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Citation for published version:
Hadden, R, Belcher, CM, Yearsley, JM, Rein, G & Prat-Guitart, N 2016, 'Propagation probability and spread rates of self-sustained smouldering fires under controlled moisture content and bulk density conditions' International Journal of Wildland Fire.

Published In:
International Journal of Wildland Fire

Propagation probability and spread rates of self-sustained smouldering fires under controlled moisture content and bulk density conditions

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Abstract

The consumption of large areas of peat during wildfires is due to self-sustained smouldering fronts that can remain active for weeks. We study the effect of peat moisture content and bulk density on the horizontal propagation of smouldering fire in laboratory-scale experiments. We used milled peat samples at moisture contents between 25% and 250% *MC* (mass of water per mass of dry peat) and bulk densities, ρ, between 50 and 150 kg m^{-3}. The samples were burnt inside an insulated box of 22×18×6 cm. An infrared camera monitored the ignition, spread and extinction. Peats below 150% *MC* are likely to self-sustain smouldering for more than 12 cm when ρ was below 75 kg m^{-3} (expected fraction of peat burnt = 0.5). When ρ was 150 kg m^{-3}, the critical moisture content for self-sustained propagation was 115% *MC*. A linear model estimated a significant effect (R^2=0.77) of *MC* and ρ on the fire spread rate ranging between 2 and 5 cm h^{-1}. The increase of *MC* had a stronger effect on the spread rate than the increase of ρ. The variation of ρ had a higher effect on the spread rate when *MC* was low than when *MC* was high.

Brief summary

We have coupled laboratory scale observations of smouldering fires with statistical models to analyse the self-sustained propagation and spread rates for horizontal distances which have not been researched before. Our findings enable the effects of peat moisture and density conditions on smouldering propagation dynamics to be understood.

Additional Keywords: peatland, fire behaviour, horizontal front, lateral, peat fire, propagation dynamics.

Introduction

Smouldering is an incomplete form of combustion affecting organic materials, such as the peat stored in peatlands and forest soils (Rein 2009). The propagation of smouldering fires is known to be very slow compared to flaming fires, moving at few centimetres per hour (Wein 1983, Frandsen 1991). The consumption of large areas of peat is often caused by self-sustained smouldering fires, which remain active and slowly propagating for weeks or months (Rein 2013).

During a peat fire, the carbon stored in the ground is released to the atmosphere. The incomplete smouldering combustion in peat emits a higher proportion of carbon emissions (e.g. CO, CH_4) than flaming fires in vegetation (Hadden 2011). These gasses contribute significantly to global emissions of greenhouse gases (Turetsky et al. 2014). Smouldering peat fires also affect the roots of vegetation close to the surface, often causing lethal plant damage and habitat loses (Miyanishi and Johnson 2002; Page et al. 2002; Davies et al. 2013). The landscape after a peat fire is often heterogeneous, as peat is consumed in irregular patches (Shetler et al. 2008). In the burnt areas, deep layers of dense peat become the new surface with a different constitution and properties (Prat-Guitart et al. 2011). These post-burn surfaces are often opportunities for colonising species and have the potential to enhance biodiversity (Benscoter and Vitt, 2008).

Factors driving smouldering fire ignition

The ignition of a smouldering fire in peat is often caused by a heat source near the surface, such as a lighting strike, adjacent flaming vegetation (Rein 2013) or burning pine cones (Kreye et al., 2013). The start of a smouldering fire is controlled by the properties of the ignition source (intensity and duration), peat conditions (primarily moisture content, bulk density and mineral content) and the oxygen availability (Frandsen 1987; Ohlemiller 2002; Hadden et al. 2013; Huang and Rein 2014). Of these, peat moisture content is the main factor limiting the ignition of peat (Van Wagner 1972; Frandsen 1987, 1991). Water in peat acts as a heat sink, requiring a large amount of energy to evaporate the water before reaching temperatures at which the pyrolysis process begins (Rein 2013). The probability of peat ignition and initial horizontal propagation of at least 10 cm from an ignition source has been estimated in previous studies (Frandsen 1997; Lawson et al. 1997; Reardon et al. 2007). When the moisture content (*MC*) of the peat is between 110 and 200% (gravimetric moisture content, mass of water per mass of dry peat expressed as a percentage) there is a 50% probability of starting a smouldering peat fire (Frandsen 1987; Frandsen 1997; Reardon et al. 2007; Rein et al. 2008). Frandsen (1997) predicted the probability of ignition and early horizontal propagation as a function of *MC* (%), mineral content (%) and bulk density (kg m^{-3}). Reardon et al. (2007) however, predicted the ignition and early propagation using only moisture and mineral content, suggesting that bulk density was implicitly included in the quantification of the other two peat properties.

