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Vegetation management with fire modifies peatland soil thermal regime

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ABSTRACT

Vegetation removal with fire can alter the thermal regime of the land surface, leading to significant changes in biogeochemistry (e.g. carbon cycling) and soil hydrology. In the UK, large expanses of carbon-rich upland environments are managed to encourage increased abundance of red grouse (*Lagopus lagopus scotica*) by rotational burning of shrub vegetation. 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. In this study thermal regime was monitored across 12 burned peatland soil plots over an 18-month period, with the aim of (i) quantifying thermal dynamics between burned plots of different ages (from <2 to 15 + years post burning), and (ii) developing statistical models to determine the magnitude of thermal change caused by vegetation management. Compared to plots burned 15 + years previously, plots recently burned (<2–4 years) showed higher mean, maximum and range of soil temperatures, and lower minima. Statistical models (generalised least square regression) were developed to predict daily mean and maximum soil temperature in plots burned 15 + years prior to the study. These models were then applied to predict temperatures of plots burned 2, 4 and 7 years previously, with significant deviations from predicted temperatures illustrating the magnitude of burn management effects. Temperatures measured in soil plots burned <2 years previously 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 plots burnt 7 years previously were most similar to plots burned 15 + years ago indicating the potential for soil temperatures to recover as vegetation regrows. 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 these peatlands.

1. Introduction

Temperature plays an important role in soil ecosystem biogeochemistry by directly moderating rates of mineral weathering and soil water solution reactions (Brady and Weil, 2013), and indirectly by influencing the decomposition of organic matter (Davidson and Janssens, 2006; Grosse et al., 2011) and uptake of nutrients by soil dwelling flora and fauna (Allison et al., 2010; Conant et al., 2011; Melillo et al., 2002). Variations in soil thermal regime have been linked to changes in the abundance and diversity of soil microfauna (Allison and Treseder, 2011; Darby et al., 2011), seed germination and vegetation growth/production (Glinski and Lipiec, 1990), and nutrient uptake by plants (Dong et al., 2001; Pregitzer and King, 2005). Soil surface temperature can also influence latent heat fluxes and thus soil moisture (Kettridge et al., 2012), and is crucial for geomorphological processes such as freeze-thaw weathering (Holden, 2007). Soil temperature therefore plays a major role in global biogeochemical cycles, and so a clear understanding of the processes influencing soil thermal regime is a key requirement for ecosystem scientists and land managers to manage terrestrial environments effectively.

Fires are a common occurrence throughout the world, both naturally and for management purposes, in landscapes dominated by forest, grassland (e.g. prairie, moorland) and shrubs (e.g. chaparral, moorland) (Anderson, 1989; Yibarbuk et al., 2001), and in

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wetland and peatland environments in the UK (Ramchunder et al., 2013) and boreal North America, northern Europe and Siberia, and South-East Asia (Aksamit and Irving, 1984; Turetsky et al., 2011). Vegetation removal with fire can significantly alter the energy balance of the land surface by exposing underlying soils to more incoming solar radiation, altering long-wave radiation emission, and increasing exposure to wind thus changing latent heat fluxes. There are also likely to be changes in evapotranspiration which will influence soil moisture and thus specific heat capacity (Kettridge et al., 2012). Observational and modelling studies on soil temperature in some northern hemisphere peatlands have showed increases in temperature for the near-surface parts of the soil profile following wildfire (Harden et al., 2006; Kettridge et al., 2012). However, wildfires may exert more serious damage to peat soils than prescribed vegetation burning because they typically burn at far higher temperatures and often ignite the underlying peat in addition to the surface vegetation. Prescribed burns are utilised by land managers to control vegetation succession but no studies to date have considered their effects on soil temperature in the years after fire. Vegetation burning on UK peatlands has been associated with increased dissolved organic carbon (DOC) release to rivers in several studies with implications for potable water treatment (Holden et al., 2012), but the processes that underpin changes in soil C cycling and DOC release to rivers following fires are still poorly understood.

Peatlands cover around 4.4 million km^2 of the Earth's surface but they store a disproportionate amount of soil carbon (C); an estimated 500 ($\pm$100) Gt has accumulated since the Last Glacial which is equivalent to > 2/3 of the atmospheric store (Yu, 2012). These systems act as a long term C sink at a rate >5 Gt C per century (equivalent to 11 g C m^{-2} y^{-1}; Yu, 2012). In peatland soils, temperature is associated strongly with the carbon balance, and in particular, the production and oxidation of CH_4 which responds exponentially to increased temperature (Yvon-Durocher et al., 2014), the production of CO_2 (Lafleur et al., 2005; Moore et al., 1998) and the production and release of dissolved organic carbon (DOC) in pore waters (Freeman et al., 2001). Management changes to peatlands that lead to alterations in soil temperature can therefore be expected to have significant effects on the C balance of these systems.

Around 15% of the UK is covered with peat, with 87% of this being blanket peat (Baird et al., 2009). An estimated 3150 km^2 (18%) of UK peatlands have been subjected to prescribed burning (Worrall et al., 2010), although the use of this technique is regionally variable (Hester and Sydes, 1992; Yallop et al., 2006). Here, vegetation burning is undertaken mainly to improve production of red grouse (*Lagopus lagopus scotica*) populations but also to benefit grazing livestock and deer (Ramchunder et al., 2013) and occasionally for forest regeneration purposes (Hancock et al., 2005), and typically occurs in 10- to 20-year rotations. There have been several recent studies of prescribed burning effects on peatland vegetation, soil hydrology and soil solution chemistry (e.g. Clay et al., 2009; Worrall et al., 2007), and the evidence suggests that this management practice is altering fluvial C loads in upland peatland streams (Holden et al., 2012). To date, though, there has not been any consideration of how managed vegetation removal with fire and exposure of the underlying peat modifies the thermal regime of the soil mass in peatlands.

This study aimed to assess the role of prescribed vegetation burning on peat soil thermal regime at a series of intensively monitored locations in northern England. Specifically, thermal regimes were monitored across 12 burned peatland soil plots over an 18-month period to (i) quantify thermal dynamics between burned plots of different ages, and (ii) develop statistical models to determine the magnitude of thermal change caused by vegetation management. Soil thermal regimes were monitored in spatially independent soil plots spanning a period of <2 to >15 years since prescribed vegetation burning. Three hypotheses were tested: (H_1) upper soil-profile mean and maximum temperatures would be elevated in recently burned plots compared with areas of mature vegetation, but the effect would decrease as time since burning increased and vegetation cover regenerated; (H_2) upper soil-profile minimum temperatures would be lowest in recently burned plots compared with mature vegetation, which retain their 'insulating' canopy cover, and this combined with H_1 would mean a wider temperature range under recent burn plots; (H_3) enhanced soil surface maxima and minima in burned plots would be transmitted down into the soil at recently burned sites, but strong thermal attenuation would be evident with depth at all monitoring points.

