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

### Citation for published version:

Hadden, R, Prat-Guitart, N, Rein, G, Yearsley, JM & Belcher, CM 2016, 'Effect of spatial heterogeneity in moisture content on the horizontal spread of peat fires' *Science of the Total Environment*.

### Link:

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### Document Version:

Peer reviewed version

### Published In:

*Science of the Total Environment*

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Manuscript Number: STOTEN-D-15-05176R3

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

Article Type: SI: Post-fire environm

Keywords: peatland, smouldering, propagation, breakpoint analysis, step-change, infrared image analysis.

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Order of Authors: Nuria Prat-Guitart; Guillermo Rein; Rory M Hadden; Claire M Belcher; Jon M Yearsley

**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 water per mass of dry peat). We found that spatial gradients of moisture content have important local effects on the horizontal spread and should be considered in field and modelling studies.

**Response to Reviewers:** Please see carefully the suggestions that I sent in the PDF attached in the last revision.

**ANSWER:** We have updated the manuscript according to the suggestions done by the reviewer in the PDF.

See comments 1 and 2.

We have also added a conclusions section to the manuscript according to the reviewer's suggestion in the PDF.

1. Explain the ANOVA analysis carried out (e.g if it is One Way, and the level of significance). Please do it where I suggested you to do. This is important for the reader.

ANSWER: We have updated the explanation of the ANOVA analyses carried out. The following text has been added to the methods section: "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 Honest Significant Difference (HSD) post-hoc test with a significance level of  $p=0.05$ ". Now in lines 210-214.

We have also updated the results of the ANOVA analysis to be more clear, in lines 284-293: ". In the experiments with PRE MC of 25% and POST of 150%, we found that the distance from the moisture content gradient was associated with differences in the peak temperature (one-way ANOVA  $F_{2,16}=11.1$ ,  $p<0.001$ ). Before the Em breakpoint (at -4 cm and +1 cm from the moisture gradient) no difference in the peak temperatures was found ( $384 \pm 25^{\circ}\text{C}$  and  $349 \pm 24^{\circ}\text{C}$ , respectively; Fig. 3a). However, the peak temperature at +6 cm from the moisture gradient ( $155 \pm 93^{\circ}\text{C}$ ) was less than peak temperatures before the breakpoint (Tukey's HSD  $p<0.05$ ). The combustion durations ( $113 \pm 11$  min,  $107 \pm 10$  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  $F_{2,16}=1.6$ ,  $p=0.2$ )".

And also in lines 295-304: "We found that PRE MC was associated with peak temperatures at +1 cm (one-way ANOVA  $F_{4,25}=6.6$   $p<0.001$ ). Peak temperatures did not differ between PRE MC of 25% and 50%, ( $349 \pm 24^{\circ}\text{C}$ ,  $329 \pm 21^{\circ}\text{C}$ , respectively), but a higher PRE moisture content significantly decreased the peak temperatures (e.g.  $137 \pm 27^{\circ}\text{C}$  in PRE=150% MC) (Tukey's HSD  $p<0.05$ ). The combustion duration differed across PRE MC treatments (one-way ANOVA  $F_{3,19}=4.3$   $p=0.02$ ). 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  $p<0.05$ )".

Finally we have deleted a sentence containing one ANOVA analysis that did not add any relevant information to the section. The updated paragraph is: "The finer resolution of the radiated energy flux data (Em) added information on the location where the changes in fire behaviour took place (Table 2, Fig 4, Fig. S2). The majority of breakpoints in Em 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 Em before the moisture gradient (Table 2, Fig. S2)". Now in lines 311-317.

2. cite the references correctly in the paper.

If you cite one author please cite (Frandsen, 1997) not (Frandsen 1997).

If you cite two authors please cite (Garlough and Keyes, 2011) not (Garlough and Keyes 2011)

If you cite three or more authors please cite (Benscoter et al., 2011) not (Benscoter et al. 2011).

Do not forget the coma, and see some example of the Journal in open access (<http://www.sciencedirect.com/science/journal/00489697/open-access>)

Please revise the paper accordingly

ANSWER: The references in the manuscript and the bibliographic list have been updated following the reviewer's examples and the most recent STOTEN open access papers, as suggested.



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Environmental Science**

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12<sup>th</sup> February 2016

Dear Damia Barcelo

We would like to thank for the constructive reviews to the manuscript “Effects of spatial heterogeneity in moisture content on the horizontal spread of peat fires” (ID STOTEN-D-15-05176R1). All comments have been addressed and detailed in our online answer to the Decision Letter, with corresponding changes made directly to the manuscript.

Yours sincerely,

A handwritten signature in black ink, appearing to read 'Nuria Prat-Guitart', with a large, stylized flourish at the end.

Nuria Prat-Guitart

Dear Ms. Nuria Prat

Please see carefully the suggestions that I sent in the PDF attached in the last revision.

ANSWER: We have updated the manuscript according to the suggestions done by the reviewer in the PDF:

-See comments 1 and 2.

-We have deleted the subsection titles in the introduction.

-We have also added a conclusions section to the manuscript according to the reviewer's suggestion in the PDF.