Self-sustained smouldering propagation

Once ignited a smouldering fire propagates by drying and igniting the fuel ahead of the smouldering front (Frandsen 1997; Huang et al. 2015). In smouldering combustion, peat particles undergo endothermal pyrolysis forming char, also known as regime I, followed by exothermal oxidation reactions where char is converted to ash, regime II (Hadden et al. 2013, Huang et al. 2015). The energy released during the exothermal oxidations is transferred to the surrounding environment, some being radiated to the atmosphere and some conducted to the peat particles ahead of the smouldering front. If the energy of this combustion of peat particles in the smouldering front produces sufficient energy to overcome the heat loses to the surroundings, the smouldering front spreads away from the ignition point and become an independent self-sustained front (Ohlemiller 1985). A smouldering front can then propagate into the peat both vertically and horizontally. However, it is the front propagating horizontally that is primarily responsible for the large areas of peat consumed, as vertical propagation is generally extinguished by deeper layers of wet peat (Wein 1983; Miyanishi and Johnson 2002; Usup et al. 2004). The propagation mechanisms of smouldering fires in peats are complex and further research is needed to understand how the peat conditions affect the dynamics of self-sustained fire propagation.

In this paper, we analyse the horizontal propagation dynamics of smouldering fires moving away from an ignition source under a range of controlled moisture content and bulk density conditions. We used beta regressions to estimate the propagation distance as a function of moisture content and bulk density. We also estimate the spread rate of the fire when self-sustained smouldering propagation was observed. Finally we use a linear model to relate the properties of the peat to the spread rate of smouldering fires. The purpose of this experimental research is to enable key peat conditions (moisture content and bulk density) that influence smouldering propagation to be understood.

Materials and methods

Experimental set-up

Laboratory smouldering experiments were designed to control environmental and peat conditions. Commercial milled peat (*Shamrock Irish Moss Peat*, Bord Na Mona, Ireland) was used to be consistent with previous studies (Belcher et al. 2010; Hadden et al. 2013) and because commercially milled peat reduces extraneous sources of variation due to their homogeneous properties (Frandsen 1987, 1991; Zaccone et al. 2014; Prat et al. 2015). The peat was placed in a 22×18×6 cm insulated burnbox made of fibreboard with a thermal conductivity of 0.07-0.11 W m^{-1} K^{-1}, similar to peat (Frandsen 1987, 1991; Benscoter et al. 2011; Garlough and Keyes 2011). Peats were oven dried at 80°C for 48 h. Water was added to the dry peat until the required *MC* was achieved. The moist peat was sealed in a plastic bag for the 24 h prior to the experiment to allow equilibration. The prepared peats had 25, 100, 150, 200 and 250% *MC*. This range of moisture contents represents peat conditions that are susceptible to smouldering ignition (Frandsen 1987; Rein et al. 2008; Benscoter et al. 2011).

A range of peat bulk densities (ρ, dry mass of peat per unit volume of wet peat) was included in our experimental data. Two bulk density treatments (BD_1, BD_2) were created for each moisture content 1) the peat was spread into the burnbox until it filled the volume (BD_1) and 2) the peat was compressed into the burnbox until it filled the volume (BD_2). This second treatment increased bulk density by reducing the bulk volume and the air spaces inside the sample.

An electric igniter coil was situated along one side of the box and used to ignite a 2 cm wide section of dry peat (approximately ~0% *MC*). The coil delivered 100 W for 30 min, similar to the heat provided by surface burning vegetation (Rein et al. 2008). This ignition protocol was sufficient to start a smouldering front in the dry peat section, which then attempted to spread to the adjacent peat sample. An infrared camera (*ThermaCAM SC640*, FLIR Systems, US) was used to image the radiative energy flux from the smouldering peat surface (Prat-Guitart et al. 2015). The position of the smouldering front was identified using the infrared images, which provided information at a resolution of 0.05×0.05 cm (one pixel). The camera took images every minute, creating sequences of between 300 and 700 images for each burn test. Experiments for each combination of *MC* and bulk density treatment were replicated four times. Due to a small amount of moisture evaporation (Table S1 in Supplementary Material available from the journal website), the moisture content conditions of the peat samples were assumed to be constant throughout the duration of the burning experiments.

