around each tube between visits.

At Bull Clough, B2, B4, and B7 plots were identified but, because of changes to land ownership, the local land manager could only clearly identify B10+ plots that had been burnt more than 15 years prior to sampling (B15+). Thus, when analyzing data across all 10 sites, we coded these plots as B10+ plots for consistency, but when the Bull Clough plots were being directly examined and compared to those at Oakner Clough then we coded the oldest burn plots as B15+ plots. In addition, a wildfire took place at Oakner Clough on 9 April 2011 and so we do not conduct comparisons on the automated dipwell records or overland flow beyond that date as our focus here is on prescribed burning effects on peat hydrology.

Rainfall was recorded using automated tipping bucket rain gauges located in each catchment logged using Gemini Tiny Tag TGPR-1201 event recorders (Gemini Data Loggers, Chichester, UK). River-gauging stations were installed on second-order streams draining each headwater catchment. Stage was measured using Druck PDCR 1830 pressure transducers interfaced with Campbell CR1000 data loggers scanning at 5 s intervals and recording 15 min averages. In this study, we use a 20 month period from March 2010 to November 2011 when data were available from all sites (although we exclude data from April 2011 onward from Oakner Clough due to the wildfire event). Stage-discharge rating curves were developed for each stream but for three of the streams, Crowden Little Brook, Lodgegill Sike, and Great Eggleshope Beck, the rating curves had low r^2 values. Hence we do not report discharge statistics for those three streams, although we do analyze some storm response variables for those catchments using the stage record as described below. For each catchment, 25 storms were sampled randomly across the full range of rainfall event sizes, avoiding times of snowfall or snowmelt. Values of rainfall length (*rainlength*), total rainfall (*totrain*), and maximum rainfall intensity in 15 min (*max15*) were extracted from the rainfall record for each storm sampled in each catchment. As different rainfall events were sampled for each catchment, the three rainfall characteristics were each tested for differences between the storms sampled in the burnt and unburnt catchments using two-sample t tests and no significant differences were found ($p > 0.05$). Corresponding hydrograph values were extracted including: time from first rain to peak flow (*tpeak*), lag time between peak rain and peak flow (*lag*), total rainfall before first rise in river flow occurs (*rainrise*), total rainfall before a steep rise in the hydrograph occurs [*Evans et al*., 1999] (*steeprise*), and recession time from peak flow to the return to prestorm level (*recession*). For the seven catchments with reliable discharge records, the peak discharge, total storm discharge (*stormQ*), the rainfall-runoff coefficient (*ratio*), and the hydrograph intensity (*HI*) (peak flow divided by total stormflow) were also extracted for each storm.

To help interpret water table and streamflow data, a soil core was extracted from each of the 12 plots in each of the 10 catchments ($n = 120$) during the summer of 2010 for measurement of soil physical properties. Each core was sectioned into 5 cm depth increments with determinations undertaken of bulk density, organic matter content, and humification on the Von Post scale [*Von Post*, 1922].

Data were analyzed in Minitab 15.1.20. Manual water table data were pooled and compared between all burnt and unburnt catchments to provide an initial overall comparison using a Student's t test. Water table data were tested for effects of burn age, slope position, and sample date using a mixed effects general linear model, with sample date as a random factor and burn age and slope position as fixed factors. Pairwise differences were then calculated using Tukey's method between either burn age or slope position categories. The proportion of crest-stage tubes indicating overland-flow occurrence between visits at each of Oakner Clough and Bull Clough as a whole was determined. These values were tested for correlation with maximum daily rain between visits using Spearman's rank. The tests were repeated at Bull Clough for data grouped by burn age class. For storm hydrograph analysis, data within burnt catchments were pooled and likewise for unburnt catchments, enabling comparison of 125 storm responses for each category. Each storm response variable was then compared for differences between the burnt and unburnt categories using Student's t tests. Storm response variables were also tested for correlation with each other by catchment and any significant correlations between rainfall and river flow variables were reported. Significant correlations between rainfall variables alone, or between river flow variables alone, were not reported as these are to be expected.

3. Results

3.1. Water Tables

Water tables were significantly deeper for burnt catchments (mean = 20.5 cm) than for unburnt catchments (mean = 15.2 cm) (pooled data, $t = -7.8$, $p < 0.001$). Time since burning ($F = 57.8$, $p < 0.001$), sample date ($F = 15.7$, $p < 0.001$), and slope position ($F = 4.3$, $p = 0.014$) were all significant factors in determining water table depth. As would be expected, plots with the shortest upslope drainage-length (topslope zones) tended to have deeper water tables than plots with greater contributing areas (footslope zones). In the burnt catchments, however, the more dominant effect was due to burn age. The most recently burnt plots had significantly deeper water table depths (B2 > B4 > B7 > B10+ = U) and greatest water table depth variability over time (Figure 1).

The effect of burn age on water table depths was found to be very stark within some catchments. A time series example is shown in Figure 2 for midslope plots in the Rising Clough catchment. Water table depths were deepest for the entire study period (based on ~3 weekly sampling) for the most recent burnt patches

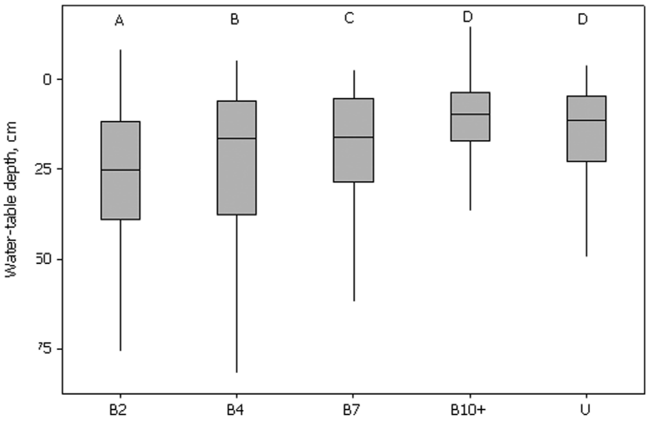

Figure 1. Water table depth measured across all study sites and plots. Data for plots subject to burning 2, 4, 7, and >10 years prior to measurement are shown on the left side of the figure while data for unburnt peat (U) is shown on the right for comparison. Letters A–D refer to data sets shown to be significantly different to each other.

with water table depths between 40 and 60 cm for most of the time, while water tables were within the upper 20 cm of the peat for the whole sampling period for the B10+ plot.

