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Assessing soil heating beneath prescribed burns undertaken by teams according to the first UK vegetation fire standards

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ABSTRACT

Background. Prescribed burning (PB) has been used on UK heathlands for centuries, with controversy over its potential to heat organic-rich soils. In recent years accredited training has been available to UK land managers providing them with improved skills with which to burn safely. **Aims.** We assessed the levels of soil heating beneath PBs undertaken by these upskilled teams and provide an assessment of a range of burns using the same methodology at each burn. **Methods.** In-field measurements of soil (3 cm depth), above-ground temperatures and fire severity assessments were taken during eight PBs across the UK, conducted under mild weather conditions and complying with PB guidance. **Key results.** Both organic-rich peaty soils and mineral soils received little heating during the PBs tested, with mean maximum soil temperatures of <43.4°C, and surface mean maximum temperatures of 784.5°C. Fire severity assessments indicated no below-ground organic matter loss. **Conclusions.** When following new accredited training, and according to Department for Environment, Food and Rural Affairs current guidance, underlying soils were not subjected to high temperatures that could directly damage long-term carbon stores. **Implications.** Our results provide valuable insights into soil temperatures reached during PBs, highlighting that well-planned fire can be used safely in respect to burning vegetation particularly over organic-rich peaty soils.

Keywords: heathland, moorland, temperature, prescribed burning, lighting, peat, soil, fire, land-management.

Introduction

Prescribed burning (PB) is the controlled application of fire and a common management technique to maintain habitats and enhance productivity (Bowman *et al.* 2011). In the UK, PB on moorlands (open upland landscapes) and heathlands (upland and lowland heath habitats) is often associated with reducing fuel loads and generating new growth of palatable young plant shoots for red grouse and livestock grazing (Worrall *et al.* 2010).

In the UK an estimated 423,000 ha of grouse moorlands are managed using PB (GWCT Peatland Report 2020), commonly over a burn cycle of every 8–25 years (Harper *et al.* 2018) alongside grazing and cutting (Appleton and Smith 2022). In addition, areas of lowland heath in Cornwall, Devon, Dorset and the New Forest (Hampshire) are also burned regularly to remove high fuel loads of gorse and manage heath for both plant and animal diversity (Allchin 1998; Smith *et al.* 2023). Yet, whilst PB has been used for centuries (Allen *et al.* 2016), the use of fire as a land and fuel management practise in the UK is heavily debated (Davies *et al.* 2019), owing in part to concerns of its impacts on the heating and potential carbon loss of organic-rich soils. Concerns over unintended fire spread and peat ignition generating smouldering of underlying peat during PBs has led to a ban (unless an explicit exception is issued) in England on burning vegetation over peat deeper than 30 cm (Defra 2025). Indeed, soils are Earth's largest terrestrial organic carbon stock (Georgiou *et al.* 2022), and peatlands constitute the most carbon-dense soils, storing over 600 Gt of carbon (Noble *et al.* 2019 and references therein). Fire affects the biological, chemical and physical properties of soils where the direct impact is governed by both temperature and the duration of heating the soil receives during a fire (Mataix-Solera *et al.* 2011; Santín and Doerr 2016).

Europe's heathlands are of considerable conservation interest (Habitats Directive 92/43 ECC) and both moorlands and heathlands are expected to meet increasing societal demands, balancing landscape management with ambitions of maintaining biodiversity, air quality, water quality as well as net zero emission goals, including maintaining the carbon stored in peat (Appleton and Smith 2022).

This aim is somewhat reflected in burn guidance such as the Heather and Grass Burning Regulations (Defra 2007; Welsh Assembly Government 2008) and the Muirburn Code (SEERAD 2008; Worrall *et al.* 2010) which aim to ensure that 'quick, cool burns' are conducted particularly over carbon-rich or peat soils to prevent damage to these carbon stores. The term 'cool burning' describes the technique used to burn vegetation with a higher moisture content, thus removing surface vegetation without damaging underlying organic-rich-soils (Worral *et al.* 2010; Evans 2021). As such PBs may only be conducted during the burning season (October/November to March/April), under certain weather conditions and when fuel moisture is high. For example, guidance indicates that burns should be conducted when wind speeds are below 5 m s^{-1} in Scotland (NatureScot 2021) and below 6.7 m s^{-1} in Wales, and only between sunrise and sunset when conditions are considered to be not too dry (Welsh Assembly Government 2008). In England, wind speeds should be below 8 m s^{-1}, the temperature below 30°C and humidity above 30% (Devon and Somerset Fire and Rescue Service 2024).

In the UK, an estimated ~114 km^2 of UK uplands are burnt yearly (Yallop *et al.* 2006) and whilst these burns are aimed to be 'cool burns', there is little published in-field evidence surrounding the temperature that soil layers reach as a result of these 'quick, cool burns' conducted to recent burning legislation.

A recent global compilation of soil temperatures and heating durations revealed that in shrublands, mineral soils up to 2.0 cm depth recorded temperatures exceeding 100°C for up to 3600 s during PBs, averaging 304°C at the soil surface (Doerr *et al.* 2025). Within the UK, maximum 'fire' temperatures during traditional PB for grouse moor management have been reported to range between 600 and 980°C (Malik and Gimingham 1983; Noble *et al.* 2019 and references therein), with average maximum temperatures of ~250°C reported at the moss surface on a peatland site in northwestern Scotland (Hamilton 2000). However, much of the data that exist are now likely out of date, as there has been a considerable drive to upskill burn teams in the UK over recent years, providing them with vegetation fire training (for example, through two formal courses 'Vegetation Fire Operator' (VFO) (Lantra 2025*a*) and 'Prescribed Fire Operator' (PFO) (Lantra 2025*b*)). In undertaking vegetation fire training, burn teams are trained to make fuel considerations, such as surface fuel type and soil type, as well as identify fire breaks and monitor weather conditions. Each of these are important aspects in preventing unintended fire spread and ensuring that the burns conducted are not capable of igniting and generating smouldering of underlying peat soils.

Moreover, existing studies have tended to focus on individual sites or individual burns (e.g. Whittaker (1961), (Schimmel and Granstrom 1996), Davies *et al.* (2010), (Grau-Andreas *et al.* 2017, 2019)) making it difficult to assess whether soil heating effects are consistent between PBs carried out according to latest training guidelines and across soil types. To address this gap, this study seeks to assess the levels of heating achieved below the surface within organic-rich soils and mineral soils, using the same experimental monitoring set-up across eight different burns undertaken across the UK stretching from Scotland in the north to Dorset in the south. Our aim was to assess the underlying soil temperature during these PBs, and evaluate whether the temperatures reached could damage the soil layers and their carbon store.

