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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.

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

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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 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 *Polytrichum* spp. frequent. *Diplophyllum albicans* (L.) Dumort. was observed on peat banks. The soil over the majority of the site was shallow peat (20–50 cm) above a stony/gravelly granite bed. The ground within the forest had been ploughed before planting with furrows cut through to the underlying mineral material. Trees were planted on mounded peat which was coarsely mixed in places with mineralsubsoil and stones brought to the surface by ploughing.

2.2. Weather conditions during the fire period

Weather data for the year of the wildfire were obtained, courtesy of the Met Office, for the Aviemore weather station, located approximately 9 km to the NW of the fire ground. Data were used to examine patterns in rainfall, temperature and humidity in the lead-up to the wildfire and to calculate fuel moisture codes and fire danger indices (Table 1) from the FWI system. The FWI system underlies the UK Met Office Fire Severity Index which is currently implemented in Wales and England to forecast "exceptional" fire weather conditions (Kitchen et al., 2006). The codes and indices were calculated using temperature, humidity and wind speed measured at 12:00 local time and with total daily rainfall. We used the "fume" package (Santander Meteorology Group, 2012) in R (R Development Core Team, 2012) to calculate FWI system codes and indices. The DMC and DC have long lag times (12 and 52 days respectively) so we calculated values starting from the 1st January 2006 (199 days prior to the fire). Long-term weather data were obtained from the National Climate Information Centre (Met Office n.d.).

2.3. Fuel consumption and carbon loss

Peat fuel consumption was estimated using a four-stage processes:

1. Cores were extracted from ground fuels in burnt and unburnt areas in order to determine pre-fire fuel structure.
2. The fuel cores were used to construct an average fuel profile for the fire site.
3. Transects were laid out across the wildfire site to record depth of burn.
4. Depth of burn and the averaged fuel profile were used to estimate the mass of organic matter consumed and the associated carbon emissions.

2.3.1. Unburnt peat fuel structure analysis

Eight peat cores were taken with a 5 cm × 5 cm box corer during the first site visit. Four cores were taken from lightly burnt areas (i.e. with litter or duff layer still intact) within the fire area and four from outside the burn perimeter but within ca. 10 m of the edge of the fire. Cores from burnt areas had been subject to flaming fire spreading through the litter layer but did not show signs of peat or duff consumption. A major issue in post-fire fuel reconstruction is that unburnt fuels may differ substantially from those in areas that burnt – such differences determining the position of the fire perimeter. Taking cores in fuels remaining within the burnt area allowed us to compare their structure to those that were not subject to any fire.

Peat cores were visually separated into distinct strata, sealed in plastic bags and returned to the laboratory for analysis. Separation of peat layers was on the basis of colour, texture and apparent degree of decomposition. Known volumes of peat from each horizon were weighed fresh and then dried in an oven for 48 h at 80 °C. Samples were then burnt in a muffle furnace and the weight of the remaining ash and mineral material recorded both with and without any stones in the sample.

Bulk density and fuel moisture content (FMC) were calculated for both the total sample (including stones) and for the organic component calculated after the mass of larger mineral particles had been removed. In this approach 'organic moisture content' describes the water content of the peat component which, given the coarse mixing of the peat and mineral material by ploughing, is more relevant for describing the fuel properties. Scatterplots of ground-fuel bulk density versus depth were used to examine patterns in the layering and bulk density of peat cores. We developed a generic profile for the area as a whole by calculating the mean depth of layers of litter and duff and the mean proportion of the remaining profile accounted for by an upper layer of light brown and relatively fibrous peat containing obvious remains of *Eriophorum vaginatum* L. and a lower layer of dark-brown to black, well humified peat. Any fuel layers that had been obviously altered by burning were excluded from this analysis.