Summary data from the 15 min water table records at Oakner Clough (unburnt) and Bull Clough (burnt) are provided in Table 2. These data suggest that the stark differences related to burn age at Rising Clough were not as clear at Bull Clough. There was a large variability in median water table depth between replicated automated dipwell measuring points within both the unburnt control and for Bull Clough, demonstrating the need for multisite, multiplot studies. However, of the 20 complete automated water table records, two of the four deepest median water table depths were for B2 plots, while all four of the deepest medians occurred at sites where burning had taken place within 7 years of measurement. Six of the seven largest interquartile ranges for water table depth occurred on the burnt catchment. Water table depth residence-curves for topslope plots, provided as an example (Figure 3), are very similar in shape for dipwells across Oakner Clough (unburnt). However, these curves are quite different to the shape of the curves for the B2 and B4 plots at Bull Clough. The B2 curve shows a deep water table depth but a gentle slope characterizing little variability. The B4 curve is very steep but its upper 70% lies in a similar zone to that of the unburnt plots at Oakner Clough while its lower 30% is steeply sloped and rather deep. The B15+ plot had a similar curve to those for Oakner Clough.

3.2. Overland Flow Occurrence

Overland flow tended to occur more frequently at Oakner Clough than at the burnt Bull Clough site (Figure 4). At Oakner Clough, there was a significant correlation between the maximum daily rainfall between sampling visits and the proportion of tubes that recorded overland flow occurrence ($r = 0.79$, $p = 0.004$). At Bull Clough, there was also a significant correlation between maximum daily rainfall between visits and overland flow occurrence for B15+ plots ($r = 0.46$, $p = 0.04$). However, there was no significant correlation when the whole data set for the Bull Clough catchment was considered, nor for B2, B4, or B7 plots on their own.

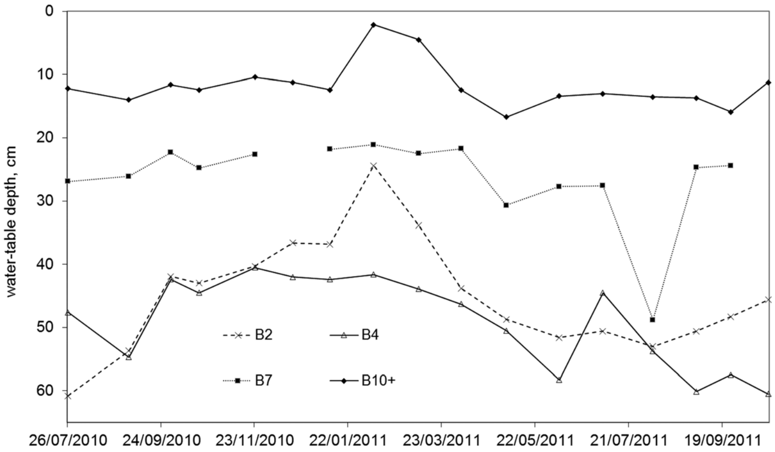

Figure 2. Rising Clough water table record for midslope burnt patches.

Table 2. Summary Water Table Depth Statistics From the Automated Dipwells on Oakner Clough and Bull Clough Catchments

Plot	Minimum (cm)	Maximum (cm)	Median (cm)	Interquartile range (cm)
Oakner Clough (Unburnt)				
Top A	33.3	2.4	21.4	5.4
Mid A	47.6	3.4	28.0	5.0
Foot A	23.0	7.2	20.1	1.2
Top B	57.7	2.7	29.2	3.7
Mid B	47.8	4.2	34.0	12.4
Top C	40.3	9.0	30.6	6.8
Mid C	57.8	9.7	30.5	7.3
Foot C	30.3	8.5	24.2	8.6
Top D	28.8	0.9	13.8	5.2
Mid D	69.0	14.5	31.7	7.7
Bull Clough (Burnt)				
Top B15+	31.8	2.0	18.0	9.0
Mid B15+	13.1	−1.1	5.7	3.7
Foot B15+	29.9	2.1	9.9	10.2
Mid B7	50.6	6.6	39.4	22.6
Foot B7	66.1	19.1	36.4	10.3
Top B4	70.7	1.0	18.6	11.5
Mid B4	21.2	6.6	16.1	8.4
Foot B4	19.5	−6.1	8.5	12.1
Top B2	41.8	32.7	38.8	1.9
Foot B2	42.1	24.1	35.8	5.5

3.3. River Flow

The rivers in each catchment were very flashy with little base flow as indicated by the steep flow-duration curves (Figure 5). There were no characteristics of the flow-duration curves that were unique to either burnt or unburnt catchments. However, the lag time from peak-rainfall to peak-discharge across all storms was significantly greater for burnt catchments ($t = 2.2$, $p = 0.032$) while the recession time for storm hydrographs was significantly longer for burnt catchments than for unburnt catchments ($t = 2.5$, $p = 0.017$) (Table 3). There were no significant differences between burnt and unburnt catchments for hydrograph-intensity or storm-runoff ratio. However, when only the largest 20% of storms from each catchment were considered, then the burnt catchments had significantly greater hydrograph intensity ($t = 2.1$, $p = 0.04$). There were no significant differences in peak lag times between burnt and unburnt catchments for these largest storms. Overall, correlations between river flow variables and *max15* were more common in burnt catchments than unburnt catchments (Table 4) as were correlations between steeprain and river flow variables.