Self-propagation distance of peat fires

Once the fire self-extinguished, we recorded the final position of the smouldering at distance (D) away from the igniter. A value between 0 and 1 indicated the fraction (y) of peat consumed along a transect across the width of the burnbox at distance D from the igniter. These fractions were transformed to avoid zeros and ones by $y_D = [y(N-1)+1/2]/N$, where N is the sample size (Smithson and Verkuilen 2006). Beta regressions were used to estimate the association of y_D to the peat's bulk density ρ (kg m^{-3}) and moisture content, MC, with a logit link function for the expectation of y_D given by <equation 1>

$$P_{yD} = 1/\left(1 + \exp\left(-(\beta_D + \beta_{D1}\,\rho + \beta_{D2}\,MC)\right)\right) \quad (1)$$

where β_D's are the regression coefficients. A total of seven beta regressions were fitted for values of D at 6, 8, 10, 12, 14, 16 and 18 cm. Each regression was a different analysis to avoid autocorrelation of residuals. A beta regression can be viewed as a flexible form of logistic regressions that allows for a continuous response variable (modelled by beta distribution) and skew in the response distribution (modelled by the precision parameter of beta distribution) (Cribari-Neto and Zeileis 2010). Similar to our beta regressions, logistic regressions were used in past studies with success/failure data to estimate the probability of peat ignition and early propagation 10 cm away from the ignition region (Frandsen 1997; Lawson et al. 1997; Reardon et al. 2007).

Image processing

The infrared images were corrected for the distortion caused by the angle of the infrared camera. The burnbox surface area was represented by approximately 150,000 pixels, each of them giving information about the dynamics of the smouldering front during the experiment. For every pixel, we built a profile of the radiated energy flux throughout the time duration of the burn (Prat-Guitart et al. 2015). The radiative energy flux increased when an approaching smouldering front heated the area, indicating that the peat was being dried prior to the start of the combustion processes, pyrolysis and oxidations. The start of the smouldering combustion (t^L) was defined as the first time a pixel's radiative energy flux increased at a rate of 10 W m^{-2} min^{-1} or more. For every experiment, we obtained a matrix of t^L giving the time when the leading edge of the smouldering front reached each pixel.

As a method to prevent boundary effects from the burnbox edges to the smouldering front, 2 cm of pixels close to the sides were removed from each image. The pixels from the 6 cm closest to the igniter were also excluded to avoid effects of the ignition heating coil. The area of pixels left, approximately 60% of the burnbox surface, was used for the subsequent image analysis and estimation of the spread rates. The image processing was undertaken using Matlab and the *Image Processing Toolbox* (Version R2012b 8.0.0.783, The MathWorks Inc., US).

Estimation of horizontal spread rates

For each burn we split the t^L matrix into sub-regions of 2×2 cm. We then estimated the spread rate and direction of spread for each sub-region by fitting a Generalised Least Squares model, assuming a linear smouldering front across the sub-region. This approach allows all the data within a sub-region to inform our estimates of spread rate and direction. The fitted model is <equation 2>

$$t^L{}_i = \beta_{xy0}\beta_x x_i + \beta_y y_i + \varepsilon_i \qquad (2)$$

$$\varepsilon_i \sim N(0, \sigma^2 A)$$

where x and y are the position of the i^{th} pixel within a sub-region. The coefficients β_x and β_y give the rate at which $t^L{}_i$ increases per unit increase in x and y, respectively. The ε_i is the error term assumed to be normal distributed with mean zero and with variance-covariance matrix $\sigma^2 A$. The spatial correlation structure of A was described with a Gaussian semivariogram (Pinheiro et al. 2013). The model was fitted using a maximum likelihood. The spread rate of the leading front in the x-direction was then estimated as <equation 3>

$$S = \frac{1}{\beta_x}\,\Delta x \qquad (3)$$

where S is the sub-region spread rate, Δx is the length of a pixel (typically 0.05 cm). A spread rate was estimated for each sub-region of the burnbox and then a median spread rate ($\bar{S}$) and median absolute deviation were estimated for each experimental burn.

We looked for detectable changes in spread rate during the long burns (burns lasting more than 7 h). We tested the constancy of the smouldering spread rate away from the igniter (x-direction) across the entire burnbox by regressing the median time taken for the smouldering front to reach a pixel against linear and quadratic terms in the distance from the igniter (see supplementary material). The quadratic term is expected to be zero if spread rate is constant. For each treatment the significance of the quadratic term was tested using F-test.