2.3.2. Fuel consumption transects

On our second site visit, three transects were located across the burn area ca. 100 m apart. Each transect was divided into 10 m sections and observations of peat consumption were made at randomly selected distances within each section in order to avoid biasing our measurements to locations close to tree bases. Transects were orientated at right angles to the direction of the plough lines to remove the possibility for bias caused by running transects along mounds or within ditches. At the selected distance within each transect section the depth of the remaining peat (or depth of ash where no peat remained) was measured at three sample points one metre apart and centred on the selected distance (Fig. 1). The depth of burn was estimated based on the difference in surface height compared to surrounding unconsumed areas, exposed tree roots and the position of upper lateral roots (Fig. 1) in a manner similar to that employed by Kasischke et al. (2008) and Mack et al. (2011). Previous research (Boggie, 1972; Coutts et al., 1990) has demonstrated that *P. sitchensis* and *P. contorta* grown on Scottish peatlands tend to produce shallow root networks and adventitious roots close to the surface making them a reliable marker for estimating depth of consumption. There were no tree roots visible above the soil surface in the unburnt areas, so our estimates of depth of burn (and carbon emissions) are likely to be conservative as the use of root and unburnt peat surfaces as a marker of pre-fire ground level may exclude layers of moss/litter and some duff.

Table 1
Definitions of fuel moisture codes and fire danger indices of the Canadian Fire Weather Information system calculated to assess fire weather conditions at the time of the burn.

Name	Abbreviation	Description
Fine Fuel Moisture Code	FFMC	Represents the moisture content of needle litter and other dead fine fuels on a forest floor
Duff Moisture Code	DMC	Represents the moisture content of loosely compacted, decomposing organic matter on a forest floor
Drought Code	DC	Represents the moisture content of deep layers of compact organic matter and potentially of peat (Waddington et al. 2012)
Fire Weather Index	FWI	Represents the energy output of a spreading fire

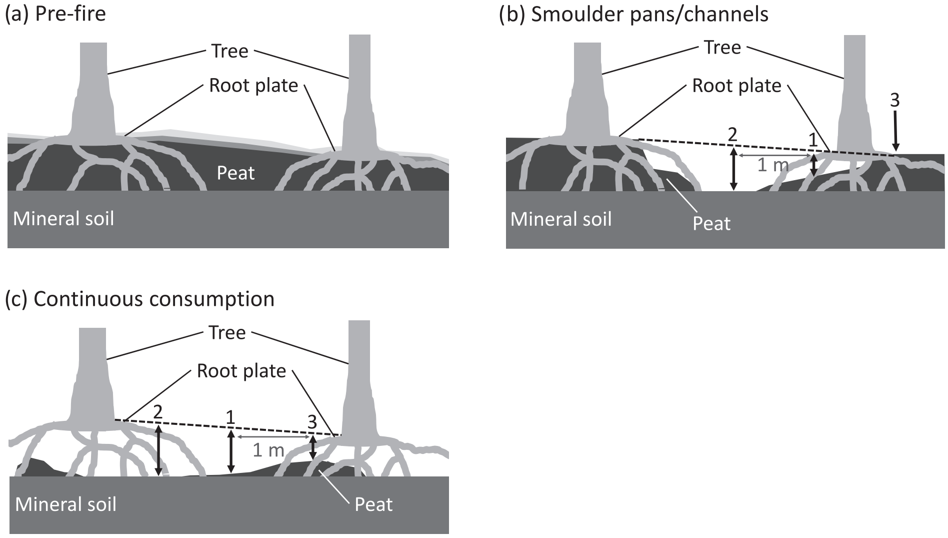

Fig. 1. Estimating the depth of peat in intact areas (a) and peat consumption in areas with patchy smoulder pans (b) and continuous, near complete, peat consumption (c). Pre-fire fuel structure (a) consisted of layers of peat, duff and pleurocarpus moss (each shown as horizontal layers of progressively lighter grey in the figure). Pre-fire peat depth was reconstructed by reference to the top of the peat layer at the edge of smoulder pans or to the height at which main lateral roots joined the tree trunk. Within each 10-m section of transect three points were sampled one metre apart starting at a random position within the section. Photographs of the site pre- and post-fire can be seen in the graphical abstract.

In addition to estimating depth of burn, we recorded the nature of the remaining substrate according to a number of categories: litter, moss, charred litter/moss, white ash, red ash or unburnt. As many trees showed either complete canopy scorch or had dropped their needles, we recorded the height of blackening of the trunk of the tree nearest to the monitoring point as a rough indicator of flaming fire intensity (Cain, 1984). The total number of trees within an area of 5 m radius around the sample position was counted as was the number of trees showing evidence of peat smouldering around their base.