3.4. Peat Physical Properties

The mean bulk density of the near-surface peat of the burnt catchments was greater than that of the unburnt catchments when all plots were pooled (Table 5). This was true for all four depth ranges across the upper 20 cm. Similarly, the organic matter content (% loss on ignition) of the peat was greater for the unburnt peat in the upper peat layers than for the peat subject to prescribed burning. The time since the last burn did not seem to have a clear effect on bulk density or organic matter content of the peat. The peat in the unburnt catchments tended to be more humified in the upper 10 cm compared to the near-surface peat in the burnt catchments (Table 5). For 10–15 and 15–20 cm depth ranges, the median humification index was the same between burnt and unburnt catchments.

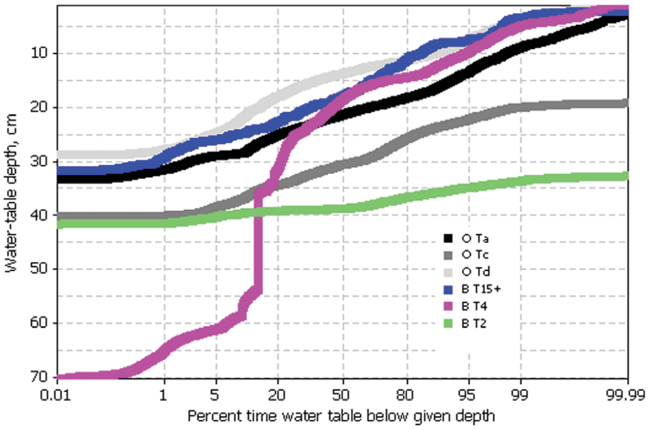

Figure 3. Water table depth residence curves for topslope plots at comparison locations (a, c, and d) for Oakner Clough (unburnt; O) and Bull Clough (burnt; B).

4. Discussion and Conclusions

Our first hypotheses suggested there would be shallower water tables in prescribed burning catchments than unburnt catchments with less variability in water tables, while our second hypotheses suggested this would vary by burn age. However, we found, for the first time, that water tables were deeper in catchments that had undergone prescribed patch vegetation burning and in locations where burning was more recent. There was also greater water table variability in more recently burnt areas with larger

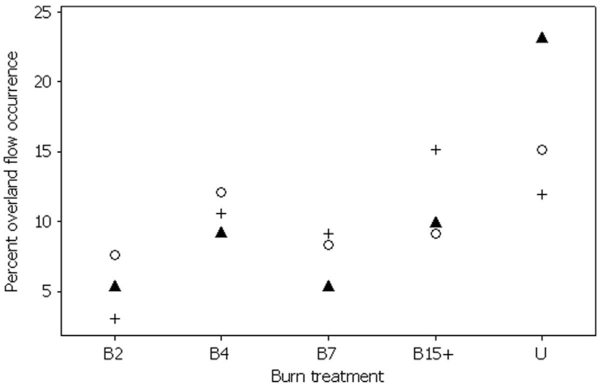

Figure 4. Percent of samples indicating that overland flow had occurred at Bull Clough (B2-B15+, burnt) and Oakner Clough (U, unburnt). Hundred percentage would indicate that all 10 sampling tubes on a plot were full on every site visit. Triangles indicate topslope value, crosses are midslope, and circles are footslope values.

fluctuations across a deeper and periodically unsaturated layer. Hence the differences in water table dynamics influenced by managed burning may also affect nutrient and carbon cycling in peatland systems. Our water table findings are supported by observations of wildfire impacts on water tables in bog peatlands in North America [*Thompson and Waddington*, 2013]. Similar disturbance effects on water table depth and variability were also identified by *Holden et al.* [2011] for blanket peat sites disturbed by drainage. However, our findings contradict those from *Worrall et al.* [2013], although they only had one control plot to which they compared four burn plots. We found considerable difference in automated water table depth and fluctuation data sets from plot to plot in one catchment even when sample points were controlled for topographic position (e.g., Table 2), showing that larger-scale multiplot, multicatchment studies such as ours may yield different results to smaller-scale studies with a limited number of controls.

We would expect water tables to be deeper after disturbance from fire because the plots would be subject to warmer surface temperatures in the years immediately following the burn, thereby enhancing evaporation. *Brown et al.* [2015] found for our study sites that near-surface soil temperatures for B2 and B4 plots had higher means, maxima and lower minima than plots with more established vegetation (B7, B15+). Temperature effects of vegetation removal could be observed to at least 50 cm depth, but were stronger nearer the surface. Statistical models were developed by *Brown et al.* [2015] to predict daily mean and maximum soil temperature in B15+ plots and then applied to predict temperatures of B2, B4, and B7 plots. Temperatures measured in B2 plots showed significant statistical disturbances from model predictions, reaching +6.2°C for daily mean temperatures and +19.6°C for daily maxima. Soil temperatures in B7 plots were most similar to those from B15+ plots indicating the potential for soil temperatures to recover as vegetation regrows. *Kettridge et al.* [2012] showed that sites subject to wildfire vegetation loss could have much greater surface peat temperatures and near-surface evaporative loss in the years following the fire which may slow the ability of the peatland to recover from fire. *Kettridge et al.* [2014] further suggested, based on water repellency tests, that *Sphagnum* peatlands would be subject to deep water tables after fire (as there was limited water repellency effect) unlike feather moss peat where severe water repellency observed after fire would restrict the upward supply of water to the peat surface, thereby restricting evaporation. While the removal of vegetation by fire might suggest that evapotranspiration should decline, *Ward et al.* [2012] observed a net increase in CO_2 uptake after prescribed burning, indirectly suggesting that plant transpiration effects due to new growth after fire could limit the decline in evapotranspiration that otherwise would be expected.

