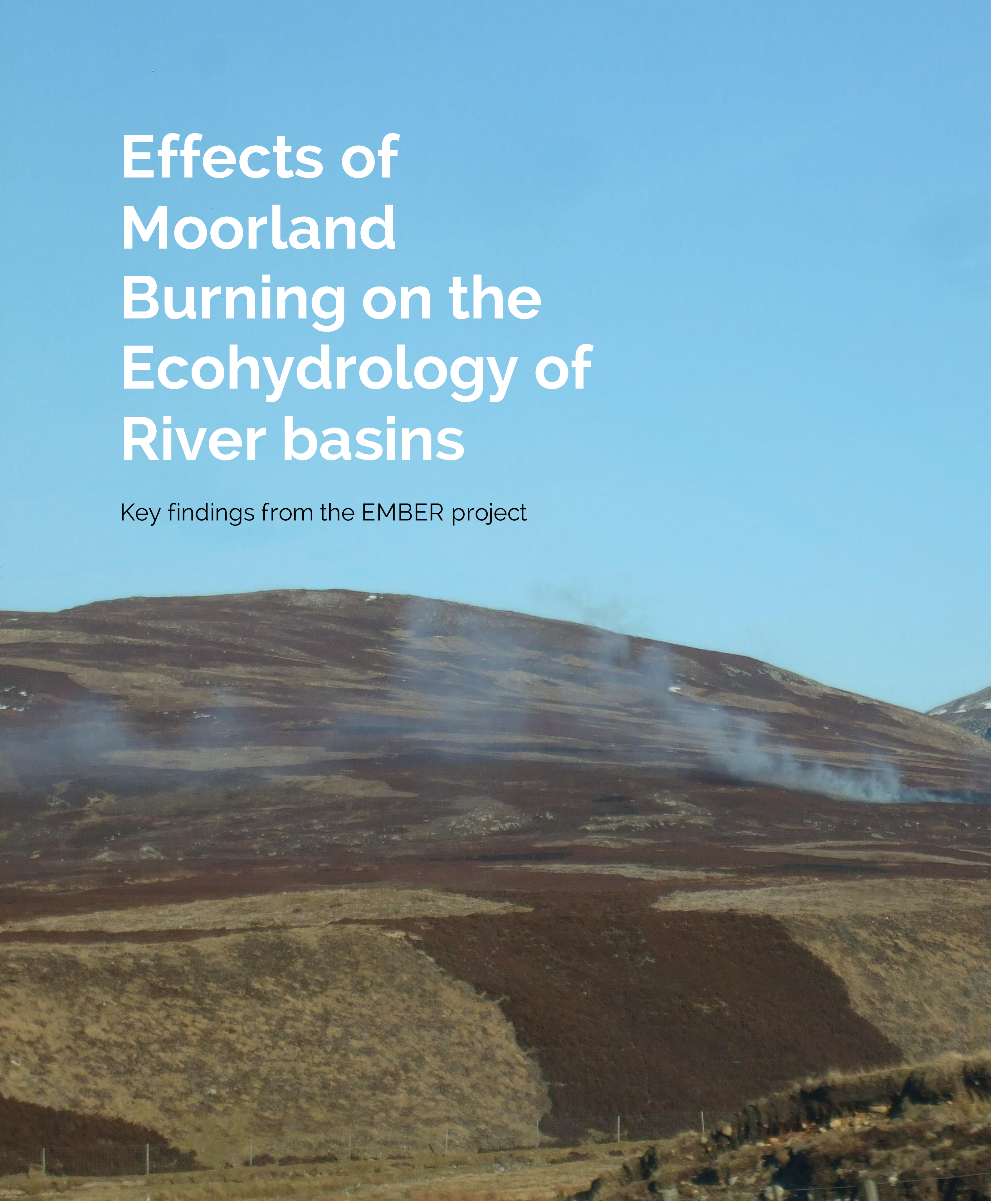
Effects of Moorland Burning on the Ecohydrology of River basins

Key findings from the EMBER project



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EXECUTIVE SUMMARY

This report outlines findings on the effects of moorland burning on peatlands, carried out by scientists working on the EMBER project. The EMBER project was funded by the Natural Environment Research Council (NERC) with additional support from Yorkshire Water. The comprehensive five-year study assessed the impacts of prescribed vegetation burning by comparing five burned and five unburned river basins and 120 soil plots across the English Pennines. The EMBER project compared the hydrology, water chemistry, soil properties and aquatic ecosystems of these burned and unburned areas.

The uplands of the UK are an important source of river water, form valuable habitats, provide a large store of carbon and deliver diverse environments for recreation and farming. There has been concern about peatland management in the uplands in terms of its impacts on river water quality and flows, river ecology, peatland hydrology, soil physical properties and carbon storage. In many areas of the UK uplands, land owners and those with sporting rights to the land actively burn vegetation on the hillside, rotating between patches from year to year. Such burning is done predominantly to support red grouse (*Lagopus lagopus scotica*) populations for gun sports. There are ongoing debates about the wider environmental impacts of burning, although the evidence base to date is limited because there has been a lack of co-ordinated research into how burning affects our upland environment.

Key findings were:

- Prescribed burning on peatlands was shown to have clear effects on peat hydrology, peat chemistry and physical properties, river water chemistry and river biota.
- Burning reduces the organic matter content of the upper peat layers. The net result is that the peat is less able to retain important particles known as exchangeable cations. In other words, the peat in burned sites is deprived of chemicals which are important for plant growth and for buffering acidic rainfall.

- Lower concentrations of nutrient elements found in peat soils in burned river basins do not support the idea that burning enriches the peat with nutrients from ash.

- Rivers draining burned catchments were characterised by lower calcium concentrations and lower pH relative to rivers draining unburned catchments. Rivers draining burned sites had higher concentrations of silica, manganese, iron and aluminium compared to unburned catchments.

- There was no difference between burned and unburned catchments in peat nitrogen concentrations or in carbon to nitrogen ratios (high C/N is considered unfavourable to microbial decomposition of peat), and no significant difference in peat soil pH.

- Water-table depth is very important in peatlands for maintaining their stability and function as a carbon store. Water tables were found to be significantly deeper for burned catchments than for unburned ones. Deeper water tables would suggest a greater scope for degradation of the peat and loss of carbon to the atmosphere.

- *Sphagnum* is an important peat-forming species. Changes in the hydrological properties of the peat after fire make the peat less conducive to *Sphagnum* moss growth.

- River flow in catchments where burning has taken place appears to be slightly more prone to higher flow peaks during heavy rain. However, this was not a conclusive finding.

- Burning vegetation alters the natural peat hydrology in the upper layers of the peat affecting the balance of where water flow occurs. Recovery of many hydrological properties appears to be possible if a site is left unburned over many years.

- Prescribed peatland vegetation burning leads to significant increases in mean and maximum near-surface soil temperatures in the years following burning as well as lower minima (and thus wider thermal variability).

- Thermal regimes appear to recover as vegetation regrows. This recovery was also seen in soil hydrology data from burned plots of different ages.

- Macroinvertebrates play a vital role in aquatic food webs by feeding on algae, microbes and detritus at the base of food chains before they themselves are consumed by birds, fish and amphibians. The research found that river macroinvertebrate diversity was reduced in burned sites.
- Particulate organic matter (predominantly peat) deposits were increased up to four-fold in the bed sediments of burned rivers compared to unburned rivers.
- In burned sites, river macroinvertebrate populations were dominated by groups that are commonly found in higher abundance in disturbed river systems, such as non-biting midge larvae (Chironomidae) and burrowing stonefly larvae (Nemouridae).
- Increases in the abundance of disturbance-tolerant taxa counteract declines and/or losses amongst some groups (e.g. mayflies) which are typically sensitive to reduced pH, increased aluminium and deposition of fine sediments. These changes show that burning increases the effect of biological stressors compared to unburned rivers.

1. PROJECT AIMS AND BACKGROUND

1.1. The EMBER project aimed to increase understanding of the processes linking prescribed moorland burning, hydrology, water quality and biota of soils and streams in upland peat-dominated river basins. The project was novel because for the first time it studied multiple linked river basin processes (soils to streams) using comparable methods across replicated study sites spanning a broad geographical region (English Pennines). The design of the research sought to provide different stakeholders with the integrated process understanding required to manage peatland ecosystems most effectively.

1.2. This summary document provides the reader with key findings from the EMBER project. Specifically, we detail the effects of moorland burning on soil and stream hydrology, soil physical and chemical properties, soil and stream biogeochemistry, and river macroinvertebrate biodiversity.

1.3. Prescribed vegetation burning is used worldwide for vegetation management, yet there are serious concerns about its environmental implications[1]. In the UK, fire has been used to control upland vegetation since ~7700–6300 BC[2], but over the last 150 years many upland landscapes have been subjected to prescribed rotational burning regimes[3]. Across northern England and Scotland, moorland burning is now considered to be a 'traditional' practice for encouraging and maintaining heather growth (75% of the world's heather cover occurs in the UK uplands[4]).

1.4. Prescribed vegetation burning on peatlands is undertaken predominantly to remove grasses and ageing dwarf shrubs (e.g. *Molinia caerulea* (moor grass) and *Calluna vulgaris* (heather)). Regeneration of young heather shoots is deemed to be suitable for increasing red grouse (*Lagopus lagopus scotica*) populations by providing a palatable food source for young birds, while older shrub cover serves as nesting sites and refuge from predators[5,6]. Burning is also practiced in some areas to create vegetation growth for livestock, for 'conservation' purposes or to reduce fuel loads and reduce wildfire severity[7]. However, while the area of burned moorland has increased in some areas of northern England significantly since 1995[8], the implications for peatland soils, their hydrology and biogeochemistry, river flow regimes, water quality and biota remain poorly understood.

1.5. Burning usually occurs on patches of c. 400 m^2, and burning cycles vary from 8 to 25 years[3,9] depending on productivity, habitat type, grazing level, traditional burning schedules or management prescriptions imposed by government agencies. Thus, the catchment of an individual river will have dozens of burning patches of different ages. Typically, burning will take place within the catchment most years (1 October to 15 April), but each year a different set of patches will be burned. Across burned peatland, there will therefore be patches that have been very recently burned (i.e. within the last 12 months) and those that have not been burned for many years, thereby creating a mosaic effect (Figure 1).