2.3.3. Estimating total fuel consumption and carbon loss

Total consumption of ground-fuel organic matter across the fire was estimated on the basis that the smouldering fire front was observed to be spreading horizontally beneath the ground surface, through the duff or upper peat, with the heat produced drying out and then igniting the duff and litter above. Estimates of the depth of pre and post fire fuel layers were made for each measurement point (where smouldering was observed) on each transect. Pre-fire fuel depth was estimated as the sum of the remaining and burn depths. The total fuel depth was then partitioned into different fuel layers on the basis of the generic fuel profile constructed from the analysis of peat cores. At each measurement point the depth of burn was sequentially attributed to each of the layers in the order moss/litter, duff, upper peat and lower peat.

Pre-fire fuel properties and mean depth of burn were calculated for each transect and an overall site mean calculated as the weighted average of the values for each transect. Standard errors of the site-level mean were calculated accounting for the unbalanced design. Pre-fire fuel load and the mass of fuel consumed per unit area for each fuel layer were estimated by multiplying the bulk density of the layer in the generic profile by the average depth of burn. Variances in fuel depth, depth of burn and bulk density were combined as appropriate. We were unable to account for the variance in the carbon content of the fuel layers though this was assumed to be minimal by comparison with other errors. Carbon emissions were calculated assuming a carbon content of 48% for litter and duff (Legg et al., 2010) whilst the carbon content of the upper (54%) and lower (48%) layers of peat were estimated from their organic bulk density using the relationship developed for Scottish peat by Smith et al. (2007). Total consumption across the burn area was estimated using GPS mapping of the fire perimeter. The area burnt by smouldering combustion was estimated from the total fire area and the proportion of measurement points where smouldering was observed. Correlation analysis (Pearson's correlation coefficient) was used to examine the relationship between pre- and post-fire peat fuel structure and peat consumption in measurement points where smouldering was observed. Statistical tests were completed in R 2.15.0 (R Development Core Team, 2012) using the Hmisc package (Harrell, 2012).

3. Results

3.1. Weather conditions during the fire period

Assuming records for the county of Inverness are generally representative of conditions in Aviemore, examination of long-term weather data and monthly average conditions for the period proceeding and including the fire (Table 2) suggested rainfall during May–July was about half the long-term average whilst temperatures were generally several degrees warmer than normal.

The indices and codes of the FWI system showed that in the period leading up to the fire there were substantial fluctuations in the Fine Fuel Moisture Code (FFMC) but values were above 80 for considerable periods of time (Fig. 2). In comparison, during the whole period for which we calculated FWI system values (1st January–31st August) FFMC was <90 on 98% of days, <80 on 70% of days and <70 on 52% of days. The Duff Moisture Code (DMC) also

Table 2
Long term average monthly values for Inverness-shire 1971–2000 for the three months leading up to and including the fire (data from the UK's National Climate Information Centre) and monthly average weather conditions from the Aviemore weather station for the same period in 2006.

	Rainfall (mm)	Max temp (°C)	Min temp (°C)
May, 1971–2000	92.3	12.1	4.1
June, 1971–2000	102.1	13.9	6.6
July, 1971–2000	113.0	15.8	8.8
May 2006	62.4	14.0	3.9
June 2006	45.2	18.7	8.6
July 2006	42.0	22.9	11.1

