Effects of spatial heterogeneity in moisture content on the horizontal spread of peat fires

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HIGHLIGHTS

• Local heterogeneity of peat moisture content affects smouldering spread.
• Fire temperatures and combustion duration are sensitive to peat moisture gradients.
• The moisture before a gradient affects few centimetres of spread into a wet peat.

GRAPHICAL ABSTRACT

ABSTRACT

The gravimetric moisture content of peat is the main factor limiting the ignition and spread propagation of smouldering fires. Our aim is to use controlled laboratory experiments to better understand how the spread of smouldering fires is influenced in natural landscape conditions where the moisture content of the top peat layer is not homogeneous. In this paper, we study for the first time the spread of peat fires across a spatial matrix of two moisture contents (dry/wet) in the laboratory. The experiments were undertaken using an open-top insulated box (22 × 18 × 6 cm) filled with milled peat. The peat was ignited at one side of the box initiating smouldering and horizontal spread. Measurements of the peak temperature inside the peat, fire duration and longwave thermal radiation from the burning samples revealed important local changes of the smouldering behaviour in response to sharp gradients in moisture content. Both, peak temperatures and radiation in wetter peat (after the moisture gradient) were sensitive to the drier moisture condition (preceding the moisture gradient). Drier peat conditions before the moisture gradient led to higher temperatures and higher radiation flux from the fire during the first 6 cm of horizontal spread into a wet peat patch. The total spread distance into a wet peat patch was affected by the moisture content gradient. We predicted that in most peat moisture gradients of relevance to natural ecosystems the fire self-extinguishes within the first 10 cm of horizontal spread into a wet peat patch. Spread distances of more than 10 cm are limited to wet peat patches below 160% moisture content (mass of...
Peatland soils are significant reservoirs of carbon, they cover <3% of the Earth’s land surface but they store 25% of the world’s terrestrial carbon, approximately ~560 Gt of carbon (Turetsky et al., 2015; Yu, 2012). The drainage of peatlands for human activities combined with a lack of external water inputs (e.g. rain) perturbs peatland hydrological feedbacks (Waddington et al., 2015), leading to a suppression of the water table and drying of the surface peat. Enhanced drainage makes peatlands highly vulnerable to drying and subsequently fires (Turetsky et al., 2011). During flaming wildfires of the surface vegetation, part of the heat can be transferred to the organic soil (e.g. duff, peat) and may ignite a smouldering fire (Rein, 2013). These flameless fires are more difficult to detect and suppress than flaming vegetation fires (Rein, 2013). Peat fires can spread both on the surface and into the peat through the sub-surface of a peatland and can ignite new flaming fires well away from the initial region of smouldering peat (Putzays et al., 2007; Rein, 2016). Very large amounts of peat can be consumed during smouldering fires, releasing carbon gases (e.g. CO₂, CO and CH₄) and other greenhouse gases to the atmosphere (Gorham, 1991; Turetsky et al., 2015). The 1997 Indonesian peat fires are estimated to have consumed approximately 3% of the soil carbon stock from Indonesia. ~0.95 Gt of carbon, which is equivalent to 15% of the global fossil fuels emissions for that year (Page et al., 2002). A 2007 peat fire event in the arctic tundra is estimated to have reduced 30% of the soil depth in the whole area studied and consumed 19% of the soil carbon stock of the region (Mack et al., 2011). The climate change projections forecast an increase in drought frequency and severity in many peatlands worldwide (Roulet et al., 1992), suggesting that peatlands will become more vulnerable to peat fires in the future (IPCC, Climate Change, 2013). This implies that larger amounts of carbon may be released to the atmosphere further contributing to the climate change and turning peatlands into carbon-sources rather than potential carbon sinks (Billett et al., 2010; Flannigan et al., 2009; Turetsky et al., 2002, 2015).