Effect of moisture content and bulk density on the spread rate

The effect of MC and ρ on $\bar{S}$ were examined using a linear model. Even though the bulk density of the peat was based on a compression treatment (BD_1 and BD_2) we took bulk density to be a continuous variable. The two explanatory variables were standardised (by subtracting the mean and dividing by the standard deviation). Spread rates were log-transformed so that model residuals were close to normality. Forward stepwise model selection was used to arrive at a best-fit model that minimized Akaike Information Criterion, AIC (Burnham and Anderson 2002). Only the model with the lowest AIC is reported in the results. <equation 4>

$$\log(\bar{S}) = \beta_0 + \beta_1\, MC_k + \beta_2\, \rho_k + \beta_3 MC_k \times \rho_k + \varepsilon_k \qquad (4)$$

where $\bar{S}$ is the median spread rate of each burn k, β_0, β_1, β_2 and β_3 are the coefficients of the dependent parameters and ε_k are the residuals assumed to be normal distributed. The data analyses were done with R project statistical software (Version 3.0.2, R Core Team, 2013), the *betareg* package (Cribari-Neto and Zeileis, 2010) the *ape* package (Paradis et al. 2004) and the *nlme* package (Pinheiro et al. 2013).

Results

The milled peats used had an intrinsic bulk density between 50 to 150 kg m^{-3} (Fig. 1). Each *MC* treatment had a range of bulk densities. Peats with low moisture content tended to have higher bulk densities than peats with high moisture content (*Spearman correlation* = −0.4, *p-value* =0.02).

[Figure 1]

The smouldering front always self-propagated across the entire box (20 cm) when the moisture content was 25% or 100% (Fig. 2). At these moisture contents, the smouldering fire was observed to propagate as a single linear front. The smouldering front always self-extinguished before reaching the end of the burnbox in peats of 200% and 250% *MC*. The fronts that self-extinguished were irregular for the last 1-2 cm of propagation. Peats with 150% *MC* had an intermediate behaviour, with fronts self-extinguishing in 75% of the experiments burns (Fig. 2a). Peats with 200% and 250% *MC* did not self-sustain propagation in peats with high bulk density. Only peats with 100% *MC* (low and high bulk density) and peats 150% *MC* and low bulk density sustained smouldering for more than 7 h. For these long burns we found no evidence that the spread rate was changing across the burnbox, as indicated by the non-significant quadratic term for each of the peat conditions (F-tests for peats with 100% and low bulk density $F_{1,48}$=1.2, p=0.28, 100% and high bulk density $F_{1,49}$=2.9, p=0.09 and 150% *MC* $F_{1,31}$=2.0, p=0.17).

[Figure 2]

Expected self-propagation distances from an ignition source

Peats at low moisture content were more likely to sustain smouldering propagation for a longer distance independently of the peat density (Fig. 3). For example, at D = 12 cm peats with 25% and 100% *MC* had an expected fraction of peat burnt (P_{yD}) of 0.72.At short distances (between 6 and 10 cm from the ignition region), P_{yD} was associated with both the moisture content and the bulk density of the peat (Table 1). Whereas P_{yD} at longer distances (≥12 cm away from an ignition area) were mainly controlled by the moisture content of the peat (Table 1, D=12 cm, Fig. S1).

[Figure 3]

[Table 1]

Effect of peat condition on the smouldering spread rates

The spread rates estimated per sub-region, S, ranged between 0.6 and 9.1 cm h^{-1} (Table 2). Due to self-extinction of the fire, experimental burns with moisture contents of 150, 200, 250% *MC* had a lower number of sub-regions where S could be estimated.

[Table 2]

The best-fit model is shown in Table 3. The spread rates, $\bar{S}$, were well explained by the model (R^2=0.77). There was a significant effect of *MC* and ρ on the spread rates of smouldering fires, where the continuous increase of *MC* had a stronger effect on the spread rates than the increase of ρ (Fig. 4). The interaction term was also significant, indicating that for low *MC* the change in ρ had a small impact on the spread rates. However, the decrease of spread rates due to the increase of ρ was stronger with higher *MC*. (e.g. −0.015±0.005 cm kg^{-1} m^{-3} h^{-1} for peats with 25% *MC* and –0.022±0.009 cm kg^{-1} m^{-3} h^{-1} for peats with 100% *MC*).

[Table 3]

[Figure 4]

Discussion

Our results support that peat moisture content is the main factor predicting the self-sustained propagation of peat fires. High peat bulk density contributes to increase the effect of moisture content on the dynamics of smouldering propagation. Peats ≤100% *MC* had a than a 70% probability of self-sustaining propagation beyond the initial 12 cm (P_{yD} ≥ 0.72). Under these conditions, oxidation reactions along the smouldering fronts produced sufficient energy to overcome heat loses, dry the peat and ensure the self-sustained propagation (Bencoster et al. 2011; Huang and Rein 2015). Even though the front propagated for 20 cm in all bulk densities tested (Fig 2), the spread rates were significantly slower when bulk density was high (Table 2).