2. Methods

2.1. Study area and field data collection

The study was undertaken in the southern Pennine hills of northern England between 28 March 2010 and 24 October 2011. The main study site was located in the Bull Clough catchment (53°28′24.8″N; 1°42′46.2″W) on Midhope Moor ~16 km SW of Barnsley, South Yorkshire. Much of the catchment is managed using prescribed burning of vegetation patches (typically ranging from 2500 to 5000 m^2) on a 20- to 25-year rotation, and it is considered to be a relatively typical peatland managed specifically for grouse. Soil plots in four age classes were studied: vegetation patches where burning took place <2 years prior to the beginning of the study (B2; recent burn), patches with burning 3–4 years prior to the study (B4; vegetation early growth phase), patches with burning 5–7 years prior to the study (B7; later growth phase) and patches that were burnt 15–25 years prior to the experiment (B15+; mature heather). Patch age was confirmed by the gamekeeper who knew when burning had taken place across the catchment. However, it was not possible to narrow down the age range of the patches that were burnt at some point between 15 and 25 years prior to sampling, although it is thought that most were last burnt around 20 years before our study.

For each age class (B2, B4, B7, B15+), three plots of approximately 400 m^2 were chosen with respect to the topographic index, $\ln(\tan\beta/\alpha)$, where β is the slope and α is drainage length per unit contour width (Beven and Kirkby, 1979). The use of the topographic index allowed us to control for any possible slope position effects, which is important because Holden (2009) showed that slope position can control the proportion of flow through macropores in several soil types, and thus soil moisture movement which would serve to moderate thermal variability. Each burn age class had one plot in a low topographic index setting, one in a mid-topographic index setting and the other in a high topographic index setting. Effectively, this was equivalent to a top-, mid- and foot-slope position. The same topographic index values were determined for plots chosen for each treatment so that slope position effects were controlled and were equal between treatments. Therefore data were collected at twelve spatially independent soil plots in total (4 age classes $\times$ 3 slope positions).

Soil temperature was measured in each plot at four depths: surface layer (0–1 cm), 5 cm, 20 cm and 50 cm. Traditional meteorological station measurements that obtain soil temperature do so at the surface, 5, 10, 20, 50 and 100 cm. However, it was not possible to instrument at all of these depths due to cost constraints and so 10 cm and 100 cm were not included. The depths we sampled conform well to typical plant structure and rooting depths in peatlands for mosses, grasses/sedges and dwarf shrubs. Soil temperature was measured at the end of each 15 min time interval using Gemini PB-5001 thermistors interfaced with Gemini Tinytag TGP-4520 dataloggers. The manufacturer's published accuracy is within ±0.3 °C across the temperature range experienced in this study. For surface measurements, probes were placed horizontally within the top 1 cm of the peat-litter complex and checked for position every three weeks. For sub-surface measurements, probes were inserted into the previously undisturbed soil using a wooden dowel (which was then subsequently retrieved) so that the probe tip containing the thermistor element was located at the desired measurement depth. Air temperature was measured using the same models of Gemini probe and logger as described above, but housed in a radiation shield mounted 1 m above ground surface. Air temperature data were collected at the same intervals and using the same logging procedure as for soil temperatures. For comparative purposes, soil temperature data were also collected from soil plots with mature *Calluna* cover on a peatland without prescribed burning at Oakner Clough, Close Moss (53°36′11.1″N; 1°58′03.4″W) near Marsden ~15 km north west of Bull Clough. Parts of the Oakner catchment were damaged in a wildfire on 9th April 2011, thus, when comparing between Bull Clough and Oakner Clough records, only those data collected pre-wildfire were used in this study to avoid any confounding effects. All dataloggers were synchronised prior to deployment in the field, and thereafter every three weeks following data download.

All soil plots at both Bull Clough and Oakner Clough had blanket peat depth of >1 m and were subject to very light sheep grazing at <0.5 sheep ha^{-1} (with no sheep November–February). Vegetation surveys conducted after the study period showed the site was dominated by *Calluna*, with widespread *Vaccinium myrtillus*, a high but patchy cover of *Rubus chamaemorus*, but very little *Sphagnum* cover and a sparse cover of *Eriophorum angustifolium* and *Eriophorum vaginatum* (Supplementary Table 1). Water tables were monitored automatically for each plot using Trafag DL/N 70 pressure transducers positioned in a dipwell located in the centre of each plot and recording at 15-min intervals; summary data are provided in Supplementary Table 1. Shallower water tables were, in general, found in the B15 + plots.

2.2. Data analysis

Raw data were summarised by calculating descriptive statistics from 15-min temperature datasets. Thereafter, all analyses used daily mean, maximum and minimum statistics calculated from 15-min resolution time series. Gaps in some temperature records (days 255–298, 2010 for B15 + plots) were applied to all other time-series to ensure comparable results. Scatter plots of air versus soil temperature data were created to illustrate the nature of thermal dynamics at all plots and depths. All graphical and statistical analyses were implemented in R 2.14 (R Development Core Team, 2014).

2.2.1. Regression model construction and evaluation

To assess whether vegetation removal with fire acted as a significant modifier of soil thermal regime, a generalised regression approach was developed to predict soil temperature time-series at burned plots (Bull Clough) from those measured at the unburned site (Oakner Clough). The approach is similar to that adopted elsewhere to model river water temperature dynamics following disturbance (Dickson et al., 2012; Gomi et al., 2006) and allows direct statistical comparison of time-series data where data are not temporally independent. Regressions were established to predict daily mean and maximum soil temperature under mature heather cover (B15+) at Bull Clough from soil temperature records collected at Oakner Clough. This approach was preferred over models utilising air temperature because it allowed the use of linear rather than logistic regressions. Datasets were split into equal length odd and even day datasets, with odd day temperatures used to build models and even day data used subsequently to evaluate model performance prior to application across fire impacted patches (see below). Initial exploratory ordinary least squares (OLS) regression, autocorrelation analyses and Durbin–Watson statistics highlighted significant residual autocorrelation for all time-series, and so generalised least squares (GLS) regression in the nlme package (Pinheiro et al., 2006) was used subsequently.

Models were developed as:

$$T_{soil[Bull]} = \alpha + \beta_1 T_{soil[Oak]} + \beta_2 \sin(2\pi j/T) + \beta_3 \cos(2\pi j/\mathrm{T}) + \varepsilon \quad (1)$$

where $T_{soil[Bull]}$ = soil temperature at either 0 cm, 5 cm, 20 cm or 50 cm measured under B15 + plots at Bull Clough, α = regression intercept, $ß$ = regression coefficients, $T_{soil[Oak]}$ = soil temperature measured at Oakner Clough for the same depth, j = calendar day of year, T = number of days in year (i.e. 365), and ε = error term. For some plots/depths, the sine and cosine terms were statistically insignificant ($p > 0.05$) and so these were omitted from analyses for those plots/depths. Error terms were modelled predominantly as either first- or second-order autoregressive processes based on *a priori* examination of autocorrelation and partial autocorrelation functions.