In peatlands, the physiochemical properties of the surface-un saturated peat layers are influenced by the position of the water table and its associated hydrological responses (Waddington et al., 2015). Changes in water table position alter surface transpiration, evaporation, and peat decomposition, which contribute to the moisture variability of the surface layers of peat (Waddington et al., 2015). The vegetation also plays a very important role in determining the moisture content distribution of the topmost peat layer. Hummock-forming Sphagnum mosses retain high levels of moisture in the whole peat profile (Hayward and Clymo, 1982; McCarter and Price, 2012). Other mosses (e.g. hollow Sphagnum species and feather mosses) do not have the same capacity to uptake water from the water table, depending more on the regularity of external water inputs (Thompson and Waddington, 2013). As a consequence, during drought periods Sphagnum hummocks remain wet while the surrounding peat becomes drier. The presence of vascular plants causes shading and interception of precipitation also affecting the surface transpiration and evaporation (Waddington et al., 2015). The rooting systems from trees are also a source of moisture spatial heterogeneity in the topmost peat layers (Rein et al., 2008). The combination of all these ecophysiological factors, specially during drought events, causes large moisture heterogeneity on the topmost layers of peatlands (Nungesser, 2003; Petrone et al., 2004).

The main factors governing the ignition and spread of smouldering are peat moisture content, organic content and bulk density (Frandsen, 1987, 1997; Reardon et al., 2007; Rein et al., 2008; Watts, 2012). Once peat is ignited, the fire is sustained by the energy released during the oxidation of the char (Hadden et al., 2013). This energy is dissipated, some being lost to the surroundings and some being transferred to drive the drying and pyrolysis of peat particles ahead of the oxidation front (Rein, 2016). If the energy produced is enough to overcome heat losses to the environment and preheat the surrounding peat, the smouldering front becomes self-propagating (Huang and Rein, 2014; Ohiemiller, 1985). The spread can be horizontal and vertical and the extent of smouldering in each direction depends largely on the conditions of the peat and the environment (Benscoter et al., 2011; Reardon et al., 2007; Rein, 2013). A vertically spreading smouldering front can penetrate a few meters into the soil (Rein, 2013). However, more often tends to be extinguished after a few centimetres as downward spread is limited by either the water table or the mineral soil layer (Benscoter et al., 2011; Huang and Rein, 2015; Zacone et al., 2014). A smouldering front that spreads horizontally can contribute to consume a large area of dry peat soils above the water table. This kind of spread coupled with the spread of vegetation wildfires, often results in large surface areas being affected (Benscoter and Wieder, 2003; Shetler et al., 2008).

Previous studies have highlighted the importance of peat moisture content on the ignition and spread of peat fires (Frandsen, 1987; Huang and Rein, 2014, 2015; Lawson et al., 1997; Reardon et al., 2007). A 50% probability of ignition and early propagation has been estimated at 110–125% MC (Frandsen, 1987; Huang and Rein, 2015; Reardon et al., 2008). Recent experimental smouldering fires reveal horizontal spread rates between 1 and 9 cm h⁻¹ in peats below 150% MC (Prat-Guitart et al., 2016). In peats with higher moisture content, between 150 and 200% MC, the smouldering is weak and self-extinguishes within the first 10 cm of the sample (Frandsen, 1997; Reardon et al., 2007).

Moisture content distributions of the topmost layer in peatlands are highly relevant to determining the spread of smouldering fires. Post peat-fire landscapes are often characterised by irregular peat consumption, were patches of peat associated with Sphagnum hummocks remain unburnt (Hudspith et al., 2014; Shetler et al., 2008; Terrier et al., 2014). Enhanced peat consumption has also been observed under trees, suggesting that fires spread through the peat adjacent to the roots (Davies et al., 2013; Miyaniishi and Johnson, 2002). However, there is little understanding of how varying the peat moisture content (e.g. transition from feather moss to Sphagnum) across a spatial landscape affects the horizontal propagation of peat fires. This study experimentally examines the behaviour of a smouldering front as it propagates through a gradient of peat moisture content in order to (1) identify local changes in the fire behaviour associated with a transition of moisture content and (2) test whether the contiguous drier moisture content ahead of a transition affects the fire behaviour into a wet peat.