Peats above 150% *MC* had a high probability of extinction after propagating through 12 cm of peat. This suggests that when the moisture content is higher than 150%, the amount of energy required to evaporate water ahead of the smouldering front is too high to self-sustain propagation for more than 12 cm. For distances of ≥12 cm we found no effect of bulk density on propagation (Table 1). This could be because (a) the bulk density does not affect the fraction of peat burnt at $D \geq 12$ cm, suggesting that moisture content of the peat is the main predictor of P_{yD} or (b) there is an effect of bulk density on P_{yD} when $D \geq 12$ cm but our data has limited power to detect this effect. To increase the power to detect effects of bulk density, future research should consider a larger sample size and greater variety of moisture content and bulk density treatments within the range tested.

The estimated P_{yD} smouldering propagation for distances up to 10 cm from an ignition source is comparable with the probability of ignition and early propagation estimated in previous studies on natural peat soils (Frandsen 1997, Lawson et al. 1997, Reardon et al. 2007). In those studies, the 50% probability of ignition and 10 cm propagation had a moisture content threshold of 120% *MC* for *Sphagnum* and feather moss peats with bulk densities between 20 and 60 kg m^{-3} and mineral contents below 30% (mass of mineral content per total mass of dry peat) (Frandsen 1997). In our analysis, peats below 160% *MC* and similar bulk densities have a $P_{yD} = 0.5$ at $D = 12$ cm, indicating that there is a 50% probability of self-sustain smouldering for more than 12 cm (Fig. 2). However, denser peats with 130 kg m^{-3} have a $P_{yD} = 0.5$ at $D = 10$ cm only when the peat moisture content is below 113% *MC* (Fig. 3). Using milled peats, Frandsen (1987) established a comparable threshold for peat ignition and early propagation of 110% *MC* and bulk density of 130 kg m^{-3}.

Compared to peats with low bulk density, the peats with high bulk density produce more energy due to the oxidation of a greater mass of peat particles (Ohlemiller 1985). However, the modification of bulk density through compression implies that high bulk density peats hold a larger mass of water per unit volume. For a successful self-propagation, all this water needs to be evaporated by the energy released from the adjacent smouldering front. Frandsen (1991) suggested that the rate of mass consumption is not sensitive to the bulk density of the peat. In that sense, the energy required to keep on-going self-sustained smouldering propagation should be proportional to the mass of peat being consumed. We found that the spread rate of the smouldering front is sensitive to the bulk density of the peat and the effect depends upon the moisture content of the peat (Table 3). For example, the spread rate in peats with high bulk density and low moisture contents (i.e. 25, 100% *MC*) is not affected as much as in peats with high moisture contents (i.e. 150-250% *MC*). Peats with high moisture content and high bulk density have a reduced rate of O_2 diffusion and a larger amount of water to be evaporated before combustion. These conditions cause slower spread rates and shorter propagation distances (Ohlemiller 2002, Belcher et al. 2010; Hadden et al. 2013). The effect of the oxygen availability to the smouldering reaction zone was not considered in Frandsen 1991, as a constant oxygen flow was supplied through the burning peat to avoid the extinction of the fire.

The spread rate of the smouldering fronts was analysed for the first time as a function of peat conditions. The effects of moisture content and bulk density upon spread rates are consistent with the estimates of energy required to dry and heat the peat (Fig. S2 and Fig. S3, estimated energy required to start thermal decomposition of peat for each peat moisture content and bulk density treatment are available in the Supplementary material). More mass of water per unit volume requires more energy to evaporate and start combustion (Fig. S2). However, peats with 100% *MC* and bulk density below 100 kg m^{-3} have a higher energy demand and propagated slower than peats with 150 and 200% *MC* and bulk density below 75 kg m^{-3} (Fig. S3). For a given moisture content, there is more energy needed to carry on smouldering combustion when the bulk density increases (Fig. S3). Increasing peat's bulk density, there is a larger energy production during the oxidation of the larger mass of peat. However, this energy produced is smaller than the energy necessary to evaporate the water in the peat. As a consequence, the spread rate of the fire is slower or not self-sustained (Fig. 4).

Controlled smouldering tests

It should be noted that our experiments were at a laboratory scale and peat conditions were controlled. Therefore caution should be taken when using our results at the field scale. The peat conditions (i.e. bulk density, mineral content, peat composition) can be very heterogeneous in real ecosystems (McMahon et al. 1980). Our laboratory-scale experiments intentionally removed these sources of variation. This allowed us to focus on the effect of two important peat conditions (moisture content and the bulk density) on the smouldering propagation dynamics.