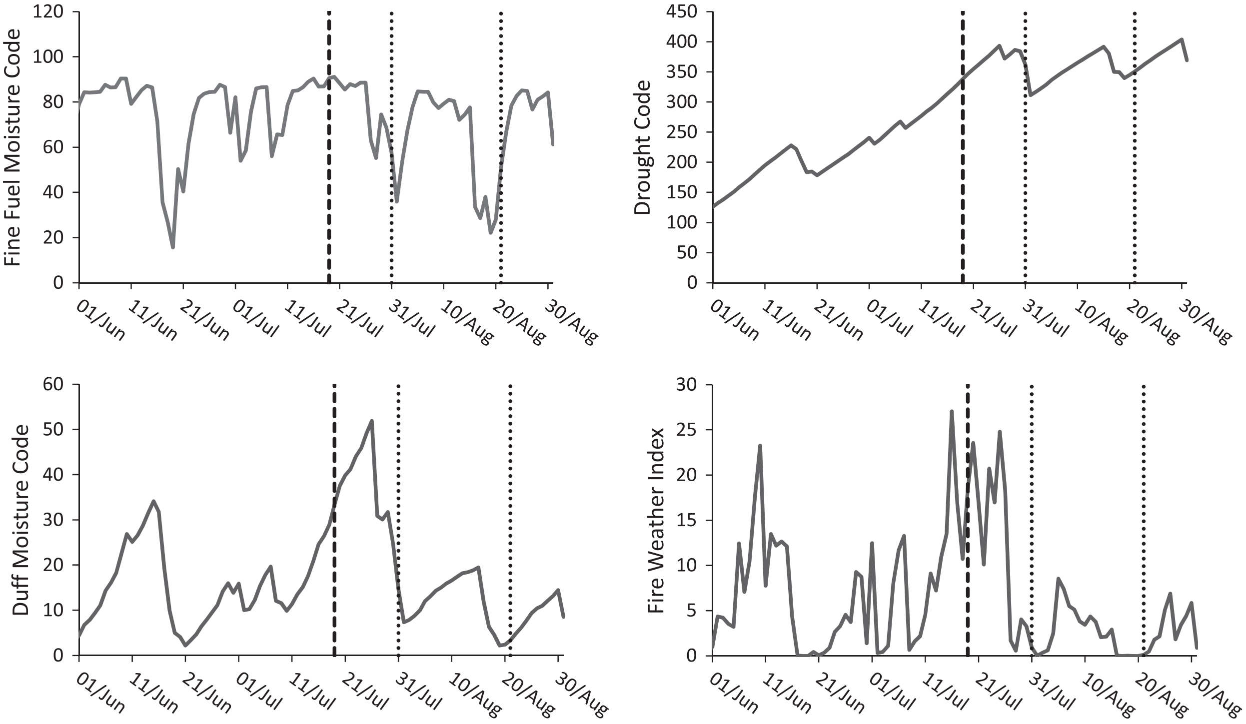

Fig. 2. Variation in three fuel moisture indices and the Fire Weather Index (broadly related to potential fireline intensity) from the Canadian Fire Weather Index system (Van Wagner, 1987) calculated for Aviemore (some 9 km to the north of the fire site) during the period leading up to and after the Rothiemurchus wildfire. The date of the initial fire is shown as a vertical dashed line whilst the dates monitoring took place are shown as dotted lines. The fire was still smouldering extensively at the first visit and in a few places at the second visit.

fluctuated substantially with a significant decline in predicted moisture content developing between the 11th and 25th of July. The Drought Code (DC) increased gradually over the month leading up to the fire reaching a value of 338 on the day of the initial burn before fluctuating slightly and peaking at 404 roughly a month later. Patterns in the Initial Spread Index (ISI) and Fire Weather Index (FWI) were similar with a noticeable peak in the FWI during the three or four days immediately surrounding the initial burn date.

3.2. Unburnt peat fuel structure analysis

The peat was strongly stratified with a distinct boundary between the forest duff (partially decomposed bryophytes and conifer litter) and the consolidated peat which contained remains of *E. vaginatum* and clearly pre-dated the plantation. Mineral material in some cores had been turned onto the surface of the peat by ploughing during site preparation.

Litter and duff showed much lower total FMC than peat. Although this could be partially accounted for by the comparatively large amount of mineral material within these layers, the differences remained substantial (Table 3). Litter and duff generally had a much lower bulk density than the peat (Table 3 and Fig. 3). Distinctive layers were obvious in the peat during field monitoring and analysis of bulk density indicated that the fibrous surface peat was often associated with noticeable differences in fuel properties from the lower humified peat (Fig. 3). Light, surface burns appeared to only affect the structure of the litter layer and there was a relatively clear differentiation in peat bulk density at a depth of 15 cm or greater (Fig. 3).