A measure of random disturbance ($\hat{u}_t$) was calculated as:

$$\hat{\mathrm{u}}_\mathrm{t} = (y_\mathrm{t} - \widehat{y}_\mathrm{t}) - \rho_1(y_{t-1} - \widehat{y}_{t-1}) - \rho_i(y_{t-i} - \widehat{y}_{t-i}) \quad (2)$$

where y = observed soil temperature for a given depth, $\widehat{y}$ = predicted soil temperature for a given depth on day t, and ρ = the lag autocorrelation coefficient(s) from the GLS regression.

Regression models developed using odd day data were evaluated in two ways; first, confidence intervals (95%) of odd day model estimates were calculated as 1.96($\sigma\ \hat{u}_t$) and compared visually with the distribution of $\hat{u}_t$ data. Second, soil temperatures under B15 + at Bull Clough for even day data were predicted following an odd-even day approach similar to Hannah et al. (2006). The production of $\hat{u}_t$explicitly accounted for autocorrelation through the incorporation of lag coefficients derived from the GLS regressions. Finally, two-sample Kolmogorov–Smirnov (K–S) tests were used (Gomi et al., 2006) to assess if $\hat{u}_t$had a similar distribution (i.e. $p > 0.05$) for both odd and even days.

2.2.2. Model application to recently burned soil plots

Odd day models derived for each slope position/depth were used thereafter to predict soil temperatures at equivalent slope positions and depths in rotationally burned heather patches B2, B4 and B7. Models were used to predict even day data for burned plots, and measures of random disturbance were calculated. K–S tests were used to compare distributions of $\hat{u}_t$between B15+ and either B2, B4 or B7; if $\hat{u}_t$had a similar distribution for these comparisons (i.e. $p > 0.05$) there would be no detectable effect of burning on soil thermal regime. For comparisons that produced statistically significant K–S test results, non-parametric effect sizes were calculated with Cliff's δ using the orddom package (Rogman, 2013). δ values range from −1 to 1, with a value of −1 denoting all observations were lower, and +1 all observations higher, than at B15+. ANOVA with Tukey HSD comparison was then used to determine whether there were differences in average estimates of daily mean and daily maximum $\hat{u}_t$at a given depth for the three plots (i.e. disregarding slope position) in each burn age category.

3. Results

3.1. Soil temperatures

Mean, maximum and variability (St. Dev) of temperature decreased with depth into the soil at all 12 plots, while minima were greater as depth increased (Table 1). With respect to fire 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 1). The greatest differences were most evident at the surface, with mean temperatures being greater by 0.5–0.9 °C under the most recent burn plots compared with under mature heather. Maximum temperature differences were extremely pronounced for B2 compared to B15 + plots, being >20 °C warmer in the top-slope plot, >12 °C warmer mid-slope and >33 °C warmer at the bottom-slope plot. In addition, minimum soil surface temperatures were consistently lowest in B2 plots by between 1.9 °C at the bottom-slope plot and 4.3 °C at the top-slope plot compared to B15 + plots. Fire effects were also notable at 5 cm depth, although the magnitude of difference was far lower than at the surface, with mean temperature increases of 0.3 °C in B2 compared to B15+, and maximum temperature differences ranging from 1.7 °C mid-slope to 7.4 °C in bottom-slope plots (Table 1).

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 (Figs. 1 and 2). For surface and 5 cm depth temperatures, soil temperature response was clearly 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 and foot-slope plots (Fig. 1). These effects were also seen in maximum soil surface temperatures, albeit much more pronounced (Fig. 2).

3.2. Model evaluation

Mean daily temperature models showed strong synchronicity between soil temperatures at Bull Clough B15 + plots and those at Oakner Clough, with β_1 coefficients >0.90 and in several cases equal to 1.0 for top and mid-slope positions (Supplementary Table 2). Maximum temperature models produced similar β_1 coefficients for 5 cm, 20 cm and 50 cm depths, although surface temperatures were more variable and β_1 coefficients were between 0.55 and 0.59, although in all cases the relationships were nevertheless statistically significant (Supplementary Table 3). Mean $\hat{u}_t$estimates for both mean and maximum daily temperature models were all close to zero, with standard deviations of <0.73 °C for all slope positions and depths, with the exception of maximum soil surface temperatures which were more varied (Table 2). Every model developed using odd day data produced no significantly different $\hat{u}_t$distributions when applied to even day data, thus it was possible subsequently to use the odd day models to determine the magnitude of thermal regime change in B2, B4 and B7 plots relative to B15+.

3.3. Model application

Disturbances for mean daily temperature data were significant at all depths and in all slope positions in B2 and B4 burn plots with the exception of B4 foot-slope surface (Table 3). Only top-slope surface measurements in B7 plots were significantly different to those in B15 + plots. Surface effect-size estimates were between 0.12 and 0.27. The magnitude of both the mean and standard deviation of significant disturbances was greatest at the surface in all B2 plots and top/mid-slope plots for B4, and decreased at greater depths (Table 3, Fig. 3). Boxplots illustrated that the effect of burning was most pronounced at top and foot-slope plots, with clear upward shifts in $\hat{u}_t$median, inter-quartile ranges and outliers from B15 + through to B2. Maximum $\hat{u}_t$estimates of 5.2 °C and 6.2 °C were observed at the surface for top-slope and foot-slope plots, respectively (Fig. 3).

Similar to daily mean temperature data, disturbances for maximum daily temperature data were significant in all B2 and B4 burn plots with the exception of B4 foot-slope surface (Table 4). Both top-slope and foot-slope surface maximum $\hat{u}_t$measurements in B7 plots were significantly different to those in B15 + plots. Surface effect size estimates for B2 and B4 maxima were generally higher than for mean daily data, ranging between 0.26 and 0.42. The magnitude of both the mean and standard deviation of significant disturbances was greatest at the surface in all plots and generally decreased with increasing depth (Table 4, Fig. 4). Boxplots illustrated strong effects of time since burning on maximum $\hat{u}_t$values at all slope positions, and clear upward shifts in $\hat{u}_t$median, inter-quartile ranges and outliers from B15 + through to B2. Maximum $\hat{u}_t$estimates reached 15.6 °C (top-slope), 9.8 °C (mid-slope) and 19.6 °C (foot-slope; Fig. 4). The range of temperature maxima also increased notably in recently burned plots, with minima being much lower in B2+ plots (−3.9 to −7.1 °C) compared to B15+ (−2.0 to −2.8 °C). Significant and relatively high

Table 1
Descriptive statistics derived from 15-min datasets for all combinations of slope position and soil depth. For each measurement location, data are presented in °C as Mean; Maximum; Minimum and St. Dev for the entire record.