Our burnbox size was designed to be suitable for the study of horizontal propagation across greater distances than in previous studies (Frandsen 1987; Frandsen 1997; Reardon et al. 2007), enhancing our understanding of propagation in larger sample sizes. The duration of our experiment and the size were limited by a maximum burn duration of 12 h in order to minimise the effect of diurnal variation in ambient temperature and humidity. The spread rates and the expected fractions of peat burnt were both estimated assuming constant moisture content and bulk density throughout the duration of an experiment. During our experiments there were not any moisture content changes that could have a substantial effect on the smouldering fire propagation (Table A1). However, substantial changes of moisture content or bulk density during the experiment duration could cause variation in the estimated spread rates with the distance.

The ignition of the peat along one side of the burnbox enabled a linear propagation of smouldering fronts moving perpendicular to the igniter coil. This ignition method was developed to estimate spread rates from infrared images that assume linear propagation (Prat-Guitart et al. 2015). A depth of only 5 cm of peat was used in this study to focus solely on horizontal smouldering propagation, avoiding vertical spread of the smouldering front and limiting the multi-dimensional spread of a peat fire. Previous experimental studies have examined peat ignition in deeper samples (Rein et al. 2008; Benscoter et al. 2011). However, deeper peat samples had smouldering fronts propagating horizontal and vertical, making more complex the study of propagation dynamics. The properties of the burnbox material created similar thermal insulation as if the peat sample would be surrounded by more peat (Frandsen 1987, 1991; Benscoter et al. 2011; Garlough and Keyes 2011). In these insulated conditions, a sample depth of 5 cm has a small impact in our results and they can be compared to other experiments looking at horizontal propagation in bigger samples.

Application to peatland fires

In this study, the smouldering dynamics were studied in areas of 22×18 cm with homogeneous moisture content conditions, comparable to the size of a dry patch of peat moss (Petrone et al. 2004). In peatlands, the moisture content of the surface peat layers is regulated by the distribution of moss species and the position of the water table (Thompson and Waddington, 2013b; Waddington et al. 2014). A heterogeneous distribution of *Sphagnum* mosses is likely to cause a heterogeneous spatial distribution of peat moisture content creating patches of 20-50 cm diameter (Benscoter and Wieder 2003; Petrone et al. 2004). During drought the surface layers dries due to, the lack of rain, which may then be followed by a decrease in the water table position (Chivers et al. 2009; Sherwood et al. 2013; Kettridge et al. 2015). In such circumstances, dry peats in the surface layers have less than 250% *MC* (Benscoter et al. 2011; Terrier et al. 2014; Lukenbach et al. 2015), thus being vulnerable to peat fires.

After a peat fire, the new surface layer is closer to the water table and consequently having a reduced fire danger. Previous studies suggested that peat fires are common in peatland ecosystem cycles (Turetsky et al. 2002). The consumption of surface layers of peat reduces the accumulation of organic material allowing *Sphagnum* mosses to access the water table being less dependent on external water inputs (Benscoter and Vitt 2008). Post fire surfaces also enable the roots of vegetation to uptake ground water and nutrients from deep mineral layers.

In peatlands, peat bulk density strongly depends on the vegetation cover and the temporal changes in the water table behaviour (Davies et al. 2013; Sherwood et al. 2013; Thompson and Waddington 2013a). Deep peat layers often have a higher degree of decomposition and a higher bulk density compared to surface layers (Benscoter et al. 2011; Thompson and Waddington 2014). Following turf cutting in drained peatlands, new dense and dry layers of bare peat become exposed at the surface being vulnerable to new peat fires.

Peats with 25% *MC* were included in the analysis to have a representation of very dry peats in our sample. However, such dry peats are uncommon in natural peatlands (Terrier et al. 2014; Lukenbach et al. 2015), being restricted to the surface of drained peatlands under extreme drought. In the present study, bulk density was experimentally manipulated using two peat compression treatments, which produced a range of bulk densities. Dry peats (25% *MC*) were only experimentally tested with high bulk densities between 108 and 145 kg m^{-3}. The high bulk density of 25% *MC* peats is due in part to the structure of milled peats and the relatively low expansion of peat particles when a small quantity of water is added to the peat sample (Huang and Rein 2015). The reduced expansion of the relatively dry peat (25% *MC*) compared to the greater expansion of relatively wetter peat (≥100% *MC*) caused the negative collinearity between moisture content and bulk density. If we exclude peats with 25% *MC* we find no collinearity between *MC* and ρ (*Spearman correlation* =−0.07, *p-value*=0.7). Therefore, the negative collinearity between *MC* and ρ (Fig. 1) is caused by the peats with 25% *MC*.

