Flammability properties of British heathland and moorland vegetation: models for predicting fire ignition

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Abstract

Temperate ecosystems, for example British heathlands and moorlands, are predicted to experience an increase in severe summer drought and wildfire frequency over the next few decades. The development of fire ignition probability models is fundamental for developing fire-danger rating systems and predicting wildfire outbreaks. This work assessed the flammability properties of the fuel complex of British moorlands as a function of their moisture content under laboratory conditions. Specifically, we aimed to develop: (1) models of the probability of fire ignition in peat/litter fuel-beds (litter of four different plant species, *Sphagnum* moss and peat); (2) flammability properties in terms of ignitability, sustainability, consumability and combustibility of these peat/litter fuel-beds; (3) the probability of ignition in a canopy-layer of *Calluna vulgaris* (the most dominant heath/moor species in Britain) as a function of its dead-fuel proportion and moisture content; (4) the efficacy of standardized smouldering and flaming ignition sources in developing sustained ignitions. For this, a series of laboratory experiments simulating the fuel structure of moor vegetation were performed. The flammability properties in peat/litter fuel-beds were influenced strongly by the fuel moisture content. There were small differences in moisture thresholds for experiencing initial flaming ignitions (35-59%), however, the threshold for sustained ignitions (i.e., spreading a fixed distance from the ignition point) varied across a much wider range (19-55%). Litter/peat fuel-beds were classified into three groups: fuel-beds with high ignitability and combustibility, fuel-beds with high levels of sustainability, and fuel-beds with low levels in all flammability descriptors. The probability of ignition in the upper *Calluna*-vegetation layer was influenced by both the proportion of dead fuels and their moisture content, ranging from 19% to 35% of moisture as dead fuel proportion increased. Smouldering sources were more efficient in igniting peat/litter fuel-beds but in the

Calluna-vegetation layer flaming sources performed better. This work can assist in improving the predictions of fire-rating systems implemented in British moorlands, by providing better warnings based on critical moisture thresholds for various fuel types.

Keywords: combustibility, consumability, fire-rating systems, fuel moisture content, ignitability, sustainability.

1. Introduction

Developing management strategies to face novel disturbance regimes associated with climate change are fundamental for mitigating their effects (Allen et al., 2013; Marino et al. 2011). Changes predicted to occur as a result of global climate-change over the next few decades are that temperate ecosystems will experience an increase in severe summer drought and wildfire frequency (Krawchuk et al., 2009). It is well known that the occurrence of wildfires in these systems is often exacerbated under drought conditions because there is no limitation in fuel availability (Pausas and Ribeiro, 2013). At present, however, adaptive strategies for facing these future scenarios are in the early stages of development, for example through the implementation of fuel management strategies to reduce fire impacts, improved education to minimize fires started by arson and the development of rating systems for forecasting fire outbreaks (Albertson et al., 2009; Allen et al., 2013; Davies and Legg, 2008).

Even though fire has played a role in shaping many temperate ecosystems, little is known about the flammability properties of the component species (van Altena et al., 2012). Previous studies have been centered mainly in ecosystems with a high burning frequency where wildfire is an ongoing problem, e.g. in Mediterranean systems. These studies deal with the general ability of vegetation to burn (flammability as proposed by Anderson, 1970; Martin et al., 1994); but this is usually broken down into four components (1) ignitability, how easily the fuel ignites, (2) sustainability, how well the combustion proceeds, (3) consumability, the amount of fuel lost during the fire, and (4) combustibility, the velocity or intensity of the combustion. One major shortcoming of these studies is that they have traditionally just used discrete fuel elements (e.g. leaves, twigs), neglecting the possible interactions aggregated within a more complex and realistic fuel-bed (Fernandes and Cruz, 2012). For instance, thin and small leaves can ignite easily on an individual basis, but burn with difficulty when presented in litter beds (Scarf and Westoby, 2006). In this respect, the flammability of the above-ground vegetation is defined mainly by the structural arrangement of the fuel materials and factors such as the size-distribution of the fuel elements, the dead:live ratio and bulk density (Chandler et al., 1983; Santana et al., 2011), whereas small-scale intrinsic properties (e.g. specific gravity, mineral content, chemical composition) have a lesser effect because usually there is a low range of inter-species variation (Fernandes and Cruz, 2012). Moreover, when modeling vegetation flammability, it is also necessary to consider environmental conditions (e.g., moisture, temperature, wind speed and direction), but especially the fuel moisture content (FMC, Marino et al., 2010; Plucinski et al., 2010). All of these environmental variables interact with, and moderate, flammability.

Heathlands and moorlands in the United Kingdom (UK) are temperate ecosystems dominated mainly by the dwarf-shrub *Calluna vulgaris* (L.) Hull (Gimingham, 1972). The vegetation fuel-complex is usually composed of three main strata: (1) the shrub stratum of the above-ground vegetation, i.e. the *Calluna*; (2) an understory stratum of litter and bryophytes; and, (3) the soil which is often an acidic podzol with a clear organic mor horizon (lowland heaths) or peat (upland moors). Most heaths and moors in the UK systems are originally anthropogenic, and are sustained by means of grazing and burning practices that combine to prevent succession to more mature woodlands (Gimingham, 1972). Land managers periodically apply rotational burning to produce a mosaic of different stages of recovery and that optimizes productivity, diversity and environmental services (Harris et al., 2011). The legal burning period is from October to mid-April (Anon, 2007), when soils are wet and/or frozen and damage to understory species and peat is minimized. However, one of the greatest threats to these ecosystems is wildfire; these occur mainly in spring (March to April) and summer (July and August) (Albertson et al., 2009). Spring wildfires comprise mainly the above-ground vegetation because soils are usually still very wet, but the shrub stems are highly-desiccated as consequence of winter frosts (Davies and Legg, 2008). Summer wildfires, in contrast, can be extraordinarily damaging because the surface peat can be dry and once ignited, it can smoulder for many months (Rein et al., 2008).