1.6. In recent years, upland managers have increasingly been requesting evidence from the scientific community regarding the environmental effects of burning[10]. Despite recent interest in the subject, detailed evaluations of the costs, benefits and sustainability of burning remain hampered by minimal and, in some cases, contrasting basic scientific data[7,9]. Consequently, many moorland owners have felt pressured to change what they see as traditional practice despite there being a lack of any convincing evidence of problems. This is causing serious tension between land owners, conservationists and regulators[7,11].

Figure 1. Photographs of vegetation patches on peatlands. The upper panel shows patches of older heather (brown) against lighter coloured patches of younger regrowth. On the lower panel, recent burn patches are visible as darker grey/black blocks of charred vegetation and deposits of ash.

2. STUDY SITES AND SAMPLING DESIGN

Study sites

2.1. The EMBER project focused on ten independent river catchments spanning the Pennines, from sites near Ladybower Reservoir in the south to Moor House National Nature Reserve in the north (Table 2.1). Sampling took place between March 2010 and October 2011.

2.2. Five of these rivers drained peatland with no recent history of vegetation burning (herein termed *unburned* management) for more than six decades (at Moor House), and likely for at least three to five decades at other sites.

2.3. Five rivers drained from catchments where there was a mosaic of contemporary burn patches ranging from <1 to 25 years since burning (herein termed *burned* management). The sites were all grouse moors and burning regimes were conducted in a manner considered to be normal for grouse management.

2.4. Study sites were identified as those having a predominant soil cover of blanket peat as mapped by the Soil Survey of England and Wales, with peat depths >1m depth at most sites based on our plot-scale measurements, and catchment areas up to 3.1 km^2. Selected sites had no confounding forest cover, mining activity, major erosion or artificial drainage, and were selected such that both burned and unburned catchments were distributed amongst the catchment geologies typical of the Pennine hills (Table 2.1). All sites were grazed by sheep but stocking densities were low, typically <1 ewe per ha.

2.5. Vegetation cover in the unburned catchments was predominantly a mixture of *Eriophorum* spp. (cotton grass), heather, *Vaccinium myrtillus* (bilberry) and mosses (inc. *Sphagnum* spp.). At the burned catchments, recent burn patches (<2 years since burning) were predominantly exposed peat with mainly a small cover of heather shoots. Older burn patches (>5 years since burning) were dominated by heather at various stages of growth, with bilberry and cotton grass also common.

2.6. One burned site (Bull Clough, Midhope Moor) and one unburned site (Oakner Clough, Marsden Moor) were selected for very intensive monitoring. The other eight sites were monitored intensively, but less so than at Bull Clough or Oakner Clough. Details of the design and sampling regime for these sites are provided below.

Table 2.1. Study site management details, locations and catchment size[12]

Management /Site	Location	WGS84 Lat/Long	Catchment area (km²)	Catchment altitude (m AOD)	Geology
Burned					
Bull Clough	Midhope Moor, Peak District	53˚28'24.8"N; 1˚42'46.2"W	0.7	455-541	Carboniferous and Jurassic sandstone
Great Eggleshope Beck	Teesdale, North Pennines	54˚40'59.6"N; 2˚04'11.9"W	1.6	480-653	Carboniferous mudstone, sandstone and limestone
Lodgegill Sike	Teesdale, North Pennines	54˚40'35.5"N; 2˚04'04.1"W	1.2	515-608	Carboniferous mudstone, sandstone and limestone
Rising Clough	Derwent Moors, Peak District	53˚23'38.4"N; 1˚40'25.0"W	1.8	344-487	Carboniferous gritstone and sandstone
Woo Gill	Nidderdale, Yorkshire Dales	54˚12'06.1"N; 1˚53'26.3"W	1.0	430-546	Carboniferous and Jurassic mudstone
Unburned					
Crowden Little Brook	Longdendale South Pennines	53˚30'51.7"N; 1˚53'29.7"W	3.1	355-582	Carboniferous gritstone and sandstone
Green Burn	Teesdale, North Pennines	54˚40'40.0"N; 2˚21'43.9"W	0.7	548-734	Carboniferous sandstone, limestone and shale
Moss Burn	Teesdale, North Pennines	54˚41'19.7"N; 2˚23'01.7"W	1.4	560-768	Carboniferous sandstone, limestone and shale
Oakner Clough	Marsden Moor, South Pennines	53˚36'11.1"N; 1˚58'03.4"W	1.2	240-451	Carboniferous gritstone and sandstone
Trout Beck	Teesdale, North Pennines	54˚40'59.6"N; 2˚24'46.0"W	2.8	595-794	Carboniferous sandstone, limestone and shale

Sampling design common to all ten sites

2.7. At all ten sites, 12 soil plots were selected. In the burned sites, patches with different ages since burning (<2 year since burning (B2), approximately 4 years since burning (B4), approximately 7 years since burning (B7) and > 10 years since burning (B10+)), and spanning the normal cycle for each site, were identified following discussions with gamekeepers. Three replicates of each age class were chosen, with one each located in top, middle and foot slope positions. At unburned sites, 12 patches were selected randomly with four per slope position.

2.8. Each soil plot had a dipwell installed at approximately its centre for measurements of water-table depth at approximately three-weekly intervals. Soil cores were extracted from each plot during the summer of 2010 for measurement of soil physical and chemical properties. Each core was sectioned into 5-cm depth increments, and combined to give one sample per depth increment per plot.

2.9. The outlet of each river catchment was instrumented using automatic dataloggers and sensors located at a stable cross section. These installations measured water depth (for subsequent conversion to discharge using rating curves), water temperature, electrical conductivity and pH. Air temperature was measured locally in a radiation shield mounted 1m above ground surface, and rainfall was measured with a tipping bucket rain gauge at ground level. All loggers recorded data at 15 min intervals.

2.10. Water samples were collected manually from the outlet stream every three weeks for analysis of dissolved major ions, metals, nutrients and suspended sediment.

2.11. Five replicate Surber samples (0.1m^2, 250µm mesh) were collected from the bed of each river at quarterly intervals for the subsequent analysis of macroinvertebrate community composition.

Additional sampling of very intensively monitored sites

2.12. At Bull Clough the 12 soil plots were divided into four age categories: <2 year since burning (B2), approximately 4 years since burning (B4), approximately 7 years since burning (B7) and > 15 years since burning (B15+). Twelve plots with no burning were established at Oakner Clough. All of the plots were instrumented with automatic water-table depth dataloggers recording at 15 min intervals. Additionally, soil temperatures were measured at 15 min intervals at the soil surface, and at 5cm, 20cm and 50cm depth.

2.13. Soil solution samples were extracted from perforated tubes at the surface, 5cm, 20cm and 50cm depth, every three weeks.

2.14. Overland flow measurements were collected using 20 crest-stage tubes per patch, and infiltration experiments were undertaken on a selection of soil patches.

2.15. Automated pump samplers were deployed on the two rivers, with high flow triggers that collected water samples for the analysis of water chemistry and suspended sediment concentrations over 24h periods at 15 min to hourly intervals.

3. PEAT PHYSICAL AND CHEMICAL PROPERTIES

3.1. The EMBER project measured exchangeable (available) cations, exchangeable acidity, soil organic matter (SOM) content, total carbon (C) and nitrogen (N) content, bulk density and pH at four depth increments to 20 cm below the peat surface.

3.2. Nitrogen and the exchangeable cations calcium (Ca), potassium (K) and magnesium (Mg) are important plant nutrients. Ca, K, Mg and sodium (Na) also play a part in buffering acidic rainwater as it passes through peat to drainage waters and rivers. If these four cations are lost from exchange sites in the soil (negatively charged particles of soil organic matter) more rapidly than they can be replaced, concentrations of exchangeable aluminium (Al) and hydrogen (H) may increase which gives rise to increased acidity.

3.3. Deep upland peats are isolated from underlying geological sources of elements, hence the main inputs of cations and nutrient elements are via dissolved sea salts (Na and Mg) and atmospheric pollution (mainly N) in rainwater, atmospheric dusts (variable composition) or from tight nutrient cycling as plants decay and decompose. When vegetation burns, some cations and nutrients may be returned to the soil as ash and some may be lost as gases.

3.4. Compared to unburned locations, peat soils at all depths in catchments that are managed by burning had lower concentrations of exchangeable Ca, Mg, Na, iron (Fe) and K, lower exchangeable H, SOM and soil C (Figure 3.1). In contrast, peat in burned catchments had higher bulk densities and exchangeable manganese (Mn) concentrations. There was no difference between burned and unburned catchments in peat N concentrations or in C/N (high C/N is considered unfavourable to microbial decomposition of peat), and no significant changes in peat soil pH.