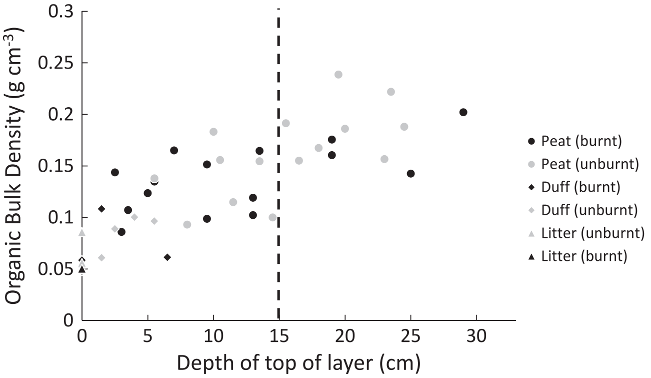

Fig. 3. Organic bulk density of samples from different visually identified layers within eight peat cores. Layers in peat were differentiated on the basis of colour and texture in the field. There appears to be a distinction between peat found above and below ca. 15 cm (dashed line).

To allow for a fire-wide estimate of the total amount of fuel consumed we used the information in Fig. 3 to create a generic ground fuel profile consisting of layers of litter, duff, surface fibrous peat and the lower humified peat (Table 3).

Table 3
Mean fuel properties (±1SE) estimated from eight ground-fuel cores taken both within and outside the fire perimeter.

Fuel layer	Thickness (cm)	Proportion of peat layers (%)	Organic bulk density (g cm^{-3})	Organic fuel moisture content (%)
Litter	3.4 ± 0.9	–	0.06 ± 0.01	106 ± 28
Duff	5.6 ± 1.2	–	0.08 ± 0.01	143 ± 15
Upper fibrous peat	9.0 ± 1.4	57 ± 11	0.13 ± 0.01	252 ± 34
Lower humified peat	8.3 ± 2.0	43 ± 11	0.18 ± 0.01	273 ± 48

3.3. Patterns of carbon loss from peat smouldering

Using the generic fuel profile (Table 3) and data on the average depth of peat consumption (Table 4) we were able to reconstruct estimates of pre-fire ground fuel structure and fuel consumption across the site by estimating the pre-fire fuel structure at each measurement point and sequentially attributing consumption to each layer.

The total area burnt by the smouldering wildfire (i.e. that proportion of the surface affected by the flaming fire where peat and duff were subsequently consumed by smouldering combustion) was estimated to be 4.1 ha (30% of the flaming fire area within the forest). Total fuel consumption across the area of smouldering wildfire was estimated as 773 ± 120 t this corresponds to an average loss of 96 ± 15 t ha^{-1} of carbon (9.6 ± 1.5 kg m^{-2}). There was no obvious, strong relationship between the average depth of burn and the average height of blackening on tree trunks, although it did appear that the areas of greatest depth of burn seemed to occur where tree density was greater (Fig. 4). There were significant correlations between pre-fire peat depth and both the depth of burn ($r = 0.50$, $P < 0.001$) and the depth of peat remaining after the fire ($r = 0.78$, $P < 0.001$). There was no significant correlation between the depth of burn and the depth of peat remaining.

4. Discussion

4.1. Patterns and implications of observed carbon loss

Smouldering combustion of peat deposits was only observed to have occurred within an area of plantation forestry and around the bases of native pine trees in adjacent areas of *Calluna*-dominated moorland. In the zone of the wildfire where active smouldering was observed to occur carbon loss averaged 96 ± 15 t ha^{-1}. This value does not include carbon losses due to consumption of surface and crown fuels during the passing of the initial flame front, nor does it account for post-fire carbon losses due to erosion or altered rates of peat decomposition. Our figure is towards the top of the range of values reported by previous studies in tropical, temperate, boreal and arctic peatlands that made direct, field-based estimates of carbon loss (Table 5). Our figure is also in agreement, though again at the higher end, of values reported by Benscoter and Wieder (2003) in a review of studies that used a range of techniques, including remote sensing, to estimate organic soil consumption during wildfires. They reported mean values of 15–25 t C ha^{-1} for North America and 17–23 t C ha^{-1} for Northern Europe and Asia.