Wildfires in British moorlands are usually caused by human negligence or malice, but there is still little documented evidence about this (McMorrow, 2011). Two types of ignition sources have been identified as being probably important: (1) smouldering sources (e.g., such as discarded cigarettes, lost barbecues embers, hot particles dropped from power lines, etc.) and (2) flaming sources (e.g. escaped prescribed burns, arson, etc.) (Schmuck et al., 2012). There is, therefore, a need for a better understanding of the ignition efficiency of these different sources in developing self-sustained wildfires on a range of ecosystems. Moreover, the variable nature of fires (i.e., canopy fires often burn independently from ground-layer fuels; Davies and Legg, 2008) means that separated assessments are needed in the different strata.

The litter layer is the medium in which ignition is most likely to occur (Davies and Legg, 2011); nonetheless the probability of ignition and subsequent fire impacts can differ significantly between species because the different flammability properties of their litters (Plucinski and Anderson, 2008; Scarf and Westoby, 2006). On the other hand, when canopy fires occur in spring, ignition is strongly related to the moisture content of dead material in the canopy fuel (Davies and Legg, 2011). Therefore, estimation of moisture thresholds for fire ignition in each fuel type is of fundamental relevance for predicting fire danger (Davies and Legg, 2008). Assessing these thresholds is difficult under field experimental conditions, because dead-fuels are usually inter-mixed with green fuels within the shrub layer (Davies and Legg, 2011).

The development of fire ignition probability models that incorporate the FMC of live and dead canopy material, the peat/litter layer and peat are needed to develop improved fire-rating systems for UK moorlands. The main aim of this work is, therefore, to assess the flammability properties of a range of common species that could contribute to the fuel complex of British heathlands/moorlands. To do this, we carried out a series of laboratory experiments simulating the fuel structure of heath/moor vegetation under controlled conditions. Specifically we aimed to develop:

(1) Predictive models of the probability of fire ignition in peat/litter fuel-beds (litter of different plant species, *Sphagnum* moss and peat), using FMC as the predicting variable.
(2) Flammability properties in terms of ignitability, sustainability, consumability and combustibility of the different peat/litter fuel-beds by means of easily measurable descriptors.
(3) Predictive models for the probability of ignition in *Calluna*-dominated heathlands/moorlands as a function of its dead-fuel proportion and FMC.
(4) An assessment of the efficacy of standardized smouldering and flaming ignition sources in developing sustained ignitions.

2. Methods

Plant material was collected throughout the summer and autumn of 2012 from three heathlands/moorlands in: (1) North Wales (*Sphagnum* spp. L. and *Vaccinium myrtillus* L.; 53°04’N, 3°10’W), (2) Peak District Natural Park (*Calluna vulgaris* (L.) Hull, *Empetrum nigrum* L. and peat; 53°25’N, 1°10’W) and (3) Wirral (*Ulex europaeus* L.; 53°21’N, 3°10’W). Hereafter, species are referred by their generic names. The plant material (stems and shoots) from the dwarf shrubs (*Calluna*, *Vaccinium, Empetrum* and *Ulex*) were collected by cutting with secateurs near the ground surface. Surface cores (0-5 cm depth) of mosses formed by *Sphagnum* and peat were collected by excavation. The sampled material was transported in plastic bags to the laboratory, where it was used to reconstruct (a) peat/litter fuel-beds and (b) stands of *Calluna* vegetation.

2.1. Laboratory preparation of the peat/litter fuel-beds

Initially, the plant material was placed in paper bags and oven-dried at 80ºC for 24 h. This allowed easy separation of the leaves from the stems; the leaves were then used to reconstruct pure leaf litter-beds for each plant species within a circular tray of 250 mm diameter and 20 mm depth (Fig. S1a). For peat, the upper part of peat cores was cut with a knife. Then, they were carefully prepared to have the same dimensions of the tray used. The tray was similar to that used by Plucinsky and Anderson (2008) and was constructed using a fireproof, fibre-base and sides of 0.5 mm stainless steel mesh. Filled trays were weighed before and after each test to assess fuel consumption; the bulk density was calculated from these weights and the known volume of the fuel-bed (982 cm^3).

Ignition experiments were run with each of the litter/peat materials; in these experiments the plant materials were manipulated to produce a range of fuel moisture contents. To do this, fuels were placed into sealed plastic bags and moistened until they reached the desired water content. The bags were then placed within an oven at 60ºC and mixed twice daily for two days to produce a uniform moisture content. The FMC was then determined as the percentage of dry mass before each test using gravimetric method (taking a sub-sample from each prepared fuel-bed and oven drying at 80ºC for two days).

Specific traits of the peat/litter fuel-beds, e.g. the surface area of the material, surface-area to volume ratio, mineral content and heat of combustion were also assessed. Assessments for litter fuel beds were made for leafs (the most part of fuels used), avoiding shoots and stems. The surface area of the materials was assessed by scanning samples of the material using an HP Scanjet 4850 (200dpi resolution) and image processing software (ImageJ; http://rsbweb.nih.gov/ij/; accessed 16 August 2013). The area of *Calluna* and *Ulex* was calculated assuming a cylindrical shape. Volume was measured by putting material in a pycnometer (van Altena et al., 2012). Fuels were ashed in a muffle furnace at 550ºC for 2h to assess their mineral content (Frandsen, 1997), and heat of combustion was determined using a bomb calorimeter (e2K, Digital Data Systems, South Africa).

2.2. Laboratory preparation of Calluna vegetation

Dead and live shoots were collected near the ground surface and transported to the laboratory to produce simulated *Calluna* vegetation arrays. These arrays were reconstructed using a similar structure to that used by Plucinski et al. (2010). This consisted of two wire cages with 64 cells where individual shrub clippings were placed upright (Fig. S1b). This structure was a 20 x 20 cm square and the area was sufficient for demonstrating that ignition of fires was sustainable (Plucinski et al., 2010). Here, the physical structure of *Calluna* vegetation was simulated using representative values from Davies et al. (2009), who, in extensive work within a series of age-stages of *Calluna* (building, late-building and mature) on British moorlands, showed that bulk density ranged between 3.5-5 kg·m^{-3} and height varied between 15-45 cm. Therefore, we produced simulated *Calluna* stands with shoots 30 cm tall with a bulk density of 4 kg·m^{-3}; this was kept constant in all experimental runs.