2. Materials and methods

2.1. Experimental system

In order to study the effect of a moisture content gradient on the smouldering spread behaviour we designed a simplified milled peat system that allows the natural sources of peat heterogeneity, such as moisture content, bulk density, mineral content and particle size to be

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1 Gravimetric moisture content is the mass of water per mass of dry peat expressed as a percentage.
controlled (Prat-Guitart et al., 2015). The smouldering experiments were conducted in an 18 × 22 × 6 cm open-top box (insulated fibreboard container) of similar thermal conductivity as peat (0.07–0.11 W m⁻¹ K⁻¹) to minimise boundary effects (Benscoter et al., 2011; Frandsen, 1987; Garlough and Keyes, 2011; Rein et al., 2008). The peat samples were 5 cm in depth. The samples were kept shallow to facilitate the formation of a plane smouldering front spreading horizontally from one side of the box to the other. As a result, we focus solely on the horizontally spread and not on the vertical spread. The experiments were limited to 12 h to avoid day-and-night temperature fluctuations.

The analysis of the spread inside the box was divided in three regions: (i) ignition region, (ii) region ahead of the moisture gradient (PRE) and (iii) region following the gradient (POST) (Fig. 1). The ignition region was at one side of the box where an 18-cm long electric igniter coil was buried in a 2-cm strip of peat at −0% MC. The PRE region was adjacent to the ignition and consisted of a 10-cm strip of conditioned peat. The POST region was a peat sample of the same size as PRE but with higher moisture content. A clear straight boundary separated PRE and POST regions creating a sharp gradient in moisture content at approximately 10 cm from the ignition location.

The milled peat samples were oven-dried at 80 °C for 48 h and then rewetted in small samples of <300 g of peat to achieve the desired moisture content. Since oven-dried peats can become hydrophobic, rewetted peat samples were sealed in plastic bags for at least 24 h prior to the experiment to reach moisture equilibrium. One day is more than an order of magnitude longer than the typical infiltration time of severely hydrophobic soil (Kettridge and Waddington 2014). This protocol therefore minimises heterogeneity within the moisture content of the peat samples. We used 14 PRE–POST moisture content combinations in our experiment (Table 1). The PRE samples never exceeded 150% MC in order to be below the threshold of 125–150% MC for self-sustained spread for more than 10 cm (Frandsen, 1997; Prat-Guitart et al., 2016; Reardon et al., 2007). The moisture content of POST peats (between 125% and 250% MC) represents wet peats around the threshold of self-sustained spread. All peats had a mineral content² of 2.6 ± 0.2%. Within the box volume, peat bulk density (mass of dry peat per unit volume) varied between 55 and 140 kg m⁻³. The variation in density was in part due to the expansion of peat when water was added (Table 1). Bulk densities were representative of peat soils from temperate and boreal peatlands (Davies et al., 2013; Lukenbach et al., 2015; Thompson and Waddington, 2013; Wellock et al., 2011).

The ignition protocol consisted in powering the ignition region with 100 W for 30 min using the electric igniter coil (Rein et al., 2008). This energy input is strong and similar to a burning tree stump and is enough to ignite dry peat (Rein et al., 2008). After 30 min the igniter coil was turned off and a linear smouldering combustion front spread through the samples of peat. A visual and infrared cameras imaged the surface of the smouldering every minute (Prat-Guitart et al., 2015). The infrared camera (SC640, FLIR Systems, US) captured the radiated energy flux from the peat at a resolution of 0.05 × 0.05 cm (i.e. one pixel equated to 0.25 mm²). The images were corrected for the angle of the infrared and webcam cameras and processed to extract the values of radiated energy flux at a pixel scale. Details of the methods are given in Prat-Guitart et al. (2015). An array of seven K-type thermocouples (1.5 mm diameter) monitored the smouldering temperatures inside the peat samples at 1 cm from the bottom of the box. One thermocouple was situated in the ignition region and the other six were distributed to capture the temperature 4 cm before the moisture gradient and then at 1 and 6 cm after the moisture increase (Fig. 1).