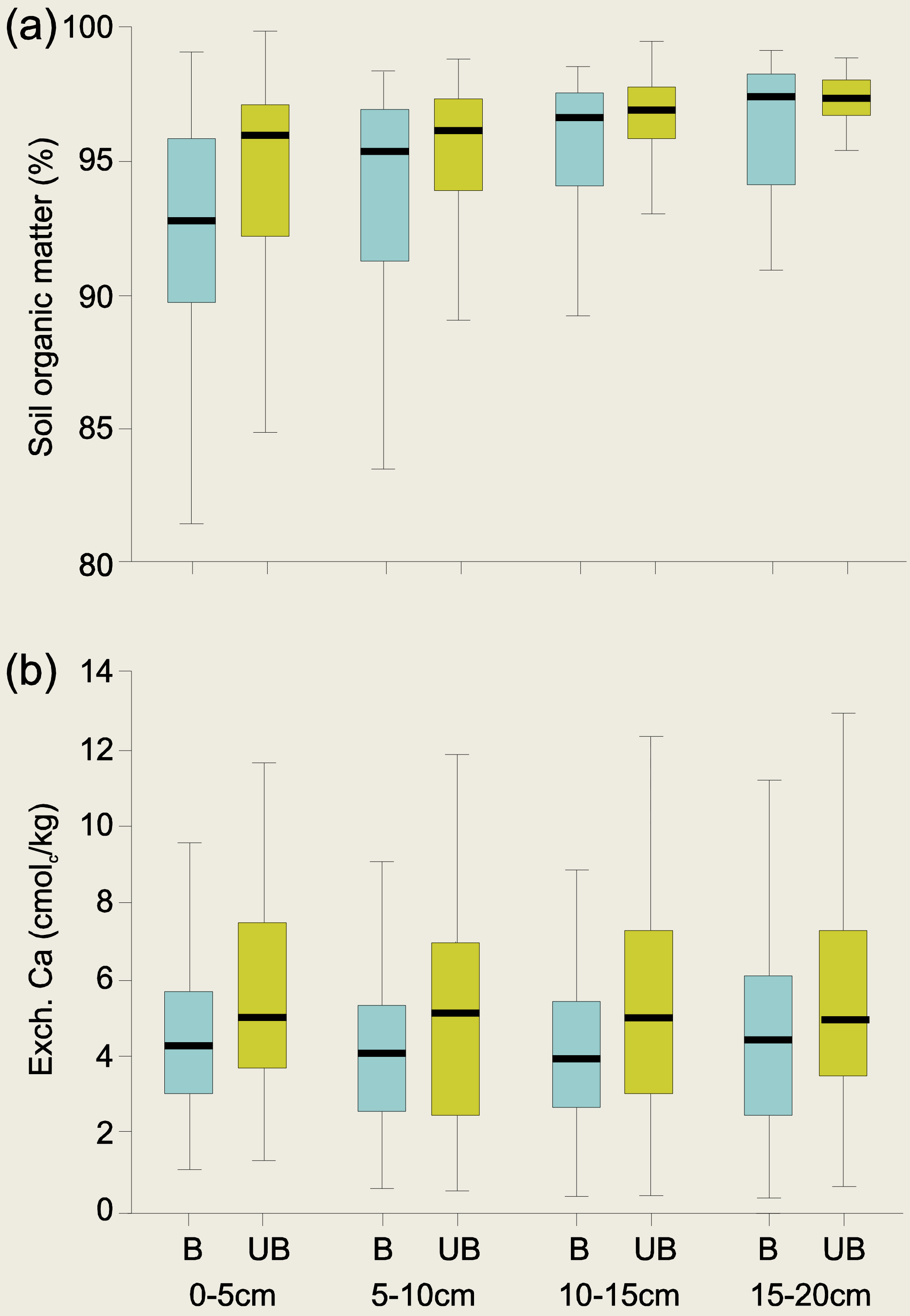

Figure 3.1. (a) Soil organic matter and (b) exchangeable calcium in burned (B) and unburned (UB) peat at four depth increments.

3.5. Lower concentrations of nutrient elements in peat soils in burned catchments do not support the idea that burning enriches the peat with nutrients from ash.

3.6. There is no evidence that reduced concentrations of the available cations Ca, K, Mg and Na have been replaced with exchangeable H and Al, or that acidity has increased as a consequence of vegetation burning. The results indicate that peat in burned catchments has an overall lower capacity to retain cations, most likely due to the decrease in SOM. The apparent loss of SOM is likely due to a dilution with relatively insoluble minerals returned to the soil as ash when vegetation burns.

3.7. For Bull Clough, which had the longest burn cycle, we compared the peat properties between patches burned most recently to those burned several years ago.

3.8. All burn ages had significantly lower SOM at the surface compared to other depths and there was no significant effect of time since burning (Fig. 3.2) at any depth. This suggests that: (i) ash is not readily dissolved during the burn cycle, and (ii) that ash dilution of peat is not readily transmitted to deeper layers.

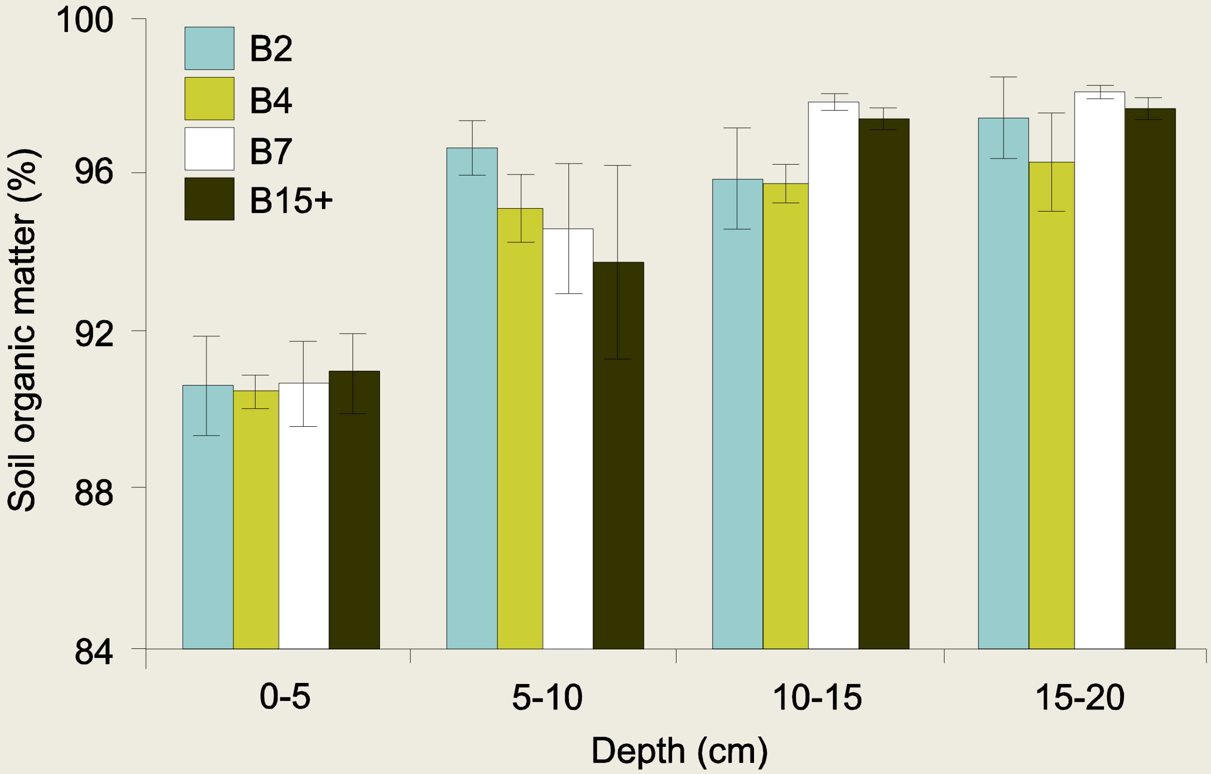

Figure 3.2. Mean (±1 St. Error) soil organic matter at four depths in peat burned < 2 years (B2), 4 years (B4), 7 years (B7) and > 15 years (B15+) prior to sampling.

3.9. There was no evidence of a Ca or any other cation or nutrient enrichment of the peat surface (0-5 cm) in peat burned less than two years before sampling (Figure 3). Higher cation and nutrient concentrations in surface peat of plots burned > 15 years prior to sampling suggests an enrichment over time, possibly due to greater entrapment from the atmosphere as the canopy closes, although the effect was not statistically significant (Figure 3.3a). In contrast, there was up to an order of magnitude enrichment of potassium at depths below the surface in the most recently burned plots (Figure 3.3b). This may be due to: (i) release from decomposing plant roots left in the soil after burning; (ii) decreased demand due to a reduction in vegetation cover, or; (iii) dissolution from ash with subsequent leaching to lower depths (heather ash has been shown to release K more readily than other less soluble nutrients[13]).