The two key variables manipulated in this study because of their known influence on fire ignition were: (1) the proportion of dead-fuel in the vegetation, and (2) the FMC of the dead-fuel (Davies and Legg, 2011). Three levels of dead-fuel proportion (20, 40 and 60%) were reproduced with the aim of simulating different states of shrub maturation (Davies et al., 2009; Davies and Legg, 2011). Shrub arrays were reproduced taking into account the stratified structure of *Calluna* vegetation, with the dead-fuel accumulating in the lower part of the canopy (Davis and Legg, 2011). For this, we cut live shoot clippings (<5mm stem diameter) to a height of 30 cm and dead-fuels shoots to a height of 15 cm. The FMC of live shoots was maintained constant at near field values by maintaining their bases in water-filled buckets, but the exact value was determined as a percentage of dry mass before each test (mean: 51.8 ± SD: 4.7, n=240). The amount of dead-fuel was determined by drying the dead shoots at 80ºC for two days and then weighing them. The FMC in dead-fuels was modified in a similar way to litter fuels, by enclosing in plastic bags and wetting the shoots to a desired level. The exact level of moisture was assessed by putting an additional sub-sample within the plastic bag. This sub-sample was separated by a permeable nylon bag that allowed the fuel have the same moisture content as the fuel to be burned. Bulk density was kept constant by proportionally decreasing or increasing the amount of live shoots regard to dead-fuel proportion, but always taking into account their moisture content.

2.3. Ignition source

The effects of the two main types of wildfire ignition sources, smouldering sources and flaming sources, were tested. The smouldering source was used in the litter/peat experiments and both sources were used in the *Calluna* litter and vegetation experiments.

The smouldering source was created electrically using a nichrome wire (300 mm long and 0.5 mm width) connected to a power supply (Skytronic 650.682 Bench Top 0-30V 10A, Netherlands). The wire acted as a resistance and warmed until it became red (temperatures *ca.* 600-700ºC, measured using a thermocouple K type). The central part of the wire was shaped into a compact cylinder 6 mm long and 7 mm diameter by giving 7 turns to the wire (Fig. S1c). The aim was to simulate the effect of a cigarette end or a stray ember. To ignite litter trays, the wire cylinder was lowered into the central part of the tray within the first cm of the fuel surface. In the *Calluna* vegetation arrays, the wire cylinder was placed at the front side of the fuel structure at a height of 70 mm within the dead-fuel. A power of 100W was supplied for 5 min in each test.

The flaming ignition source was provided through the use of commercial kerosene ignition pills, designed for barbecues (Zip, Standard Brands, UK; Fig. S1d). The pills were rectangular (19 x 17 x 12 mm; L x W x W). The flaming ignition source, when lit, remained on fire for 383 ± 32 s (mean ± SD, n=6) and the flames reached a maximum height of 101 ± 7 mm.

2.4. Experimental conditions

All ignition experiments were performed within a glasshouse with a temperature of 17.1 ± 5.9°C (Mean ± SD, n=528) and a relative humidity of 44.8 ± 15.4%. The incidence of wind in these types of experiments has an increasing effect in igniting litter beds (Marino et al. 2010). In order to simulate wind, a domestic fan was used to provide a constant air flow of 0.3 $m \cdot s^{-1}$ (measured with an anemometer-Viking ART 02041, Sweden) in the central point of the tray. Wind speed was minimal in order to be conservative in obtaining flammability parameters. Air-flow was supplied at angle of 45° to the experimental trays to avoid fuel particles being blown-off (Marino et al. 2010).

[INSERT TABLE 1]

2.5. Assessment of fuel flammability properties

The probability of ignition in litter, mosses and peat was assessed as a function of FMC. In addition, this ignition was assessed in two different ways: (1) initial flaming ignition and (2) sustained ignition. Initial flaming ignition was considered successful if flames appeared after the ignition source was applied (only for the smouldering source). Sustained ignition was considered positive if the fire front reached the tray edge. The distance from the ignition point to the edge (125 mm) allowed enough fire development to demonstrate sustainability of fire spread (Plucinsky and Anderson, 2008). A note was made if the fire front reached the edge of the tray as well as whether the fire front was a smouldering or flaming one. A minimum of 40 tests were performed for each fuel type. In addition, flammability components (ignitability, sustainability and consumability, combustibility) of the fuel types were determined using easily measurable descriptors (Table 1). The time elapsed by the fire front to reach the edge of the tray and for the end of combustion was recorded directly with a chronometer. This allowed us to estimate the rate of spread (ROS) and mass loss rate (MLR). All tests were recorded with a digital camera separated 50 cm horizontally from the tray, providing an estimate of time to ignition (TTI), flaming time (FT) and flame height (FH, using a ruler located behind the tray). The maximum temperature achieved (TMAX) and the time above 300°C

(T300) were obtained using four thermocouples (1 mm thick, K type) placed equally around the tray and linked to a data logger (OM-DAQPRO-5300, Omega, USA). The tip of each thermocouple was placed 6 cm from the center and at 1 cm of depth below the fuel surface. Measurements were taken every second and the mean value of temperatures from the four thermocouples was estimated for each sample.

The probability of sustained ignition was also assessed for *Calluna* vegetation. Ignition was considered successful if fire reached the bottom part of the cage (20 cm). The shrub support cages were weighed before and after fires in order to determine fuel consumption. These *Calluna* vegetation experiments included 40 tests for each of the three dead-fuel proportions and the two ignition sources (240 tests in total).

2.6. Statistical analysis

Differences in specific traits of peat/litter fuel-beds were analyzed by means of one-way ANOVA with Bonferroni pair-wise comparisons. The probability of ignition was modelled using Generalized Linear Models (GLM) with a binomial error distribution and a logit-link function for each peat/litter fuel-bed (Crawley, 2012). Initially, we considered FMC, air temperature and relative humidity as predictor variables. Then, starting from the full model, the minimum adequate GLM was obtained by sequential removal of non-significant model terms (Analysis of deviance, F tests, $P>0.05$; Crawley, 2012). Because temperature and relative humidity were mainly constant throughout the experiment, only FMC was selected as significant in all cases. The goodness of fit was measured by Nagelkerke's pseudo R^2 statistic, and the area under Receiver Operating Characteristic (ROC) curve used to determine the discriminative ability of the models over a range of cut-off points (Hosmer and Lemeshow, 2000). Thereafter, the FMC at which 50% of ignitions were successful (M_{50}) was estimated for each fuel type. The maximum FMC at which a successful ignition occurred (M_{max}) was also estimated. M_{50} values were obtained by using the logit model whereas M_{max} values were from observed data. In order to ascertain the influence of the different specific fuel traits in ignition, the relationships between these specific traits and the M_{50} values were assessed by mean of linear regressions. The different efficiency in initiating sustained ignitions between smouldering and flaming ignition sources in *Calluna* litter was tested by means of analysis of deviance. Flammability descriptors of each peat/litter fuel-bed were modelled as a function of FMC using GLMs with a Poisson error distribution and a log-link function. A summary of all the Minimum Adequate Models derived from the GLM analysis is provided in Table S1.