2.2. Behaviour of the smouldering front

Smouldering temperatures have often been analysed to study the peat combustion and fire spread (Benscoter et al., 2011; Rein et al., 2008; Zaccone et al., 2014). We analysed the thermocouple data to identify changes in the combustion temperatures due to the sharp transition of peat moisture. For each thermocouple, we estimated the combustion duration, as the time taken since the start of the combustion (increase above 100 °C) and until the peat burnout (decreased below 200 °C for the last time). We also estimated the peak temperature as the 90th percentile of the thermocouple temperature profile. To demonstrate the effect of PRE moisture content on the spread into POST peats, we statistically compared the temperatures of 22 experiments with the same POST moisture content (150% MC) but different PRE moisture contents (25%–150% MC). The effects of moisture content treatment and distance from the moisture gradient on peak temperature and combustion duration were estimated using one-way ANOVAs. The differences between treatment levels were estimated using Tukey’s Honesty Significant Difference (HSD) post-hoc test with a significance level of p = 0.05. Temperature profiles from all the PRE–POST combinations are provided in the supplementary materials (Fig. S1).

We also analysed the radiation flux from the smouldering of peat in order to identify changes in the smouldering behaviour due to the transition of moisture content. Even though the information from infrared imagery was limited to spread on the peat’s surface, it allowed the smouldering spread to be monitored at a finer resolution than any array of thermocouples. We built a time-profile of each pixel’s radiation flux (kW m⁻²) and the radiation flux rate (kW m⁻² min⁻¹) (Fig. 2). The start of the smouldering fire is defined by a peak in the radiation flux rate (Prat-Guitart et al., 2015). The last occurrence of a similar radiation flux value is used to define the end of the smouldering fire. From our defined start and end times of combustion we calculated the median radiated energy flux during combustion (E). Repeating this procedure for each pixel of the infrared box image gave a matrix of median radiation fluxes E during combustion.

We analysed the spatial autocorrelation of E by computing the data’s semivariance (half average squared difference between pairs of pixels) (Bivand et al., 2008). The semivariogram was produced using a subset of E from each experimental burn. Subsets of E were selected from a central area of PRE peat away from any boundary. We then fitted a theoretical spherical model to the semivariogram. The spatial range of the semivariogram indicated the distance where the data exhibited no spatial autocorrelation. To avoid statistical issues of spatial autocorrelation we considered 48 sub-regions (2 × 1 cm) from each box and ensured that sub-regions were separated by at least 1 cm. This separation is

² Mass of mineral particles per mass of dry organic peat.
greater than the scale of autocorrelation in the data for $E$. We estimated the median $E$ in each sub-region ($E_{m}$) and the median absolute deviation.

Piecewise linear regression was used to identify a step-change in $E_{m}$ as a function of distance from the moisture gradient (Crawley, 2013). The analysis was performed on data from each moisture combination (i.e. extinguished due to the box wall) were discarded since it was not possible to quantify $D_{T}$.

The image processing was done in Matlab with the Image Processing Toolbox (Mathworks, version R2012b 8.0.0.783). The data analysis was done with R project statistical software (Development Core Team, 2013). The spatial autocorrelation analysis was done with packages automap (Hiemstra et al., 2009) and gstat (Pebesma, 2004).

3. Results

3.1. Smouldering behaviour

In experiments combining PRE MC of 25% and POST of 150% a breakpoint in $E_{m}$ was identified at $c_{1} = 1.5$ cm after the moisture gradient (Table 2). The $E_{m}$ before the breakpoint was 3.92 $\pm$ 0.05 kW m$^{-2}$ (mean $\pm$ standard error), whereas after the breakpoint it decreased to

| PRE (% MC) | Breakpoint (cm) | CI (cm) | $E_{m}$ before (kW m$^{-2}$) | $E_{m}$ after (kW m$^{-2}$) |
|------------|-----------------|---------|-----------------------------|-----------------------------|
| 25         | 1.5             | 1.0, 2.1| 3.92 $\pm$ 0.05             | 2.89 $\pm$ 0.12             |
| 50         | 0.8             | 0.5, 1.1| 3.03 $\pm$ 0.03             | 2.90 $\pm$ 0.07             |
| 100        | 1.5             | 1.0, 2.1| 2.86 $\pm$ 0.08             | 2.13 $\pm$ 0.17             |
| 125        | 0.8             | 0.5, 1.1| 2.78 $\pm$ 0.11             | 1.59 $\pm$ 0.26             |
| 150        | 1.5             | 2.0, 0.9| 3.13 $\pm$ 0.09             | 2.33 $\pm$ 0.11             |