Methods

All PBs monitored were undertaken by four different trained burn practitioner teams in the surface fuels of moorland and heathlands covering both upland and lowland heath, where at least one member of the four burn teams had been trained, and where that trained person led the burns. This number of trained team members was typically greater than one. All of those trained were trained by a UK Wildland Fire Tactical Advisor and at a minimum level of Lantra VFO (Lantra 2025*a*). This meant that each burn identified aims and objectives, proposed a clear area of burn, identified fuel breaks, made considerations of e.g. soil type, surface fuel types, whether there were fuel ladders or aerial fuels present (where close to forestry), and the topography and aspect of the proposed burn plots. Weather and fuel conditions were monitored over potential burn periods, and burns only ran in safe fire weather conditions.

The land management practitioners we studied employed gas torches or drip torches as the form of ignition and lit the fires to run either as head fires or a combination of head and flanking fires across varying slope aspects (up-slope, down-slope and across slope fire propagation), with the overall aim to generate 'quick cool burns'.

Eight sites were selected to capture both *Calluna* dominated and mixed heath habitats (home to multiple species including *Erica* sp., *Ulex* sp., *Molinia* sp. and *Calluna*) as both have a long history of management in the UK using fire (Tucker 2003; Harper *et al.* 2018). As these habitats are underlain by both organic-rich peaty soils (wet heath habitats) as well as acidic-sandy mineral soils (dry heath habitats), we selected sites to capture both soils types. The sites underlain by peaty soils were The Cawdor Estate, Scotland,

and Spaunton Moor, England. For the Cawdor subsites, three of the four sites are classed as having underlying peaty gleyed podzols, with one site classified as blanket bog (Scottish Natural Heritage 2023). At Spaunton Moor, the soil is described as acid upland soils with a peaty soil surface (UK Soil Observatory 2025). Those sites underlain by mineral soils (acid sandy soils, Fig. 1) were Corfe Common, England and Rempstone Forest, England.

Each of the sites comprised varying fuel types and loads, with maximum heights ranging from 0.3 to 1.6 m (see Table 1). At Cawdor and Spaunton the vegetation was dominated by *Calluna vulgaris*. At Rempstone Forest the vegetation was heather dominated (a mix of *Erica* spp. and *Calluna*) with intermixed *Ulex* spp., *Molinia Caerulea* and *Pteridium aquilinum* and small *Pinus* sp. saplings, whilst Corfe Common, Dorset, was primarily *Ulex europeaus* and *Molinia caerulea* mix (Table 1).

Across the four sites, eight burns were conducted (Table 1), with four burns undertaken at the Cawdor Estate, two at Spaunton Moor and one each at Rempstone and Corfe Common. Prior to ignition a network of K-type thermocouples were deployed across each burn plot. 20–35 Testo 176T4 data loggers (Testo 2024) were set up at regular ~2 m intervals, starting at least 1 m from the edge of the burn plot (Fig. 2). Each logger was attached to four Type K-310 thermocouples.

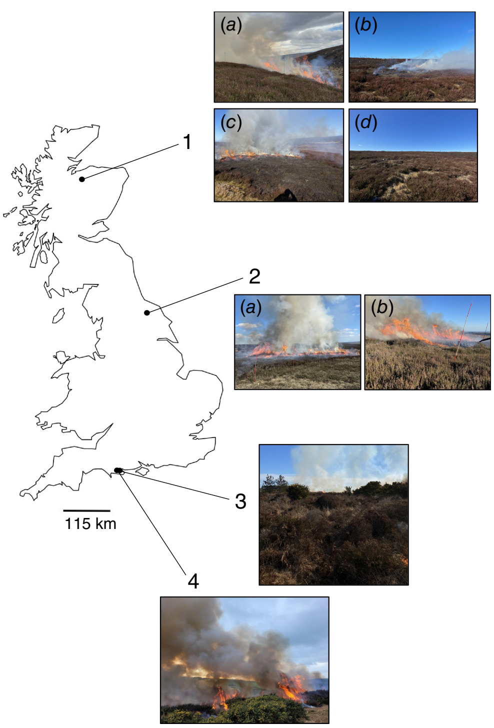

Fig. 1. Map illustrating the site locations of the management burns tested, and photographs of the sites in this study. 1. The Cawdor Estate, Scotland (photographs *a* – 23 March 2023 burn; *b* – Fire 1; *c* – Fire 2; *d* – Fire 3); 2. Spaunton Moor, England (photographs *a* – Fire 1; *b* – Fire 2); 3. Rempstone Forest, England; 4. Corfe Common, England.

Soil temperature measurements were taken where one thermocouple for each logger was placed ~2–3 cm beneath the litter and duff layer into the soil at each location. Another thermocouple was placed on the litter surface, a third was attached to a pole and secured at 40 cm height above the ground (with the end of the thermocouple ~40 cm away from the pole so that any heating generated from the pole did not impact the thermocouple), and the fourth was secured 80 cm above the ground. The 40 and 80 cm thermocouples sought to measure within shrub canopy and above shrub canopy temperature, as well as the duration of heating as the fire front passed each logger within the plot.

The PBs were not interfered with and were left to be conducted by each trained burn team, ensuring that we captured the typical behaviour generated by the teams. We recorded the ignition method and propagation of each fire with regard to slope aspect and wind direction (Fig. 2). Every thermocouple location was photographed (both pre- and post-burn) and the vegetation type and average height recorded in a 50 × 50 cm quadrat adjacent to each datalogger. Each of the quadrats were then scored for their fire severity post-burn. Fire severity scores provide a qualitative visual evaluation of aboveground and belowground organic matter loss (Keeley 2009). For aboveground, severity scores evaluate evidence of superficial charring of vegetation with fine-fuels still intact (giving a low severity score of 2 'scorched') or whether fine-fuels were consumed (severity score of 4 'moderate-severe surface burn'). For soil layers, where the litter layer is charred but the soil organic layer is still intact, a low severity score is given ('light burn'), compared to where the soil organic layer has been consumed (severity score of d – 'deep burn'). We adapted the fire severity scoring descriptors for heathlands of New *et al.* (2018), with the descriptors used given in Supplementary Table S2.

The PBs captured a range of slope aspects within three of the burns conducted at the Cawdor Estate, capturing upslope propagation (23 March), downslope (Cawdor Fire 1 (CF1)) and across slope (Cawdor Fire 2 (CF2) and 3 (CF3)) and no slope (Spaunton Moor, Rempstone).