This collinearity could contribute to the interaction reported in the spread rate model (Table 3) and effect extrapolated predictions of spread rates (Dormann et al., 2013). The same spread rate model but excluding peats with 25% *MC*, had similar β_0, β_1 (*MC*) and β_2 (ρ) coefficients but no significant interaction term. Therefore, the main effects of moisture content and bulk density on the spread rates are qualitatively not affected by the collinearity.

All the milled peats used in this study had a low mineral content of less than 5%. Natural peats are characterized as having less than 20-35% mineral content (Turetsky et al. 2014) and often <6% (Benscoter et al. 2011). Previous studies have suggested that large quantities of mineral content could reduce the capacity of smouldering fires to ignite and propagate (Frandsen 1987; Hungerford et al. 1995). Our peats had an intrinsic mineral content of 2.6±0.2% similar to the 3.7% of Frandsen's 1987 peats. This implies that our low mineral content peats would give an upper limit on the spread rates and propagation distance. However, small quantities of certain minerals such as salts of calcium or magnesium, common in plant material and soil, have been shown to have no effect on propagation (Benscoter et al. 2011) or rather enhance heat conduction in the fuel media that could help the smouldering propagating faster (Frandsen 1998; Reardon et al. 2007).

Differences in bulk density can be associated with other properties of peat soils such as soil structure, particle size, pore space and decomposition (Ingram 1978). The variation of these physicochemical properties can also affect the energy produced during peat oxidation and the energy transferred through peat particles (Reardon et al. 2007; Huang et al. 2015). The presence of artefacts (e.g. roots, stones, etc.) may also play a role in creating variability in peat conditions, which could affect the propagation of smouldering fires. Twigs and roots for example, have been reported to promote the propagation of smouldering fires (Miyanishi and Johnson 2002; Davies et al. 2013), this is likely a result of local changes to *MC* around the root.

The hydrology of peatlands as well as peat properties should be carefully observed in order to estimate variations in moisture and bulk density as we have shown that these peat conditions strongly influence the propagation of smouldering fires even on a fine-scale. The spatial variability and dynamics of peat conditions remains a challenge to studies of peat fires in the field (McMahon et al. 1980; Hungerford et al. 1995) and highlights why laboratory scale studies are required to understand measured effects on smouldering. The control of individual properties such as moisture content and bulk density can then be used to piece together the broader relationship between peat conditions and smouldering in the natural environment. Milled peats like those used here, have been the most utilised alternative to reduce the variability of natural peats and study the influence of external factors (moisture, mineral content, bulk density, oxygen availability, etc.) on smouldering combustion of peat (Frandsen 1987, 1991; Belcher et al. 2010; Hadden et al. 2013; Zaccone et al. 2014; Prat et al. 2015).

Conclusions

This study has built on previous work on ignition and early horizontal propagation of smouldering fires in peats. We have coupled laboratory scale observations of smouldering fires with statistical models to estimate and analyse the fire spread rate and the expected fraction of peat burnt at distance longer than 12 cm. Our findings enable understanding the effects of a variety of peat moisture content and bulk density conditions on smouldering propagation dynamics. Self-sustained fronts were observed to propagate in peats with moisture content below 150% *MC*. The bulk density of the peat was also found to affect the propagation of smouldering fires. The increase of bulk density enhances the effects of moisture content on the propagation dynamics.

Our approaches highlighted that laboratory scale experimental research can contribute to the study of theoretical insights of the behaviour of smouldering fires. Data from this study is fundamental to integrate a wide range of realistic peat conditions and their associated horizontal and vertical dynamics to modelling approaches at larger scales.

Acknowledgements

The authors thank the School of Mechanical Engineering at University College Dublin, especially to David Timoney for the support and John Gahan for his help during the lab set up, Xinyan Huang for valuable discussions and three anonymous reviewers for their helpful suggestions. This project is funded by the Irish Higher Education Authority PRLTI 5. Claire M. Belcher acknowledges a European Research Council Starter Grant ERC-2013-StG-335891-ECOFLAM.

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Table 1. Coefficient estimates from beta regression models (*D*=6, 8, 10, 12, 14, 16 and 18 cm) for the expected fraction of peat burnt (P_{yD}) at each distance (*D*) from the igniter (equation 1).

β_D, β_{D1} and β_{D2} are coefficients estimates (± standard error) for intercept, bulk density and moisture content. Wald test *p-value* significance has been added to the coefficients where '***' <0.001, '**' 0.01, '*' 0.05. *Phi* is the model precision, *Log-Like* is the model Log-likelihood and R_p^2 is the pseudo R-squared. Sample size in each regression = 36.