Fig. 2. Smouldering fire detection in radiation flux from infrared images. a) Time-profile of a pixel’s radiation flux. b) Time-profile of the pixel’s rate of radiation flux. Red dots indicate start and end of the smouldering fire.
was associated with differences in the peak temperature (one-way ANOVA $F_{2,16} = 11.1, p < 0.001$). Before the $E_m$ breakpoint (at $-4$ cm and $+1$ cm from the moisture gradient) no difference in the peak temperatures was found ($384 \pm 25$ °C and $349 \pm 24$ °C, respectively; Fig. 3a). However, the peak temperature at $+6$ cm from the moisture gradient ($155 \pm 93$ °C) was less than peak temperatures before the breakpoint (Tukey’s HSD $p < 0.05$). The combustion durations (113 ± 11 min, 107 ± 10 min and 56 min at $-4$ cm, $+1$ and $+6$ cm, respectively) were not associated with the distance from the moisture gradient (one-way ANOVA $F_{2,16} = 1.6, p = 0.2$).

At $+1$ cm from the moisture gradient both combustion duration and peak temperatures were affected by the PRE moisture contents (red lines in Fig. 3). We found that PRE MC was associated with peak temperatures at $+1$ cm (one-way ANOVA $F_{3,25} = 6.6, p < 0.001$). Peak temperatures did not differ between PRE MC of 25% and 50%, $349 \pm 24$ °C, $329 \pm 21$ °C, respectively), but a higher PRE moisture content significantly decreased the peak temperatures (e.g. $137 \pm 27$ °C in PRE = 150% MC) (Tukey’s HSD $p < 0.05$). The combustion duration differed across PRE MC treatments (one-way ANOVA $F_{3,15} = 4.3, p = 0.02$). The combustion duration was similar for PRE MC of 25% and 50% ($107 \pm 10$ min and $99 \pm 18$ min, respectively) but at higher PRE moisture contents (100%, 125% and 150% MC) the combustion duration decreased to $43 \pm 5$ min, $81 \pm 9$ min and $78 \pm 9$ min respectively (Tukey’s HSD $p < 0.05$). At $+6$ cm from the moisture gradient (blue lines in Fig. 3) the combustion duration and peak temperatures were not different from to the ones reported for PRE MC of 150% (one-way ANOVAs $F_{3,7} = 1.1, p = 0.4, F_{3,3} = 0.65, p = 0.5$, respectively).

The finer resolution of the radiated energy flux data ($E_m$) added information on the location where the changes in fire behaviour took place (Table 2, Fig. 4, Fig. S2). The majority of breakpoints in $E_m$ were located after the increase of moisture content, indicating a continuation of PRE-moisture gradient behaviour for up to 6 cm into the POST peat. Two moisture content combinations (PRE = 150%, POST = 150% and PRE = 125%, POST = 250%) had breakpoints in $E_m$ before the moisture gradient (Table 2, Fig. S2).

3.2. Spread distance into wet peat

The spread distance ($D_T$) showed no difference between PRE of 25% and 50% MC (ANOVA $F_{1,22} = 0.067, p = 0.8$) (Fig. 5). For all other peat combinations, the smouldering front spread no further than 5 cm into the wetter peat ($D_T < 5$ cm). Experiments that combined PRE MC of 125% or POST MC of 250% MC always had self-extinction < 1 cm after the moisture transition.

The spread distance into wet peat was well described by PRE and POST moisture content conditions (Table 3, Fig. 6). Increasing either PRE or POST moisture contents decreased the spread distance. The coefficient $\beta_1$ was higher ($-0.06, -0.04, 95\%$ confidence interval) than $\beta_2$ ($-0.03, -0.02$), indicating a bigger effect of PRE moisture content on $D_T$ than POST moisture content. The interaction term PRE × POST showed that the effect of PRE on reducing the spread distance was larger when POST peats had lower moisture content.