Slope-position/depth	B15+	B7+	B4	B2
Top-slope				
Surface	8.1; 29.0; −2.8; 5.5	8.4; 37.7; −2.4; 5.5	8.6; 46.2; −5.0; 6.5	8.9; 49.1; −7.1; 7.3
5 cm	7.9; 18.2; −0.1; 4.5	8.0; 17.3; −0.1; 4.2	8.2; 22.4; −2.0; 4.8	8.2; 20.6; −0.9; 4.9
20 cm	7.8; 13.8; 1.0; 3.7	7.8; 12.8; 1.1; 3.5	8.1; 14.0; 0.4; 3.9	8.0; 15.4; 0.3; 4.2
50 cm	7.3; 11.4; 2.4; 2.9	7.5; 11.2; 2.3; 2.7	7.9; 11.7; 2.1; 3.0	7.6; 12.4; 1.4; 3.3
Mid-slope				
Surface	8.2; 32.2; −2.0; 5.4	8.0; 26.3; −1.1; 5.1	9.0; 49.5; −4.3; 7.3	8.7; 44.6; −5.2; 6.5
5 cm	8.0; 18.5; −0.3; 4.5	7.9; 17.3; −0.1; 4.3	8.1; 21.6; −1.9; 4.9	8.3; 20.2; −0.7; 4.8
20 cm	7.7; 13.6; 0.9; 3.8	7.6; 13.8; 0.7; 3.6	8.4; 15.5; 0.7; 4.3	7.7; 14.6; 0.6; 4.1
50 cm	7.3; 11.4; 2.5; 2.9	7.4; 11.6; 1.8; 3.1	7.7; 11.7; 2.5; 3.0	7.3; 11.8; 2.1; 3.2
Bottom-slope				
Surface	8.2; 29.0; −2.0; 5.4	8.5; 44.6; −2.9; 6.0	8.3; 39.0; −3.8; 6.0	9.3; 52.8; −3.9; 7.5
5 cm	7.8; 15.4; 0.1; 4.1	8.3; 21.3; −0.5; 4.5	8.3; 17.7; −0.2; 4.4	8.1; 22.8; −0.5; 4.6
20 cm	7.7; 13.5; 1.1; 3.7	7.9; 13.1; 1.1; 3.6	8.1; 14.1; 0.8; 3.9	8.1; 13.8; 1.1; 3.8
50 cm	7.2; 11.0; 2.6; 2.8	7.4; 11.1; 2.3; 2.9	7.7; 11.5; 2.5; 3.0	7.7; 11.8; 2.5; 3.0

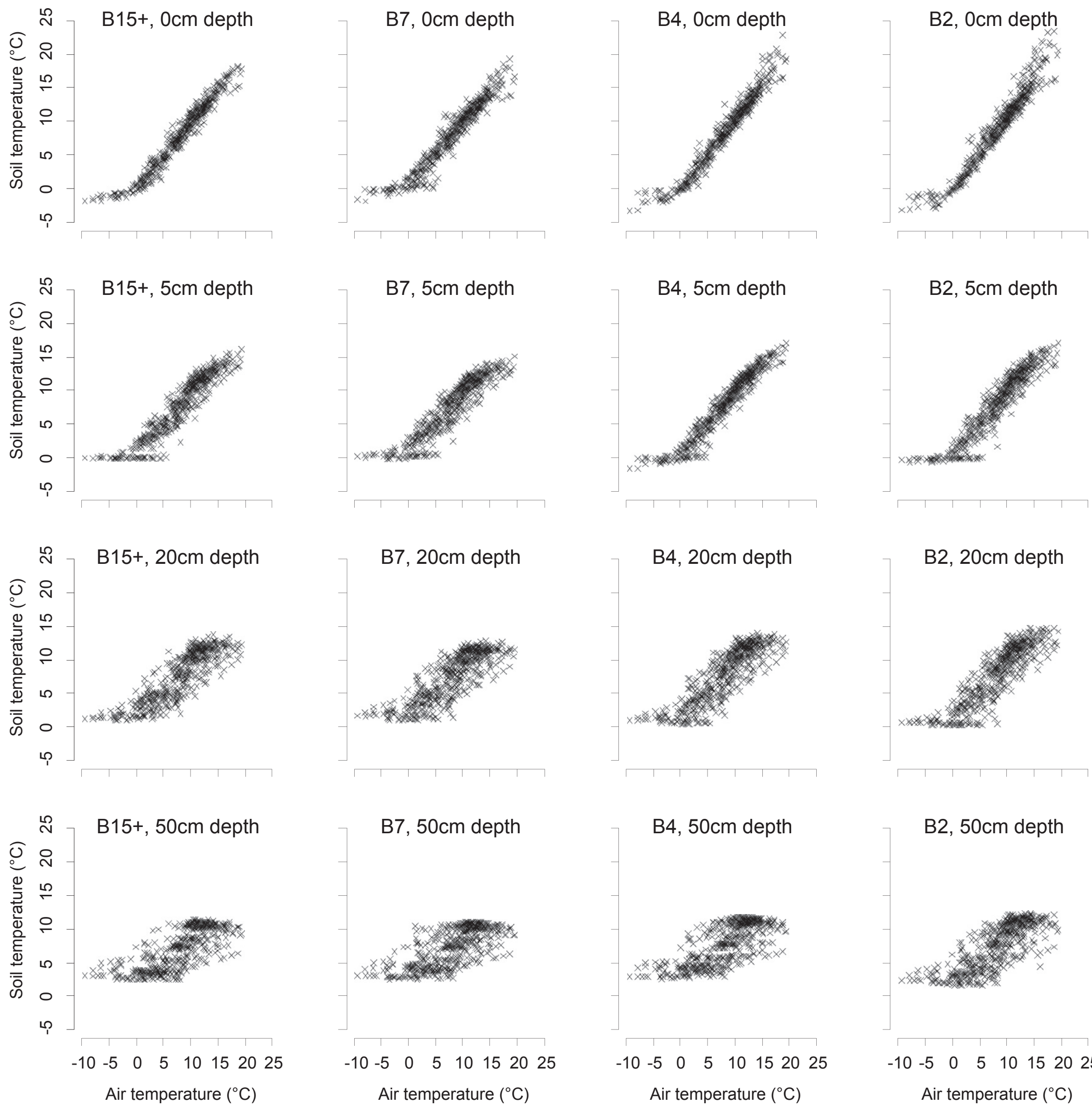

Fig. 1. Relationships between mean daily air and soil temperatures at four depths in top-slope plots. [See Supplementary Fig. 1 and 2 for mid- and foot-slope data].

temperature maxima effects were also recorded at 5 cm depth with up to 4.0 °C (top-slope), 3.1 °C (mid-slope) and 8.5 °C (foot-slope) difference. ANOVA showed significant differences in the magnitude of average daily mean $\hat{u}_t$between B2 plots and B15 + at the surface, and between B2 and both B7 and B15 + at 5 cm depth (Table 5). For daily maximum $\hat{u}_t$the only significant differences were observed between B2 and B15 + plots at the surface.