The total amount of carbon released due to ground-fuel consumption was estimated to be 396 ± 63 t. A recent study (Worrall et al., 2003) estimated that the amount of carbon sequestered annually by UK peatlands lies between 0.15 and 0.29 Mt yr^{-1}. The relatively small peat fire of 4.1 ha studied here released between 0.1% and 0.3% of that estimate. Given the likely post-fire changes in hydrology due, for example, to hydrophobicity of charred peat (Mallik and Rahman, 1985) and changes in ground-surface microclimate (Mallik, 1986), total C loss as a result of the fire will be greater due to peat oxidation, increased fluxes of dissolved organic carbon and potential erosion of the exposed peat. Though the fire we studied here only covered an area of 13.7 ha, it should be noted that peatland wildfires associated with smouldering combustion of peat deposits have been observed to cover much greater areas (e.g. Maltby et al., 1990; Albertson et al., 2010).

Contrasting with the results reported here, Mack et al. (2011) found no relationship between pre-fire fuel depth and depth of burn in their study of fire in Alaskan organic soils. They ascribed the relatively constant consumption depth of surface soil layers across their site to factors such as depth-related changes in peat bulk density or the position of the water table. Their results, where smoulder depth was controlled by relatively constant site hydrology (depth of water table), contrast to our own where we found considerable variation in the depth of consumption and a significant correlation between consumption and pre-fire fuel depth. We also found considerable spatial variation in the amount of smouldering across the fire area. Smouldering was limited to the area beneath isolated trees in the moorland and within the plantation forestry and even here we estimated that only a third of this area showed any sign of peat consumption. Benscoter et al. (2011) demonstrate that key controls on peat ignition potential include moisture content, bulk density and ground layer vegetation composition. Our results suggest that the potential for the initiation and spread of smouldering is increased by afforestation as the presence of trees, and pre-planting disturbance and drainage, lead to reduced peat moisture and bulk density. Our carbon emissions per unit area is considerably higher than many previously reported studies largely because the degraded peat structure meant that when smouldering was initiated the entire peat profile was at risk.

4.2. Observations of fire spread and impact

Tree mortality appeared to be high in areas where smouldering had occurred and a large number of trees had either fallen or were very unstable due to the exposure of their roots. Some relatively large areas of crown fire were observed and these were associated with small clearings, high *Calluna* fuel loadings and steep slopes; crowned trees being located at the top of *Calluna*-covered banks. A number of deciduous trees (mostly *Betula*) were re-sprouting despite severe scorch and smouldering having occurred around some of their roots. Previous research has shown that there were significant physical and chemical differences in the soils in areas with and without smouldering combustion (Prat et al., 2011) which, combined with the combustion and extensive heating on below-ground propagules (Rein et al., 2008; Granström and Schimmel, 1993), may contribute to substantial variation in post-fire vegetation dynamics.

Compared with laboratory studies of peat flammability, smouldering at our wildfire seemed to have been continuing at relatively high fuel moisture contents. Average peat moisture contents in our cores were between 252 ± 34% and 273 ± 48% dry weight. In comparison, Rein et al. (2008) showed a critical moisture content for ignition of 125% for peat and Frandsen (1997) a 50% ignition probability limit for peat of ca. 60%. Though our cores were by

Table 4

Estimated mean pre-fire fuel structure, fuel consumption and carbon release from the 2006 Rothiemurchus wildfire. Values given are means (±1SE) for the randomised sample locations on the three transects. Means are weighted by the number of observations on each transect and errors calculated accordingly. The standard error accounts for variance in both the estimation of fuel layer bulk density and the estimation of the depth of consumption of each fuel layer.