PRE MC above 125% lead to smouldering self-extinction immediately after the transition (<1 cm) for any POST MC (Fig. 7). Similarly, high POST MC (>260% MC) spreads for <1 cm for any PRE MC. Eq. (2) predicts that spread for more than 10 cm can be achieved when most PRE MC is below 50% combined with POST MC below 160%.

4. Discussion

4.1. Effects of peat moisture content heterogeneity on the propagation dynamics

We have analysed the behaviour of smouldering fires through a gradient in peat moisture. We find that the peat moisture before the gradient influences the fire spread into the wet peat beyond. The smouldering ignition and spread in peats with homogeneous moisture
conditions are primarily limited by the moisture content of the peat (Frandsen, 1987, 1997; Garlough and Keyes, 2011; Lawson et al., 1997; Reardon et al., 2007). However, we show that fire spread in milled peats with heterogeneous moisture conditions is strongly influenced by the moisture conditions of adjacent peat as well as the immediate moisture content of the peat.

Whilst, this study reports limited spread distances of 10 cm into a more moist peat, the scale of the experiment was enough to examine local changes in fire behaviour during the spread through a moisture gradient. Our analysis of radiation flux suggests two main effects of the PRE peat conditions on the fire behaviour after a moisture gradient. First, the strongest effect of PRE peat conditions happens within the first centimetres (<7 cm) after the moisture gradient (Fig. 4, Fig. S2). In this region the combustion duration and the peak smouldering temperatures have similar behaviour to the adjacent drier peat. The smouldering front spreading close to the moisture gradient evaporates part of the water from the wet peat (Ohlemiller, 1985). Consequently, a few centimetres ahead of the moisture gradient are already drier when the smouldering front reaches the wetter POST peat. Second, the location of the breakpoint could be interpreted as a new moisture gradient created by the dynamics of the smouldering fire. After the breakpoint the smouldering fire continues spreading but is less affected by the PRE MC conditions (Fig. 4). Experiments with PRE = 50% and POST = 150% did not have a substantial change in $E_m$ after the breakpoint but an increase of the standard error of the $E_m$ after (Table 2). We tested conditions are primarily limited by the moisture content of the peat (Frandsen, 1987, 1997; Garlough and Keyes, 2011; Lawson et al., 1997; Reardon et al., 2007). However, we show that fire spread in milled

![Fig. 4. Median radiation flux during smouldering combustion ($E_m$) as a function of distance from the moisture gradient. Data are for moisture contents of POST = 150% MC and PREs of (a) 25%, (b) 50%, (c) 100%, (d) 125% and (e) 150% MC. Solid vertical red line indicates location of a breakpoint in $E_m$ (Table 2) and dashed red lines the 95% confidence interval. Solid horizontal red lines are the $E_m$ means over the four experiment replicates estimated using Eq. (1).](image)

**Table 3**

| Coefficient (cm$^{0.5}$) | Standard error (cm$^{0.5}$) | p-Value  |
|--------------------------|-----------------------------|----------|
| $\beta_0$, intercept     | 8.0                         | 0.6      | <0.0001 |
| $\beta_1$, PRE           | $-0.054$                    | 0.006    | <0.0001 |
| $\beta_2$, POST          | $-0.026$                    | 0.003    | <0.0001 |
| $\beta_3$, PRE $\times$ POST | 0.00018                   | 0.00003  | <0.0001 |

![Fig. 5. Observations of spread distance ($D_s$) into POST peat. Subplots are for PRE peats of (a) 25%, (b) 50%, (c) 100% and (d) 125% MC.](image)
the sensitivity of the results obtained to changes in the methods used to analyze the infrared images. Variation of the thresholds used to determine $E$ produced different $E$ and $E_m$ outputs, although the results did not change qualitatively.