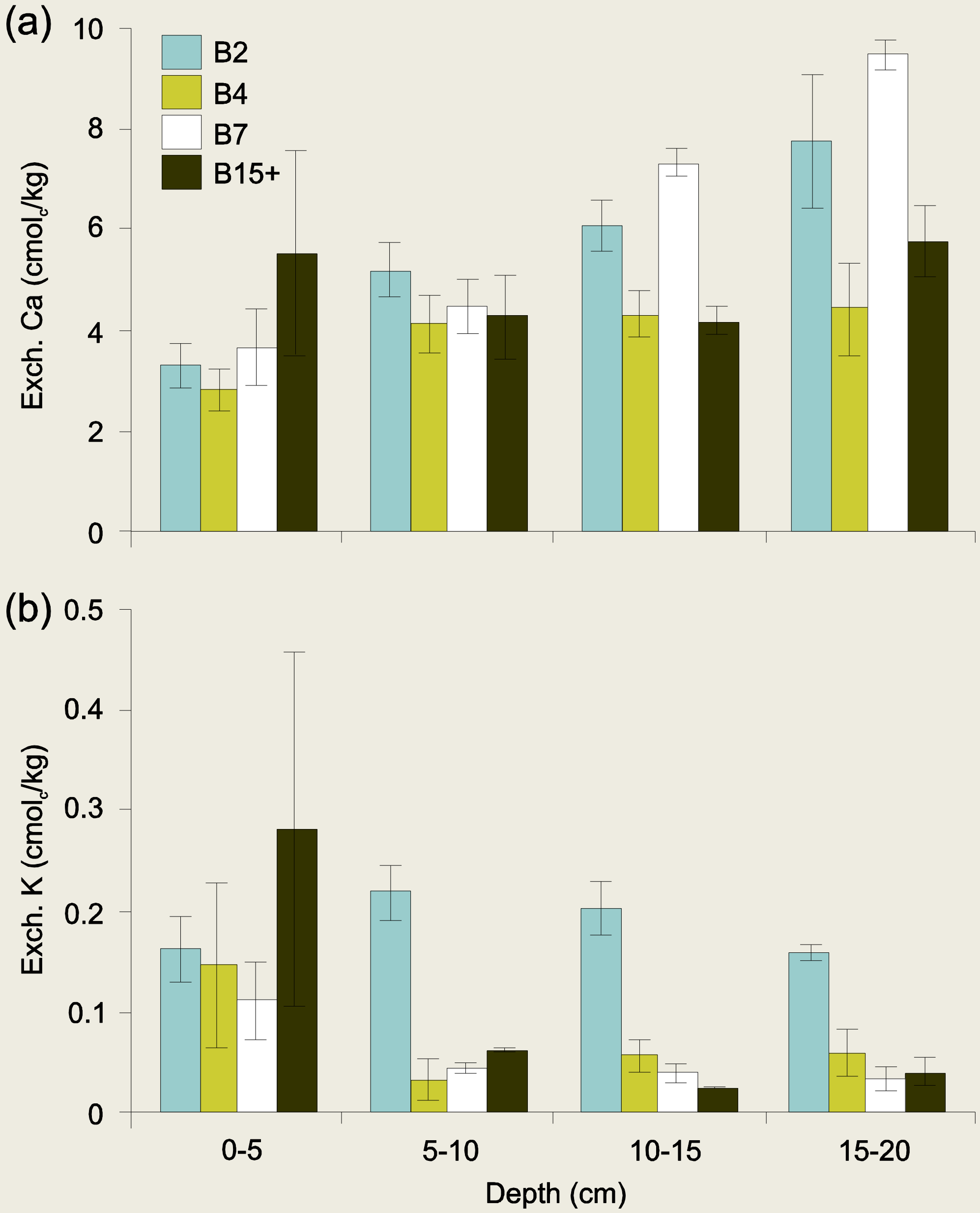

Figure 3.3. Mean (±1 St. Error) exchangeable (a) Ca and (b) K at four depths in peat burned <2 years (B2), 4 years (B4), 7 years (B7) and >15 years (B15+) prior to sampling.

3.10. In summary, we hypothesise that the main effect of burning on peat properties is a reduction in the organic matter content, which in turn means that peat is less able to retain exchangeable cations which are important for plant growth and for buffering acidic rainfall as it percolates through soil. This apparent loss of organic matter mostly occurs in near-surface peat and appears not to recover with time since burning. In this sense, the peat retains a ‘memory’ of past burning. Since flow generation in peat is mainly in the near-surface zone[14], this loss of soil function may explain the lower pH and Ca concentrations in streams draining burned river basins relative to streams draining unburned systems (see Section 6).

4. HYDROLOGY

4.1. The EMBER project measured water tables, overland flow, hydraulic conductivity (rate at which water can move through the peat) and river flow. A full description of some major findings from this work has been published in reference 15.

4.2. Water-table depth is very important in peatlands for maintaining their stability and function as a carbon store. The depth of the water table is the distance from the peat surface to the point under the ground where the peat is fully saturated. The peat needs to be kept close to saturation in order for it to be a well-functioning system. If the water-table depth becomes deeper, then the peat system can degrade and lose more carbon each year than it gains.

4.3. Water tables were significantly deeper for burned catchments than for unburned ones (Figure 4.1). In the burned catchments, more recently burned plots had significantly deeper mean water-table depths and the peat was much less frequently saturated in the upper layers over time. Recent burning (B2 - within previous two years) was associated with significantly deeper water tables than where burning last took place four years prior to measurements (B4; Figure 4.1). In turn, B4 was subject to deeper water tables than where burning occurred seven years previously (B7), and B7 peat had deeper water tables than peat burned more than a decade beforehand.

4.4. These data suggest that the peat system appears able to recover over time if there is no more burning, and so the water-table depths for peat last burned more than a decade before measurement were similar (not significantly different) to unburned peat.

4.5. The occurrence of overland flow was impacted by both burning and time since burn, with significantly less overland flow recorded for more recently burned sites (Figure 4.2). This ties in well with the water-table data since blanket peat systems are dominated by saturation processes and tend to produce overland flow when the peat is full of water. Deeper water tables mean that the peat is less likely to reach saturation and produce overland flow.

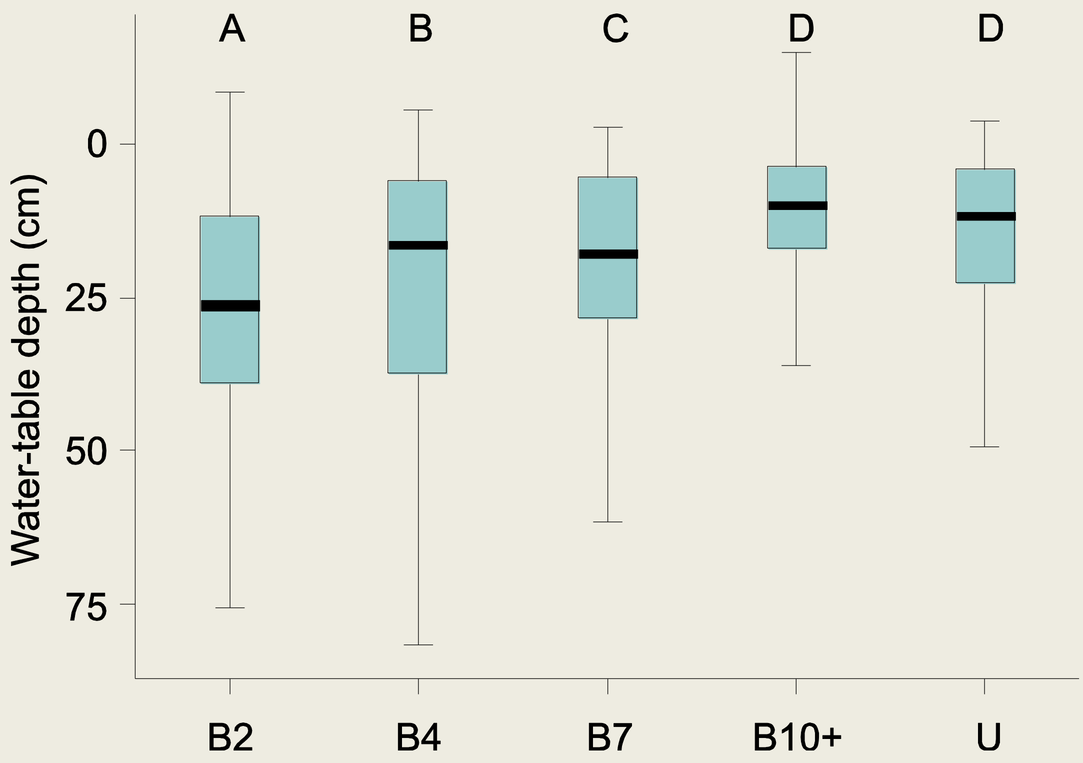

Figure 4.1. Water-table depth measured across all study sites and plots for unburned peatland (U) compared to peatland last subject to burning 2, 4, 7 and >10 years prior to measurement. Letters A-D refer to datasets shown to be significantly different to each other.

4.6. For unburned sites there was a significant correlation between maximum daily rainfall between visits and the number of points where overland flow was recorded.

4.7. For burned sites there was a significant correlation between maximum daily rainfall between visits and overland flow occurrence only for points where burning last happened >15 years prior to measurement. Where burning had taken place more recently this relationship broke down and did not exist. Hence, prescribed burning was found to alter the natural hydrological balance of upland peatlands.

4.8. The rate at which water can move through the peat is known as the hydraulic conductivity. This was tested for the upper peat layers in the EMBER project. Figure 4.3 shows that where there has been recent burning (B2, B4) the hydraulic conductivity is significantly lower than where burning last occurred > 15 years prior to measurement. The latter has equivalent hydraulic conductivity to unburned peat. This is more evidence to show that fire affects peat hydrology but that recovery of hydrological properties might be possible if a site is left unburned.

Figure 4.2. Percent of sampling times that overland flow had occurred at Bull Clough plots between visits. There are 528 samples per burn age and sites were visited approximately every three weeks. Data compare unburned peatland (U) to peatland last subject to burning 2, 4, 7 and >15 years prior to measurement.

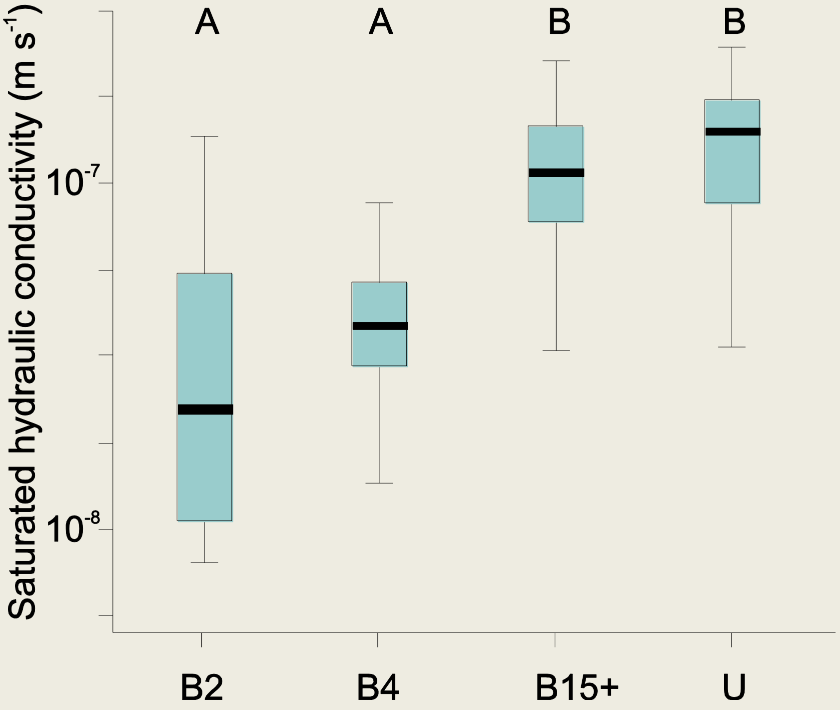

Figure 4.3. Saturated hydraulic conductivity of the upper peat layer. Data compare unburned peatland (U) to peatland last subject to burning 2, 4 and >15 years prior to measurement. Note that data are presented on a log scale so that there is a 10 fold difference between 10^{-8} and 10^{-7} m s^{-1}.