1. Explain the ANOVA analysis carried out (e.g if it is One Way, and the level of significance). Please do it where I suggested you to do. This is important for the reader.

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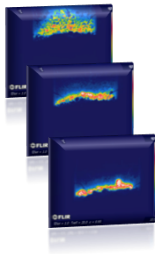
Please revise the paper accordingly

ANSWER: The references in the manuscript and the bibliographic list have been updated following the reviewer’s examples and the most recent STOTEN open access papers, as suggested.

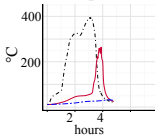
# Graphical Abstract



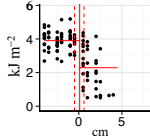
## Smouldering fire monitoring



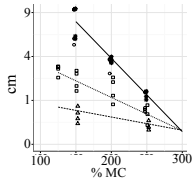
## Fire Temperatures



## Radiation flux



## Spread distance





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

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2  
3 1 **Effects of spatial heterogeneity in moisture content on the horizontal spread of**  
4 **peat fires**  
5 2  
6 3

7  
8 4 *Nuria Prat-Guitart*<sup>a,\*</sup>, *Guillermo Rein*<sup>b</sup>, *Rory M. Hadden*<sup>c</sup>, *Claire M. Belcher*<sup>d</sup>, and  
9 5 *Jon M. Yearsley*<sup>a</sup>

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13 9 [2AZ](#), UK.

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16 12 UK.

17 13 \*corresponding author. prat.nur@gmail.com

18 14  
19 15 **Abstract (limit: 400 words)**

20 16 The [gravimetric](#) moisture content of peat is the main factor limiting the ignition and  
21 17 spread propagation of smouldering fires. [Our aim is to use controlled laboratory](#)  
22 18 [experiments to better understand how the spread of smouldering fires is influenced in](#)  
23 19 [natural landscape conditions where the moisture content of the top peat layer is not](#)  
24 20 [homogeneous](#). In this paper, we study for the first time the spread of peat fires across  
25 21 a spatial matrix of two moisture contents (dry/wet) in the laboratory. The experiments  
26 22 were undertaken using an open-top insulated box (22×18×6 cm) filled with milled  
27 23 peat. The peat was ignited at one side of the box initiating smouldering and horizontal  
28 24 spread. Measurements of the peak temperature [inside the peat](#), fire duration and  
29 25 [longwave](#) thermal radiation from the burning samples revealed important local  
30 26 changes of the smouldering behaviour in response to sharp ~~transitions~~ [gradients](#) in  
31 27 moisture content. Both, peak temperatures and radiation [in wetter peat](#) (after ~~a~~  
32 28 ~~the transition of peat~~ [moisture gradient](#)), were sensitive to the ~~drier previous~~ [moisture](#)  
33 29 [condition \(preceding the moisture gradient\)](#).

34 30 Drier peat conditions before the moisture ~~transition~~ [gradient](#) led to higher  
35 31 temperatures and higher radiation flux from the fire during the first 6 cm of horizontal  
36 32 spread into a wet peat patch. The total spread distance into a wet peat patch was

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2  
3 33 | affected by the moisture content ~~content of the peat before and after a moisture~~  
4 34 | ~~transition~~gradient. We predicted that in most peat moisture ~~transitions~~ gradients of  
5  
6 35 | relevance to natural ecosystems the fire self-extinguishes within the first 10 cm of  
7  
8 36 | horizontal spread into a wet peat patch. Spread distances of more than 10 cm are  
9  
10 37 | limited to wet peat patches below 160% moisture content (mass of water per mass of  
11 38 | dry peat).

12  
13 39 | ~~Our aim is to use controlled laboratory experiments to better understand how the~~  
14 40 | ~~spread of smouldering fires is influenced in natural landscape conditions where the~~  
15 41 | ~~moisture content of the top peat layer is not homogeneous.~~ We found that spatial  
16 42 | ~~changes~~ gradients of moisture content have important local effects on the horizontal  
17  
18 43 | spread and should be considered in field and modelling studies.

19  
20  
21 44 | **Keywords:** peatland, smouldering, propagation, breakpoint analysis, step-change,  
22 45 | infrared image analysis.

## 26 47 | **1. Introduction**

### 28 48 | *1.1. Smouldering fires in peatlands*

29  
30 49 | Peatland soils are significant reservoirs of carbon, they cover less than 3% of the  
31 50 | Earth's land surface but they store 25% of the world's terrestrial carbon,  
32  
33 51 | approximately ~560 Gt of carbon (~~Yu 2012;~~ Turetsky et al., 2015; Yu, 2012). The  
34 52 | drainage of peatlands for human activities combined with a lack of external water  
35 53 | inputs (e.g. rain) perturbs peatland hydrological feedbacks (Waddington et al., 2015),  
36 54 | leading to a suppressiones of the water table ~~causing and~~ drying of the surface peat  
37 55 | ~~leading to alterations in the system's hydrology. Despite external water inputs (e.g.~~  
38 56 | ~~rain) being the primary control on peatland hydrology.~~ Enhanced drainage makes  
39 57 | peatlands highly vulnerable to drying and subsequently fires (Turetsky et al., 2011).  
40  
41 58 | During flaming wildfires of the surface vegetation, part of the heat can be transferred  
42 59 | to the organic soil (e.g. duff, peat) and may ignite a smouldering fire (Rein, 2013).  
43 60 | These flameless fires are more difficult to detect and suppress than flaming vegetation  
44 61 | fires (Rein, 2013). Peat fires can spread both on the surface and in-depth through the  
45 62 | sub-surface of a peatland and can initiate new flaming fires well away from the initial  
46 63 | region of smouldering peat (Putzeys et al., 2007; Rein, 2016). Very large amounts of  
47 64 | peat can be consumed during smouldering fires, releasing carbon gases (e.g. CO<sub>2</sub>, CO