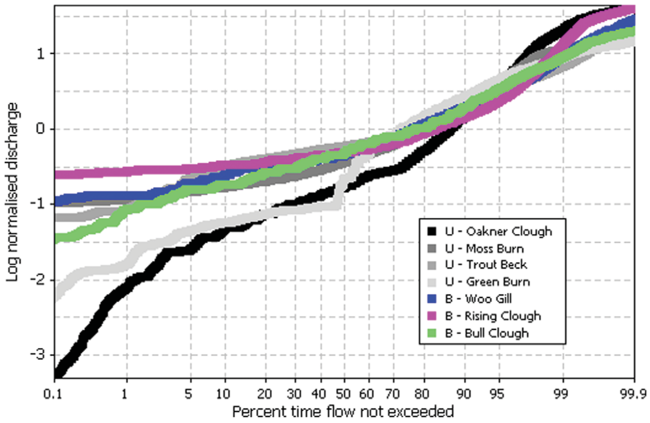

Figure 5. Flow duration curves for the study catchments (normalized using the mean discharge for each catchment). U indicates unburnt catchment. B indicates burnt catchment.

The compression of the peat that we observed associated with more recent burning is likely to be related to the enhanced warming and drying of

Table 3. Mean Characteristics of Hydrograph Response (15 min Resolution Data) for All Catchments Based on 25 Storms Per Catchment

Catchment	Time From Start of Rain to Peak Flow (h)	Time From Peak Rain to Peak Flow (h)	Rainfall Before Rise in Stage (mm)	Rainfall Before Steep Rise in Hydrograph (mm)	Recession Time (h)	Hydrograph Intensity $\times 10^{-5}$	Storm Runoff Ratio
Unburned							
Oakner Clough	8.0	3.3	0.9	4.0	33.6	3.6	0.66
Trout Beck	7.6	2.7	0.8	3.6	34.0	2.5	0.59
Green Burn	9.4	3.0	0.7	4.4	38.6	2.8	0.43
Moss Burn	10.3	3.7	1.8	5.0	33.8	2.8	0.56
Crowden Little Brook	11.6	3.9	1.0	3.8	40.1		
Burned							
Bull Clough	6.7	3.0	1.2	3.5	46.3	4.5	0.44
Rising Clough	8.2	4.3	1.3	4.1	44.6	3.9	0.35
Great Eggleshope Beck	12.2	6.3	0.6	3.6	50.3		
Lodgegill Sike	7.7	2.7	0.7	3.9	47.8		
Woo Gill	16.3	5.8	1.0	6.7	57.0	2.9	0.60

near-surface peat. The compression may also be linked to changes in water table behavior on burnt sites. With greater compression, any increase in water table depth that occurs for a given unit volume of evaporation would be greater than that for unburnt peat, because the soil pore space volume would be smaller. Our data suggest that over time since prescribed fire, as vegetation regenerates, the surface peat compression reduces. This is likely to be because litter from recovering vegetation and new root growth results in peat formation and enhanced pore space within the peat. The cooler peat surface will also enable the peat to retain more moisture on warm days, resulting in less peat compaction. The compression of near-surface peat in burnt catchments has been found to be associated with significantly reduced saturated hydraulic conductivity and reduced macropore flow for the burnt plots compared to unburnt peat at our study sites [*Holden et al*., 2014]. However, these effects have also been found to be greater for plots most recently burnt and to become insignificant for plots that had not been burnt for 15 years or more, thereby providing further evidence of temporal recovery of peat system processes after prescribed fire.

The above combined processes of warmer temperatures, enhanced evaporation, and peat compression would explain our findings of deeper water tables in burnt catchments. As vegetation develops in the years

Table 4. Significant Correlations (Pearson), at $p < 0.05$, Between Rainfall Variables and Hydrograph Response Variables for All Catchments[a]

Catchment	Significant Correlations
Unburnt	
Oakner Clough	tpeak & rainlength; peak Q & max15; peakQ & totrain; stormQ & max15; stormQ & totrain; ratio & totrain;
Trout Beck	tpeak & rainlength; tpeak & totrain; peakQ & rainlength; peak Q and totrain; stormQ and totrain; stormQ and rainlength; HI & max15; recession & riserain; ratio & stormQ
Green Burn	tpeak & rainlength; tpeak & totrain; riserain & max15; recession & rainlength; recession & totrain; peakQ & rainlength; peak Q and totrain; ratio & totrain; ratio & rainlength; stormQ & tpeak; ratio & tpeak; peak Q and recession; ratio & peakQ; ratio & stormQ
Moss Burn	tpeak & rainlength; tpeak & totrain; peakQ & rainlength; peakQ & totrain; stormQ & rainlength; stormQ & totrain; ratio & totrain; recession & totrain; peakQ & max15;
Crowden Little Brook[b]	tpeak & rainlength; recession & rainlength; steeprain & totrain; recession & tpeak; *recession & totrain*
Burnt	
Bull Clough	tpeak & max15; *lag & max15*; recession & max15; peak Q & totrain; stormQ & rainlength; stormQ & totrain; HI & max15; riserain & tpeak; steeprain & riserain;
Rising Clough	tpeak & rainlength; peak Q & totrain; stormQ and rainlength; stormQ & totrain; ratio & rainlength; ratio & totrain; recession & rainlength; recession & max15; HI & steeprain;
Great Eggleshope Beck[b]	tpeak & totrain; lag & rainlength; recession & rainlength; recession & totrain; steeprain & tpeak; recession and max15
Lodgegill Sike[b]	tpeak & rainlength; tpeak & totrain; recession & totrain; recession & rainlength;
Woo Gill	tpeak & rainlength; lag & max15; peakQ & totrain; stormQ & totrain; *HI & tpeak*;

[a] Italics indicate negative correlation, underlined correlations are significant at $p < 0.01$. n = 25 storms per catchment. Correlations between only rainfall variables or between only hydrograph variables alone are not shown.