4. Discussion

Virtually all biogeochemical processes occurring in soils are temperature dependent (Pregitzer and King, 2005). However, near-surface processes within the peat can be extremely important in peatlands for both C processing (Cole et al., 2002) and hydrological fluxes (Holden and Burt, 2003). Therefore, our findings that prescribed peatland vegetation burning leads to significant increases in mean and maximum near-surface soil temperatures (H_1) as well as lower minima and thus wider thermal variability (H_2), 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. Our study spanned two summers but only one winter, therefore there are more observations of high versus low temperatures in our dataset. Nevertheless, the extreme warming seen in recently burned plots relative to those with mature vegetation may be one of the contributory factors associated with enhanced DOC release from peatlands subject to prescribed burning (Holden et al., 2012); this is because DOC generated in the upper few centimetres of the peat often dominates the stream water DOC signal (Clark et al., 2008).

Upper soil profile temperatures were elevated in recently burned patches compared with patches of mature vegetation, thus H_1 was accepted. 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 (Post et al., 2000). The exposure is partly related to the removal of vegetation by burning, but it is also due to the lack of protective litter cover in recently burnt plots compared to B15 + plots. The protective canopy and litter of plots that have not been burnt for many years would also insulate against heat loss at night and on cold days, reducing the temperature range compared with recently burnt peat (thus supporting H_2). While

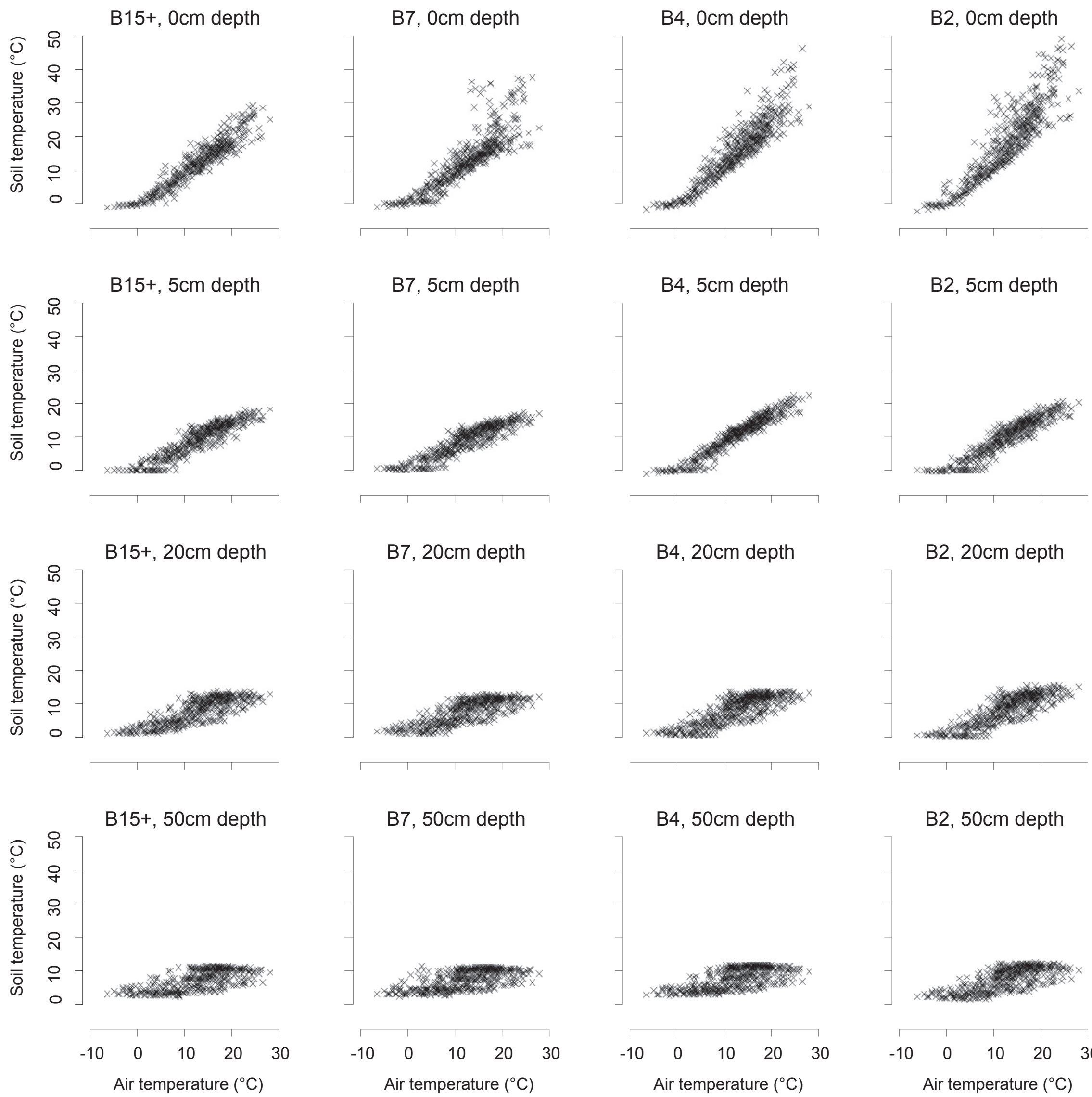

Fig. 2. Relationships between maximum daily air and soil temperatures at four depths in top-slope plots. [See Supplementary Fig. 3 and 4 for mid- and foot-slope data].

Table 2
Mean (±1 St.Dev) $\hat{u}_t$ estimates for mean and maximum daily temperature model validations, with significance results from K–S tests.

Slope-position/depth	Daily mean			Daily maximum		
	Odd	Even	p	Odd	Even	p
Top-slope						
Surface	0.0007 ± 0.66	0.002 ± 0.72	0.99	−0.005 ± 1.91	0.01 ± 1.93	0.59
5 cm	0.007 ± 0.44	0.01 ± 0.44	0.69	0.006 ± 0.63	0.03 ± 0.64	0.92
20 cm	0.0002 ± 0.32	0.0005 ± 0.32	0.92	0.0002 ± 0.32	−0.007 ± 0.31	0.92
50 cm	0.001 ± 0.08	0.0008 ± 0.08	0.51	0.001 ± 0.09	0.001 ± 0.10	0.97
Mid-slope						
Surface	−0.005 ± 0.69	0.01 ± 0.69	0.78	−0.005 ± 1.97	0.002 ± 1.82	0.92
5 cm	0.003 ± 0.38	0.02 ± 0.39	0.99	0.0001 ± 0.56	0.04 ± 0.59	0.35
20 cm	−0.003 ± 0.23	−0.008 ± 0.23	0.51	−0.004 ± 0.23	−0.01 ± 0.26	0.97
50 cm	−0.002 ± 0.05	−0.004 ± 0.05	0.92	−0.003 ± 0.05	−0.005 ± 0.05	0.97
Foot-slope						
Surface	−0.003 ± 0.70	0.005 ± 0.73	0.51	−0.007 ± 2.02	0.02 ± 1.86	0.50
5 cm	0.002 ± 0.27	0.002 ± 0.26	0.69	0.0002 ± 0.33	0.001 ± 0.37	0.92
20 cm	−0.003 ± 0.20	−0.007 ± 0.20	0.78	−0.005 ± 0.20	−0.01 ± 0.23	0.99
50 cm	−0.001 ± 0.05	−0.002 ± 0.05	0.86	−0.002 ± 0.05	−0.004 ± 0.05	1.00

Table 3
Mean (±1 St. Dev) $\hat{u}_t$estimates for odd day mean daily temperature predictions, with significance results from K–S tests for each age plot relative to B15+ [* = p < 0.05; **p < 0.01; ***p < 0.001]. Values in square parentheses are Cliff's δ estimates of effect size.