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3 65 and CH<sub>4</sub>) and other greenhouse gases to the atmosphere (Gorham, 1991; Turetsky et  
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5 66 al., [2014](#)[2015](#)). The 1997 Indonesian peat fires are estimated to have consumed  
6  
7 67 approximately [32%](#) of the soil carbon stock [from Indonesia](#), ~0.95 Gt of carbon, ~~the~~  
8  
9 68 [which is](#) equivalent to 15% of the global fossil fuels emissions for that year (Page et  
10  
11 69 al., 2002). A 2007 peat fire event in the arctic tundra is estimated to have [reduced](#)  
12  
13 70 [30% of the soil depth in the whole area studied and](#) consumed 19% of the soil carbon  
14  
15 71 stock [of the region](#) (Mack et al., 2011). The [IPCC-climate change](#) projections forecast  
16  
17 72 an increase in drought frequency and severity in many peatlands worldwide ([Roulet et](#)  
18  
19 73 [al., 1992](#)), suggesting that peatlands will become more vulnerable to peat fires in the  
20  
21 74 future (IPCC, 2013). This implies that larger amounts of carbon may be released to  
22  
23 75 the atmosphere further contributing to the climate change and turning peatlands into  
24  
25 76 carbon-sources rather than potential carbon sinks (Billett et al., 2010; Flannigan et al.,  
26  
27 77 2009; Turetsky et al., 2002, [2014](#)[5](#)).

#### 28 29 78 30 31 79 *[1.2. Variability of moisture content in topmost peat layers](#)*

32  
33 80 In peatlands, the physiochemical properties of the surface-unsaturated peat layers are  
34  
35 81 influenced by the position of the water table and its associated hydrological responses  
36  
37 82 (Waddington et al., [2015](#)[4](#)). Changes in water table position alter surface  
38  
39 83 transpiration, evaporation and peat decomposition, which contribute to the moisture  
40  
41 84 variability of the surface layers of peat (~~Turetsky et al., 2014~~[Waddington et al., 2015](#)).  
42  
43 85 The vegetation also plays a very important role in determining the moisture content  
44  
45 86 distribution of the topmost peat layer. Hummock-forming *Sphagnum* mosses retain  
46  
47 87 high levels of moisture in the whole peat profile (Hayward and Clymo, 1982;  
48  
49 88 McCarter and Price, 2014). Other mosses (e.g. hollow *Sphagnum* species and feather  
50  
51 89 mosses) do not have the same capacity to uptake water from the water table,  
52  
53 90 depending more on the regularity of external water inputs (Thompson and  
54  
55 91 Waddington, 2013). As a consequence, during drought periods *Sphagnum* hummocks  
56  
57 92 remain wet while the surrounding peat becomes drier. The presence of vascular plants  
58  
59 93 causes shading and interception of precipitation also affecting the surface  
60  
61 94 transpiration and evaporation (Waddington et al., [2015](#)[4](#)). The rooting systems from  
62  
63 95 trees are also [a](#) source of moisture spatial heterogeneity in the topmost peat layers  
64  
65 96 (Rein et al., 2008).- [The combination of all these ecohydrological factors, specially](#)

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3 97 during drought events, causes large moisture heterogeneity on the topmost layers of  
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5 98 peatlands (Nungesser, 2003; Petrone et al., 2004).

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9 100 *1.3. Factors controlling peat ignition and propagation*

10  
11 101 The main factors governing the ignition and spread of smouldering are peat moisture  
12 102 content, organic content and bulk density (Frandsen, 1987, 1997; Reardon et al.,  
13 103 2007; Rein et al., 2008; Watts, 2012). Once peat is ignited, the fire is sustained by the  
14 104 energy released during the oxidation of the char (Hadden et al., 2013). This energy is  
15 105 dissipated, some being lost to the surroundings and some being transferred to drive  
16 106 the drying and pyrolysis of peat particles ahead of the oxidation front (Rein, 2016). If  
17 107 the energy produced is enough to overcome heat losses to the environment and  
18 108 preheat the surrounding peat, the smouldering front becomes self-propagating  
19 109 (~~Ohlemiller 1985~~, Huang and Rein, 2014; Ohlemiller, 1985). The spread can be  
20 110 horizontal and vertical and the extent of smouldering in each direction depends  
21 111 largely on the conditions of the peat and the environment (Benscoter et al., 2011;  
22 112 Reardon et al., 2007; Rein, 2013). A vertically spreading smouldering front can  
23 113 penetrate a few meters into the soil (Rein, 2013). However, more often tends to be  
24 114 extinguished after a few centimetres as downward spread is limited by either the  
25 115 water table or the mineral soil layer (Benscoter et al., 2011; Huang and Rein, 2015;  
26 116 Zacccone et al., 2014). A smouldering front that spreads horizontally can contribute to  
27 117 consume a large extension area of dry peat soils above the water table. This kind of  
28 118 spread (Benscoter and Wieder, 2003; Shetler et al., 2008), and coupled with the spread  
29 119 of vegetation wildfires, often results in large surface areas being affected (Benscoter  
30 120 and Wieder, 2003; Shetler et al., 2008).