[b] Note three discharge characteristics (peak flow, hydrograph intensity, and storm runoff ratio) were not included for three of the catchments which had unreliable ratings curves at their higher end.

Table 5. Means and Standard Deviations (in Parentheses) of Bulk Density and Loss on Ignition (LOI) and Median (With Minimum and Maximum in Parentheses) Humification Indices for the Upper 20 cm of Peat in Burnt and Unburnt Sites

	B2	B4	B7	B10+	Burnt Overall	Unburnt Overall
0–5 cm						
Bulk density	0.156	0.146	0.154	0.164	0.154	0.124
(g cm^{-3})	(0.07)	(0.04)	(0.09)	(0.15)	(0.09)	(0.05)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 60
% LOI	89.7	87.4	88.3	88.4	88.7	94.3
	(12)	(14)	(16)	(14)	(14)	(3.8)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 60
Humification	4	4	3	3	4	6
(von Post scale)	(2,9)	(2,7)	(2,8)	(2,7)	(2,9)	(2,9)
	n = 14	n = 14	n = 13	n = 15	n = 56	n = 59
5–10 cm						
Bulk density (g cm^{-3})	0.177	0.166	0.171	0.196	0.177	0.153
	(0.13)	(0.09)	(0.11)	(0.20)	(0.13)	(0.11)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 60
% LOI	86.6	83.2	89.4	87.0	87.0	95.2
	(22)	(23)	(19)	(19)	(20)	(3.1)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 59
Humification	6	6	7	5	6	7
(von Post scale)	(3,9)	(3,8)	(3,8)	(2,9)	(2,9)	(3,9)
	n = 13	n = 12	n = 13	n = 14	n = 52	n = 58
10–15 cm						
Bulk density (g cm^{-3})	0.188	0.156	0.168	0.179	0.170	0.137
	(0.21)	(0.07)	(0.10)	(0.22)	(0.16)	(0.07)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 60
% LOI	88.9	89.5	90.5	88.9	89.8	95.6
	(22)	(16)	(20)	(20)	(19)	(7.0)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 59
Humification	8	6.5	8	7	7	7
(von Post scale)	(4,9)	(2,9)	(3,9)	(4,9)	(2,9)	(4,10)
	n = 14	n = 14	n = 14	n = 14	n = 56	n = 58
15–20 cm						
Bulk density	0.221	0.141	0.172	0.137	0.165	0.133
(g cm^{-3})	(0.29)	(0.07)	(0.13)	(0.07)	(0.16)	(0.07)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 60
% LOI	89.0	88.3	91.2	90.1	90.1	96.1
	(25)	(18)	(21)	(16)	(19)	(7.0)
	n = 15	n = 15	n = 15	n = 15	n = 60	n = 60
Humification	8.5	7	8	6	7	7
(von Post scale)	(5,10)	(3,9)	(5,9)	(3,10)	(3,10)	(3,10)
	n = 14	n = 13	n = 14	n = 14	n = 55	n = 58

after fire, these effects become weaker and so water tables of individual plots can recover over time since the last burn. Our space-for-time plot approach within burnt catchments suggests that water table dynamics recover on the order of a decade toward those observed in unburnt catchments. These apparent "slow recovery" trajectories suggest that if burning activity is stopped in a catchment, then over time, hydrological processes may return to conditions that are more typical of unburnt peatlands, as long as the site is not too degraded by other management activity.

Plots that were burnt more recently were subject to less frequent overland flow occurrence than unburnt plots in the Oakner Clough catchment or B15+ plots in the Bull Clough catchment. This is despite the smaller proportion of macropore flow and smaller near-surface hydraulic conductivity in the more recently burnt peat compared with B15+ plots or unburnt peat determined by *Holden et al*. [2014]. The reduction of overland flow occurrence on more recently burnt peat is likely to be strongly related to increased water table depths and therefore a reduction in saturation-excess overland flow [*Holden and Burt*, 2003c]. However, smaller near-surface hydraulic conductivity linked to drying and compaction of the peat associated with prescribed burning (Table 5) is likely to affect flow production on burnt peat when water tables do move close to the surface during more prolonged and heavier rainfall events. The greater near-surface peat bulk density that was associated with burning is also likely to make *Sphagnum* reestablishment after fire more difficult [*Price and Whitehead*, 2001].

There were high storm runoff coefficients from the study catchments but this is in line with those from previous studies on blanket peatlands [*Holden*, 2006]. The storm analysis from the 10 study catchments suggested there was a slight buffering impact on river flow storm response caused by deeper water tables in burnt catchments. The result of deeper water tables is a delay in the time to saturation of the peat and therefore a reduction of saturation-excess overland flow. These changes would slow delivery of water to the stream system, with a greater proportion of flow occurring at depth rather than at the peat surface. Therefore, we observed longer lag times for burnt catchments than for unburnt catchments where peat would be more readily saturated leading to rapid generation of saturation-excess overland flow [*Holden*, 2005]. However, storm analysis also suggested that this buffering in catchments that have undergone prescribed