Slope-position/depth	B15+	B7+	B4	B2
Top-slope				
Surface	0.0007 ± 0.66	0.21 ± 0.70** [0.20]	0.36 ± 0.97** [0.23]	0.54 ± 1.32*** [0.27]
5 cm	0.007 ± 0.44	0.02 ± 0.43	0.18 ± 0.89*** [0.12]	0.14 ± 0.69* [0.12]
20 cm	0.0002 ± 0.32	−0.07 ± 0.27* [-0.12]	0.02 ± 0.43** [0.12]	−0.02 ± 0.67** [-0.03]
50 cm	0.001 ± 0.08	0.05 ± 0.41* [0.11]	0.11 ± 0.19*** [0.57]	0.03 ± 0.43*** [-0.01]
Mid-slope				
Surface	−0.005 ± 0.69	−0.008 ± 0.74	0.25 ± 1.11** [0.12]	0.23 ± 0.75*** [0.20]
5 cm	0.003 ± 0.38	0.003 ± 0.38	−0.07 ± 0.73** [-0.07]	0.17 ± 0.66*** [0.18]
20 cm	−0.003 ± 0.23	−0.06 ± 0.38** [-0.15]	0.06 ± 0.34*** [0.20]	0.08 ± 0.44*** [0.20]
50 cm	−0.002 ± 0.05	−0.01 ± 0.21*** [-0.15]	0.01 ± 0.07*** [0.23]	0.006 ± 0.10*** [0.18]
Foot-slope				
Surface	−0.003 ± 0.70	0.12 ± 0.92	0.01 ± 0.91	0.53 ± 1.47*** [0.23]
5 cm	0.002 ± 0.27	0.03 ± 0.54*** [0.03]	0.02 ± 0.86*** [0.07]	0.18 ± 0.76*** [0.12]
20 cm	−0.003 ± 0.20	0.003 ± 0.41* [-0.04]	0.09 ± 0.40*** [0.23]	0.10 ± 0.49*** [0.21]
50 cm	−0.001 ± 0.05	0.0005 ± 0.23*** [0.09]	0.02 ± 0.09*** [0.28]	0.02 ± 0.12*** [0.24]

transpiration would be expected to be much lower in recently burnt patches, evaporation might be greater if water tables are sufficiently close to the surface and so these effects might, in some circumstances, cancel each other out and not greatly impact soil temperatures (Thompson, 2012).

The exact nature of any evapotranspirative cooling effects and related feedbacks requires further study in these peatland systems, but evidence from other northern peatlands suggest evapotranspiration (ET) may depend on antecedent soil moisture conditions (Bridgham et al., 1999) and also on whether sites are *Sphagnum*-rich or not (Thompson and Waddington, 2013). At our sites, which had an almost complete lack of *Sphagnum* cover, recently burnt plots had lower near-surface hydraulic conductivity, smaller proportions of bypassing macropore flow and higher bulk density compared to B15 + or unburnt plots (Holden et al., 2014) demonstrating related physical and hydrological impacts of fire management. Slowed through flow of water and a reduction in bypassing flow would mean that recently burnt plots would have less moderation of their temperature because water moving through the peat would be warmed or cooled more by local plot conditions than water moving more quickly through the plot from upslope.

It is not clear why the soil temperatures of mid-slope plots were less affected by burning than the other plots, but one explanation may be related to water residence times. Soil water flowing through mid-slope plots may remain on the plot for a shorter period of time, and have less chance to be influenced by plot surface conditions, than water on the flatter top or foot slope areas. This effect may be enhanced by differences in hydraulic conductivity such as those found by Lewis et al. (2012) who suggested that near-surface hydraulic conductivity may decrease towards the centre of a peatland. Topographic exposure to wind may also contribute to temperature differences across the peatland system (Kettridge et al., 2012) such that more exposed top-slope plots may undergo enhanced evaporative cooling which may counteract (slightly) the warming effects on burnt top slopes on hot days when compared to mid-slope or foot-slope plots.

Overall there were very large surface temperature disturbances in B2 plots based on daily data. Even at 5 cm depth, mean and maximum daily temperature disturbances were of the order of 4–6 °C in B2 plots, supporting H_3 that surface thermal disturbances would be transmitted into the soil, whilst at B15+ and B7 plots temperature disturbances were less pronounced at 5 cm. Hence, the effect of surface vegetation modification by fire on peat temperatures is strong and appears to persist in plots that were burned several years previously. In line with our predictions for H_1 and H_2, however, there is strong 'space for time' evidence that the effects decrease over time since burning, as temperature disturbances from model predictions were typically lower for B7 plots compared with B2 and B4 plots at equivalent slope positions. This 'recovery' has also been seen in soil hydraulic conductivity and macropore flow analyses across the Bull Clough plots (Holden et al., 2014). The area of bare peat (Supplementary Table 1) was generally greatest on B2 plots with less than 4% on all B4 plots to 0% on B7 plots, thus the loss of the burn effect on soil temperatures appears to coincide with canopy closure which would alter surface albedo (Post et al., 2000). However, there were some small areas of bare peat (<4%) on one of B15 + plots where vegetation became more degenerated (as at the Oakner control plot) but at the same time there was a large increase in litter cover across two of the B15 + plots to a similar level to that at the Oakner plot, compared to all other plots. Litter cooling effects on surface peat during hot days has been observed during peat restoration projects (Price et al., 1998) and these effects, plus the insulating effects on cold days, have long been known from studies of soils in other environments (MacKinney, 1929).

The wider range of temperatures observed in recently burned plots compared to older plots is likely to contribute towards peat decomposition and erosion. At higher temperatures, microbial breakdown processes that enhance the production and supply of dissolved organic compounds to stream water could proceed more quickly (Holden et al., 2012), though so could the respiration of this organic matter (Yvon-Durocher et al., 2012). The balance between DOC production and respiration as a function of temperature needs to be studied in more detail in these systems to determine whether the warming effect is concomitant with net DOC increases or decreases (or no change) in soils, especially as some studies have found significant interactive effects of temperature and moisture availability on soil metabolism (O'Donnell et al., 2009). Alternatively, at the lower temperatures there could be enhanced generation of more particulates by freeze-thaw mechanisms. These particulates could subsequently be eroded and transported by wind and water to nearby streams (Imeson, 1971), where some recent studies have noted higher quantities of fine sediment in river bed sediments compared with streams in catchments that have no burning at all (Brown et al., 2013; Ramchunder et al., 2013). Thus, both dissolved and particulate C losses need to be considered when linking altered soil thermal regime to net changes in C.