4.9. Typically a reduced hydraulic conductivity is indicative of a collapse of the peat mass as it compresses on drying. This would therefore match the water table findings. This is backed up by Table 4.1 which shows the density of the peat is much greater where it has been recently burned (e.g. B2) compared to where it was last burned >15 years ago (B15+) or where it is not been subject to burning. Importantly, a more dense upper peat layer will reduce *Sphagnum* re-establishment after fire as the plants would find it more difficult to draw water out of the peat soil to keep their moisture levels high.

4.10. There was reduced water movement in larger pores (like plant root holes) when the fire had occurred more recently compared to unburned (U) peat or sites where the last burn was more than 15 years before measurements took place (Figure 4.4).

4.11. River flow in catchments where burning has taken place appears to be slightly more prone to higher flow peaks during heavy rain (relative to the overall flow regime of the river). In Figure 4.5 this is shown on the right hand side of the graph by the burned catchments being located higher on the graph than the unburned catchments. Of course this cannot be entirely conclusive since different catchments may naturally be flashier than others.

Table 4.1. Mean bulk density (±1 St. Error) of the upper peat for different times since last burn. Values for U are calculated across all unburned plots/sites, while those for burn plots are for Bull Clough plots.

Treatment	Bulk density (g cm^{-3})
U	0.124±0.050
B2	0.249±0.013
B4	0.166±0.008
B15+	0.136±0.047

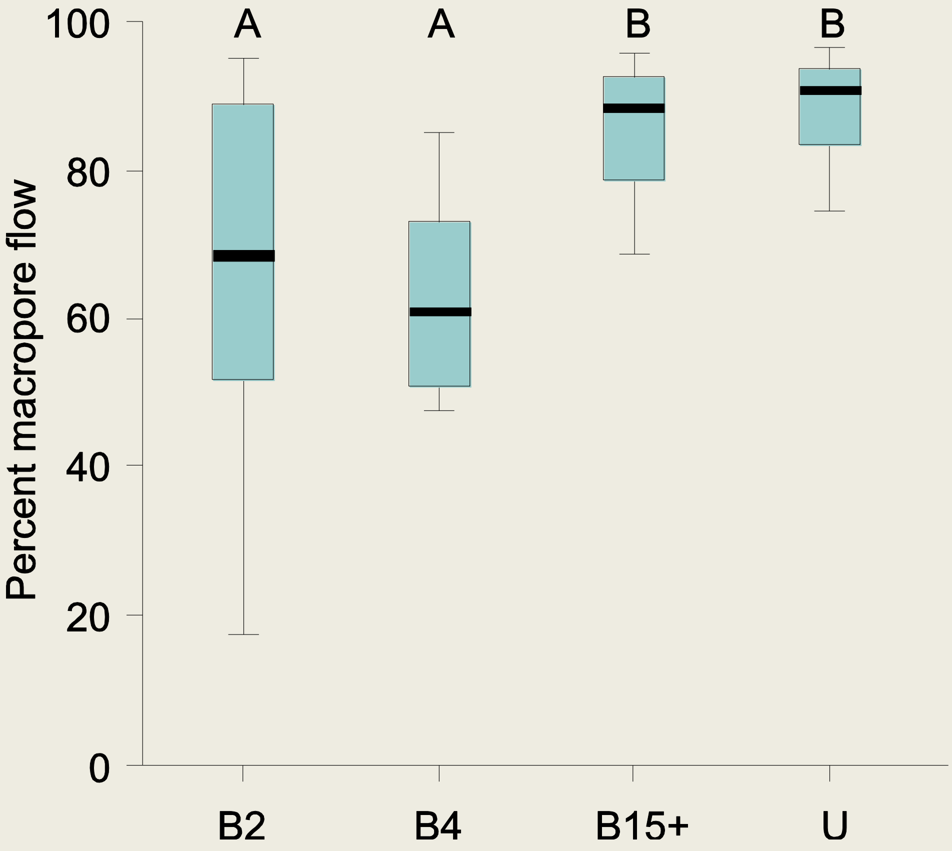

Figure 4.4. Percent flow moving through macropores in the peat. Data compare unburned peatland (U) to peatland last subject to burning 2, 4 and >15 years prior to measurement.

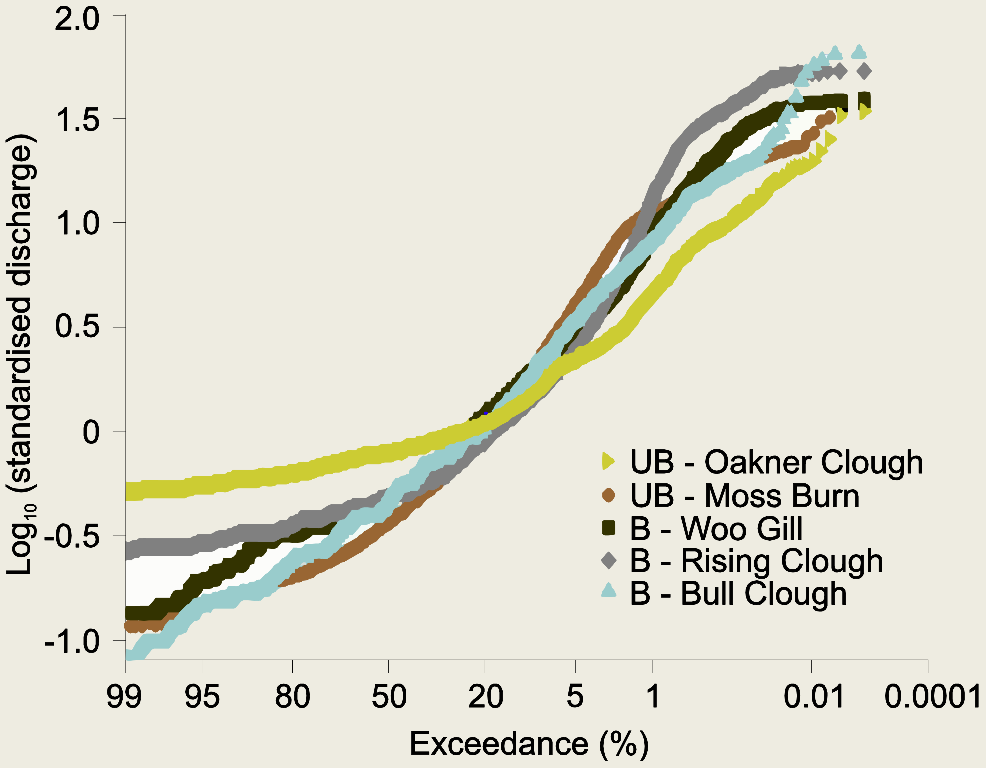

Figure 4.5. River flow duration curves for five catchments. The flow records from each river are standardised by dividing each observation by mean flow.

4.12. Our previously published field data measuring how fast flow moves across peat with different vegetation covers suggests that bare peat is associated with much faster flow movements than peat which has a dense cover of *Sphagnum* moss[16]. A modelling approach[17] based on these field data shows that if bare peat patches are placed across the catchment (e.g. covering 10% of the catchment) the flood peak would be expected to increase and the peak time would be earlier in response to a sharp rainfall event. This result is confirmed no matter whether lots of very small patches are applied, or if a smaller number of bigger burn patches are applied.

4.13. Figure 4.6 outlines a conceptual diagram of what we believe to be the hydrological response of the peatland system to burning. While in general there is less overland flow when burning has been more recent, this does not mean overland flow never occurs. During heavier rainfall events, overland flow still occurs on burned peat (i.e. numbers are not zero on Figure 4.2) and, because there is a reduced vegetation density and surface roughness, this results in faster water movements across the peat. This leads to theoretically higher flow peaks in the river during more intense rainfall events.

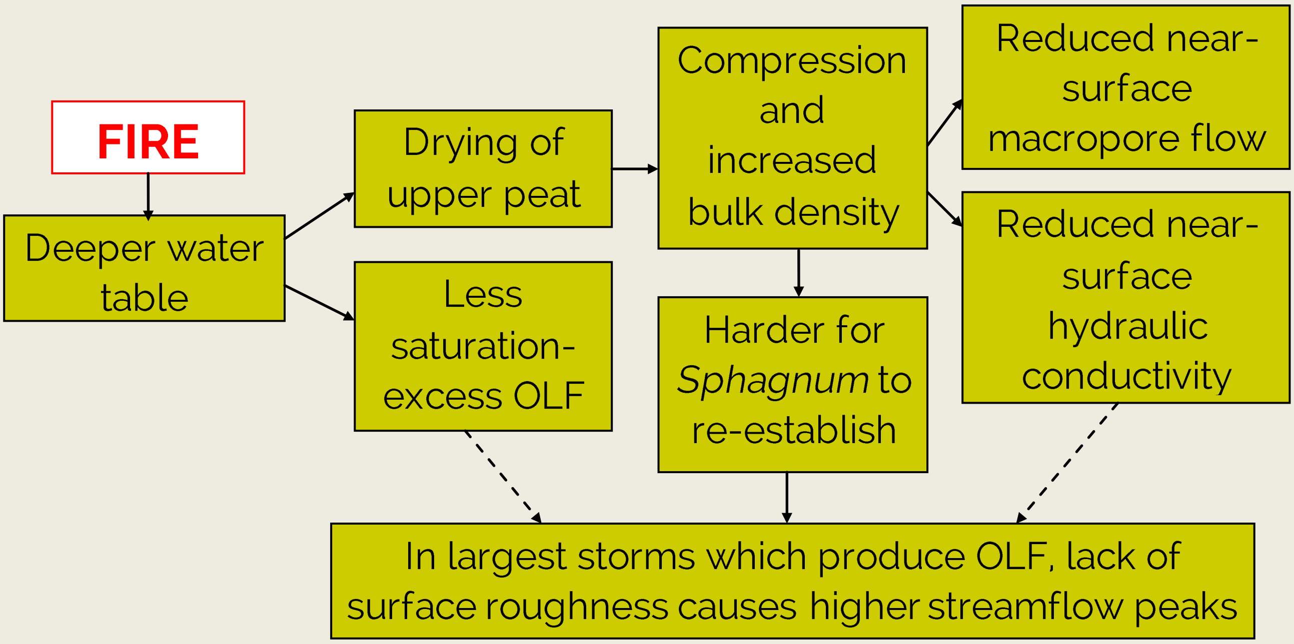

Figure 4.6. Schematic diagram outlining how the peat hydrological system responds to burning

5. SOIL THERMAL REGIME

5.1. Vegetation removal with fire can significantly alter the thermal regime of the land surface, with linked effects on biogeochemistry and soil hydrology. For example, temperature directly moderates rates of mineral weathering and soil water solution reactions[18], and indirectly influences the decomposition of organic matter[19] and uptake of nutrients by soil dwelling flora and fauna. Variations in soil thermal regime have been linked to changes in the abundance and diversity of soil microfauna[20], seed germination and vegetation growth/production[21], and nutrient uptake by plants[22,23]. Soil surface temperature can also influence heat fluxes and thus soil moisture[24] so is crucial for geomorphological processes such as sediment loosening by freeze-thaw or desiccation. To date, though, there has not been any consideration of whether prescribed vegetation burning on peatlands modifies the thermal regime of the soil mass in the years after fire.