The probability of ignition of the *Calluna* vegetation was also modelled using GLM with a binomial error distribution and a logit-link function. Initially, we considered the FMC of the dead-fuel, dead-fuel proportion, ignition source, air temperature and relative humidity as predictor variables. Interactions between FMC of dead-fuel, dead-fuel proportion and ignition source were also included in the initial model. In these models the flaming ignition source was used as the baseline. As before, the final model was obtained by sequential removal of non-significant terms (Analysis of deviance, F tests, $P>0.05$). M_{50} and M_{max} values for each dead-fuel proportion and ignition source were also calculated as above. All statistical analyses were performed in the R statistical environment (version 2.14.2., Development Core Team 2012, Vienna).

[INSERT TABLE 2]

3. Results

3.1. Flammability of peat/litter fuel-beds

There was considerable variation in the basic properties of the fuel-bed materials. In terms of bulk density there were three groups (Table 2): peat had the greatest bulk density at 289 kg m^{-3}, *Calluna* and *Empetrum* litter had intermediate values (112-149 kg m^{-3}) and *Sphagnum, Vaccinium* and *Ulex* had least (<50 kg m^{-3}). In terms of surface area *Empetrum* and *Ulex* had the lowest whereas *Calluna*, *Vaccinium* and *Sphagnum* had the greatest. Area to volume ratio was higher for *Calluna* and *Vaccinium*, intermediate values were for *Ulex*, and *Empetrum* and *Sphagnum* were the lowest (Table 2). Peat and *Vaccinium* had the largest high mineral content (11% and 6% respectively) in comparison to the other species (2-3%). The heat of combustion was greatest in the dwarf shrub, intermediate in peat and least in the *Sphagnum* (Table 2).

The probability of ignition was well explained by FMC (Table 3). When smouldering ignition sources were applied, *Sphagnum* had the largest M_{50} values for both the threshold of initial and sustained ignition (56.5% and 54.6% respectively). Litter of *Ulex* also had high values with 51.4% and 34.5% (Table 3). In contrast, litter of *Calluna*, *Empetrum* and *Vaccinium* had high values for the thresholds of initial ignition (53.6%, 59.2% and 46.8%), but the threshold of sustained ignition was very much lower (26.9%, 19.1% and 25.1%). Peat had low values for both variables (34.9% and 21.6%; Table 3). M_{max} values followed similar trends for *Calluna*, *Empetrum*, *Vaccinium* and *Ulex*, with an increase of *ca.* 5-15% with respect to M_{50} values. In contrast, M_{max} values for *Sphagnum* and peat experienced an increase of *ca.* 25%. The threshold of sustained ignition decreased when a flaming source was applied, as for example, observed in *Calluna* litter (Analysis of Deviance, F= 36.65, P<0.001), where M_{50} values decreased from 26.9% to 15.2% (Table 3B). No clear relationships were found between specific fuel traits and M_{50} values, either for initial and sustained ignition (Figure 2S). Only the mineral content of fuels had a significant relationship for the initial ignition (R^2=0.851, *P*=0.009).

[INSERT TABLE 3]

Sustained ignitions which spread successfully to the edge of the tray occurred mainly as smouldering fires. Successful sustained ignitions as a flaming fire occurred with *Sphagnum* and *Ulex*, and only when the FMC was under *ca.* 30%.

Flammability descriptors were clearly influenced by FMC (Fig. 1). The litter/peat materials could be classified into three groups on the basis of these relationships. Group 1 comprised *Ulex* and *Sphagnum*; these species experienced the highest levels of ignitability (low TTI and high ROS), consumability (high MLR and RMF) and combustibility (high FH). Group 2, composed of *Calluna*, *Empetrum* and Peat, experienced lower values of these flammability descriptors, but had the highest sustainability values (high FT and T300). Finally, *Vaccinium* experienced low values for all flammability descriptors. No large differences were observed in TMAX between any of the fuel-beds; although *Empetrum* and *Vaccinium* experienced slightly lower TMAX values (Fig. 1).

[INSERT FIGURE 1]

3.2. *Flammability of Calluna vegetation*

The selected GLM for the probability of ignition included the dead-fuel moisture, dead-fuel proportion, ignition source and the interaction between the ignition source and dead-fuel proportion as predictor variables (Table 4). For flaming ignition sources, FMC was the main factor controlling the probability of ignition; the proportion of dead-fuel did not affect it significantly. M_{50} values were all around 30% of FMC and M_{max} around 45-50%. In contrast, for the smouldering ignition source, the proportion of dead-fuel increased the ignition threshold with M_{50} values increasing from 19% to 35% of FMC as the dead fuel proportion increased from 20% FMC to 60% (Fig. 2). In general, M_{max} values followed a similar trend compared to M_{50} values, with an increase of *ca.* 5-10%.

[INSERT TABLE 4 AND FIGURE 2]

4. Discussion

4.1. *Fire danger in peat/litter fuel-beds*

In British heathlands and moorlands, most wildfires have been shown to start within the litter layer (Davies and Legg, 2011), from where it can spread upwards into the canopy and downwards into the underlying peat (Plucinski et al., 2010; Rein et al., 2008). Initially, flaming ignition in the litter fuel-beds can propagate fire to the upper canopy through contact with the lower branches of vegetation. Here, we suggest that there are small differences in the moisture threshold for initial flaming combustion between litter fuel-beds of the different species (M_{50} from 47-59%). Nonetheless, despite these low differences in initial ignition probability, there is variation in other flammability properties that may confer different efficiencies in fire propagation. Fuel-beds with high ignitability (low time-to-ignition, TTI) and combustibility (high flame height, FH), e.g. *Ulex* and *Sphagnum*, may make contact quickly with higher branches in the vertical structure of vegetation and expedite flame upwards transfer. In contrast, fuel-beds with high sustainability (high flaming time, FT), e.g. *Calluna* and *Empetrum*, may maintain a flame for longer and hence could propagate fires more easily because the flame will have a longer contact time. In this sense, further studies assessing which flammability properties (ignitability and combustibility *vs.* sustainability) are more important in propagating fire to the aboveground vegetation are needed.

