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Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland

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ABSTRACT

Temperate peatlands represent a substantial store of carbon and their degradation is a potentially significant positive feedback to climate change. The ignition of peat deposits can cause smouldering wildfires that have the potential to release substantial amounts of carbon and to cause environmental damage from which ecosystem recovery can be slow. Direct estimates of the loss of carbon due to smouldering wildfires are needed to inform global estimates of the effect of wildfire on carbon dynamics and to aid with national emissions accounting. We surveyed the effect of a severe wildfire that burnt within an afforested peatland in the Scottish Highlands during the summer of 2006. The fire ignited layers of peat which continued to burn as a sub-surface smouldering wildfire for more than a month after the initial surface fire and despite several episodes of heavy rain. The smouldering fire perimeter enclosed an area of 4.1 ha. Analysis of weather records showed that the fire coincided with unusually warm, dry conditions and a period when the Canadian Fire Weather Index system predicted both generally high danger conditions (high Fire Weather Index) and low fuel moisture content in deep organic soil layers (high Drought Code values). Remaining peat layers in the burn area had comparatively low fuel moisture contents of ca. 250% dry weight. Within the smouldering fire's perimeter, mean depth of burn was estimated at 17.5 ± 2.0 cm but ranged from 1 to 54 cm. Based on field measurements, our estimates suggested that, in total, the smouldering wildfire burnt 773 ± 120 t of organic matter corresponding to 396 ± 63 t of carbon and a carbon loss per unit area burnt of 96 ± 15 t ha^{-1} (9.6 ± 1.5 kg m^{-2}). This corresponds to between 0.1% and 0.3% of the estimated total amount of carbon sequestered annually by UK peatlands. Our results also provide circumstantial evidence that afforestation of peatland soils, and associated site preparation, may contribute to an increased risk of peat fires. Smouldering fires are difficult to detect using remotely sensing techniques due to their low temperature and low heat release and the fact that the tree canopy remains intact for months afterwards. If similar smouldering fires are underreported in other temperate, boreal and tropical peatland regions then emissions from peatland burning may well be a substantially greater issue than currently assumed.

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1. Introduction

Peat deposits in temperate regions represent a significant global carbon sink. Estimates of stocks in Great Britain vary fairly wildly from ca. 3 Gt (Cannell et al., 1993; Worrall et al., 2011) for the whole region to between 4.5 Gt (Milne and Brown, 1997) and 16 Gt (Howard et al., 1995) for Scotland alone. In the UK the use of management fire on peatlands is controversial because good evidence of the long-term effects of management (e.g. burning, grazing, drainage and afforestation) on the ecology, hydrology and carbon balance of peatlands is lacking (Birkin et al., 2011; Worrall et al., 2011). Nevertheless the immediate impacts of severe wildfires are likely to be much more apparent than the gradual changes caused by land management. Severe fires in peatlands can lead to the ignition of peat deposits and extensive smouldering combustion particularly following periods of extended drought or where peat structure and moisture have been altered by drainage and/or afforestation. Peat fires are dominated by smouldering which is the slow, low temperature (peak ~ 600 °C), flameless combustion of organic matter (Rein et al., 2008; Hadden et al., 2013). This is the most persistent type of combustion and exhibits fire behaviour drastically different from flaming wildfires (Rein, 2013). Peat megafires have been identified as the largest fires on

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Earth in terms of fuel consumption and can burn up to 100 times more fuel per unit area than flaming fires (Rein, 2013).

Wildfires that ignite peat require considerable resources to control and can have impacts that last decades if not centuries (e.g. Legg et al., 1992). Peat fires can also release significant amounts of stored carbon (Maltby et al., 1990; Page et al., 2002) and, with climate predictions forecasting increased fire risk across a number of areas that hold substantial peat deposits (Flannigan et al., 2009; Krawchuk et al., 2009; Jenkins et al., 2010), they may represent an important positive feedback on the atmospheric radiative forcing that exerts a controlling influence on climate warming (Field et al., 2007; Rein, 2013).

Many countries have pledged to reduce carbon emissions by 2050, however, current emission estimates, for example in the UK, do not take into account those from peatlands (Bain et al., 2012). This is because there is still considerable uncertainty as to whether peatlands represent a net carbon source or sink (Worrall et al., 2011), the reporting of peatland emissions is currently voluntary under Article 3.4 of the Kyoto Protocol, and reporting is only considered for wetland drainage and rewetting (Bain et al., 2012). In addition there is little evidence for the long or short term effects of wildfires on carbon emissions from peatlands despite the global importance of fire in these systems (e.g. Turetsky et al., 2002; Couwenberg et al., 2010) The potential of peatland wildfires to release significant amounts of carbon needs to be taken into account and incorporated into global carbon emission budgets.