Weather data were collected using a Kestrel 5400 Fire Weather Pro, where relative humidity, temperature and wind speed were recorded every 60 s throughout the burns (Table 1). At low humidity levels, fine vegetation fuels dry out, becoming easier to ignite with lower fuel moistures, whilst high wind speeds can help increase fire propagation causing it to spread faster. Hence, burning safety regulations state that wind speeds should be below 5–8 m s^{-1} and fuel moisture high (Welsh Assembly Government 2008; NatureScot 2021; Devon and Somerset Fire and Rescue Service 2024). Each of the burns conducted were representative of these conditions (Table 2). Weather conditions during the burns were mild, with wind speeds for all burns below 5 m s^{-1}, pre-burn relative humidity remaining above 40% and air temperature remaining low, sitting below 10°C prior to all of the burns (Table 2).

Table 1. Summary of the different ignition sources, slope aspect; pre-fire vegetation details of how each of the controlled burns propagated for each of the burn sites used in this study and the placement of thermocouples in each of the burns.

Location	**Cawdor 23 March Inverness-shire, Scotland**	**Cawdor fire 1 Inverness-shire, Scotland**	**Cawdor fire 2 Inverness-shire, Scotland**	**Cawdor fire 3 Inverness-shire, Scotland**	**Rempstone Dorset, England**	**Spaunton fire 1, North Yorkshire Moors, England**	**Spaunton fire 2, North Yorkshire Moors, England**	**Corfe Common Dorset, England**
PB reference in text	**Cawdor 23 March**	**CF1**	**CF2**	**CF3**	**Rempstone**	**SF1**	**SF2**	**Corfe Common**
Grid reference	**(57.42600, -3.83516)**	**(57.42600, -3.83516)**	**(57.42600, -3.83516)**	**(57.42600, -3.83516)**	**(50.65889, -1.99041).**	**(54.32167, -0.89578)**	**(54.32167, -0.89578)**	**(50.62684, -2.06269)**
Date of burn	23 March 2023	27 March 2023	27 March 2023	27 March 2023	28 February 2023	28 March 2023	28 March 2023	24 Feb. 2023
Area of burn monitored (m^2)	365	334	331	536	753	580	360	271
Ignition source	Gas torch	Gas torch	Gas torch	Gas torch	Drip torches	Gas torch	Gas torch	Drip torch
Burn propagation	Head fire	Head fire	Head fire	Head fire	Head fire	Head fire	Head fire	Flanking head fire
Measurements taken	Soil, surface, 40 and 80 cm height	Soil, surface, 40 and 80 cm height	Soil, surface, 40 and 80 cm height	Soil, surface, 40 and 80 cm height	Soil, surface, 40 and 80 cm height	Soil, surface, 40 and 80 cm height	Soil, surface, 40 and 80 cm height	Soil, surface, 40 and 80 cm height
Heathland type	Upland	Upland	Upland	Upland	Lowland	Upland	Upland	Lowland
Slope aspect	Burn propagated upslope	Burn propagated downslope	Burn propagated at right angle to slope	Burn propagated across slope	No slope	No slope	No slope	No slope
Vegetation type	Heather dominated	Heather dominant, some *Molinia* interspersed within heather (<10% cover)	Heather dominant, some *Molinia* interspersed within heather (<10% cover)	Heather dominated	Mixture of ferns, *molinia*, gorse and *Erica* sp. with interspersed young pine trees[A]	Heather dominant (*Calluna vulgaris*)	Heather dominant (*Calluna vulgaris*)	*Molinia* and gorse
Maximum height of vegetation recorded (m)	0.30	0.30	0.30	0.35	0.85	0.65	0.80	1.60
Average vegetation height recorded (m)	0.25	0.25	0.25	0.3	0.65	0.60	0.60	0.67

[A]No data loggers were set up next to the young interspersed pine trees. 'PB' refers to 'prescribed burning'.

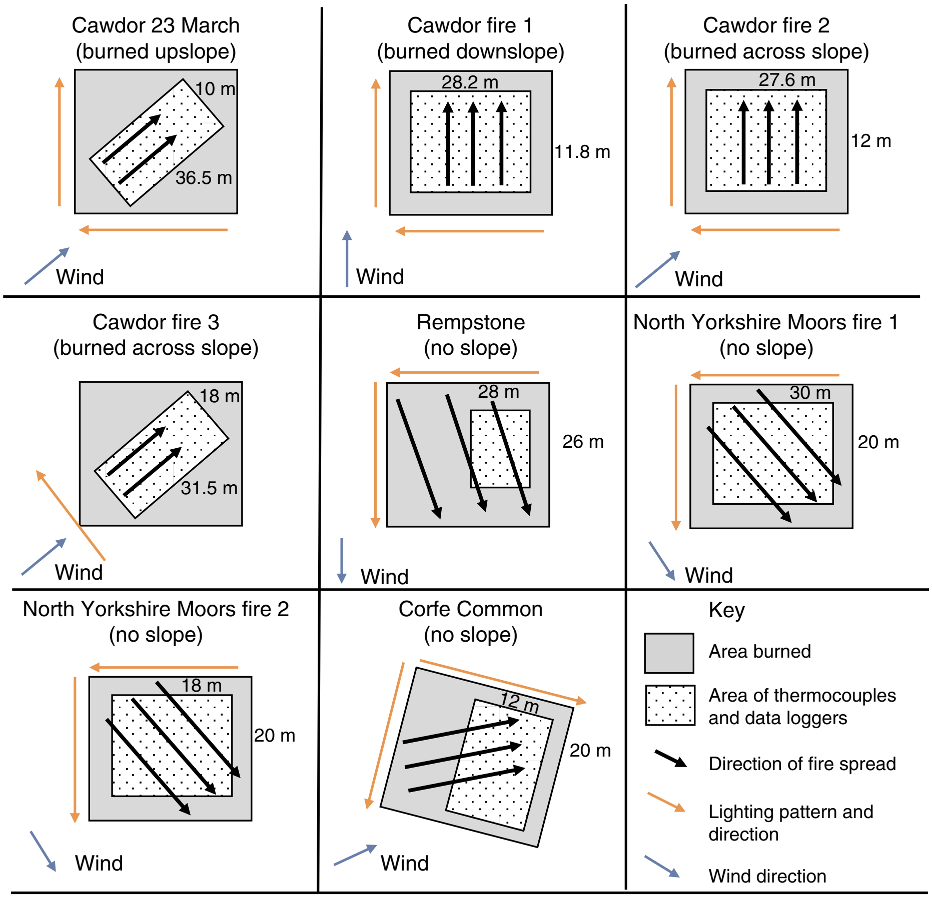

Fig. 2. Lighting patterns and wind direction for each of the prescribed burns monitored. Measurements represent the area covered by thermocouples.