31  
32  
33 121 Previous studies have highlighted the importance of peat moisture content on the  
34 122 ignition and spread of peat fires (Frandsen, 1987; Huang and Rein, 2014, 2015;  
35 123 Lawson et al., 1997; Reardon et al., 2007; Huang and Rein 2014; Huang and Rein  
36 124 2015). A 50% probability of ignition and early propagation has been estimated at 110-  
37 125 125%  $MC^1$  (Frandsen, 1987; Huang and Rein, 2015; Rein et al., 2008; ~~Huang and~~

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54 <sup>1</sup> Gravimetric moisture content is the mass of water per mass of dry peat expressed as  
55 a percentage.

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3 126 ~~Rein 2015~~). Recent experimental smouldering fires reveal horizontal spread rates  
4 127 between 1 to 9 cm h<sup>-1</sup> in peats below 150% MC (Prat-Guitart et al., ~~PhD Thesis in~~  
5 128 ~~press~~). In peats with higher moisture content, between 150-200% MC, the  
6 129 smouldering is weak and self-extinguishes within the first 10 cm of the sample  
7  
8 130 (Frandsen, 1997; Reardon et al., 2007).

9  
10  
11 131 Moisture content distributions of the topmost layer in peatlands are highly relevant to  
12 132 determining the spread of smouldering fires. Post peat-fire landscapes are often  
13 133 characterised by irregular peat consumption, where patches of peat associated with  
14 134 *Sphagnum* hummocks remain unburnt (~~Hudspith et al., 2014; Shetler et al., 2008;~~  
15 135 Terrier et al., 2014; ~~Hudspith et al., 2014~~). ~~Enhanced~~P peat consumption has also been  
16 136 observed under trees, suggesting that fires spread through the peat adjacent to the  
17 137 roots (Davies et al., 2013; Miyanishi and Johnson, 2002). However, there is little  
18 138 understanding of how varying the peat moisture content (~~e.g. transition from feather~~  
19 139 ~~moss to Sphagnum~~) across a spatial landscape affects the horizontal propagation of  
20 140 peat fires. This study experimentally examines the behaviour of a smouldering front  
21 141 as it propagates through a ~~sharp transition of gradient of~~ peat moisture content in order  
22 142 to (1) identify local changes in the fire behaviour associated with a transition of  
23 143 moisture content and (2) test whether the ~~previous contiguous drier~~ moisture content  
24 144 ahead of a transition affects the fire behaviour into a wet peat.  
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## 36 146 **2. Materials and Methods**

### 37 147 *2.1. Experimental system*

38 148 In order to study ~~the effect of a moisture content gradient on the~~ smouldering ~~spread~~  
39 149 behaviour ~~in conditions that mimic the varying moisture content of real peatlands,~~ we  
40 150 designed a simplified milled peat system that allows ~~the natural sources of peat~~  
41 151 ~~heterogeneity, such as moisture content, bulk density, mineral content and particle~~  
42 152 ~~size moisture content~~ to be controlled (Prat-Guitart et al., 2015). The smouldering  
43 153 experiments were conducted in an 18×22×6 cm open-top box (insulated fibreboard  
44 154 container) of similar thermal conductivity as peat (0.07-0.11 W m<sup>-1</sup> K<sup>-1</sup>) to minimise  
45 155 boundary effects (~~Benscoter et al., 2011; Frandsen, 1987; Garlough and Keyes, 2011;~~  
46 156 Rein et al., 2008; ~~Benscoter et al., 2011; Garlough and Keyes 2011~~). The peat samples

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3 157 were 5 cm in depth. The samples were kept shallow to facilitate the formation of a  
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5 158 plane smouldering front spreading horizontally from one side of the box to the other.  
6  
7 159 As a result, we focus solely on the horizontally spread and not on the vertical spread.  
8  
9 160 The experiments were limited to 12 h to avoid day-and-night temperature fluctuations.  
10  
11 161 The analysis of the spread inside the box was divided in three regions: (i) ignition  
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13 162 region, (ii) region ahead of the moisture ~~transition-gradient~~ (*PRE*) and (iii) region  
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15 163 following the ~~transition-gradient~~ (*POST*) (Fig. 1). The ignition region was at one side  
16  
17 164 of the box where an 18-cm long electric igniter coil was buried in a 2-cm strip of peat  
18  
19 165 at ~0% *MC*. The *PRE* region was adjacent to the ignition and consisted of a 10-cm  
20  
21 166 strip of conditioned peat. The *POST* region was a peat sample of the same size as *PRE*  
22  
23 167 but with higher moisture content. A clear straight boundary separated *PRE* and *POST*  
24  
25 168 regions creating a sharp ~~increase-gradient~~ in moisture content at approximately 10 cm  
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27 169 from the ignition location.  
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[Figure 1]

