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Research article

Leaving moss and litter layers undisturbed reduces the short-term environmental consequences of heathland managed burns

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ABSTRACT

Variation in the structure of ground fuels, i.e. the moss and litter (M/L) layer, may be an important control on fire severity in heather moorlands and thus influence vegetation regeneration and soil carbon dynamics. We completed experimental fires in a *Calluna vulgaris*-dominated heathland to study the role of the M/L layer in determining (i) fire-induced temperature pulses into the soil and (ii) post-fire soil thermal dynamics. Manually removing the M/L layer before burning increased fire-induced soil heating, both at the soil surface and 2 cm below. Burnt plots where the M/L layer was removed simulated the fuel structure after high severity fires where ground fuels are consumed but the soil does not ignite. Where the M/L layer was manually removed, either before or after the fire, post-fire soil thermal dynamics showed larger diurnal and seasonal variation, as well as similar patterns to those observed after wildfires, compared to burnt plots where the M/L layer was not manipulated. We used soil temperatures to explore potential changes in post-fire soil respiration. Simulated high fire severity (where the M/L layer was manually removed) increased estimates of soil respiration in warm months. With projected fire regimes shifting towards higher severity fires, our results can help land managers develop strategies to balance ecosystem services in *Calluna*-dominated habitats.

1. Introduction

The severity of a fire was defined by Keeley (2009) as the direct, immediate fire effects such as degradation and loss of organic matter. Variation in severity can influence post-fire vegetation regeneration due to mechanisms occurring during the fire itself and altered post-fire environmental conditions. Immediate fire mechanisms include thermal damage to plant structures (Legg et al., 1992), and germination cues related to temperature pulses (Whittaker and Gimingham, 1962) and chemicals from smoke and ash (Bargmann et al., 2014). Altered post-fire environmental conditions include loss of nutrients (Rosenburgh et al., 2013), substrate change due consumption of ground fuels, e.g. the moss and litter (M/L) layers, during high severity fires (Davies et al., 2010), and changes to post-fire soil microclimate resulting from loss of vegetation cover (Mallik, 1986; Brown et al., 2015). The latter is important as microclimate is a control on soil respiration and soil carbon dynamics (Lloyd and Taylor, 1994; Kettridge et al., 2012; Walker et al., 2016). Fire can also alter soil chemistry and structure (Granged et al., 2011) and soil microbiology (Ward et al., 2012; Fontúrbel et al., 2016), can be associated with increased rates of soil erosion (Fernández and Vega, 2016) and can lead to a loss of organic matter at high fire severities (Neary et al., 1999). Where ecosystems have peat or thick organic soils, the ignition of these during extremely severe fires can have considerable consequences for carbon storage and ecological function (Maltby et al., 1990; Davies et al., 2013; Turetsky et al., 2015).

Calluna vulgaris (L.) Hull (hereafter *Calluna*) dominated heathlands are internationally rare habitats of substantial conservation importance (Thompson et al., 1995). Typically found in north-west Europe, including Sweden, Norway, Denmark, the Netherlands, Italy and Spain, *Calluna* heathlands are perhaps best represented in the UK and Ireland (Gimingham, 1972). *Calluna* heathlands are semi-natural ecosystems that resulted from human land-use since the Mesolithic (Simmons and Innes, 1987). Management activities

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have included forest clearance, intensified grazing mainly from cattle and sheep, and burning to promote nutritious new growth for livestock (Webb, 1998). Anthropogenic fire played a significant role in the expansion and maintenance of *Calluna* heathlands (Dodgshon and Olsson, 2006).

Under a changing climate, it is projected that alterations to the seasonality of rainfall and warmer temperatures throughout heathlands' range will result in increased frequency and/or severity of summer drought (Murphy et al., 2009; Stocker et al., 2013; Cook et al., 2014). These climatic changes suggest the potential for increased wildfire activity (Westerling et al., 2006; Krawchuk et al., 2009) and higher severity wildfires that consume a larger proportion of ground fuels (Davies et al., 2016a). With many heathlands overlying peat deposits or organic soils that store substantial amounts of carbon (Bradley et al., 2005; Ostle et al., 2009), there is concern that higher severity fires could increase carbon emissions from both direct combustion and greater soil respiration resulting from an altered post-fire soil microclimate (Brown et al., 2015).

In the UK, managed burning remains a common, though controversial, practice and is particularly strongly associated with red grouse (*Lagopus lagopus scoticus* Latham) and deer (*Cervus elaphus* L.) management on sporting estates (Davies et al., 2016b). Current forms of management date back approximately 200 years and aim to increase *Calluna* productivity and forage quality, and to produce a range of habitat structures by burning narrow (ca. 30 m wide) strips to create a mosaic of different stand-ages (Allen et al., 2016). Such traditional burning can have benefits for habitat maintenance, biodiversity (Allen et al., 2016; Glaves et al., 2013) and fire risk reduction (Davies et al., 2008a). However, negative consequences have been noted for other ecosystem services such as carbon sequestration (Garnett et al., 2000) and stream water chemistry and ecology (Ramchunder et al., 2013). In order to minimise wildfire risk and reduce potentially negative ecological effects, managed burning is only permitted between, approximately, 1 October and 15 April (exact dates depend on country, altitude, etc.; see DEFRA, 2007; WAG, 2008; SEERAD, 2011). This means managers do not burn after mid-spring when heathland birds are nesting and when drier, warmer weather is likely to lead to difficult-to-control, high intensity fires.