Results

Temperatures and duration of heating recorded during the prescribed burns

All burns recorded similar maximum soil temperatures (Fig. 3) where median maximum temperatures ranged between 8°C, recorded during a PB at the Cawdor Estate, Scotland and 21°C at the PB conducted at Rempstone, Dorset (Table 3, Fig. 3).

Across the sites underlain by organic-rich soils, median maximum soil temperatures reached between 8 and 13°C, with a maximum temperature of 93°C recorded at Cawdor. In the acidic sandy soils, median maximum soil temperatures were similar recording ~20°C with a maximum soil temperature of 77°C recorded at Corfe Common (Table 3).

Two of the burns (CF3 and SF2) had one within soil thermocouple at each site that gave very high readings of >700°C. Additionally high maximum soil readings of 228°C and 124°C and 160°C were recorded by another at the 23 March Cawdor burn and CF2 respectively. These readings are likely caused by the thermocouple becoming dislodged from the soil prior to or during the fire and recording in-fire temperatures, as these temperatures match those measured on the surface of the litter. This is evidenced, for example, by the fact that the temperature profile for these outlier thermocouples (Supplementary Fig. S3), shows that the 228°C recorded at Cawdor jumps from 7.4 to 228.4°C within 1 s, occurring as the fire front passed, compared to the surface thermocouple that records a more gradual increase in temperature from 10.1 to 257.5°C in ~40 s. Similar profiles are seen in Spaunton Moor thermocouple number 11 which recorded a maximum temperature of 742.4°C. The soil thermocouple temperature jumps by 706°C in 30 s to closely follow the surface thermocouple profile. For the other Cawdor thermocouples peak soil temperatures are recorded prior to the fire front passing (see SI and Supplementary Figs. S3, S4 for further details). As such, each of these temperature profiles suggest that the ground thermocouple has become loose, recording surface temperatures as the fire-front approaches.

Discarding the data from these likely dislodged thermocouples reveals that all thermocouples remaining embedded in the soil recorded peak temperatures of above 70°C (the average temperature at which plant protein denatures (Sim *et al.* 2021) for a mean maximum duration of 29 s (Table 3, Supplementary Fig. S5). This comprises three thermocouples in three burns where one thermocouple recorded a maximum temperature of 77°C, exceeding 70°C for 7 s (Corfe Common); another thermocouple recording 93°C, with time spent above 70°C of 34 s (CF2) and a third thermocouple recording a

Table 2. Weather conditions both pre-fire and during the burns for each of the burns.

Location	Cawdor 23 March	Cawdor fire 1	Cawdor fire 2	Cawdor fire 3	Rempstone	Spaunton fire 1	Spaunton fire 2	Corfe Common
Date of burn	23 March 2023	27 March 2023	27 March 2023	27 March 2023	28 February 2023	28 March 2023	28 March 2023	24 February 2023
Avg. relative humidity during the burn (%)	70	No data	No data	No data	63	41	50	78
Avg. relative humidity prior to the burn (%)	62	55	50	48	66	41	49	76
Avg. wind speed (m s^{-1})	1.2	1.1	1.4	1.7	3.3	2.4	2.6	1.5
Mean air temperature prior to burns (°C)	9.5	2.0	4.0	5.0	6.9	7.6	6.9	8.8
Mean air Temperature during burns (°C)	10.4	No data	No data	No data	7.3	7.6	6.8	9.5
Days without precipitation prior to burns	0	0	0	0	3	3	3	1

Note that the relative humidity, air temperature and wind speed are taken as an average over duration of prescribed burn. Unfortunately the kestrel failed to record and store some of the weather data at the Cawdor fires 1, 2 and 3, 'Avg.' refers to 'average'.

maximum temperature of 91°C, exceeding 70°C for 45 s (SF2) (Supplementary Figs S4, S5). The remaining 185 thermocouples deployed across all of the burns recorded temperatures below 70°C throughout the duration of the burns.

Temperatures monitored on the litter surface were substantially higher than those measured from thermocouples installed within the soil. (Fig. 4), with maximum surface temperatures reaching between 707°C (at Corfe Common) and 1006°C (at SF2) (Table 3). All litter surface temperatures exceeded 70°C, for between 36 s (Corfe Common) and 112 s (Rempstone). Vegetation temperatures, measured at 40 cm height and 80 cm height above the ground, were similar. Thermocouples at 40 cm height recorded maximum temperatures of between 499°C (CF1) and 985°C (at Rempstone), whist the thermocouples at 80 cm height recorded maximum temperatures of between 398°C (at the Cawdor burns) and 888°C (Corfe Common) (Table 3. See also Supplementary Figs S2 and S3). The readings exceeded 70°C for a duration of between 51 and 124 s at 40 cm height and between 23 and 108 s at 80 cm height. On plotting surface litter temperatures against soil temperatures, we found no correlation between the litter surface temperatures recorded and the soil temperatures recorded across the PBs (see Supplementary Fig. S4*b*).

Fire severity

There was no evidence of moderate-severe (severity 4) or deep burning (severity 5) in response to any of the PBs (Supplementary Fig. S2, Supplementary Table S2). Fire severity scores from all sites indicate no below-ground organic matter loss during any of the burns. Moreover, above-ground organic matter loss was generally also limited. None of the sites recorded a fire severity score of above 3 (light burn). The majority of quadrats at all sites scored between 1 and 2 varying between patches of green and unaltered plant parts (1) through to areas that are scorched (2) where the surface fuels are of superficially charred heather and gorse that mainly exhibit leaf loss from radiated heat but with fine fuels on the ground intact with some evidence of charring (see Supplementary Fig. S2 for photographic examples from each site). Rempstone was the only site where a severity score of 3 was given, with 100% of all quadrats across the site showing evidence of either charring of grass tussocks, heather or gorse as well as some of the surface litter (consistent with a light burn, severity 3). Corfe Common and Cawdor Burns were all similar in their post-burn scores, with the majority of the quadrats given a severity score of between 1 and 2 (Table 4). CF1 also had some quadrats scoring 1 – 'unburned'. The burns at Cawdor on 27 March followed a couple of days of snow, and whilst most had melted ahead of the burns, some snow patches remained within the burn plots both prior to and after the fire had passed over them. This highlights that the short duration of surface heating was too minimal to lead to snow melt. Whilst low severity scores