The analysis of thermocouple temperature data also supports the effect of $PRE$ peat conditions on the smouldering spread into $POST$ peat. While the temperatures measured at 1 cm after the moisture gradient correspond to the region of $POST$ peat more affected by the $PRE$ $MC$ conditions, the temperatures recorded at 6 cm after the moisture gradient were less affected by the $PRE$ peat conditions (Fig. 4). We found that $POST$ $MC$ of 150% reach temperatures between 100 and 500 °C at 1 cm after the moisture gradient. Some of these temperatures are lower than typical oxidation temperatures 400–600 °C reported for natural peats ≤ 100% $MC$ (Benscoter et al., 2011; Rein et al., 2008). Only temperatures above 300 °C indicate on-going peat oxidation (Chen et al., 2011). Between 100 °C and 300 °C evaporation and pyrolysis processes dominate the smouldering and little oxidation is expected (Huang and Rein, 2014). Compared to the infrared images, the resolution of thermocouple data are limited and only providing data from fire behaviour around the thermocouple. In some burns, the thermocouples registered oscillations in combustion temperatures between 50 and 300 °C (i.e. Fig. 3a and b), which could be caused by the local dynamics of the particles surrounding the thermocouple. The milled peat particle size was below 1 cm in diameter and had variable density due to differences in the degree of decomposition. Differences in the infiltration rates and hydropathicity of the peat particles during the rewetting process (Kettridge and Waddington 2014) could cause short-term heterogeneity (~10 min) in the moisture content of a peat sample. This short-term heterogeneity was minimised by our protocol, which allowed samples to equilibrate for 24 h prior to an experiment. Any remaining variation in peat moisture will impact the fine-scale spread of the fire between particles (i.e. <1 cm), but have a minor effect on the average spread of the fire throughout a peat sample of 20 × 20 cm.

The moisture gradient between $PRE$ and $POST$ peat could cause movement of the water through the transition boundary. Higher moisture content in $POST$ peat could move to $PRE$ peat, due to differences in unsaturated hydraulic conductivity (capacity of water movement in unsaturated soil per unit volume) (Boelter, 1965; Hillel, 1980). Milled peats below 250% $MC$ have a small unsaturated hydraulic conductivity and therefore very little water movement is expected for the duration of the experimental burns (Holden and Ward, 1997). The smouldering fronts reached $POST$ peat < 4 h after ignition implying minimal water movement during that time. Only peat samples with $PRE$ of 125% and $POST$ 250% and homogenous 150% $MC$ had a breakpoint in $E_m$ before the moisture gradient (Fig. S2). This breakpoint before the initial location of the gradient could be caused by a weak smouldering spread due to the high moisture content in those $PRE$ peat. Even after several hours, little moisture evaporation is expected for peat moisture contents below 250% $MC$ (Kettridge et al., 2012). Our data (Prat-Guitart et al., 2016) confirm that there is little change in peat moisture content after 12 h at ambient temperature. Movement of water is therefore mainly due to evaporation and condensation ahead of the smouldering front, which is driven by the oxidative combustion reactions (Rein, 2016).

The spread distance into a wet peat is also affected by local changes in fire behaviour caused by the moisture gradient. The moisture content conditions of $PRE$ peat conditions control the fire spread during the first 10 cm into a wet peat (Table 3). Only $PRE$ $MC$ of 25 or 50% combined with $POST$ $MC$ of 100 or 150% and few homogeneous peats with 150% $MC$ led to peat fires that could propagate more than 10 cm. The fire behaviour found for these moisture content combinations agrees with results from previous studies indicating self-sustained spread for 10 cm or more in similar moisture conditions (Frandsen, 1997; Prat-Guitart et al., 2015; Reardon et al., 2007; Rein et al., 2008).

Our simplified laboratory experiments enabled the effect of moisture content on the spread of smouldering fires to be studied whilst controlling for mineral content, bulk density and other artefacts in the peat (Belcher et al., 2010; Frandsen, 1987; Hadden et al., 2013; Zaccone et al., 2014). We note that studying smouldering fire behaviour in field samples of peat soil would make the analysis more complex and the results more difficult to interpret because of the multiple uncontrolled factors (e.g. bulk density, organic composition, pore size) that vary between field samples (McMahon et al., 1980). Our results (Prat-Guitart et al., 2016) and those of others indicate that the spread of smouldering fire in natural peats will also be influenced by peat bulk density (Frandsen, 1991; Lukenbach et al., 2015), mineral content (Frandsen, 1987; Garlough and Keyes, 2011), depth (Benscoter et al., 2011; Huang and Rein, 2015), as well as the organic composition, structure, pore size distribution and the degree of decomposition. Future research should aim to further develop our experimental work to understand