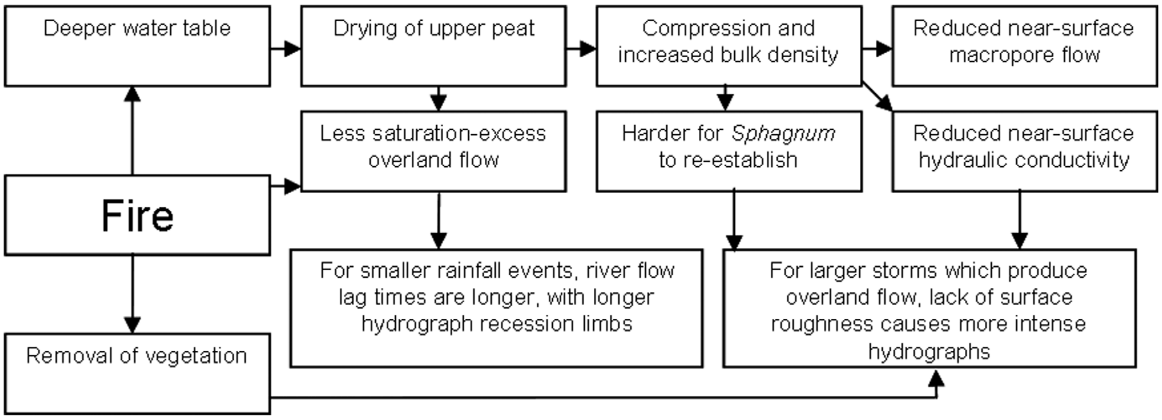

Figure 6. Conceptual diagram showing how prescribed vegetation burning impacts hydrological processes operating within blanket peat catchments.

vegetation burning was ineffective for the highest magnitude rainfall events where the flow peaks were instead exacerbated by burning with more intense (spikier) hydrographs, despite longer hydrograph recession limbs for burnt catchments overall. These novel findings therefore have direct relevance to catchment managers and policy makers who are keen to reduce downstream flood risks from upland peat systems [*Acreman and Holden*, 2013]. The longer hydrograph recession periods are likely to be a function of the deeper water table drawdown in the burnt catchments compared to the unburnt systems. During the wettest events, when overland flow is more widespread, velocities of water across the peat surface are important for driving hydrograph flow peaks in peat catchments [*Ballard et al*., 2011; *Gao et al*., 2015; *Lane and Milledge*, 2012]. *Holden et al*. [2008] showed that measured flow velocities were generally an order of magnitude greater on bare peat compared to *Sphagnum* covered peat. *Sphagnum* cover was significantly lower on burnt plots compared to unburnt ones at our study sites. Thus, the loss of a dense and rough understory due to prescribed burning may result in enhanced flow velocities over the peat surface during the wettest events. This overland flow—roughness interaction process may explain why in the wettest events, peak flows were greater in the burnt catchments compared to the unburnt catchments.

A conceptual diagram that summarizes the above process-based discussion and highlights the potential key impacts of prescribed burning on blanket peat hydrology is shown in Figure 6. In terms of our third hypothesis, we have provided evidence that some river flow variables in blanket peat catchments which have undergone prescribed patch burning do behave differently to those in unburnt catchments. However, we expected that burnt catchments would be more responsive to rainfall events and produce flashier river regimes. Our novel findings indicate that there is, instead, a nonlinear response as indicated by Figure 6. Such a nonlinear response has not been reported previously in fire studies in other environments. For smaller rainfall events, the deeper water table associated with more recent prescribed burning (caused by enhanced warming and evaporation), resulted in less frequent overland flow occurrence, longer streamflow lag times, and longer hydrograph recession limbs. However, for larger rainfall events where peat saturation is more widespread, then river flow hydrographs were more intense and peaky in the burnt catchments compared to the unburnt ones. Based on the recent literature, prime processes responsible for this effect would be the removal of the rough understorey of dense vegetation such as *Sphagnum capillifolium* and the compaction of the upper peat, which reduces flow moving laterally through the near-surface zone in favor of overland flow. We would expect these effects to have a larger impact on river flow as the proportion of the catchment that has undergone more recent burning increases (i.e., the shorter the prescribed burn rotation interval). This could be tested in future projects by examining catchments with different prescribed burn frequencies.

Together, the above results indicate that prescribed vegetation burning has important effects on blanket peatland hydrology at both the plot and headwater catchment scale. Combined with other environmental impacts of prescribed vegetation burning on blanket peatlands that have been determined in recent years, such as those on stream water quality and ecology [*Brown et al*., 2013; *Holden et al*., 2012, 2014; *Ramchunder et al*., 2013], these data should support policy makers and practitioners in undertaking more holistic environmental assessments of burn management practice.

Acknowledgments

The research was conducted as part of the EMBER project funded by the UK's Natural Environment Research Council (grant NE/G00224X/1). Yorkshire Water also contributed to the funding for which we are grateful. We thank the landowners and gamekeepers, Natural England, and The National Trust for granting permission to access the field sites. We are grateful to Natural England for funding vegetation surveys at our sites and to Stuart Hedley for conducting these and Alice Noble for analyzing vegetation data. We acknowledge the UK's Environmental Change Network for providing background flow data at one of the study sites: data set accessed 12 November 2014 at http://data.ecn.ac.uk—data citation code: ECN:JH11/14. Data available upon request to the corresponding author.

References

Acreman, M., and J. Holden (2013), Do wetlands reduce floods, *Wetlands*, *33*, 773–786, doi:10.1007/s13157-013-0473-2.

Ballard, C., N. McIntyre, H. Wheater, J. Holden, and Z. E. Wallage (2011), Hydrological modelling of drained blanket peat, *J. Hydrol.*, *407*, 81–93.

Benscoter, B. W., K. Thompson, J. M. Waddington, M. D. Flannigan, B. M. Wotton, W. J. de Groot, and M. R. Turetsky (2011), Interactive effects of vegetation, soil moisture and bulk density on depth of burning of thick organic soils, *Int. J. Wildland Fire*, *20*, 1–12.

Beven, K. J., and M. J. Kirkby (1979), A physically based, variable contributing area model of basin hydrology, *Hydrol. Sci.*, *24*, 43–69.