Peat fires can have significant and long-term impacts on the physical and ecological structure of peat by destroying seedbanks (Maltby et al., 1990; Legg et al., 1992; Granström and Schimmel, 1993; Rein et al., 2008), causing hydrophobicity (Doerr et al., 2000) and altering the soil from having a low pH and high organic matter content to one composed of almost entirely mineral material with a raised pH and comparatively high nutrient content from the deposited ash (e.g. Prat et al., 2011). A substantial number of studies describe carbon emissions from peat fires in tropical and boreal regions (e.g. Page et al., 2002; de Groot et al., 2009; Mack et al., 2011; Turetsky et al., 2011a) but we have little knowledge of the effect of severe burns in more temperate regions like the UK. Additionally, relatively few studies provide field-based measurements of peat combustion by wildfires. Further data are needed to inform remote sensing and modelling studies of smouldering phenomena, to provide case-studies for use in the development of fire danger rating systems, to direct future forest and fire management, to provide baselines from which the ecological impact of burns can be tracked, and to fill the knowledge gap regarding positive feedbacks to climate change.

Although peatland wildfires are relatively common in the UK, no records of occurrence or severity are collected at a national level and many fires in remote regions probably go unreported. Protocols have been developed for the collection of data on wildland fires in the UK (Gazzard, 2009) but these have yet to be adopted. The UK also lacks a robust fire danger rating system (Legg et al., 2007). The Canadian Fire Weather Index system (FWI system; Van Wagner, 1987) has been adapted in Wales and England to forecast the potential for "exceptional" fire weather conditions (Kitchen et al., 2006) but the system has not been widely adopted by managers and there has been little research into how the system's underlying moisture codes and fire weather indicesrelate to fire activity or severity. Case studies of notable or unusual wildfire events provide one means of examining the system's utility although there is also a need for broad-scale research into linkages between fuel structure, fire weather, wildfire activity, burn severity and post-fire ecosystem response.

This paper provides a case study of the effects of a wildfire that ignited layers of litter, duff and peat. Understanding and documenting the effects of such wildfires is important as not only is the financial cost of restoring such areas significant (Aylen et al., 2011), but there are wider impacts on a range of ecosystem services such as the provision of livestock grazing, the use of moorland areas for sport shooting, their importance as a source for drinking water and their potential role as a carbon store. The objectives of this study were therefore to: record observations of patterns in smouldering fire spread; assess fire weather conditions prior to and during the fire; characterise pre-fire peat fuel conditions; and to estimate the total amount of carbon released due to smouldering combustion.

2. Materials and methods

Visits to the fire were made on 31st of July and 21st August 2006, 12 and 33 days after the start of the fire (19th of July 2006) respectively. On both occasions the fire was still observed to be smouldering at certain locations despite rain in the intervening period (23 mm between the initial fire and visit 1 and 70 mm between the initial fire and visit 2). Qualitative notes were recorded on the apparent effects of the burn and the behaviour of the smouldering fire front.

2.1. Site description

The fire occurred near Aviemore, within the Caringorms National Park in the Scottish Highlands (57.144°N, 3.740°W) and is thought to have been ignited close to a track by sparks from a vehicle fire. The flaming wildfire burnt across both heathland and plantation forest but smouldering combustion of litter, duff and peat was concentrated in the ca. 14 ha of forest. Despite large numbers of volunteers and two Fire and Rescue Service tenders being at hand considerable effort was required to extinguish the surface fire. More than 60 helicopter water drops were made over the course of two hours. Some vegetation around the edges of the fire was back-burnt to prevent flame spread to surrounding forest. The peat fire continued burning and was only contained by bull-dozing trenches down to the mineral soil around the fire (up to 2 m deep). At the time of the first site visits the smouldering wildfire was observed to be spreading horizontally through the peat and under the duff/litter above. By the second visit the fire was largely extinguished though small isolated smoulder fronts persisted in some locations. The smouldering fire burnt only a proportion of the area affected by the flaming fire front and covered 4.1 ha at the time of our second visit. Areas where there was complete combustion of ground fuels, down to the mineral soil were, however, common. Rough estimates of the financial costs include £15,000 for fire control; £25,000 for felling timber to waste; £3000 for loss of timber and the total eventual cost is estimated to be in the region of ca £50,000 (McGregor A. pers. comm.).

The area of heath adjacent to the plantation was a statutory designated Site of Special Scientific Interest. Heath vegetation was dominated by *Calluna vulgaris* (L.) Hull with *Vaccinium myrtillus* L. and *V. vitis-idaea* L. commonly occurring beneath the *Calluna* canopy in addition to occasional grasses including *Molinia caerulea* (L.) Moench and *Agrostis* spp. The forest was a plantation of roughly 40 year old *Pinus contorta* Douglas ex Loudon with small numbers of *Picea sitchensis* (Bong.) Carrière and occasional birch (*Betula* spp.). Samples taken near the north-east corner of the fire gave an estimated height of ca 12 m (mean of 5 trees, 8.5–15.2 m); a dbh of 15 cm (mean of 15 trees, range8–23 cm) and a stem density of ca 3600 ha^{-1}. The surface vegetation within the forest was dominated by needle-litter and a dense cover of mosses with *Hylocomium splendens* (Hedw.) Schimp. and *Pleurozium schreberi* (Willd. ex Brid.) Mitt. dominant and *Hypnum cupressiforme* Hedw., *Dicranum scoparium* Hedw., *Plagiothecium undulatum* (Hedw.) Schimp. and

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