5.2. Soil temperatures were measured in all twelve plots at Bull Clough but, for brevity, here we present only the results from soil plots located in top-slope positions; similar thermal regimes were observed in mid- and bottom-slope positions within each burn age category.

5.3. Mean and maximum temperature decreased with depth into the soil at all plots, while minima were greater as depth increased (Table 5.1).

5.4. With respect to burn effects, a general pattern of higher mean and maximum temperatures was found in B2 and B4 plots for all depths compared to B15+ plots (Table 5.1). The greatest differences were most evident at the surface, with mean temperatures being greater by 0.5 to 0.9˚C under the most recent burn plots compared with under mature heather.

5.5. Maximum temperature differences were extremely pronounced for B2 compared to B15+ plots, being >20˚C warmer. Minimum soil surface temperatures were consistently lowest in B2 plots by 4.3˚C compared to B15+ plots.

Table 5.1. Descriptive statistics derived from 15-min datasets for top slope-position at four depths. For each measurement location, data are presented as Mean, Maximum and Minimum for the entire record.

Slope-position/depth	**B15+** Mean; Max; Min	**B7** Mean; Max; Min	**B4** Mean; Max; Min	**B2** Mean; Max; Min
Top-slope				
Surface	8.1; 29.0; -2.8	8.4; 37.7; -2.4	8.6; 46.2; -5.0	8.9; 49.1; -7.1
5cm	7.9; 18.2; -0.1	8.0; 17.3; -0.1	8.2; 22.4; -2.0	8.2; 20.6; -0.9
20cm	7.8; 13.8; 1.0	7.8; 12.8; 1.1	8.1; 14.0; 0.4	8.0; 15.4; 0.3
50cm	7.3; 11.4; 2.4	7.5; 11.2; 2.3	7.9; 11.7; 2.1	7.6; 12.4; 1.4

5.6. Fire effects were also notable at depth, although the magnitude of difference was far lower than at the surface. For example at 5cm, mean temperature increases were 0.3˚C, and maximum temperatures were only 2.4˚C higher, in B2 compared to B15+.

5.7. Scatter plots showing relationships between air and soil temperature showed clearly that increasing soil depth led to a strong reduction in soil temperature response both for daily mean and daily maximum temperatures (Figure 5.1 & 5.2). For surface and 5cm depth temperatures, soil temperature response was damped when air temperature dropped below 0˚C. For each depth/slope combination, relationships between air and soil temperature were quite similar across burn ages with the main differences evident at air temperature extremes, with B2 and B4 plots displaying elevated soil temperatures at high air temperature, particularly for surface top-slope plots. These effects were also seen in maximum soil surface temperatures, albeit much more pronounced (Figure 5.2).

5.8 Near-surface processes within the peat can be extremely important in peatlands for both C processing[25] and hydrological fluxes[16]. Therefore, our findings that prescribed peatland vegetation burning leads to significant increases in mean and maximum near-surface soil temperatures as well as lower minima (and thus wider thermal variability), provide a clear indication that the use of fire to remove patches of vegetation is likely to be having unintended consequences for C processing and release.

5.9. The extreme warming seen in recently burned plots relative to those with mature vegetation may be one of the contributory factors associated with enhanced dissolved organic carbon (DOC) release from peatlands subject to prescribed burning[26]; this is because DOC generated in the upper few centimetres of the peat often dominates the stream water DOC signal[27].

5.10. Upper soil profile temperatures were elevated in recently burned patches compared with plots of mature vegetation, and the effects were most likely due to the exposure of soils to incoming solar radiation and reduced albedo due to the dark colour of exposed peat[28]. The exposure is related partly to the removal of vegetation by burning, but it is also due to the lack of protective litter cover in recently burned plots compared to B15+ plots. The protective canopy and litter of sites that have not been burned for many years would also insulate against heat loss at night and on cold days, reducing the temperature range compared with recently burned peat.

5.11. While recently burned soil patches had higher mean and maximum temperatures, it can also be inferred that thermal regimes 'recover' as vegetation regrows. This recovery has also been seen in soil hydraulic conductivity and macropore flow analyses across the Bull Clough plots[15].

5.12. Our findings that prescribed peatland vegetation burning alters soil thermal regime should provide an impetus for further research to understand the consequences of thermal regime change for carbon processing and release, and hydrological processes, in peatland managed by vegetation burning.

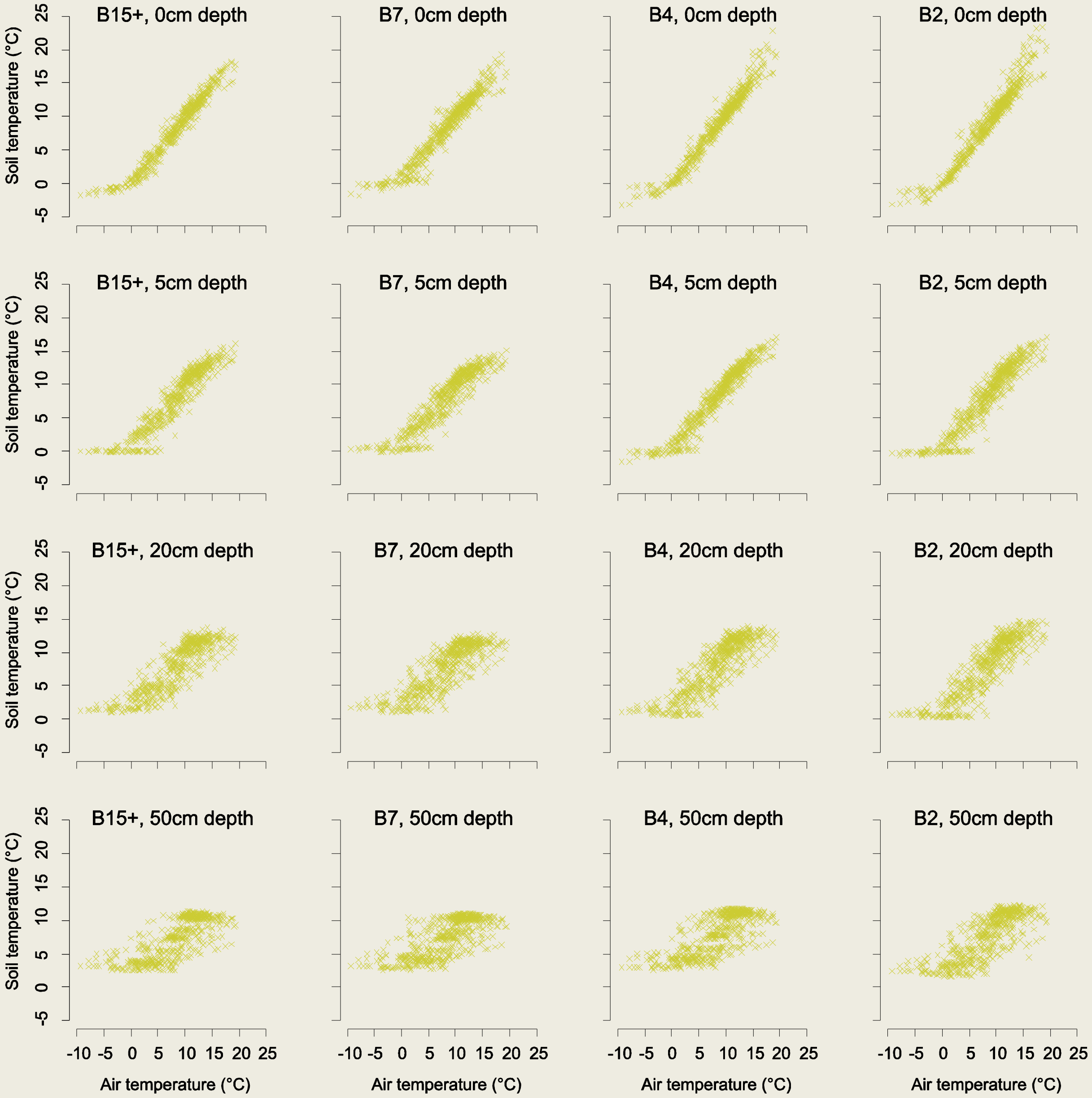

Figure 5.1. Relationships between mean daily air and soil temperatures at four depths in top-slope plots.