In contrast to the thresholds of producing initial flaming ignition, the thresholds of sustained ignitions within the different litter fuel-beds varied across a wide range of FMC (M_{50} from 19-55%). Fuel-beds able to keep sustained ignitions at higher FMC values were again *Ulex* and *Sphagnum.* This ability was probably a consequence of their high consumability and combustibility, observed in their high values of ROS, MLR and RMF. In addition, these fuel-beds were the only ones able to spread as a flame, albeit at low FMC values. The other fuel-beds, *Calluna*, *Empetrum* and *Vaccinium*, experienced the opposite trends. No clear relationship was found among fuel-bed traits of the species studied and flammability properties. Bulk density was probably the most influential trait; low-density litter beds composed of big particles tend to pack more sparingly and allow better aeration for fire development (Ganteaume et al. 2011; Plucinski and Anderson 2008; Scarf and Westoby 2006). For all but one species, flammability properties followed this pattern, as we found that species with the lowest bulk densities (*Ulex* and *Sphagnum*) experienced a greater flammability than species with high bulk densities (*Calluna*, *Empetrum* and Peat). The exception was *Vaccinium* which had a low bulk density but its flammability was low. It is possible that this result was brought about through interactions with other fuel traits, for example area to volume ratio, mineral content, the physical arrangement of fuel particles or others factors not examined here. In addition, it is worth noting that area to volume ratios assessed in our study may be underestimated; for example, *Calluna* value (7922 m^{-1}) was slightly lower than values reported in other studies (e.g., 10050 m^{-1} in Fernandes and Rego 1998). This may be because the different methodologies used, and because the scanning procedure can be less accurate than other procedures with direct assessments of particle size.

The results presented give a broad view in describing fire danger in litter fuel-beds on the basis of FMC; however, it is worth noting that our results are based on artificial simulations, and further research is needed to contrast our results with real fuel-beds and fires. Previous field studies, however, observed similar moisture of extinction values in litters of maritime pine stands in Portugal (M_{50} values of 35% to obtain sustaining fires; Fernandes et al., 2008). Davies and Legg (2011) observed significant burning and smouldering of *Pleurocarpus* mosses at FMC less than 70%; i.e., similar values to our M_{max} value of 71.4% observed for *Sphagnum* in this study. In addition, our M_{50} values are within the ranges observed in laboratory experiments testing different soil fuel-beds (Lin, 1999; Plucinski and Anderson, 2008).

Peat is the deepest strata of the fuel-complex, and it is usually covered by litter and vegetation. It is, therefore unlikely that fires start in this layer directly from small ignition sources such as accidentally-dropped embers or cigarettes ends. In addition, the thresholds of initial flaming ignition and sustained ignition observed for this kind of source was restricted to low FMC values (M_{50} of 34.9% and 21.6% respectively). However, it is more likely that peat ignition occurs when the litter layer is smouldering; when this occurs wildfire spread will occur upwards into the canopy, then laterally through the canopy and litter-bed and downwards into the peat. The energy available in this situation would be expected to be much greater than that provided from small ignition sources (cigarette ends, embers, etc.). Previous studies with more intense ignition sources (greater size and longer duration times: i.e., a coil spiral of 10 mm of diameter, 95 mm long and heated during 30 min) showed that peat was able to ignite at FMC of approximately 115% (Frandsen, 1997; Rein et al., 2008). Therefore, further studies disentangling fire transmission from the litter layer to peat are needed. Fuel-beds with different flammability properties may, therefore, show variable efficiency in fire propagation within British heathlands and moorlands.

4.2. Fire danger in Calluna vegetation

Dead-fuels play a fundamental role in the probability of ignition of *Calluna* vegetation, being influenced by both FMC and dead-fuel proportion. In fact, it has been proposed that the most likely point where fire starts in the vegetation strata is within these dead fuels (Davies and Legg, 2011). This laboratory approximation determined the values of FMC and dead-fuel proportion that influences these ignition processes. M_{50} values were variable depending on the source of ignition. When a smouldering source was used, an increasing dead-fuel proportion increased the M_{50} from 19% to 35%. In contrast, the proportion of dead fuel had little effect when a flaming source was used, where M_{50} remained stable at *ca.* 30%. These results suggest that management strategies to keep heath/moorlands in a "young state" with less than 20% dead-fuel may be an effective measure for reducing wildfire risk (i.e. building phase – Watt, 1947). Similar management suggestions were proposed for *U. europaeus* gorse in northern Spain (Marino et al. 2011).

Our laboratory experiments used a representative fuel bulk density but clearly variations in this parameter may modulate fire ignition (Marino et al. 2011; Weise et al.,

2005) and further research modeling this effect is needed. Other parameters such as the dead-fuel continuity or the crown base height may also influence fire initiation (Plucinski et al., 2010). Our work, therefore, needs corroboration in field-based studies. However, previous field studies have reported that both fire ignition and sustained spread are correlated strongly with the moisture content of the dead-fuel in the canopy. Davies and Legg (2011) observed in *Calluna*-dominated ecosystems that fire ignition failed at FMC greater than *ca.* 70%, but fires started to develop at 60% FMC. These results are in the same order of magnitude as the M_{max} observed here (*ca.* 40-50%), given that the field studies would overestimate FMC because live-fuels in the lower canopy were included. The important role of dead-fuels and their FMC in fire ignition and spread have been also reported for other shrub-dominated systems, for example the Mediterranean gorse (*U. parviflorus*; Baeza et al., 2002) and the European gorse (*Ulex europaeus*; Anderson and Anderson, 2010).