Fuel layer	Pre-fire depth (cm)	Depth of burn (cm)	Pre-fire fuel load (kg m^{-2})	Fuel consumption (kg m^{-2})	Pre-fire C pool (kg m^{-2})	C loss (kg m^{-2})
Litter	3.4 ± 0.0	3.3 ± 0.1	2.0 ± 0.3	2.0 ± 0.3	1.0 ± 0.2	1.0 ± 0.2
Duff	5.5 ± 0.2	4.9 ± 0.5	4.4 ± 0.6	3.9 ± 1.6	2.1 ± 0.3	1.9 ± 0.3
Peat 1	12.6 ± 2.4	7.8 ± 1.8	16.3 ± 3.4	10.1 ± 2.5	8.8 ± 1.8	5.5 ± 1.3
Peat 2	9.5 ± 1.8	1.5 ± 0.8	17.1 ± 3.4	2.6 ± 1.4	8.2 ± 1.6	1.3 ± 0.7
Total	30.9 ± 3.0	17.5 ± 2.0	39.8 ± 4.9	18.7 ± 2.9	20.1 ± 2.5	9.6 ± 1.5

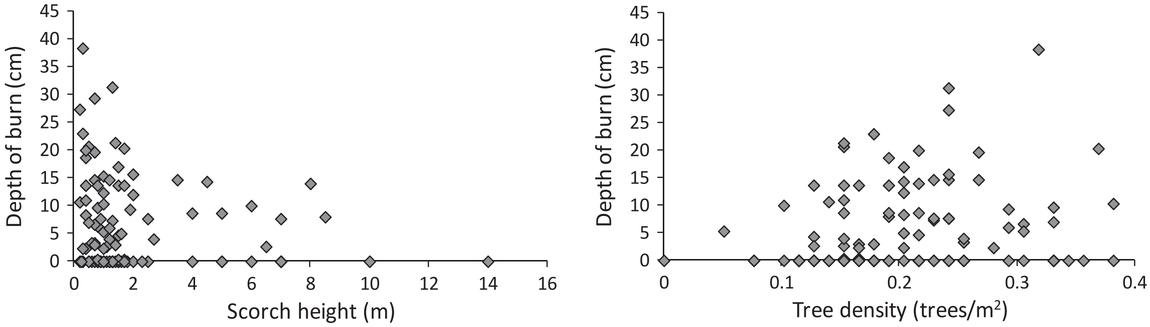

Fig. 4. Scatterplots showing the relationships between tree scorch height and peat consumption (left) and tree density and peat consumption (right).

Table 5
A summary of studies making direct (field-based) estimates of carbon loss due to the smouldering of peat and organic soil deposits during wildfires. Where multiple fires were studies the maximum and minimum values observed are given. Where authors studied a single fire but described maximum and minimum consumption the range is given in the average/maximum column (Av/Max).

Authors	Consumption (t C ha^{-1})		
	Min	Av/Max	Primary fuel
Shetler et al. (2008)	–	11	Boreal organic soil (AK,USA)
Mack et al. (2011)	–	12	Tundra peat (AK, USA)
Turetsky and Wieder (2001)	–	22	Boreal peat (Canada)
de Groot et al. (2009)	3	24	Boreal litter/duff (Canada)
Benscoter and Wieder (2003)	–	15–28	Boreal peat (Canada)
Kasischke and Hoy (2011)	13	26	Boreal ground fuels (AK, USA)
This study	–	**96**	**Temperate peat (Scotland)**
Poulter et al. (2006)	–	2–110[a]	Temperate peat (NC, USA)
Turetsky et al. (2011b)	20[b]	168[c]	Boreal peat/duff
Page et al. (2002)	–	260–315	Tropical peat (Indonesia)

[a] Estimate based on remote sensing and including above ground fuels, included here for comparison here due to limited number of studies in temperate peatlands.
[b] Pristine black spruce fen peatland.
[c] Drained black spruce fen peatland.

necessity taken from areas without smouldering, and after the flaming surface fire had been extinguished, smouldering was still underway when these samples were collected. In further lab experiments Benscoter et al. (2011) achieved successful peat combustion at moisture contents as high as 295% and observed smouldering continuing at higher moisture contents than those required for ignition. Both our and Benscoter et al.'s (2011) results therefore have implications for forecasting the potential maximum spread of smouldering wildfires. It is important that ignition and combustion limits are explored in greater detail as they appear to be highly sensitive to fuel structure, fuel moisture and ignition mechanisms.