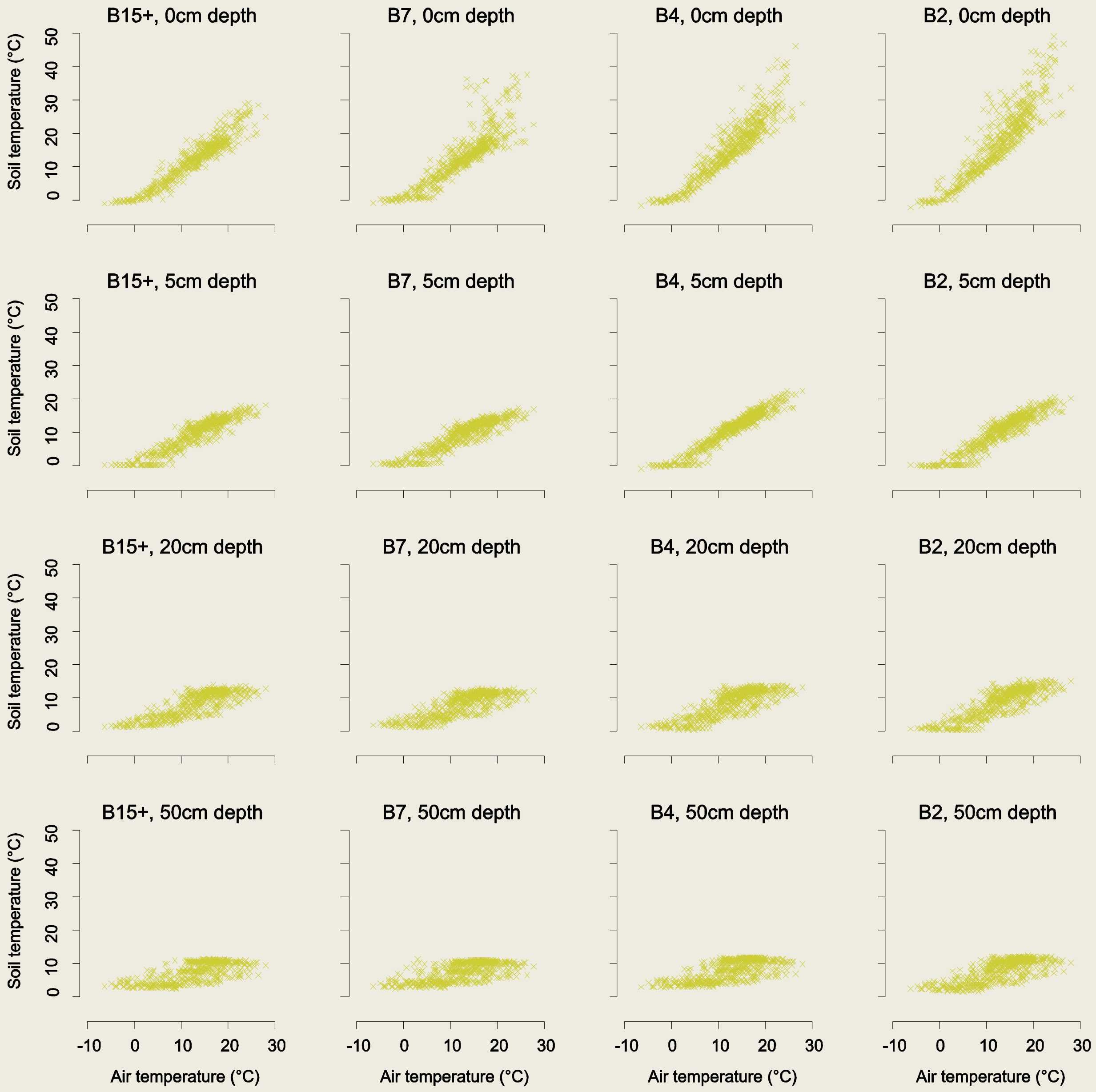

Figure 5.2. Relationships between maximum daily air and soil temperatures at four depths in top-slope plots.

6. RIVER ECOSYSTEMS

6.1. We sought to improve understanding of whether prescribed vegetation burning on blanket peatland is associated with significantly different benthic (riverbed) macroinvertebrate community structure and composition when compared with unburned systems. The work also examined associations between macroinvertebrates, water quality and benthic organic matter in rivers draining burned and unburned catchments. A full description of the major findings has been published in reference 12.

6.2. We sampled the larval stages (plus adult aquatic beetles) of macroinvertebrates in the study streams at quarterly intervals. Macroinvertebrates are organisms retained on a 1/4mm mesh, and which live in, on and under the sediments that form the river bed. They play a vital role in aquatic food webs by feeding on algae, microbes and detritus at the base of food chains before they are consumed by larger organisms such as birds, fish and amphibians. Common taxa collected during the study included mayflies (Ephemeroptera), Stoneflies (Plecoptera), Caddisflies (Trichoptera), Beetles (Coleoptera) and True Flies (Diptera, in particular Chironomidae (non-biting midges) and Simuliidae (black flies)).

6.3. We identified 95 taxa from the 300 samples collected as part of the study. There were statistically significant effects of burning on river macroinvertebrate communities. In particular, burned rivers had lower taxonomic richness and Simpson's diversity (Figure 6.1).

6.4. Macroinvertebrate density ranged from 76 to almost 2000 per m^2, but there was no statistical effect of burning on total invertebrate density (Figure 6.1). One potential reason for this lack of density response across the entire macroinvertebrate cohort is that increases in the abundance of disturbance tolerant taxa counteract declines and/or losses amongst more sensitive groups.

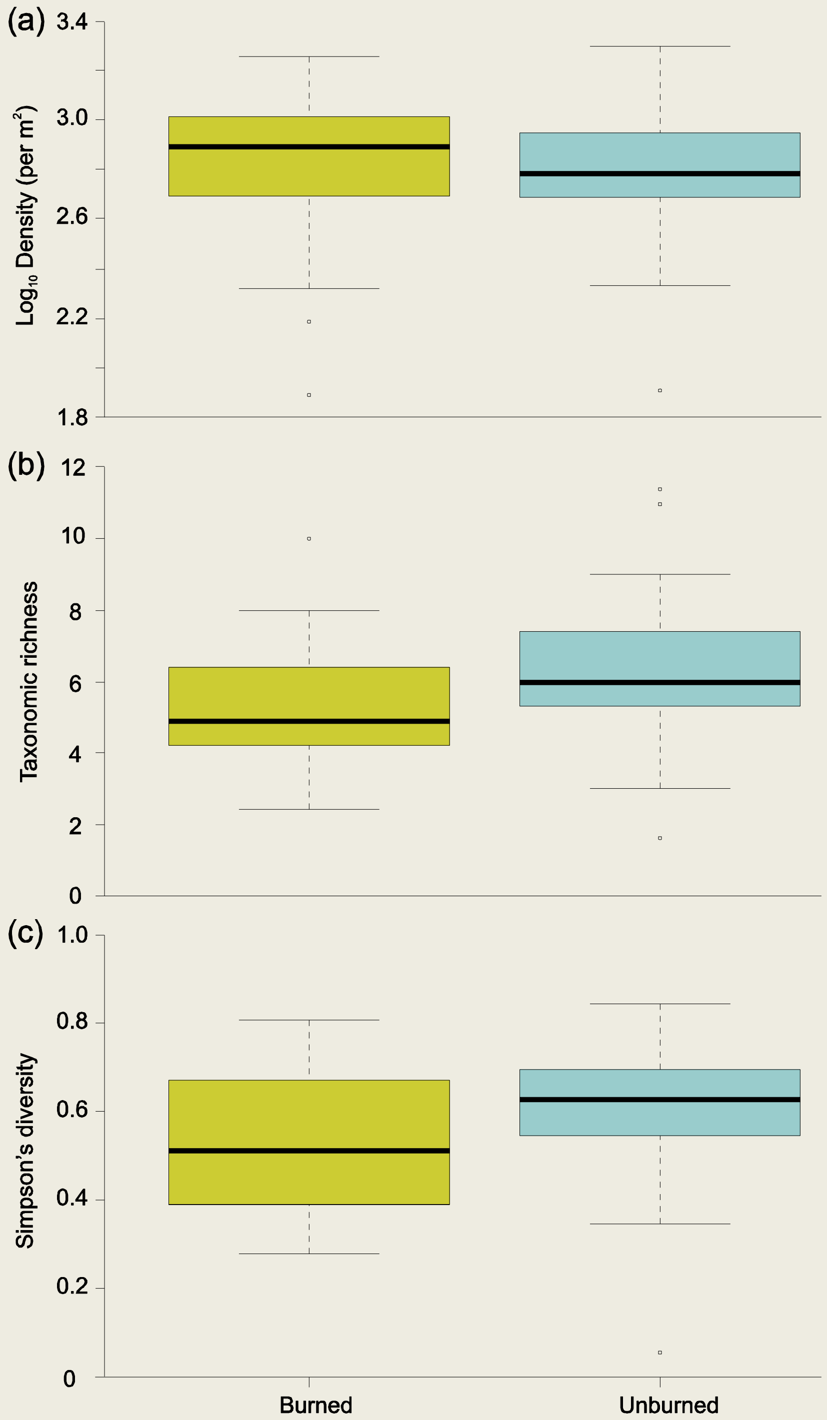

Figure 6.1. Boxplots summarising (a) Log10 total macroinvertebrate abundance, (b) Taxonomic richness and (c) Simpson's diversity between Burned and Unburned catchments.

6.5. At the population level, Plecoptera and Chironomidae were numerically the most abundant groups across all of the samples, although Ephemeroptera were notably less abundant in burned rivers. The relative abundance (%) of Ephemeroptera, Coleoptera and other taxa were all significantly reduced in burned rivers.

6.6. Burning was associated with a significant increase in the relative abundance of Chironomidae (Figure 6.2). Actual abundances of

Chironomidae and Nemouridae were also significantly elevated in burned rivers.

6.7. We typically observed *Baetis rhodani* to be the dominant Ephemeroptera species in burned rivers, although there were occasional collections of *Leptophlebia*, *Paraleptophlebia* and *Siphlonurus* spp.. These taxa were also present in unburned rivers but, in these systems, overall mayfly assemblages were more diverse and included *Serratella ignita*, various heptagenids and *Ameletus inopinatus.* The Ephemeroptera could therefore be a useful group for rapid, focused assessments of prescribed vegetation burning impacts rather than focusing on whole community responses.

6.8. There were significantly lower relative abundances of grazers and filterers (Figure 6.2) in burned rivers.

6.9. Multivariate analysis showed a strong separation of entire community composition between burned and unburned sites, particularly along axis 2 (Figure 6.3). There was some overlap between the two management categories, primarily because Oakner Clough samples plotted more negatively on axis 2 with most of the burned rivers. Analysis of Similarity (ANOSIM) revealed a significant effect of burning on the macroinvertebrate community composition.