173 The milled peat samples were oven-dried at 80°C for 48 h and then rewetted in small  
174 samples of less than 300 g of peat to achieve the desired moisture content. Since  
175 oven-dried peats can become hydrophobic, ~~The~~ rewetted peat samples were sealed in  
176 plastic bags for at least 24 h prior to the experiment to reach moisture equilibrium.  
177 One day is more than an orders of magnitude longer than the typical infiltration time  
178 of severely hydrophobic soil (Kettridge et al., 2014). This protocol therefore  
179 minimises heterogeneity within the moisture content of the peat samples. We used 14  
180 *PRE-POST* moisture content combinations in our experiment (Table 1). The *PRE*  
181 samples never exceeded 150% *MC* in order to be below the threshold of 125-150%  
182 *MC* for self-sustained spread for more than 10 cm (Frandsen, 1997; Prat-Guitart et al.  
183 in press; Reardon et al., 2007; ~~Prat-Guitart et al. PhD-Thesis~~). The moisture content of  
184 *POST* peats (between 125% and 250% *MC*) represents wet peats around the threshold  
185 of self-sustained spread. All peats had a mineral content<sup>2</sup> of  $2.6 \pm 0.2\%$ . Within the

<sup>2</sup> Mass of mineral particles per mass of dry organic peat.

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186 box volume, pPeat bulk density (mass of dry peat per unit volume)<sup>3</sup> varied between  
187 55 and 140 kg m<sup>-3</sup>. ~~T~~, the variation in density was ~~being due~~ in part due to the  
188 expansion of ~~wet~~ peat when water was addeds (Table 1). Bulk densities were  
189 representative of peat soils from temperate and boreal peatlands (Davies et al., 2013;  
190 Lukenbach et al., 2015; Thompson and Waddington, 2013; Wellock et al., 2011).

[Table 1]

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194 The ignition protocol consisted in powering the ignition region with 100 W for 30  
195 minutes using the electric igniter coil (Rein et al., 2008). This energy input is strong  
196 and similar to a burning tree stump and is enough to ignite dry peat (Rein et al., 2008).  
197 After 30 minutes the igniter coil was turned off and a linear smouldering combustion  
198 front spread through the samples of peat. A visual and infrared cameras imaged the  
199 surface of the smouldering every minute (Prat-Guitart et al., 2015). The infrared  
200 camera (SC640, FLIR Systems, US) captured the radiated energy flux from the peat at  
201 a resolution of 0.05×0.05 cm (i.e. one pixel equated to 0.25 mm<sup>2</sup>). The images were  
202 corrected for the angle of the infrared and webcam cameras and processed to extract  
203 the values of radiated energy flux at a pixel scale. Details of the methods are given in  
204 Prat-Guitart et al. (2015). An array of seven K-type thermocouples (1.5 mm diameter)  
205 monitored the smouldering temperatures inside the peat samples at 1 cm from the  
206 bottom of the box. One thermocouple was situated in the ignition region and the other  
207 six were distributed to capture the temperature 4 cm before the moisture ~~transition~~  
208 gradient and then at 1 and 6 cm after the ~~transition~~ moisture increase (Fig. 1).

210 2.2. Behaviour of the smouldering front

211 Smouldering temperatures have often been analysed to study the peat combustion and  
212 fire spread (~~Rein et al., 2008;~~ Benscoter et al., 2011; Rein et al., 2008; Zacccone et al.,  
213 2014). We analysed the thermocouple data to identify changes in the combustion  
214 temperatures due to the sharp transition of peat moisture. For each thermocouple, we

<sup>3</sup>Mass of dry peat per unit volume.



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215 | estimated the combustion duration ~~of combustion temperatures~~, as the time taken  
216 | since the start of the combustion (increase above 100°C) and until the peat burnout  
217 | (decreased below 200°C for the last time). We also estimated the peak temperature as  
218 | the 90<sup>th</sup> percentile of the thermocouple temperature profile. To demonstrate the effect  
219 | of *PRE* moisture content on the spread into *POST* peats, we statistically compared the  
220 | temperatures of 22 experiments with the same *POST* moisture content (150% *MC*) but  
221 | different *PRE* moisture contents (25% - 150% *MC*). The effects of moisture content  
222 | treatment and distance from the moisture gradient on peak temperature and  
223 | combustion ~~burn~~ duration were estimated using one-way ANOVAs. The differences  
224 | between treatment levels were estimated using Tukey's Honest Significant  
225 | Difference (HSD) post-hoc test with a significance level of  $p \leq 0.05$ . Temperature  
226 | profiles from all the *PRE-POST* combinations are provided in the supplementary  
227 | materials (Fig. S1).

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

240

[Figure 2]

242

243 | We analysed the spatial autocorrelation of *E* by computing the data's semivariance  
244 | (half average squared difference between pairs of pixels) (Bivand et al., 2008). The  
245 | semivariogram was produced using a subset of *E* from each experimental burn.