D (cm)	β_D	β_{D1} (ρ)	β_{D2} (*MC*)	*Phi*	*Log-Lik*	R_p^2
6	6.53±1.18 ***	−0.032±0.008 ***	−0.018±0.003 ***	1.53±0.38 ***	57.11	0.71
8	6.81±1.19 ***	−0.034±0.008 ***	−0.021±0.003 ***	1.52±0.37 ***	56.98	0.77
10	4.79±1.16 ***	−0.021±0.008 **	−0.018±0.003 ***	1.09±0.25 ***	53.36	0.68
12	3.23±1.09 **	−0.008±0.008	−0.018±0.003 ***	1.16±0.26 ***	54.01	0.71
14	3.23±1.09 **	−0.008±0.008	−0.018±0.003 ***	1.16±0.26 ***	54.01	0.71
16	3.23±1.09 **	−0.008±0.008	−0.018±0.003 ***	1.16±0.26 ***	54.01	0.71
18	2.79±1.09 *	−0.003±0.008	−0.018±0.003 ***	1.22±0.28 ***	53.07	0.73

Table 2. Estimated spread rates of the experimental smouldering fires.

MC is the moisture content, *BD* is the bulk density treatment, ρ is the mean bulk density (± standard deviation). Num. Burns is the total number of experimental burn replicates. Num. Sub-regions is the total number of sub-regions used to estimate spread rates, *S,* across all experimental burn replicates. $\bar{S}$ is the median spread rate (± median absolute deviation) for repeated burns under the same *MC* and *BD* conditions.

MC (%)	BD	ρ (kg m^{-3})	Num. Burns	Num. Sub-regions	*S Min-max* (cm h^{-1})	$\bar{S}$ (cm h^{-1})
25	BD_1	116 ± 9	4	191	2.3 − 7.2	4.33 ± 0.91
100	BD_1	80 ± 7	4	178	1.0 − 7.8	2.63 ± 1.08
150	BD_1	62 ± 5	4	96	1.0 – 4.8	2.07± 0.59
200	BD_1	60 ± 10	4	45	1.2 − 5.2	2.16 ± 0.62
250	BD_1	71 ± 9	3	6	1.0 − 2.2	1.42 ± 0.43
25	BD_2	141 ± 5	3	147	1.5 − 6.2	2.86 ± 0.75
100	BD_2	80 ± 8	4	179	0.6 − 9.1	1.71 ± 0.90
150	BD_2	111 ± 8	3	13	0.7 – 1.9	1.23 ± 0.45
200	BD_2	124 ± 11	3	−	−	−
250	BD_2	114 ± 3	3	−	−	−

Table 3. Best-fit linear model for median spread rates ($\bar{S}$).

Coefficients β_0, β_1, β_2, β_3 are parameter estimates for variables: peat moisture content, bulk density and the interaction between them. Number of data points in the model = 36, R^2 = 0.77. Residual standard error: 0.173.

	Estimate	*Standard error*	*p-value*
β_0 (Intercept)	0.514	0.056	<0.001
β_1 (MC)	-0.545	0.061	<0.001
β_2 (ρ)	-0.325	0.058	<0.001
β_3 ($MC \times \rho$)	0.151	0.046	0.003

Figure captions

Fig. 1. Bulk density of the peat samples as a function of moisture content. Circles are peat samples treated with BD_1 and triangles are peats treated with BD_2.

Fig. 2. Hours taken by the smouldering front (t^L) to self-propagate through the peat sample until self-extinction. Circle, triangle, square, diamond and star correspond to 25, 100, 150, 200 and 250% moisture content, respectively. (a) uncompressed peats (treatment BD_1) and (b) compressed peats (treatment BD_2). Standard errors of the means are smaller than the symbol size. Lines are linear regression fits. Only moisture contents where self-sustained smouldering propagation occurred are plotted.

Fig. 3. Expected fraction of peat burnt (P_{yD}) to a distance, *D*, away from the ignition region. *D* values of 6 cm, 8 cm, 10 cm and 12 cm are shown, results from *D*=14 cm, 16 cm and 18 cm are similar to *D*=12 cm (Table 1). Panels are for (a) 25%, (b) 100%, (c) 150%, (d) 200% and (e) 250% moisture content. Symbols represent fractions of peat burnt (*y*) along a transect at distance *D*.

Fig. 4. Spread rate as a function of peat bulk density (y-axis is on a square-root scale). Panels are for (a) 25%, (b) 100%, (c) 150%, (d) 200% and (e) 250% moisture content. Each dots and error bar corresponds to median spread rate and median absolute deviation for an experimental burn. Solid lines correspond to model predictions (Table 3) and dashed lines the prediction's 95% confidence intervals.

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