The temperature maxima recorded in this study exceeded 50 °C in some plots, which was similar to peak temperatures that have been recorded in Canadian peatlands impacted by wildfire (Kettridge et al., 2012). Significant reductions (>50%) in mycorrhiza biomass are thought to occur only when vegetation burning results in soil temperatures >50–60 °C (Allison and Treseder, 2011; Certini,

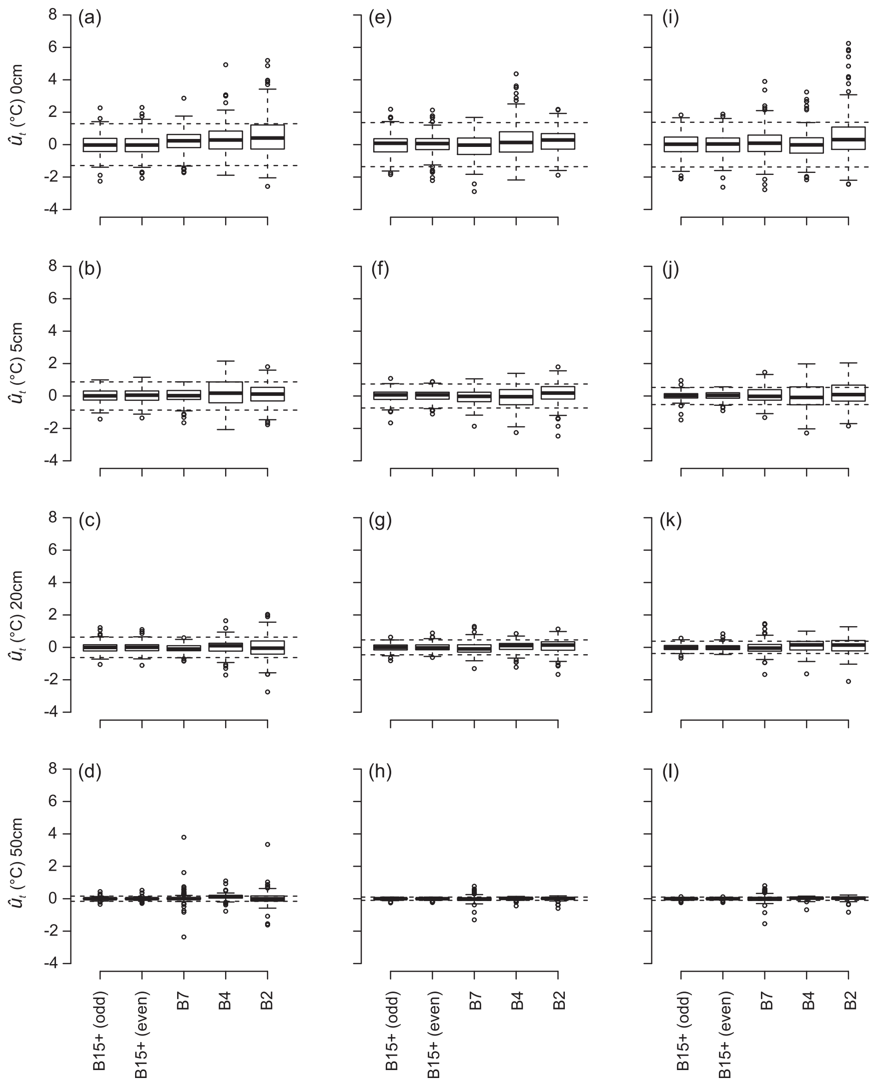

Fig. 3. Boxplots for mean daily soil temperature $\hat{u}_t$ estimates at: (a–d) top-slope, (e–h) mid-slope, (i–l) foot-slope plots. Broken horizontal lines denote the 95% confidence intervals of predictions from B15 + odd day models.

2005). However, while temperatures were not recorded concurrently with any vegetation burning, our results illustrate that temperatures above 50 °C occur during warm periods long after fires have passed. In a study of burned vegetation plots elsewhere in northern England, Ward et al. (2012) reported a significant reduction (83%) in fungal phospholipid fatty acids which may have been due to the loss of ericoid mycorrhiza. While Ward et al. (2012) did not report data on the thermal behaviour of their study sites, the

Table 4
Mean (±1 St. Dev) $\hat{u}_t$ estimates for odd day maximum daily temperature predictions, with significance results from K–S tests for each age plot relative to B15+ [^{x} = $p > 0.05$; * = $p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$]. Values in square parentheses are Cliff's δ estimates of effect size.

Slope-position/depth	B15+	B7+	B4	B2
Top-slope				
Surface	−0.005 ± 1.91	0.63 ± 2.37* [0.15]	1.88 ± 3.65*** [0.35]	2.77 ± 4.49*** [0.42]
5 cm	0.006 ± 0.63	0.009 ± 0.64	1.21 ± 1.67*** [0.47]	0.48 ± 1.13*** [0.27]
20 cm	0.0002 ± 0.32	−0.08 ± 0.27** [-0.18]	0.03 ± 0.44* [0.10]	0.06 ± 0.68*** [0.07]
50 cm	0.001 ± 0.09	0.05 ± 0.46	0.12 ± 0.18*** [0.58]	0.03 ± 0.33*** [0.02]
Mid-slope				
Surface	−0.005 ± 1.97	−0.21 ± 1.99	1.46 ± 3.50*** [0.26]	1.04 ± 2.44*** [0.26]
5 cm	0.0001 ± 0.56	0.006 ± 0.66	0.48 ± 1.17*** [0.27]	0.47 ± 0.99*** [0.34]
20 cm	−0.004 ± 0.23	−0.04 ± 0.38** [0.11]	0.07 ± 0.33*** [0.21]	0.10 ± 0.43*** [0.24]
50 cm	−0.003 ± 0.05	−0.01 ± 0.21*** [0.14]	0.01 ± 0.07*** [0.23]	0.006 ± 0.10*** [0.18]
Foot-slope				
Surface	−0.007 ± 2.02	0.89 ± 3.46* [0.12]	0.30 ± 2.65	2.27 ± 4.66*** [0.31]
5 cm	0.0002 ± 0.33	0.80 ± 1.40*** [0.33]	0.39 ± 0.74*** [0.35]	0.37 ± 1.48*** [0.15]
20 cm	−0.005 ± 0.20	0.08 ± 0.23** [0.22]	0.14 ± 0.35*** [0.34]	0.16 ± 0.34*** [0.42]
50 cm	−0.002 ± 0.05	0.0008 ± 0.07	0.02 ± 0.09*** [0.31]	0.03 ± 0.12*** [0.34]