Blundell, A. J., and J. Holden (2014), Using palaeoecology to support blanket peatland management, *Ecol. Indicators*, *49*, 110–120.

Bond-Lamberty, B., S. D. Peckham, S. T. Gower, and B. E. Ewers (2009), Effects of fire on regional evapotranspiration in the central Canadian boreal forest, *Global Change Biol.*, *155*, 1242–1254.

Brown, L. E., K. L. Johnston, S. Palmer, K. L. Aspray, and J. Holden (2013), River ecosystem response to prescribed vegetation burning on blanket peatland, *PLoS ONE*, *8*, e81023, doi:10.1371/journal.pone.0081023.

Brown, L. E., S. M. Palmer, C. Wearing, K. Johnston, and J. Holden (2015), Vegetation management with fire modifies peatland soil thermal regime, *J. Environ. Manage.*, *154*, 166–176, doi:10.1016/j.jenvman.2015.02.037.

Cawson, J. G., G. J. Sheridan, H. G. Smith, and P. N. J. Lane (2012), Surface runoff and erosion after prescribed burning and the effect of different fire regimes in forests and shrublands: A review, *Int. J. Wildland Fire*, *27*, 857–872.

Clay, G. D., F. Worrall, E. Clark, and E. D. G. Fraser (2009), Hydrological responses to managed burning and grazing in an upland blanket bog, *J. Hydrol.*, *376*, 486–495.

Clymo, R. S. (1983), Peat, in *Ecosystems of the World 4A, Mires: Swamp, Bog, Fen and Moor*, edited by A. J. P. Gore, pp. 159–224, Elsevier, Oxford, U. K.

Davies, G. M., A. Gray, G. Rein, and C. J. Legg (2013), Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland, *For. Ecol. Manage.*, *308*, 169–177, doi:10.1016/j.foreco.2013.07.051.

Evans, M., and J. Warburton (2007), *The Geomorphology of Upland Peat: Pattern, Process, Form*, Wiley-Blackwell, Oxford, U. K.

Evans, M. G., T. P. Burt, J. Holden, and J. K. Adamson (1999), Runoff generation and water table fluctuations in blanket peat: Evidence from UK data spanning the dry summer of 1995, *J. Hydrol.*, *221*, 141–160.

Freckleton, R. P. (2004), The problems of prediction and scale in applied ecology: The example of fire as a management tool, *J. Appl. Ecol.*, *41*, 599–603.

Gao, J., J. Holden, and M. J. Kirkby (2015), A distributed TOPMODEL for modelling impacts of land-cover change on river flow in upland peatland catchments, *Hydrol. Processes*, *29*, 2867–2879, doi:10.1002/hyp.10408.

Holden, J. (2005), Peatland hydrology and carbon cycling: Why small-scale process matters, *Philos. Trans. R. Soc. A*, *363*, 2891–2913.

Holden, J. (2006), Peat hydrology, in *Peatlands: Basin Evolution and Depository of Records of Global Environmental and Climatic Changes*, edited by I. P. Martini et al., pp. 319–346, Elsevier, Amsterdam, Netherlands.

Holden, J. (2009), Topographic controls upon soil macropore flow, *Earth Surf. Processes Landforms*, *34*, 345–351.

Holden, J., and T. P. Burt (2002), Infiltration, runoff and sediment production in blanket peat catchments: Implications of field rainfall simulation experiments, *Hydrol. Processes*, *16*, 2537–2557.

Holden, J., and T. P. Burt (2003a), Hydraulic conductivity in upland blanket peat: Measurement and variability, *Hydrol. Processes*, *17*, 1227–1237.

Holden, J., and T. P. Burt (2003b), Hydrological studies on blanket peat: The significance of the acrotelm-catotelm model, *J. Ecol.*, *91*, 86–102.

Holden, J., and T. P. Burt (2003c), Runoff production in blanket peat covered catchments, *Water Resour. Res.*, *39*(7), 1191, doi:10.1029/2003WR001956.

Holden, J., et al. (2007), Environmental change in moorland landscapes, *Earth Sci. Rev.*, *82*, 75–100.

Holden, J., M. J. Kirkby, S. N. Lane, D. G. Milledge, C. J. Brookes, V. Holden, and A. T. McDonald (2008), Factors affecting overland flow velocity in peatlands, *Water Resour. Res.*, *44*, W06415, doi:10.1029/2007WR006052.

Holden, J., Z. E. Wallage, S. N. Lane, and A. T. McDonald (2011), Water table dynamics in drained and restored blanket peat, *J. Hydrol.*, *402*, 103–114.

Holden, J., P. J. Chapman, S. Palmer, R. Grayson, and P. Kay (2012), The impacts of prescribed moorland burning on water colour and dissolved organic carbon: A critical synthesis, *J. Environ. Manage.*, *101*, 92–103.

Holden, J., C. Wearing, S. Palmer, B. Jackson, K. Johnston, and L. E. Brown (2014), Fire decreases near-surface hydraulic conductivity and macropore flow in blanket peat, *Hydrol. Processes*, *28* 2868–2876, doi:10.1002/hyp.9875.

Ingram, H. A. P. (1983), Hydrology, in *Ecosystems of the World 4A, Mires: Swamp, Bog, Fen and Moor*, edited by A. J. P. Gore, pp. 67–158, Elsevier, Oxford, U. K.

Kettridge, N., D. K. Thomposon, and J. M. Waddington (2012), Impact of wildfire on the thermal behavior of northern peatlands: Observations and model simulations, *J. Geophys. Res.*, *117*, G02014, doi:10.1029/2011JG001910.

Kettridge, N., R. E. Humphrey, J. E. Smith, M. C. Lukenbach, K. J. Devito, R. M. Petrone, and W. J. M. (2014), Burned and unburned peat water repellency: Implications for peatland evaporation following wildfire, *J. Hydrol.*, *513*, 335–341.