On many heathlands *Calluna* forms dense, continuous stands (Gimingham, 1960) comprised of an upper canopy with a high proportion of live vegetation, a lower canopy with mainly dead foliage, a lower layer of dead and live stems without foliage and finally a M/L layer on top of a carbon-rich soil (Davies and Legg, 2011). During managed burns the M/L layer typically has a high fuel moisture content (>250%) and plays an important role in insulating soil from substantial temperature pulses, and possibly ignition, during the passage of a flaming fire-front (Davies and Legg, 2011). This often means that despite high fireline intensities, fire severity at the ground level, and thus impact on vegetation regeneration and soil properties, is low (Davies et al., 2009). However, where the moisture content of the M/L layer is below its ignition threshold (ca. 70%; Davies and Legg, 2011; Santana and Marrs, 2014), fuel available for combustion increases substantially, leading to higher soil heating (Bradstock and Auld, 1995) and difficulties with fire control (Davies et al., 2010).

Currently we have little quantitative evidence of how heathland fuel structure influences fire severity. In particular, additional knowledge of how the M/L layer controls fire-induced soil heating and post-fire soil thermal dynamics is needed. We investigated this by manipulating the structure of the M/L layer in experimental burn plots. Our objectives were to (i) quantify the role of the M/L layer in insulating soils from raised temperatures during managed burning, (ii) model post-fire soil thermal dynamics in relation to simulated variation in fire severity, and (iii) estimate the potential effect of altered soil microclimate on soil respiration.

2. Material and methods

2.1. Study area

The experiment was completed at Glen Tanar Estate, Aberdeenshire, Scotland (latitude 57.013°N, longitude 2.957°W, elevation of 330 m a.s.l.). Weather records from 1994–2007 at Aboyne weather station, 13 km east of the site, elevation 130 m, show an average annual rainfall of 837 mm, mean summer temperature of 13.8 °C and mean winter temperature of 3.1 °C (Met Office, 2012).

Soils at the site are peaty podzols with a mean organic horizon depth of 9 cm. Vegetation is dominated by a dense and homogenous canopy of mature (*sensu* Gimingham, 1989) *Calluna*, with *Erica cinerea* L., *Vaccinium myrtillus* L., *Trichophorum cespitosum* (L.) Hartm. and *Carex* spp. also common. Beneath the *Calluna* canopy we found a discontinuous layer of pleurocarpous mosses (dominant species: *Hypnum jutlandicum* Holmen and Warncke, and *Pleurozium schreberi* (Brid.) Mitt.) which are replaced by layers of *Calluna* litter where stand canopies were particularly dense. There are frequent wet flushes dominated by *Molinia caerulea* (L.) Moench, *Eriophorum vaginatum* L. and *Sphagnum* spp. More recently-burnt areas include patches of building phase *Calluna* and areas dominated by *Nardus stricta* L. and *M. caerulea*.

2.2. Experimental design and measurements

We completed seven experimental fires on four separate days between 12 and 26 April 2013. All fires were ignited with a drip torch, burnt as head fires (i.e. main fire spread direction was the same as wind direction) and covered an area of around 25 × 30 m. Within each fire we established six 1 × 1 m plots assigned to one of three treatments (each treatment replicated twice in each fire): (i) plots where the M/L layer was not manipulated, (ii) the M/L layer was removed after the fire, (iii) the M/L layer was removed before the fire. We manually removed the M/L layer down to the top of the O-horizon in the latter two fuel treatments. The treatments allowed us to quantify the effect of the M/L layer on fire-induced soil heating by comparing plots where the M/L layer was present at the time of burning versus plots where it had been removed. Furthermore, the treatments simulated fuel structure after low severity fires where M/L layer consumption is limited, and after higher severity where the M/L layer is consumed (Davies et al., 2016a), and thus allowed estimation of the effect of fire severity on post-fire soil thermal dynamics. The simulated approach is useful as when ground fuels become flammable (low moisture content), fuel available for combustion increases substantially (Davies et al., 2010), normal control methods have limited effectiveness and managed burning becomes too hazardous. This has limited the ability of previous research to capture a wide range of severities.

There can be substantial fine-scale (1 m^2) spatial variability in the behaviour of surface fires (Bradstock and Auld, 1995; Thaxton and Platt, 2006; Davies et al., 2010). Our experimental design therefore followed the "microplot" approach for fire behaviour: plots within fires are treated as independent observations due to the significant variation in fire behaviour that results from interactions between heterogeneity in fuel structure, moisture content and fire weather (principally wind speed) during a burn (Fernandes et al., 2000). We assessed the validity of the microplot approach by partitioning the variance of fuel structure metrics (e.g. fuel load, bulk density, M/L layer thickness) in "within fires" and "between fires" components using a random effects model (see Table S1 in supplementary material). We used the non-destructive FuelRule method (Davies et al., 2008b), which is based on visual