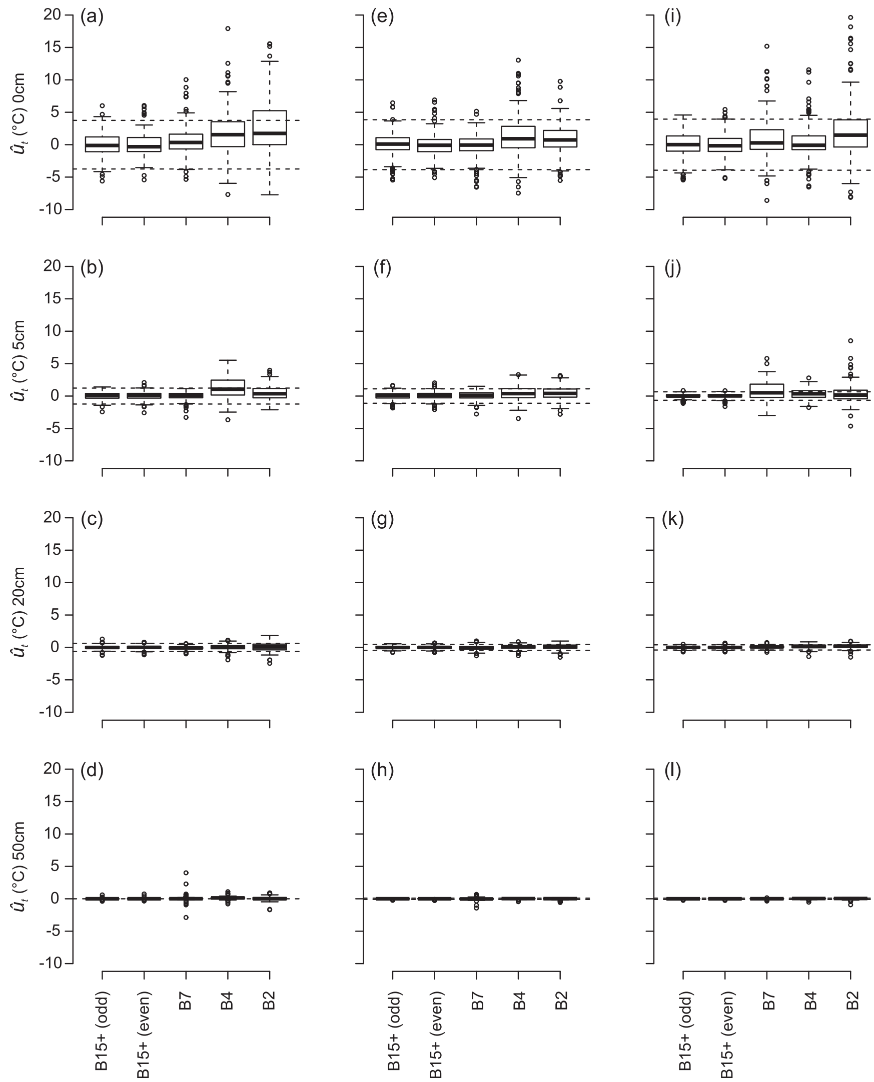

Fig. 4. Boxplots for maximum daily soil temperature $\hat{u}_t$ estimates at: (a–d) top-slope, (e–h) mid-slope, (i–l) foot-slope plots. Broken horizontal lines denote the 95% confidence intervals of predictions from B15 + odd day models.

soil temperatures recorded in our plots under similar burn regimes suggest that alterations to thermal regimes are likely to be a key driver of altered plant-soil function until re-vegetation with heather occurs.

The statistical modelling approach adopted as part of this study shows clearly the magnitude of effect that vegetation removal has on soil thermal regime. However, its main limitation is that it does not provide us with a mechanistic basis for understanding the thermodynamic processes that are driving such alterations (Kettridge et al., 2012). Such approaches are necessary to quantify, for example, the magnitude of any changes in incoming solar radiation reaching the peat surface under different canopy structures (Williams and Quniton, 2013), long-wave radiation emission, and the interactions between soil moisture, temperature, microtopography and air movement in driving latent heat fluxes (Bridgham et al., 1999). Future studies should therefore aim to monitor numerous meteorological and hydrological parameters at the soil surface across different aged plots.

The significant alteration of soil thermal regime following vegetation removal by burning indicates a potential need to rethink the ways in which vegetation management could be optimised to provide the desired open canopy for growth of fresh shoots, but still retain shading of the soil surface to minimise warming. One possibility that could be considered is to switch to cutting of vegetation (Glaves et al., 2013; Worrall et al., 2013) and leave a thick brash cover on the soil surface. However, while this may moderate any thermal effects it could prevent heather shoot regrowth and thus make foraging harder for young grouse, or lead to enhanced DOC generation from the decomposition of the cut vegetation litter. An alternative, that maintains aspects of burning but could still possibly mitigate against significant soil thermal regime alteration, is the burning of narrow strips that run east-west rather than burning larger open blocks. Thus, mature vegetation would provide some shading to the adjacent cleared strip, and it could also be a useful technique for reducing losses of game birds to aerial predators (The Heather Trust, 2013). Other considerations would be avoiding vegetation removal on south-facing slopes to minimise warming effects on exposed soils. Before any major changes in management approaches are considered though, it would be prudent to study in more detail the process links between energy inputs/losses, soil thermal regime and biogeochemical cycling in peatlands.

Table 5
Adjusted p-values from the ANOVA of average daily mean and maximum $\hat{u}_t$. Significant differences are highlighted in bold font.

	Daily mean				Daily maximum			
	B2	B4	B7	B15	B2	B4	B7	B15
Surface								
B2	–	0.26	0.08	0.02	–	0.44	0.09	0.02
B4	–	–	0.81	0.31	–	–	0.62	0.20
B7	–	–	–	0.76	–	–	–	0.72
B15	–	–	–	–	–	–	–	–
5 cm								
B2	–	0.23	**0.01**	**0.008**	–	0.77	0.92	0.40
B4	–	–	0.24	0.14	–	–	0.43	0.11
B7	–	–	–	0.97	–	–	–	0.74
B15	–	–	–	–	–	–	–	–
20 cm								
B2	–	0.84	0.85	0.14	–	0.84	0.62	0.05
B4	–	–	1.00	0.42	–	–	0.97	0.15
B7	–	–	–	0.40	–	–	–	0.27
B15	–	–	–	–	–	–	–	–
50 cm								
B2	–	0.70	1.00	0.87	–	0.75	1.00	0.88
B4	–	–	0.73	0.31	–	–	0.71	0.37
B7	–	–	–	0.34	–	–	–	0.91
B15	–	–	–	–	–	–	–	–

5. Conclusions

This study has demonstrated that prescribed vegetation burning in the UK uplands leads to significant changes in soil thermal regime. The greatest effects were observed at the soil surface, and in most plots were transmitted into the soil to depths of up to 20 cm. Thermal regime changes were most notable in soil plots that had been burned within 2 years of the study, but showed a clear tendency to recover in plots as vegetation regrows. 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 peatlands.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.02.037.

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