4.3. Effect of the ignition source in fire danger

Ignition source is very important in determining the probability of ignition in both peat/litter fuel-beds and vegetation. Smouldering sources were more effective in igniting peat/litter fuel-beds (i.e., igniting them at higher FMC). These sources may be in contact with the soil fuel-bed all along its surface, and therefore, penetrate deeper into the fuel as it is consumed. In contrast, the flaming sources produce a flame plume that is not constantly in intimate contact with the soil fuel-bed, and hence it transfers less energy to the underlying fuel. However, an ignition source can proceed from glowing embers that combine an initial flaming phase with a later smouldering phase (Marino et al. 2010). Further efforts are, therefore, needed to disentangle this interaction.

For shrubs, the contact of smouldering sources with fuel is restricted to the source surface area, whereas a flame plume can contact vertically with fuel surfaces higher in the vegetation strata, and hence ignite them more efficiently. This is likely to be the reason why ignition in smouldering sources was influenced by the proportion of dead-fuel. Higher densities and proportions of dead-fuel may be needed to produce the initial flame and burn at higher FMC. Other factors related to the nature of ignition sources, and not studied here, may also be important in fire ignition, for example, source size, shape and the exposure time to the ignition source (Davies and Legg, 2011; Manzello et al. 2006; Plucinski and Anderson, 2008).

4.4. Implications for fire danger rating systems

Wales and England currently use a fire danger rating system (Meteorological Office Fire Severity Index (MOFSI) (http://www.metoffice.gov.uk/weather/uk/firerisk/; accessed 16 August 2013). Based on the Canadian Wildland Fire Information System (CWFIS), this system consists of a series of basic codes and derived meteorological indices which are used to predict wildfire occurrence (van Wagner, 1987). It has been observed, however, that this system is not well adapted to British moorlands and often fails in its predictions (Davies and Legg, 2008). Only one of its basic codes, the Fine Fuel Moisture Code (FFMC), is able to forecast fire occurrence with acceptable accuracy (Davies and Legg, 2008). FFMC is a numeric rating of the moisture content of litter and other cured fine fuels, and it is computed from data on rainfall, relative humidity, wind speed, and temperature collected over the previous 24 h (van Wagner, 1987). Moreover, the moisture content of these fuels can be estimated from FFMC values using simple equations (Aguado et al. 2007; van Wagner, 1987). Therefore, M_{50} and M_{max} values presented for the peat/litter fuel-beds in this work can assist in improving the predictions of heath/moorland fire danger. For example, better warnings of the critical periods when the different fuel beds drop in fire-prone moisture conditions can be provided by estimating the fuel moisture content through FFMC. Nonetheless, further efforts in calibrating the estimated fuel moisture contents with real field data would be needed. It will also be necessary to take into account the different nature of spring and summer wildfires. In spring the canopy often burns independently from the ground layer because the peat/litter fuel-beds are still wet and frozen. Therefore, further studies to ensure that FFMC is well correlated to the moisture content of dead-fuels are needed to predict this kind of canopy fires.

5. Conclusions

This work helps to disentangle the complex interactions generating wildfire on British heathlands and moorlands. There are four important results reported here. First, there were small differences in moisture thresholds where peat/litter fuel-beds start to ignite into a flame (35-59% FMC), however, the probability of sustained ignitions varied across a wider range (19-55% FMC). Second, we demonstrated that flammability (i.e, ignitability, sustainability, consumability and combustibility) of the peat/litter fuel-beds differs depending on the intrinsic characteristics of species making up the fuel layer. These properties were also influenced strongly by their fuel moisture content. Third, in the upper canopy layer, often composed solely of *Calluna*, the probability of ignition was influenced both by the proportion of dead fuel accumulated within the vegetation and their FMC. Finally, the source of ignition may play a fundamental role in fire risk assessment, since smouldering sources are more efficient in igniting peat/litter fuel-beds, but in the *Calluna* vegetation layer flaming sources are superior.

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Table 1. Parameters used as flammability descriptors for peat/litter fuel-beds in experimental simulations.

Parameter descriptor	Variable	Units	Definition
Ignitability	Ignition time (TTI)	s	Time elapsed since the ignition source is applied until flames appear.
	Rate of spread (ROS)	mm min^{-1}	Speed at which the combustion front propagates.
Sustainability	Flaming time (FT)	s	Time of flaming combustion.
	Elevated temperatures (T300)	s	Time above 300ºC.
Consumability	Mass loss rate (MLR)	mg min^{-1}	Speed at which fuel is burnt.
	Residual mass fraction (RMF)	%	Percentage of fuel remaining after fire
Combustibility	Flame height (FH)	mm	Maximum height reached during flaming.
	Maximum temperature (TMAX)	ºC	Temperature reached during fuel combustion.

Table 2. Specific traits of peat/litter fuel-beds derived from British heath/moorlands; mean values ± SD are presented. Letters show significant differences among fuel-beds (One-way ANOVA with Bonferroni pair-wise comparisons).

Species	Fuel-bed bulk density (kg m^{-3})	Particle specific area (m^{2} kg^{-1})	Particle area to volume ratio (m^{-1})	Mineral content (%)	Heat of combustion (MJ kg^{-1})
Calluna	112.9±21.5b	34.4±1.4a	7922±551a	3.2±0.4b	21.2±0.7ab
Vaccinium	42.1±8.1c	39.9±1.3a	7580±1539a	5.9±0.1a	19.9±1.1abc
Empetrum	149.5±24.9b	16.7±1.2b	3592±408b	3±0.1b	22.8±0.4a
Ulex	39.9±8.9c	14.6±1.4b	5619±435ab	1.9±0.2c	21.3±1.1ab
Sphagnum	16.2±5.9c	41.9±5.4a	3658±908b	2.8±0.4b	16.6±0.5c
Peat	288.7±134.5a	-	-	11.2±3.4a	18.5±1.5bc
F	131.1	350.5	31.1	81.4	15.9
P	<0.001	<0.001	<0.001	<0.001	<0.001
n	>40	5	5	5	3

Table 3. GLM models relating flammability properties (a. the probability of initial flaming ignition, and b. the probability of sustained ignition) of a range of different peat/litter fuel-beds derived from British heath/moorlands in relation to fuel moisture content (FMC).