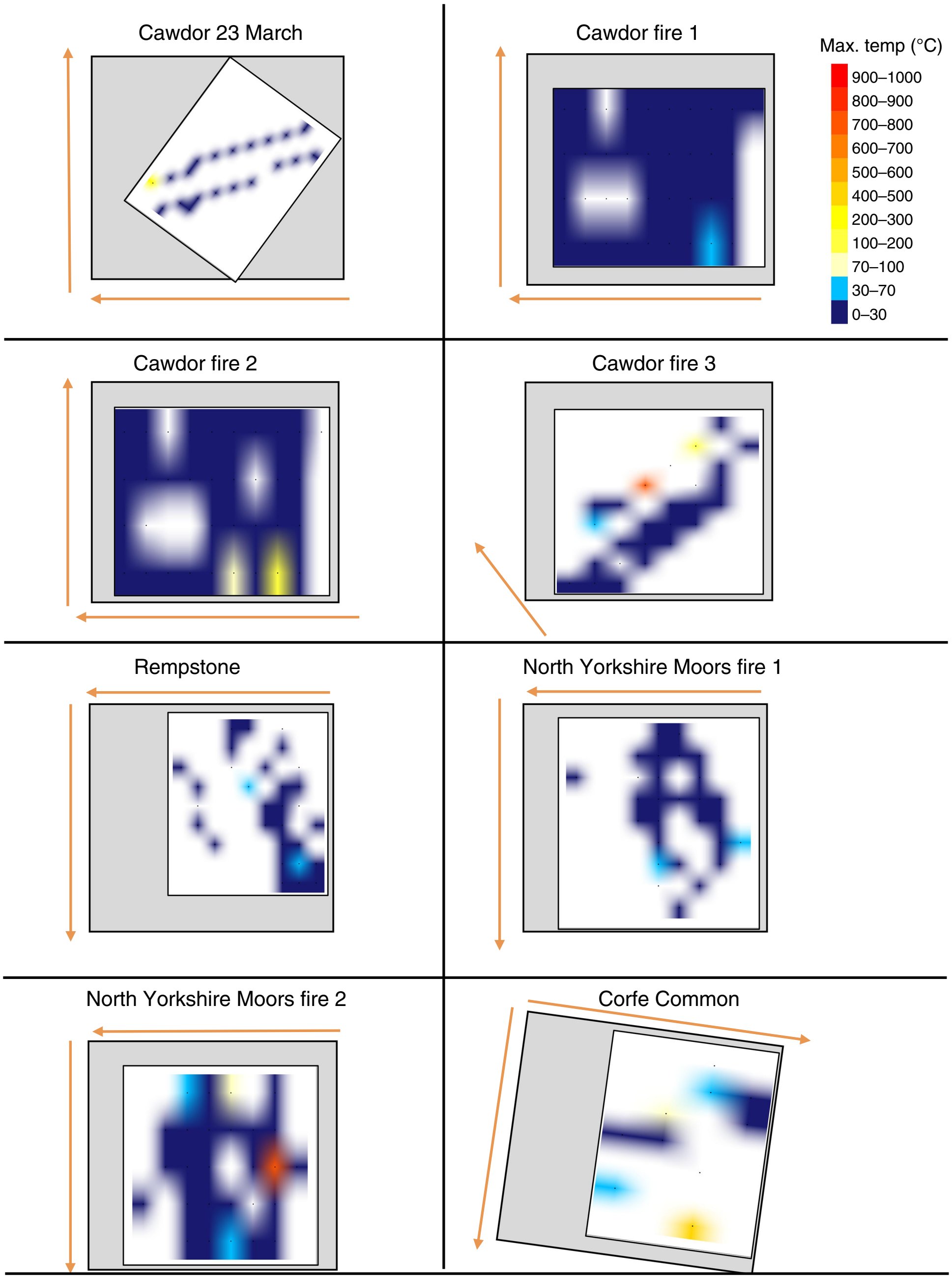

Fig. 3. Maximum soil temperatures recorded from thermocouples during each of the burns. Orange arrows depict the lighting pattern.

were observed, with some as low as 1 – 'unburned', a reduction in aboveground vegetation fuels was achieved in each burn, thus meeting the objective by the land managers for fuel reduction and management.

Discussion

Soil temperatures and soil organic matter ignition risk

We found minimal heating of the soil in response to the range of PBs undertaken by the four teams trained to the current Lantra standards. Each of the sites recorded similar mean maximum within soil temperatures, ranging between 12 and 43°C for all burns.

More important than absolute temperatures is that soil temperatures were rarely >70°C, with just four thermocouples out of 189 recording a temperature above 70°C for a mean maximum duration of 29 s. Whilst extended periods of >50°C can prove lethal to cambium of woody plant stems, they may also improve *Calluna* seed germination, whilst temperatures >70°C have often been associated with the killing of plants and seeds (Davies *et al.* 2010 and references therein). Another widely used threshold is temperatures >60°C being applied for at least 1 min.

Table 3. Results of maximum soil, litter surface, 40 cm height above ground and 80 cm height above-ground temperatures recorded during each burn and maximum amount of time (s) recorded temperatures exceeded 70°C.