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246 Subsets of  $E$  were selected from a central area of *PRE* peat away from any boundary.  
247 We then fitted a theoretical spherical model to the semivariogram. The spatial range  
248 of the semivariogram indicated the distance where the data exhibited no spatial  
249 autocorrelation. To avoid statistical issues of spatial autocorrelation we considered 48  
250 sub-regions ( $2 \times 1$  cm) from each box and ensured that sub-regions were separated by  
251 at least 1 cm. This separation is greater than the scale of autocorrelation in the data for  
252  $E$ . We estimated the median  $E$  in each sub-region ( $E_m$ ) and the median absolute  
253 deviation.

254 Piecewise linear regression was used to identify a step-change in  $E_m$  as a function of  
255 distance from the moisture gradienttransition (Crawley, 2013). The analysis was  
256 performed on data from each moisture combination ( $i$ ) separately as

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$$258 \quad E_{mi} = \beta_{d1}(x_i < c_i) + \beta_{d2}(x_i > c_i) \quad \text{Eq. (1)}$$

259

260 where  $x_i$  is the distance (cm) from the moisture transitiongradient,  $c_i$  is the position of  
261 the breakpoint,  $\beta_{d1}$  and  $\beta_{d2}$  are the estimated intercepts before and after the a- $E_m$   
262 breakpoint-(e). To estimate the position of the breakpoint, eEquation 1 was fitted for  
263 values of  $c_i$  ranging from -4cm to +8cm in steps of 0.1 cm, and multiple times to find  
264 the values of  $c_i$  that produced the minimum residual standard error was selected. We  
265 tested possible values of  $e$  in a distance step of 0.1 cm between -4 and +8 cm from  
266 the transition of moisture content

267

### 268 2.3. Spread distance after a moisture transitiongradient

269 The spread distance was estimated from the firstlast visual image taken after the fire  
270 had extinguished (assessed with the infrared images). We used the visual images to  
271 distinguish by eye between the burnt and unburnt peat based on the colour; white and  
272 grey for the char and ash and brown for the unburnt peat (#Fig. 1). We estimated the  
273 final position of the smouldering front into *POST* peat using the boundary between  
274 burnt and unburnt peat regions, (often of irregular shape). The median spread distance  
275 after the moisture transition-gradient ( $D_T$ ) was estimated by manually removing the

276 areas where fresh peat had collapsed. We associated  $D_T$  with the moisture content of  
277  $PRE$  and  $POST$  peats using the following statistical model

$$\sqrt{(D_T)_i} = \beta_0 + \beta_1 PRE_i + \beta_2 POST_i + \beta_3 PRE_i \cdot POST_i + \varepsilon_i \quad \text{Eq. (2)}$$

281 where  $\beta_0$ ,  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are regression coefficients and  $\varepsilon_i$  are normally distributed  
282 residuals of the  $i^{\text{th}}$  experimental replicate of each  $PRE$  and  $POST$  combination. The  
283 dependent variable ( $D_T$ ) was square root transformed to normalise the distribution of  
284 the residuals. Experiments where the smouldering front completely consumed the  
285  $POST$  sample (i.e. extinguished due to the box wall) were discarded since it was not  
286 possible to quantify  $D_T$ .

287 The image processing was done in Matlab with the *Image Processing Toolbox*  
288 (*Mathworks, version R2012b 8.0.0.783*). The data analysis was done with *R project*  
289 statistical software (Development Core Team, 2013). The spatial autocorrelation  
290 analysis was done with packages *automap* (Hiemstra et al., 2009) and *gstat* (Pebesma,  
291 2004).

## 4. Results

### 4.1. Smouldering behaviour

295 In experiments combining  $PRE$  MC of 25% and  $POST$  of 150% a ~~step-~~  
296 ~~change~~breakpoint in  $E_m$  was identified at  $c_i = 1.5$  cm after the moisture ~~transition~~  
297 ~~gradient~~ (Table 2). The  $E_m$  before the ~~step-change~~break-point was  $3.92 \pm 0.05$  kW  
298  $\text{m}^{-2}$  (mean  $\pm$  standard error), whereas after ~~the~~that breakpoint it decreased to  $2.89 \pm$   
299  $0.12$  kW  $\text{m}^{-2}$ . ~~In the experiments with PRE MC of 25% and POST of 150%, we~~  
300 ~~found that the distance from the moisture content gradient was associated with~~  
301 ~~differences in the~~ peak temperature ~~peaks estimated across the experiments of PRE~~  
302 ~~MC of 25% and POST of 150% (one-way ANOVA  $F_{2,16}=11.1, p<0.001$ ). Before the~~  
303 ~~breakpoint in  $E_m$  breakpoint,~~ (at  $-4$  cm and  $+1$  cm from the ~~transition~~moisture  
304 ~~gradient}) no difference in the peak temperatures was found ~~were similar~~ (ere similar  
305 ( $384 \pm 25^\circ\text{C}$  and  $349 \pm 24^\circ\text{C}$ , respectively.) (Fig. 3a). However, ~~while~~ ~~the peak~~~~