	Species	Tests (n)	Initial ignition	M_{50}	M_{max}	Model parameters						Pseudo R^2	ROC area
						Predictor	Estimate	SE	z-value	Odds ratio	*P*		
(a)	*Calluna*	43	30	53.6	61.3	Intercept	14.46	6.20	2.33		0.019	0.75	0.97
						FMC	-0.27	0.11	-2.44	0.76	0.015		
	Vaccinium	40	23	46.8	51.3	Intercept	8.42	2.79	3.02		0.003	0.66	0.95
						FMC	-0.18	0.06	-3.09	0.83	0.002		
	Empetrum	43	38	59.2	62.8	Intercept	11.25	3.93	2.86		0.004	0.57	0.95
						FMC	-0.19	0.07	-2.74	0.83	0.006		
	Ulex	40	32	51.4	52.9	Intercept	8.74	2.94	2.97		0.003	0.58	0.96
						FMC	-0.17	0.06	-2.873	0.84	0.004		
	Sphagnum	40	17	56.5	80.4	Intercept	4.52	1.58	2.86		0.004	0.34	0.86
						FMC	-0.08	0.03	-3.12	0.92	0.002		
	Peat	41	13	34.9	60	Intercept	2.78	0.99	2.79		0.005	0.26	0.93
						FMC	-0.08	0.02	-3.61	0.93	<0.001		
	Species	Tests (n)	Sustained ignition	M_{50}	M_{max}	Model parameters						Pseudo R^2	ROC area
						Predictor	Estimate	SE	z-value	Odds ratio	*P*		
(b)	*Calluna*	43	16	26.9	33.2	Intercept	7.79	2.87	2.77		0.007	0.65	0.96
						FMC	-0.29	0.11	-2.72	0.75	0.006		
	Calluna (flame)	41	13	15.2	12.8	Intercept	3.61	1.31	2.75		0.005	0.59	0.96
						FMC	-0.43	0.15	-2.81	0.65	0.005		
	Vaccinium	40	13	25.1	51.3	Intercept	2.26	0.95	2.37		0.018	0.38	0.86
						FMC	-0.09	0.03	-3.17	0.91	0.001		
	Empetrum	43	10	19.1	36.2	Intercept	2.29	1.11	2.05		0.039	0.34	0.86
						FMC	-0.12	0.04	-3.09	0.89	0.002		
	Ulex	40	22	34.5	52.9	Intercept	4.49	1.41	3.18		0.001	0.41	0.91
						FMC	-0.13	0.04	-3.1	0.88	0.002		
	Sphagnum	40	17	54.6	71.4	Intercept	7.64	2.66	2.87		0.004	0.52	0.93
						FMC	-0.14	0.05	-2.98	0.87	0.003		
	Peat	41	9	21.6	46.1	Intercept	2.81	1.24	2.26		0.024	0.60	0.97
						FMC	-0.13	0.05	-2.49	0.88	0.013		

Table 4. A GLM model relating the probability of ignition in simulated *Calluna* vegetation to the proportion of dead-fuel moisture content and the type of ignition source. The intercept of this model was the flaming ignition source; df = 235, a Pseudo $R^2 = 0.33$ and a ROC area = 0.85.

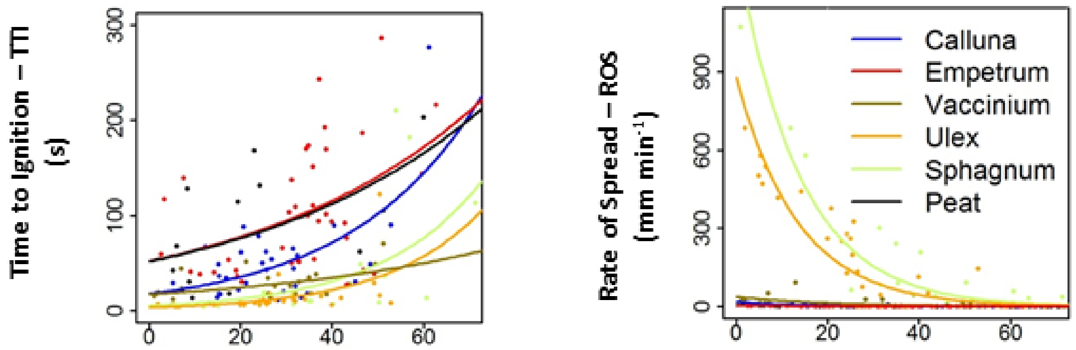
Predictor	Model parameters				
	Estimate	SE	z value	Odds ratio	*P*
Intercept	4.05	0.86	4.68		<0.001
Dead-fuel moisture	-0.13	0.01	-7.74	0.87	<0.001
Dead-fuel proportion	<-0.00	0.01	-0.03	0.99	0.972
Smouldering	-2.51	0.94	-2.65	0.08	0.008
Smouldering x Dead-fuel proportion	0.05	0.02	2.41	1.05	0.015

FIGURE CAPTIONS

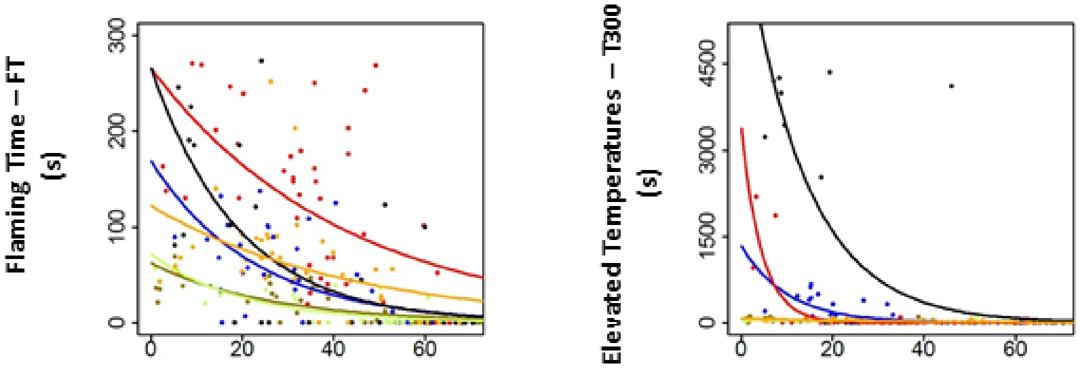
Fig.1. Flammability descriptors variation of different peat/litter fuel-beds as a function of fuel moisture content: (a) Ignitability, (b) Sustainability, (c) Consumability, (d) Combustibility. Results shown correspond to tests using smouldering ignition sources.