Location	Fire date	Metric	Soil temp (°C)	Surface litter temp (°C)	40 cm temp (°C)	80 cm temp (°C)
Cawdor	23 March 2023	Max. Temp.:	16.9	846.6	616.5	702.2
		Avg. Max. Temp.:	12.6 ± 0.53 (s.e.)	621.9 ± 42.8 (s.e.)	260.7 ± 28.3 (s.e.)	196.6 ± 31.7 (s.e.)
		Max. Time > 70°C:	N/A	135 s	131 s	202 s
		Avg. Time > 70°C:	N/A	85.4 ± 6.4 (s.e.)	70.4 ± 6.2 (s.e.)	53.7 ± 11.8 (s.e.)
Cawdor Burn 1	27 March 2023	Max. Temp.:	42.7	952.9	498.7	398.4
		Avg. Max. Temp.:	14.3 ± 1.2 (s.e.)	447.3 ± 53.7 (s.e.)	229.8 ± 18.8 (s.e.)	29.3 ± 11.4 (s.e.)
		Max. Time > 70°C:	N/A	133 s	227 s	78 s
		Avg. Time > 70°C:	N/A	48.4 ± 5.8 (s.e.)	72.2 ± 7.5 (s.e.)	22.6 ± 3.8 (s.e.)
Cawdor Burn 2	27 March 2023	Max. Temp.:	93.2	904.3	597.0	539.7
		Avg. Max. Temp.:	13.9 ± 2.9 (s.e.)	524.8 ± 48.4 (s.e.)	78.8 ± 21.2 (s.e.)	127.4 ± 18.2 (s.e.)
		Max. Time > 70°C:	34 s	139 s	139 s	133 s
		Avg. Time > 70°C:	1.1 ± 1.1 (s.e.)	70.6 ± 5.2 (s.e.)	76.8 ± 5.7 (s.e.)	32.7 ± 7.3 (s.e.)
Cawdor Burn 3	27 March 2023	Max. Temp.:	60.0	920.6	748.7	533.3
		Avg. Max Temp.:	10.6 ± 2.5 (s.e.)	479.3 ± 46.4 (s.e.)	36.1 ± 28.3 (s.e.)	9.7 ± 25.4 (s.e.)
		Max. Time > 70°C:	N/A	145 s	249 s	234 s
		Avg. Time > 70°C:	N/A	74.6 ± 5.3 (s.e.)	124.4 ± 13.1 (s.e.)	108.4 ± 13.7 (s.e.)
Rempstone	28 February 2023	Max. Temp.:	63.8	945.6	984.8	841.9
		Avg. Max. Temp.:	21.3 ± 2.2 (s.e.)	523.9 ± 46.2 (s.e.)	825.5 ± 15.0 (s.e.)	657.5 ± 33.7 (s.e.)
		Max. Time > 70°C:	N/A	244 s	127 s	84 s
		Avg. Time > 70°C:	N/A	111.9 ± 9.8 (s.e.)	73.3 ± 3.1 (s.e.)	64.4 ± 2.1 (s.e.)
Spaunton Moors Burn 1	28 March 2023	Max. Temp.:	58.9	1005.6	939.6	711.3
		Avg. Max. Temp.:	12.3 ± 2.1 (s.e.)	703.8 ± 34.5 (s.e.)	642.4 ± 25.1 (s.e.)	551.0 ± 21.6 (s.e.)
		Max. Time > 70°C:	N/A	116 s	145 s	144 s
		Avg. Time > 70°C:	N/A	79.6 ± 3.2 (s.e.)	90.8 ± 4.4 (s.e.)	104.0 ± 5.5 (s.e.)
Spaunton Moors Burn 2	28 March 2023	Max. Temp.:	91.1	968.6	904.3	739.7
		Avg. Max. Temp.:	43.4 ± 27.1 (s.e.)	784.5 ± 34.7 (s.e.)	702.0 ± 20.7 (s.e.)	550.7 ± 25.0 (s.e.)
		Max. Time > 70°C:	45 s	123 s	130 s	133 s
		Avg. Time > 70°C:	4.5 ± 3.3 (s.e.)	81.9 ± 3.9 (s.e.)	89.0 ± 4.5 (s.e.)	89.7 ± 5.2 (s.e.)
Corfe Common	24 February 2023	Max. Temp:	77.2	707.0	923.2	888.4
		Avg. Max. Temp.:	37.5 ± 10.7 (s.e.)	308.0 ± 84.0 (s.e.)	536.1 ± 85.0 (s.e.)	396.1 ± 86.0 (s.e.)
		Max. Time > 70°C:	7 s	70 s	93 s	113 s
		Avg. Time > 70°C:	1.0 ± 1.0 (s.e.)	35.6 ± 9.2 (s.e.)	51.3 ± 5.5 (s.e.)	53.5 ± 8.5 (s.e.)

Averages are taken at each of the thermocouple locations, and standard errors (s.e.) calculated. 'Avg. Max.' refers to 'average maximum' temperature recorded, 'Max.' refers to 'maximum' and 'Temp.' refers to 'temperature'.

Pingree and Kobziar (2019) reviewed this threshold, irrespective of soil moisture content for soil biota mortality and found that for no group of organisms, and in no single study was this threshold consistently evidenced, and instead often ranged across temperatures and durations. For example, soil fungi and bacteria mortality thresholds occurred between 2 and 30 min with temperatures ranging 60–400°C. Whilst Rempstone had one ground thermocouple recording a maximum temperature of 64°C, all remaining thermocouples recorded temperatures below 60°C.

Hence within our study, there appears to have been little heating of the soil beneath the PBs that occurred in a range

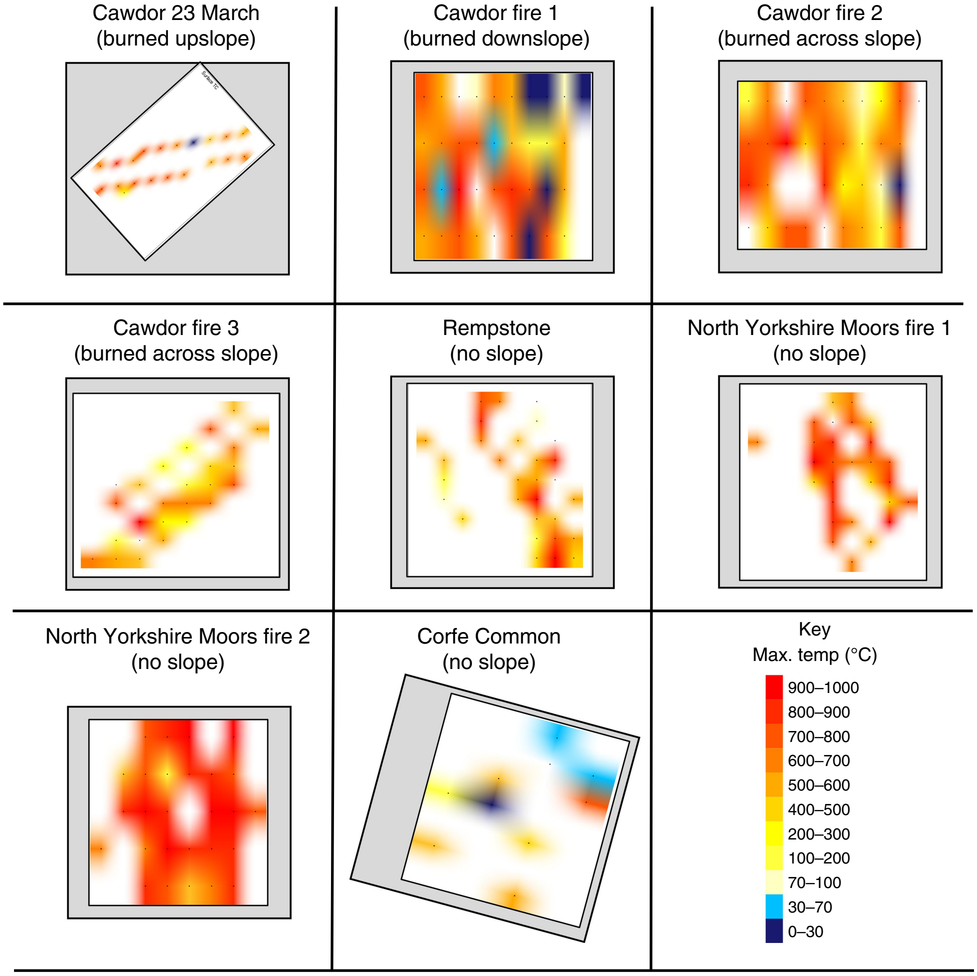

Fig. 4. Heat maps demonstrating maximum temperatures reached at the surface during each of the prescribed burns monitored.