6.10. Seven environmental variables (all representing water quality) were correlated significantly with the NMDS output. Burned sites were positively associated with higher Si, Mn, Fe and Al, whereas calcium and pH were positively associated with unburned sites. Higher Ca concentrations and pH in the rivers of unburned catchments may reflect the greater capacity of their soils to retain exchangeable base cations (see Section 3) and consequently to buffer acidity of percolating waters. The higher metal concentrations in rivers draining burned sites may indicate an influence of flow through underlying mineral soils, possibly as a result of lower water tables (see section 4).

6.11. The findings are supported by earlier detailed studies reported by Ramchunder et al.[29] on different rivers throughout the Pennines. However, for EMBER we sampled a greater number of rivers over a longer time-scale.

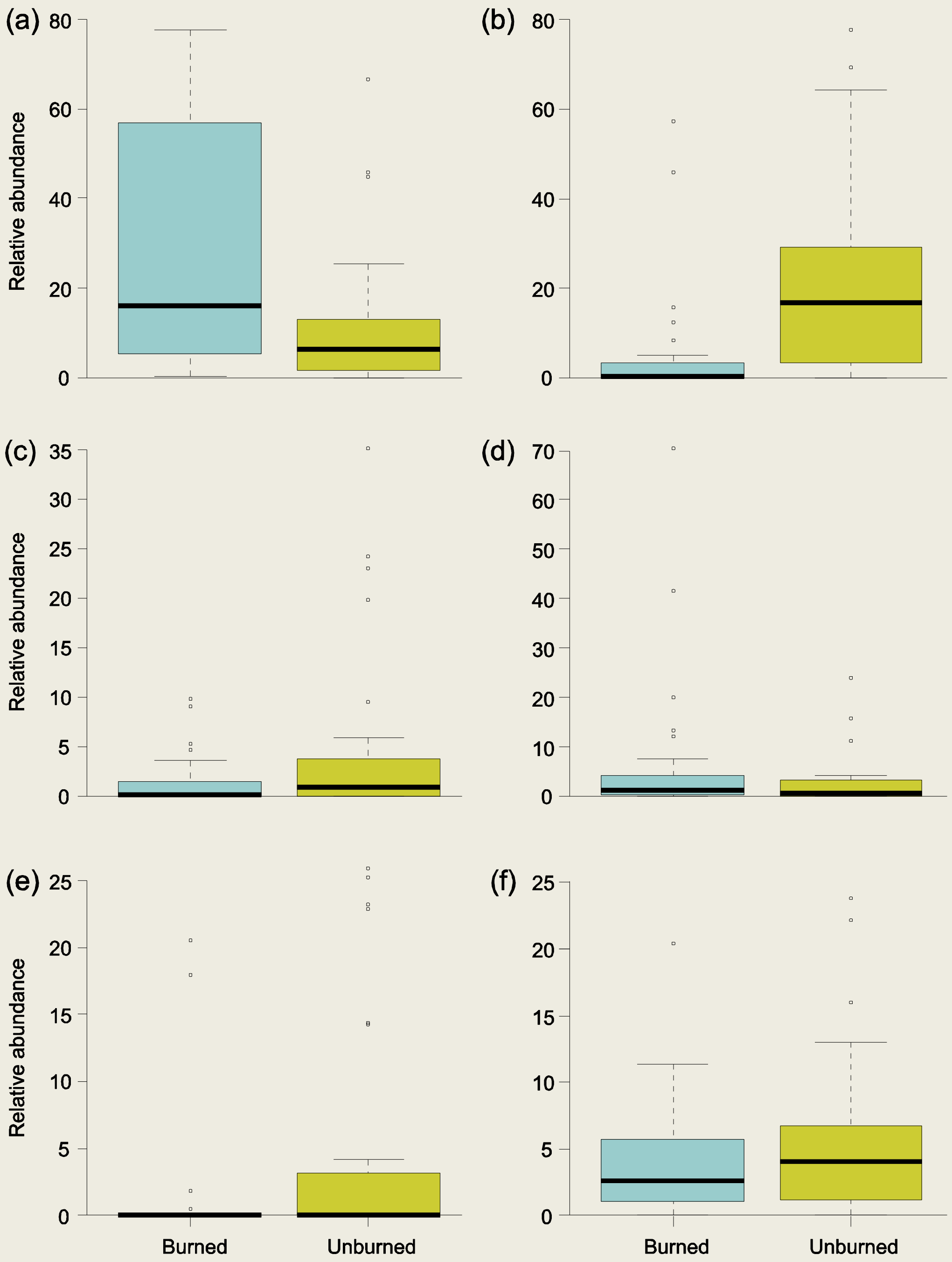

Figure 6.2. Boxplots summarising relative abundance of (a) Chironomidae, (b) Ephemeroptera, (c) Coleoptera, (d) Other taxa, (e) grazers and (f) filterers between Burned and Unburned catchments.

6.12. The similarity of EMBER macroinvertebrate results to those of the previous study[29] is a strong indication that there are some common effects of prescribed vegetation burning on upland river ecosystems. Further research is now needed to determine whether upland burning has effects on other riverine biological groups (e.g. microbes, algae, fish).

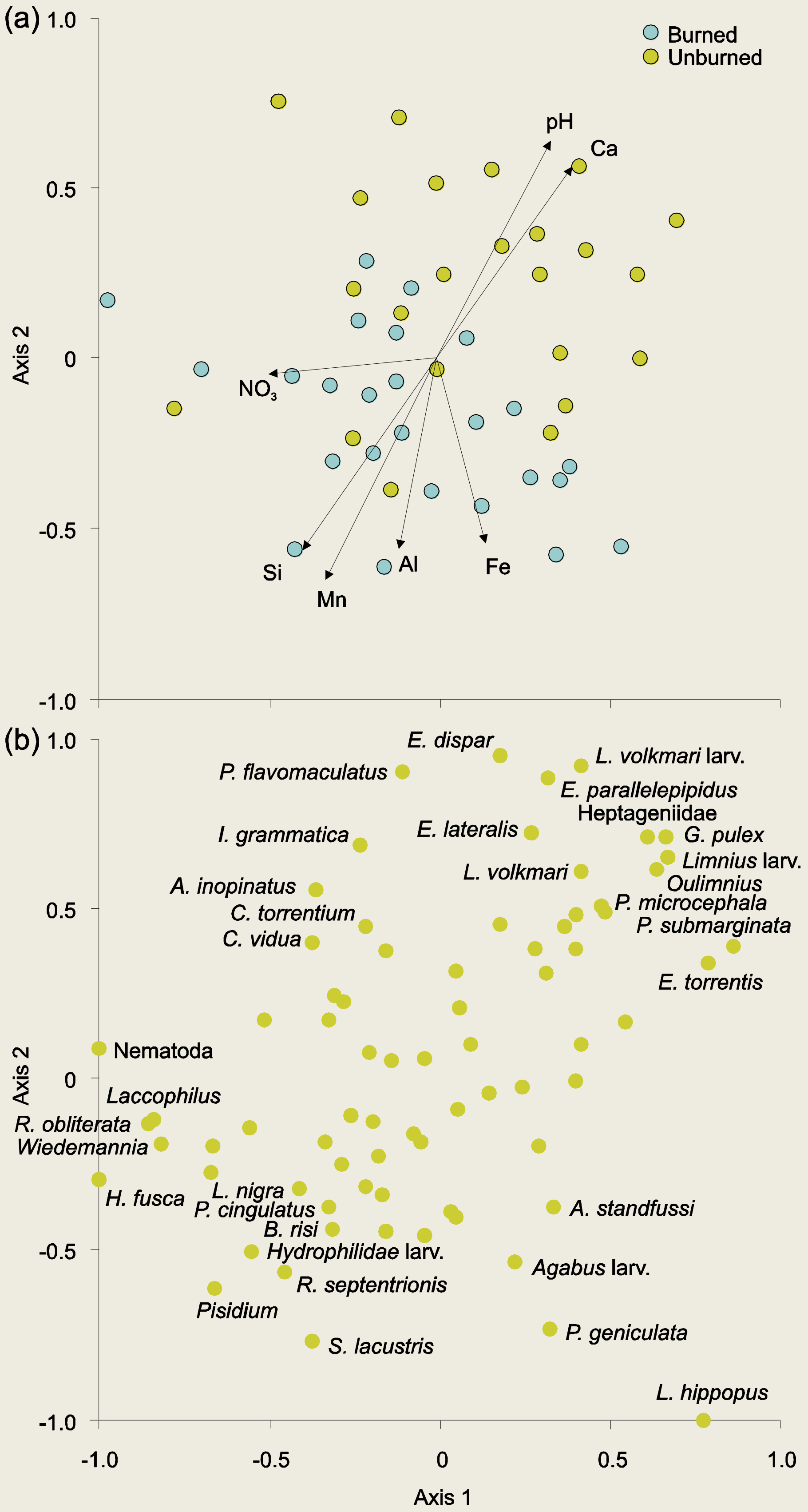

Figure 6.3. (a) NMDS biplot of samples and significantly correlated environmental variable vectors (pH: R^2=0.43, p=0.001; NO_3 (nitrate): R^2=0.20, p=0.014; Al (aluminium): R^2=0.27, p=0.001; Ca (calcium): R^2 = 0.39, p=0.001; Fe (iron): R^2=0.27, p=0.003; Mn (manganese): R^2=0.46, p=0.001; Si (silica): R^2=0.42, p=0.001), and (b) benthic macroinvertebrates.

7. SUMMARY

The University of Leeds EMBER project has provided new evidence that prescribed vegetation burning has clear effects on upland peat hydrology, peat chemistry and physical properties, river water chemistry and river ecology. We hope that the findings assist moorland managers in understanding some of the environmental effects of burn management on blanket peat. The project has provided new integrated understanding across multiple linked river basin processes (soils to streams), using comparable methods at replicated study sites and over a broad geographical region (English Pennines). Our data should help all parties who are involved in assessing the full range of socio-economic and environmental benefits and impacts of prescribed burning. We look forward to becoming involved in these assessments, and welcome further discussions and engagement with our future research activity.

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