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3 306 ~~temperature After the breakpoint in  $E_m$  peak temperature~~ at +6 cm from the ~~transition~~  
4 307 ~~moisture gradient was significantly decreased~~ ( $155 \pm 93^\circ\text{C}$ ) ~~was less than peak~~  
5 308 ~~temperatures before the breakpoint~~ (~~(ANOVA  $F_{2,16}=11.1$ ,  $p$ -value $<0.001$  with~~  
6 309 Tukey's HSD ~~post hoc test  $p<0.05$~~ ). ~~The re~~ ~~combustion durations~~ ( $113 \pm 11$  min,  $107$   
7 310  $\pm 10$  min and  $56$  min at  $-4$  cm,  $+1$  and  $+6$  cm, respectively) ~~did not show~~ ~~were no~~  
8 311 ~~significant differences~~ ~~were not associated with the distance from the moisture~~  
9 312 ~~gradient~~ (one-way ANOVA  $F_{2,16}=1.6$ ,  $p=0.2$ ) ~~in combustion duration that could be~~  
10 313 ~~matched associated to the effect of changes in the a moisture gradient  $E_m$  breakpoint~~  
11 314 ( $113 \pm 11$  min,  $107 \pm 10$  min and  $56$  min for  $-4$  cm,  $+1$  and  $+6$  cm, respectively)  
12 315 (~~ANOVA  $F_{2,16}=1.6$ ,  $p$ -value $=0.2$~~ ).

13 316 At  $+1$  cm from the ~~transition~~ ~~moisture gradient~~ both combustion duration and peak  
14 317 temperatures were affected by the *PRE* moisture contents (red lines in ~~F~~fig. 3). ~~We~~  
15 318 ~~found that *PRE MC* was associated with peak temperatures at  $+1$  cm to differ between~~  
16 319 ~~*PRE MC* (one-way ANOVA  $F_{4,25}=6.6$   $p<0.001$ ).~~ ~~Peak temperatures were higher~~ ~~did~~  
17 320 ~~not differ between~~ ~~similar when~~ ~~*PRE MC* were of~~  $25\%$  and  $50\%$ , ( $349 \pm 24^\circ\text{C}$ ,  $329 \pm$   
18 321  $21^\circ\text{C}$ , respectively), ~~but a higher *PRE* moisture content significantly~~ ~~and~~ ~~decreased~~  
19 322 ~~the peak temperatures for higher *PRE* moisture~~ (e.g.  $137 \pm 27^\circ\text{C}$  in  $PRE=150\%$  *MC*)  
20 323 (~~ANOVA  $F_{4,25}=6.63$   $p$ -value $<0.001$  with~~ Tukey's HSD ~~post hoc test  $p<0.05$~~ ).

21 324 ~~Similarly,~~ ~~the~~ ~~combustion duration was different~~ ~~differed~~ ~~across *PRE MC*~~  
22 325 ~~treatments~~ (one-way ANOVA  $F_{3,19}=4.3$   $p=0.02$ ). The combustion duration was  
23 326 ~~similar for~~ ~~were also found when~~ ~~*PRE MC* of~~  $25\%$  and  $50\%$ , ( $107 \pm 10$  min and  $99 \pm$   
24 327  $18$  min, respectively) ~~but at higher *PRE* moisture contents,~~ ( $100\%$ ,  $125\%$  and  $150\%$   
25 328 *MC*); the combustion duration decreased to ~~than  $100\%$  *MC*~~ ( $43 \pm 5$  min, ~~min~~  $81 \pm 9$   
26 329  $\text{min}$  and  $78 \pm 9$  min) ~~or more~~ ~~respectively~~ (ANOVA  $F_{3,19}=4.3$   $p$ -value $=0.02$  with  
27 330 Tukey's HSD ~~post hoc test  $p<0.05$~~ ). At  $+6$  cm from the ~~transition~~ ~~moisture gradient~~  
28 331 (blue lines in ~~F~~fig. 3) the combustion duration and peak temperatures were ~~similar~~ ~~not~~  
29 332 ~~different from~~ to the ones reported for *PRE MC* of  $150\%$  (one-way ANOVAs  $F_{3,7}=1.1$   
30 333  ~~$p$ -value $=0.4$ ,  $F_{2,3}=0.65$   $p$ -value $=0.5$ , respectively).~~

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51 335 [Figure 3]  
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3 337 The finer resolution of the radiated energy flux data ( $E_m$ ) added information on the  
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5 338 location where the changes in fire behaviour took place (Table 2, Fig 4, Fig. S2).  
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7 339 The majority of breakpoints in  $E_m$  were located after the increase of moisture content,  
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9 340 indicating a continuation of ~~PRE-transition-moisture gradient~~ behaviour for up to 6  
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11 341 cm into the *POST* peat. ~~The radiation flux emitted after the breakpoint continued to be~~  
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13 342 ~~associated to PRE MC (ANOVA  $F_{4,309}=15.5$ ,  $p$  value  $<0.001$  with Tukey HSD post~~  
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15 343 ~~hoc test).~~ Two moisture content combinations ( $PRE=150\%$ ,  $POST=150\%$  and  
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17 344  $PRE=125\%$ ,  $POST=250\%$ ) had breakpoints in  $E_m$  before the moisture ~~transition~~  
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19 345 ~~gradient~~ (Table 2, Fig. S2).  
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20 347 [Figure 4]