Table 4. Summary of the percentage of quadrats conducted at each site and the fire severity score given.

Location	Date of burn	% of quadrats with a severity score of 1 (%)	% of quadrats with a severity score of 'between 1 and 2' (%)	% of quadrats with a severity score of 2 (%)	% of quadrats with a severity score of 3 (%)
Cawdor	23 March 2023	0	19	81	0
Cawdor Burn 1	27 March 2023	14	64	22	0
Cawdor Burn 2	27 March 2023	0	43	57	0
Cawdor Burn 3	27 March 2023	0	66	34	0
Rempstone	28 February 2023	0	0	0	100
Spaunton Moors Burn 1	28 March 2023	0	32	68	0
Spaunton Moors Burn 2	28 March 2023	0	50	50	0
Corfe Common	24 February 2023	0	70	30	0

of fuel types. We also found no correlation between the temperatures recorded on the litter surface and the soil temperatures beneath throughout the PBs (Supplementary Fig. S4*b*).

Prescribed burning in the UK is tightly regulated, with guidance given in the Heather and Grass Burning Regulations (Defra 2007; Welsh Assembly Government 2008) and the Muirburn Code (SEERAD 2008). The Department for Environment, Food and Rural Affairs (Defra 2007) indicates that 'quick, cool burns' should be conducted in order to not damage moss or litter layers, with recent Heather and Grass Burning (2025) legislation banning burning on deep peat (>0.3 m depth). The burn severity scores of 3 or less highlights that there was very limited charring of the litter or moss layers. In fact all burns except those at Rempstone had fire severity of 2 or less, such that the burns we have observed conducted by accredited trained teams, would appear to conform to Defra's guidelines and those aimed for based on PB training guidelines and the plans of the operators for these habitats.

The Heather and Grass Burning Regulations also indicate that burning should be conducted with the wind (burn propagating in the same direction as the wind direction) and ideally downhill (Defra 2007). Within our study, the burn conducted at Cawdor (23 March) propagated upslope with the wind. This compares to three other burns also conducted on the Cawdor Estate, where burn 1 propagated downslope with the wind and burn 2 propagated across the slope with the wind. Comparing maximum soil temperatures recorded between the different slope aspects, we find that the upslope burn (a short slope that soon levelled out) produced a soil temperature of 17°C, compared with the downslope burn which recorded a maximum soil temperature of ~43°C. The burns propagating at a right angle to the slope reached a maximum soil temperature of 93°C. Burning upslope has the potential to increase the amount of heat radiated down into soil layers as the flames lengthen and tilt upslope (Planas and Pastor 2013). However, average maximum temperatures recorded across the fire indicates a maximum soil temperature of 17°C, averaging ~13°C. This is similar to the soil temperatures recorded in the downslope burn at Cawdor, where average maximum temperatures reached ~14°C and the across slope burns averaging ~19°C. Hence whilst the regulation guidance is based on a firm understanding in the case of the dwarf-shrub dominated ecosystems, burning upslope appeared to have little overall impact on soil temperatures. This may be because fires burning upslope tend to travel faster due to expansion of the fireline owing to flame tilt.

At temperatures above 200°C, soil organic matter loss begins to occur (Busse *et al.* 2005). Once data from the likely dislodged thermocouples were removed just four of the burns had a single thermocouple experiencing temperatures above 70°C (Fig. 3). For these few thermocouples, the maximum time where soil temperatures exceeded 70°C was 45 s in Spaunton burn 2, where a temperature of 91°C was recorded. The probability of ignition of peat is determined by its inorganic content and moisture content (Frandsen 1997); typically pyrolysis, where peat is converted into volatile gases and char, begins at temperatures of between 250 and 300°C (Usup *et al.* 2004; Rein *et al.* 2008). Thus, none of the soil temperatures measured reached temperatures capable of causing pyrolysis.

Additionally, these high temperatures must be applied for long enough to initiate self-sustained smouldering of peat. As temperature and duration of heating is difficult to measure (due to the need to deploy thermocouples ahead of a fire), previous studies rely on laboratory-based experiments linking prolonged heating of soils with loss of soil mass and therefore burn severity. Authors highlight that the severity of smouldering peat on soil is quantified in terms of temperature vs residence time (Rein *et al.* 2008), where peak temperatures for a peat soil sample that burned completely (where the moisture content was below a critical threshold), was 500–600°C for more than 20 min, generating sterilisation of the soil and severe damage. Even if we were to not discount the thermocouples that appear to have come dislodged and take their temperature readings to be reflective of true soil temperatures, recorded temperatures did not exceed 70°C for more than 2.5 min, or 250°C for more than 42 s (Supplementary Table S2). Thus none would likely have been of sufficient in duration to initiate self-sustaining smouldering.

Comparison of vegetation type and fuel loads

Vegetation type and its respective flammability is a key determinant of fire behaviour (Dent *et al.* 2019), therefore variability in temperatures reached are likely to be driven by differences in the dominant vegetation/fuel types at each location. The Cawdor and Spaunton Moors sites are heather (*Calluna vulgaris*) dominated, interspersed with *Molinia caerulea* in patches. This compares with Corfe Common and Rempstone that contained a considerable amount of *Ulex spp.* with interspersed *Erica cinerea* and/or *Molinia caerulea*.

An important plant trait that drives flammability is the production/retention of dead material (see Dent *et al.* 2019 and references therein). *Ulex* spp. and *Molinia caerulea* are both considered to be overall highly flammable and high risk in terms of ignitability (Pausas *et al.* 2012; Santana and Marrs 2016; Belcher *et al.* 2025). Moreover, dwarf shrubs such as *Calluna* have been found to vary in its flammability and resulting impact on fire behaviour depending on its stand age (Davies 2005; Davies *et al.* 2009) and phenology (Belcher *et al.* 2025). For example, Davies *et al.* (2010) reported fireline intensity varying between 75 and 530 kW m^{-2} in the building phase to between 347 and 3389 kW m^{-2} in the late-building phase. Whilst Belcher *et al.* (2025) measured peak heat release rate of live

Calluna varying from ~450 kW m^{-2} in late March (dormant phase) through to ~90 kW m^{-2} in May (during green up). Peak heat release rate also varies between species and within these heathland ecosystems where *U. gallii* produced a high peak heat release rate of ~650 kW m^{-2} (late March) whilst *E. cinerea* produced ~400 kW m^{-2} during the same period (Belcher *et al.* 2025). Higher energy release rates have the ability to transfer more energy (and therefore heat) to the surrounding fuels when compared to a fire that has a lower energy and heat release rate (Hadden 2020). We therefore suggest that any variations in soil and surface litter temperatures found between our sites are likely to be driven by differences in vegetation composition and respective flammability of surface fuels and their associated fuel-load where dense fuel loads *of Ulex* sp. have the ability to impart more energy and heat to the surroundings compared to other heathland species. This may explain the slight elevation in surface-litter fire temperatures recorded at *Ulex* sp. dominated sites Rempstone and Corfe Common, compared with the two heather dominated sites at Cawdor and Spaunton Moors. We also note that the vegetation height was greater (i.e. also higher fuel-load) at Rempstone and Corfe Common than in Cawdor.