Lane, S. N., and D. G. Milledge (2012), Impacts of upland open drains upon runoff generation: A numerical assessment of catchment-scale impacts, *Hydrol. Processes*, *27*, 1701–1726.

Lindsay, R. (2010), *Peat Bogs and Carbon: A Critical Synthesis*, R. Soc. for the Prot. of Birds, Edinburgh.

Lukenbach, M. C., K. J. Hokanson, P. A. Moore, K. J. Devito, N. Kettridge, D. K. Thompson, B. M. Wotton, R. M. Petrone, and J. M. Waddington (2015), Hydrological controls on deep burning in a northern forested peatland, *Hydrol. Processes*, doi:10.1002/hyp.10440, in press.

Martin, D. A., and J. A. Moody (2001), Comparison of soil infiltration rates in burned and unburned mountainous watersheds, *Hydrol. Processes*, *15*, 2893–2903.

Neris, J., M. Tejedor, J. Fuentes, and C. Jiménez (2013), Infiltration, runoff and soil loss in Andisols affected by forest fire (Canary Islands, Spain), *Hydrol. Processes*, *27*, 2814–2824, doi:10.1002/hyp.9403.

Pierson, F. B., P. R. Robichaud, C. A. Moffet, K. E. Spaeth, S. P. Hardegree, P. E. Clark, and C. J. Williams (2008), Fire effects on rangeland hydrology and erosion in a steep sagebrush-dominated landscape, *Hydrol. Processes*, *22*, 2916–2929, doi:10.1002/hyp.6904.

Price, J. S. (1992), Blanket bog in Newfoundland. Part 2. Hydrological processes, *J. Hydrol.*, *135*, 103–119.

Price, J. S., and G. S. Whitehead (2001), Developing hydrological thresholds for Sphagnum recolonization on an abandoned cutover bog, *Wetlands*, *21*, 32–40.

Ramchunder, S., L. E. Brown, and J. Holden (2013), Rotational vegetation burning effects on peatland stream ecosystems, *J. Appl. Ecol.*, *50*, 636–648, doi:10.1111/1365-2664.12082.

Rawes, M., and R. Williams (1973), Production and utilisation of Calluna and Eriophorum, *Colloquim Proc. Potassium Inst.*, *3*, 115–119.

Robichaud, P. R. (2000), Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA, *J. Hydrol.*, *231–232*, 220–229.

Rodwell, J. S. (1991), *British Plant Communities. vol. 2. Mires and Heath*, Cambridge Univ. Press, Cambridge, U. K.

Simmons, I. G. (2003), *The Moorlands of England and Wales: An Environmental History 8, 000 BC-AD 2, 000*, Edinburgh Univ. Press, Edinburgh.

Smith, H. G., and D. Dragovich (2008), Post-fire hillslope erosion response in a sub-alpine environment, south-eastern Australia, *Catena*, *73*, 274–285.

Thompson, D. K. (2012), *Wildfire Impacts on Peatland Ecohydrology*, 174 pp., McMaster Univ., Hamilton, Ontario, Canada.

Thompson, D. K., and J. M. Waddington (2013), Wildfire effects on vadose zone hydrology in forested boreal peatland microforms, *J. Hydrol.*, *486*, 48–56, doi:10.1016/j.jhydrol.2013.01.014.

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

Verble, R. M., and S. P. Yanoviak (2013), Short-term effects of prescribed burning on ant (Hymenoptera: Formicidae) assemblages in Ozark forests, *Ann. Entomol. Soc. Am.*, *106*, 198–203.

Von Post, L. (1922), Sveriges Geologiska Undersoknings torvinventering och nogra av dess hittils vunna resultat (SGU peat inventory and some preliminary results), *Svenska Mosskulturforeningens Tidskrift*, *36*, 1–37.

Ward, S., N. Ostle, S. Oakley, H. Quirk, A. Stott, P. Henrys, W. A. Scott, and R. Bardgett (2012), Fire accelerates assimilation and transfer of photosynthetic carbon from plants to soil microbes in a northern peatland, *Ecosystems*, *15*, 1245–1257.

Worrall, F., A. Armstrong, and J. K. Adamson (2007), The effect of burning and sheep-grazing on water table depth and soil water quality in a blanket bog, *J. Hydrol.*, *339*, 1–14.

Worrall, F., J. Rowson, and S. Dixon (2013), Effects of managed burning in comparison with vegetation cutting on dissolved organic carbon concentrations in peat soils, *Hydrol. Processes*, *27*, 3994–4003, doi:10.1002/hyp.9474.

Yallop, A. R., J. I. Thacker, G. Thomas, M. Stephens, B. Clutterbuck, T. Brewer, and C. A. D. Sannier (2006), The extent and intensity of management burning in the English uplands, *J. Appl. Ecol.*, *43*, 1138–1148, doi:10.1111/j.1365-2664.2006.01222.x.

Yibarbuk, D., P. J. Whitehead, K. Russel-Smith, D. Jackson, C. Godjuwa, A. Fisher, P. Cooke, D. Choquenot, and D. M. J. S. Bowman (2001), Fire ecology and aboriginal land management in central Arnhem Land, Northern Australia: A tradition of ecosystem management, *J. Biogeogr.*, *28*, 325–343.

Yu, Z., J. Loisel, D. P. Brosseau, D. W. Beilman, and S. J. Hunt (2010), Global peatland dynamics since the Last Glacial Maximum, *Geophys. Res. Lett.*, *37*, L13402, doi:10.1029/2010GL043584.

Erratum

In the originally published version of this article, the four legend labels in Figure 2 were incorrect. The errors have been fixed, and the lines in the figure and associated text in the article were correct. This version may be considered the authoritative version of record.