Smouldering appeared to have occurred preferentially around the bases of trees and to have followed the root network, meeting those from the adjacent plants, thus propagating along the line of trees. Whether this was a result of peat being drier due to mounding from ploughing or due to the presence of the trees themselves was unclear as there was little peat left around tree bases leaving no or little evidence of the original micro-topography. However, a number of isolated trees on the moorland area outside the forest had significant peat consumption around their bases matching the observations of Miyanishi and Johnson (2002). Our results suggest that it is important to investigate the extent to which plantation forestry on peat soils, and associated ploughing, draining and ridging prior to planting, leads to peat desiccation and increased peat fire hazard.

Smouldering was still occurring in isolated locations at the perimeter of the fire 33 days after the initial surface fire despite a number of days with rain. The fire spread was primarily through the peat and the propagation front formed a cavity beneath the damp moss/duff layer undercutting it by up to a metre. The heat produced by smouldering dried out the overlying material which subsequently ignited and burnt via smouldering or flaming combustion. This produced a pattern of fire spread characterised by gradual extension of the smouldering front below the duff, moss and litter followed by sudden ignitions and collapses of this surface material. This observed spread pattern compares favourably with changes in fuel moisture indices during and after the fire (Fig. 2). An initial period of high fire risk with conditions suitable for the spread of both surface flaming and subsurface smouldering combustion (high FFMC and high DC, Fig. 2) gave way to low FFMC (low fire danger) at the time of our visit. The DC however remained high, suggesting smouldering could continue, due to the long lag-time of this moisture code and the need for more substantial amounts of precipitation to re-wet subsurface fuel layers. Such fuel moisture "inversions" have previously been observed in the duff layers of boreal forests (Lawson and Dalrymple, 1996) These patterns are also in agreement with Alexander & Cole's (2001) suggested FWI system moisture code flammability thresholds for Alaskan forests: FFMC > 74 for ignition of surface fuels and DC > 300 for ignition of deep organic layers. At DC values greater than 500 persistent smouldering is likely to occur. However, smouldering of the duff layer and pleurocarpous mosses seems to have been initiated at lower levels of the DMC (33) than those recorded by Lawson et al. (1997) for similar fuels (80–90 for white spruce duff, 76–81 for pleurocarpous mosses). Further research should determine such flammability thresholds for fire-prone vegetation types in the UK.

4.3. Conclusions

The UK is currently poorly placed to either assess the overall impact of peatland fires on national carbon emissions or to forecast the conditions under which such fires occur. As Davies et al. (2008)

previously pointed out, there is an urgent need to develop a coordinated approach to collecting data on the incidence and impact of peatland wildfires. Existing tools, such as the FWI system, should also be modified to forecast conditions when peat fires can occur. To achieve this further research is needed on the relationship between peat fuel moisture and the moisture codes of the FWI system when fire events are more likely to occur. Wildfires that ignite peat deposits represent a significant potential feedback to climate change and improved tools and tactics to forecast, prevent and fight them are urgently needed.

Study of the carbon release associated with smouldering combustion during the Rothiemurchus wildfire has added to a growing body of evidence (Table 5) showing that even small events of this nature can release significant quantities of carbon. Our results also provide circumstantial evidence that afforestation of peatland soils, and associated site preparation, may contribute to an increased risk of peat fires. This requires further study and should be accounted for in the planning of future forestry operations particularly in the light of climate change forecasts that suggests conditions suitable for severe summer wildfires may become more frequent (Jenkins et al., 2010). Increases in the frequency and severity of peatland wildfires have been shown to be a potentially significant positive feedback on climate change in other regions (Field et al., 2007; Turetsky et al., 2011a) and it would be sensible for peatland managers in the UK to also be concerned. Attempts have recently been made to estimate the relative contribution of different types of burn to global C emissions from wildland fire (van der Werf et al., 2010). This research was based on MODIS active fire and burned area maps but it is not clear if such remotely sensed data is able to catch the kind of smouldering wildfire that accounted for most of the ground fuels consumed in our study. If burns such as our are common in other forested temperate, boreal and tropical peatlands then emissions from peatland burning may well be a substantially greater issue than assumed at present.

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