Implications for the controlled burning debates in the UK

Although forms of PB (Swailing, Muir Burn, Rotational Burning) have been traditionally used across heathlands for centuries, the use of fire has become an increasingly contentious management tool within the UK (Smith *et al.* 2023). In 2021 new government legislation was passed prohibiting burning on peats deeper than 0.4 m in England (Heather and Grass Burning Regulation 2021). This has since been extended with burning on peat deeper than 0.3 m now banned (Defra 2025). With an estimated ~18% of UK peatlands undergoing PB (Defra 2010) a significant volume of previous studies have been conducted on peatland ecosystems (e.g. see Ashby and Heinemeyer 2021). Yet there remains concerns regarding the risk of ignition and subsequent loss of carbon stores, key peatland plant and animal species and ecosystem health (Davies *et al.* 2016*a*, 2016*b*). For example, Thompson *et al.* (2016) suggest degradation to peatland health, loss of carbon and bog-forming species such as *Sphagnum* following traditional burn practices, with Glaves *et al.* (2013) concluding that there is 'moderate evidence' from the literature reviewed that burning reduces peat accumulation and therefore carbon stores. In contrast other studies have shown that regular burning of every ~10 years can benefit species such as *Sphagnum* and cotton grass, and reduce wildfire risk by reducing fuel loads whilst still maintaining carbon stores, when compared to longer burn rotation intervals (e.g. Milligan *et al.* 2018; Whitehead and Bains 2018; Whitehead *et al.* 2021), such that evidence appears to remain inconclusive. Reviews conducted by Harper *et al.* (2018) and Ashby and Heinemeyer (2021) further highlight that overall, studies suggest that managed burning has a variety of impacts on peatland ecosystems, including both positive and negative as well as 'neutral' impacts, with many suggesting that there is a need for further assessment to resolve this controversial issue, particularly as many species within these habitats possess fire adaptive traits and thus may in fact be reliant on the use of fire as a management tool (Simpson *et al.* 2025).

The research presented here provides useful information about the application of 'quick, cool burns' carried out by specifically trained PB teams on the moorland and heathland sites studied. This includes those over organic-rich soils conducted under mild weather conditions within the legal burning window of February–March. Under these conditions, our study demonstrates that training of burn teams according to new standards appears to produce burns where soil temperatures average below 17°C and rarely exceeded 70°C. Although we note that this is a relatively small set of burns studied to date, it is not a simple task to monitor large numbers of PBs in this detail, particularly due to the erratic nature of suitable windows being available for burning and getting scientific measurement teams to the right place at the right time. Nonetheless our monitoring of four trained burn teams across different regions, soil types and vegetations demonstrates that for the burns carried out in this study, when the Heather and Grass Burning Regulation (Defra 2007; Welsh Assembly Government 2008) and the Muirburn Code (SEERAD 2008) are followed, coupled with those of Lantra VFO and PFO, then underlying organic-rich soils appear not to be subjected to high temperatures that could otherwise directly damage long-term carbon stores.

This is the first study to assess the soil heating effects of UK trained burn teams and examine multiple PBs on both peat and mineral soils across heathland sites in Scotland and northern and southern England as part of the same experimental set-up. Despite this we must acknowledge that our results for the eight burns studied, may not be representative of every trained burn team nor for all conditions in UK heathlands. However, the results do appear to be in agreement with older, smaller studies that also show limited transfer of heat into surface soil layers including Whittaker (1961), Schimmel and Granstrom (1996), Davies *et al.* (2010) and (Grau-Andreas *et al.* 2017, 2019). For example, (Grau-Andreas *et al.* 2017, 2019) recorded mean ground temperatures of 9°C at 2 cm depth peaking at 12°C on a dry Scottish heath site. Davies *et al.* (2010) recorded temperatures <50°C with the exception of one thermocouple in peat whilst Schimmel and Granstrom (1996) recorded no temperatures above 100°C 2 cm below a mineral soil surface at two PB boreal forest sites. Whittaker (1961) also found little temperature change 1 cm below the peat surface across seven PBs in Scotland.

Notwithstanding the findings above, it will be important to continue to monitor the potential for soil heating beneath the PBs of trained teams as the UK's weather and climate evolves in the future. For example, the moisture regime of the UK's organic rich soils may shift, where in some areas soils may be more susceptible to drier conditions (Kay *et al.* 2022), whilst in other areas warmer, wetter winters may bring complications by restricting available conditions for burning during the legal burn window for land managers (Hsu *et al.* 2025). Additionally, we suggest that future research should look to assess the implications of prescribed fire return intervals/burn rotations and examine to what extent the frequency of reburning might impact the potential for soil heating, biodiversity and carbon fluxes and stores.

Conclusion

In this study we found little penetration of energy down into underlying soil layers during UK prescribed burns undertaken by teams trained to VFO or PFO level in moorland and heathland fuels. Our study highlights that for the PBs carried out according to the most recent UK training guidance, despite the variations in fuel type and slope aspect, soil temperatures rarely exceeded 70°C, with maximum temperatures averaging below 17°C. The aim of PBs, particularly when conducted in peatland settings, is to conduct a quick, cool burn that does not damage moss or litter layers or impact on carbon stores. Here, we demonstrate that up-to-date burn management practices in the UK appear to cause minimal increases in temperature of underlying soils at 2–3 cm depth as the fire front passes over, despite surface temperatures in the burning dwarf shrubs above reaching up to ~1000°C. Following the fires, low fire severity was observed across all sites further indicating little impact on the moss or litter layers beneath the burning shrubs. All fires monitored were found to be well within the current guidance given in the Heather and Grass Burning Regulations and Muirburn Code, and were not observed to directly damage long-term carbon stores. This study provides an important dataset that highlights that PBs can have minimal soil heating when undertaken by trained PB teams and contributes to debates surrounding the use of PB in maintaining aboveground ecosystem health and biodiversity, whilst also preserving important long-term carbon stores.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study are available in the article and accompanying online supplementary material. Any other materials can be shared upon reasonable request to the corresponding author.

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