Fig. 2. Effect of different proportions of dead-fuel and Fuel Moisture Content at which 50% of ignitions were successful (M_{50}) and the maximum moisture at which a successful ignition occurred (M_{max}) for *Calluna* vegetation derived from British moorlands.

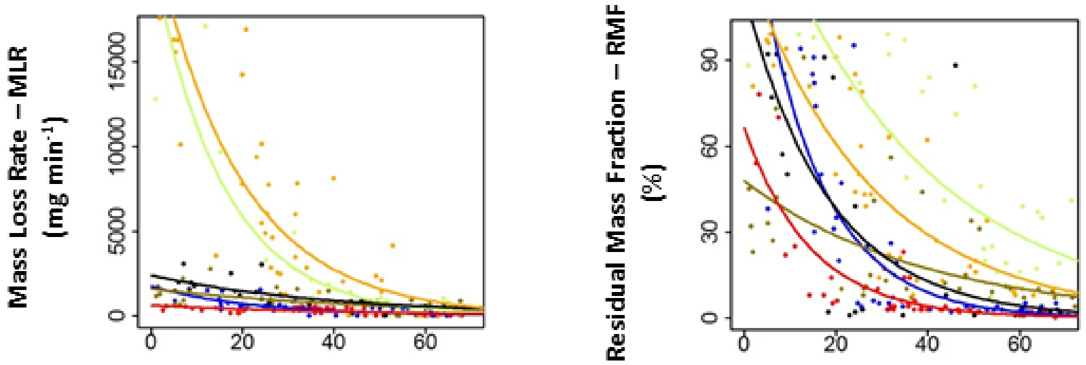
(a) Ignitability



(b) Sustainability



(c) Consumability



(d) Combustibility

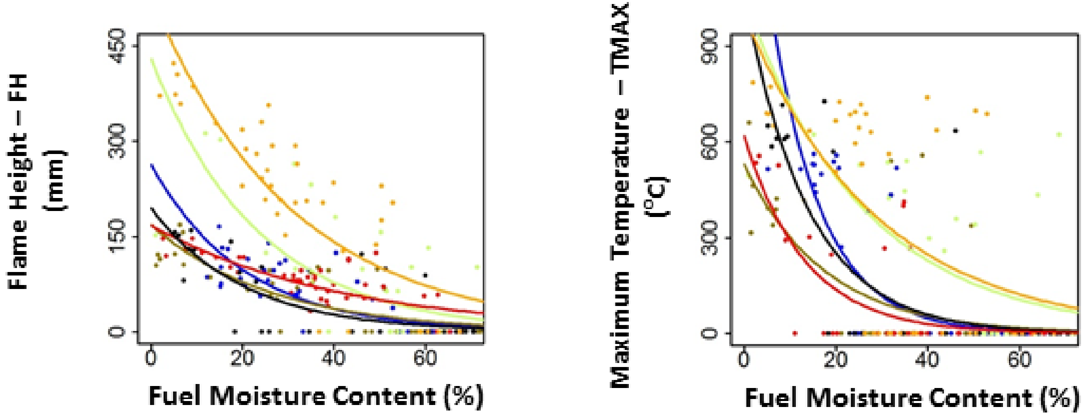
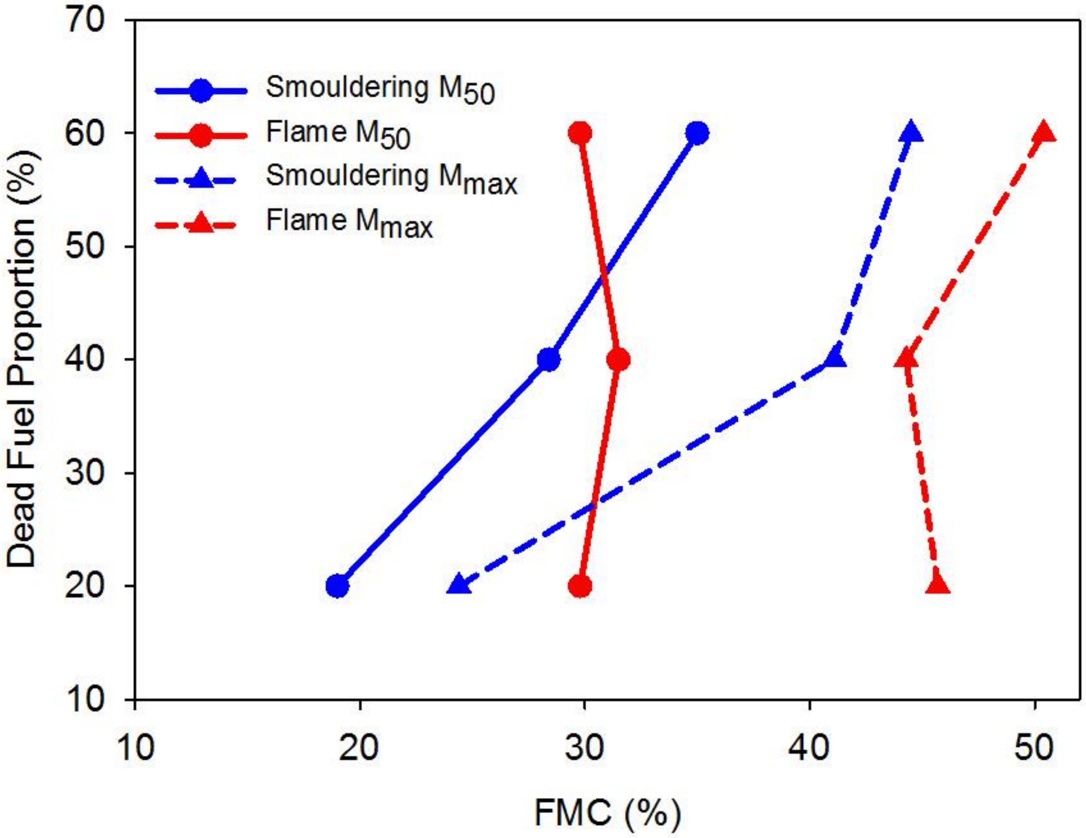


FIGURE 1



Smouldering M_{50}
Flame M_{50}
Smouldering M_{max}
Flame M_{max}
Dead Fuel Proportion (%)
70
60
50
40
30
20
10
10
20
30
40
50
FMC (%)

FIGURE 2