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**Fig. 6.** Spread distance ($D_r$) as function of $POST$ moisture gradient. Symbols represent experimental observations for $PRE$ conditions, circle = 25%, star = 50%, square = 100%, triangle = 125% $MC$. Lines are model predictions from the coefficients in Table 3.

**Fig. 7.** Predicted spread distance (cm) into a wet peat for a range of $PRE$ and $POST$ moisture content combinations using the model in Table 3.
how other peat properties contributing to the heterogeneity of moisture content of peatlands affect the spread of peat fires.

4.2. Application to peatland fires

The results obtained in our milled peat experiments in the laboratory where a moisture content gradient was implemented for the first time, give a first insight to the understanding of the peat fire behaviour and interpretation of post peat–fire landscapes. Often, post fire studies report irregular consumption of peat, where wet Sphagnum hummocks are left unburnt (Benscoter and Wieder, 2003; Hudspith et al., 2014; Shetler et al., 2008). Our results suggest that differences in peat moisture content could cause smouldering consumption in the dry peat surrounding Sphagnum hummocks and likely reduced the size of the wet patches.

In peatlands, smouldering fires happen during extreme weather events, due to reductions of surface moisture content (Terrier et al., 2014; Turetsky et al., 2015). Peat fires in surface peat layers are part of the natural cycle of peatlands, often limited by the spatial heterogeneity of moisture content. These fires reduce peat accumulation, enhance biodiversity and facilitate the access of surface vegetation to the water table (Waddington et al., 2015). The spatial distribution of moisture content at a microtopographical scale has a strong influence on the smouldering fire spread (Benscoter and Wieder, 2003). We predicted fire spread of < 10 cm into a wet patch for most of the moisture content combinations involving peat ≥ 160% MC (Fig. 7). Sphagnum hummocks have a variable size, between 20 and 200 cm diameter (Nungesser, 2003; Petrone et al., 2004), meaning than most of the hummock surface can remain unburnt. Natural peatlands have high water table levels and heterogeneous distributions of surface moisture (Waddington et al., 2015). Our controlled peat experiments have only looked at surface horizontal spread. This is one kind of spread that, together with vertical spread, happens during peat fires due to the three-dimensional shape of the smouldering front (Ohlemiller, 2002). Future modelling of peatland fires needs to consider variations in the underlying moisture content because of its effect on the smouldering propagation at a fine-scale in more complex smouldering spread scenarios. Modelling of peat fires incorporating the effect of peat moisture changes will lead to more accurate estimates of carbon emissions, fire perimeter and area burned (Benscoter and Wieder, 2003). Finally, ecosystem management and fire management should also take into account the spatial variation of peat moisture content to manage the fire risk, avoid large areas of peat being consumed by fires and moisture maps may allow better estimates of fire or burn severity to be made. It may be that peat fires can be managed by assuming that extinction could be achieved by rising the moisture content of strategically located peat areas above 200% MC. This technique may have a wider range of ecological benefits than flooding entire areas by blocking ditches or using destructive techniques such as bull-dozer trenching (Davies et al., 2013; Watts, 2012).

5. Conclusions

We studied the role of moisture content as a limiting factor of smouldering propagation in situations where peat moisture content is not homogeneous. Our approach presents a useful method toward building an understanding peatland smouldering fire behaviour that enable new information about the influence of moisture content transitions in peatland systems. We show that fire spread into wet peat patches is strongly affected by local transitions of moisture content. The moisture content of the peat before the transition governs the fire behaviour into a wet peat for the first centimetres of spread. After that distance it is likely that peat fires self-extinguish leaving unburnt patches of wet peat. Future research on peat fire behaviour should consider local variation in moisture content to better understand the spread of smouldering fronts through peat layers.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.02.145.

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