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24 349 [Table 2]

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#### 28 351 4.2. Spread distance into wet peat

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30 352 The spread distance ( $D_T$ ) showed no difference between *PRE* of 25% and 50% *MC*  
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32 353 (ANOVA  $F_{1,22}=0.067$   ~~$p$  value = -0.8~~) (Fig. 5). For all other peat combinations, the  
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34 354 smouldering front spread no further than 5 cm into the wetter peat ( $D_T < 5$  cm).  
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36 355 Experiments that combined *PRE MC* of 125% or *POST MC* of 250% *MC* always had  
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38 356 self-extinction less than 1 cm after the moisture transition.  
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41 358 [Figure 5]

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45 360 The spread distance into wet peat was well described by *PRE* and *POST* moisture  
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47 361 content conditions (Table 3, Fig. 6). Increasing either *PRE* or *POST* moisture  
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49 362 contents decreased the spread distance. The coefficient  $\beta_1$  was higher ( $-0.06$ ,  $-0.04$ ,  
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51 363 95% confidence interval) than  $\beta_2$  ( $-0.03$ ,  $-0.02$ ), indicating a bigger effect of *PRE*  
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53 364 moisture content on  $D_T$  than *POST* moisture content. The interaction term *PRE* $\times$ *POST*

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3 365 showed that the effect of *PRE* on reducing the spread distance was larger when *POST*  
4 366 peats had lower moisture content.

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9 368 [Table 3]

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13 370 [Figure 6]

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17 372 *PRE MC* above 125% lead to smouldering self-extinction immediately after the  
18 373 transition (<1 cm) for any *POST MC* (Fig. 7). Similarly, high *POST MC* (greater than  
19 374 260% *MC*) spreads for less than 1 cm for any *PRE MC*. Equation 2 predicts that  
20 375 spread for more than 10 cm can be achieved when most *PRE MC* is below 50%  
21 376 combined with *POST MC* below 160%.

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27 378 [figure-Figure 7]

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## 32 381 5. Discussion

### 33 382 5.1. Effects of peat moisture content heterogeneity on the propagation dynamics

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36 383 We have analysed the behaviour of smouldering fires through a ~~transition-gradient~~ in  
37 384 peat moisture. We find that the peat moisture before the ~~transition-gradient~~ influences  
38 385 the fire spread into the wet peat beyond. The smouldering ignition and spread in peats  
39 386 with homogeneous moisture conditions are primarily limited by the moisture content  
40 387 of the peat (Frandsen, 1987, 1997; ~~Garlough and Keyes, 2011~~; Lawson et al., 1997;  
41 388 Reardon et al., 2007; ~~Garlough and Keyes 2011~~). However, we show that fire spread  
42 389 in milled peats with heterogeneous moisture conditions is strongly influenced by the  
43 390 moisture conditions of adjacent peat as well as the immediate moisture content of the  
44 391 peat.

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47 392 Whilst, this study reports limited spread distances of 10 cm into a more moist peat,  
48 393 the scale of the experiment was enough to examine local changes in fire behaviour  
49 394 during the spread through a moisture ~~transitiongradient~~. Our analysis of radiation flux

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3 395 suggests two main effects of the *PRE* peat conditions on the fire behaviour after a  
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5 396 moisture ~~transition~~gradient. First, the strongest effect of *PRE* peat conditions happens  
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7 397 within the first centimetres (<7 cm) after the moisture ~~transition~~gradient (Fig. 4, Fig.  
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9 398 S2). In this region the combustion duration and the peak smouldering temperatures  
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11 399 have similar behaviour to the adjacent drier peat. The smouldering front spreading  
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13 400 close to the moisture ~~gradient~~transition evaporates part of the water from the wet peat  
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15 401 (Ohlemiller, 1985). Consequently, a few centimetres ahead of the ~~moisture~~ gradient  
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17 402 ~~transition~~are already drier when the smouldering front reaches the wetter *POST* peat.  
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19 403 Second, the location of the breakpoint could be interpreted as a new moisture ~~gradient~~  
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21 404 ~~transition~~created by the dynamics of the smouldering fire. After the breakpoint the  
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23 405 smouldering fire continues spreading but is less affected by the *PRE MC* conditions  
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25 406 (Fig. 4). Experiments with *PRE*=50% and *POST*=150% did not have a substantial  
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27 407 change in  $E_m$  after the breakpoint but an increase of the standard error of the  $E_m$  after  
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29 408 (Table 2). We tested the sensitivity of the results obtained to changes in the methods  
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31 409 used to analyse the infrared images. Variation of the thresholds used to determine  $E$   
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33 410 produced different  $E$  and  $E_m$  outputs, although the results did not change qualitatively.  
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35 411 The analysis of thermocouple temperature data also supports the effect of *PRE* peat  
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37 412 conditions on the smouldering spread into *POST* peat. While the temperatures  
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39 413 measured at 1 cm after the moisture ~~gradient~~transition correspond to the region of  
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41 414 *POST* peat more affected by the *PRE MC* conditions, the temperatures recorded at 6  
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43 415 cm after the ~~transition~~moisture gradient were less affected by the *PRE* peat  
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45 416 conditions (Fig. 4). We found that *POST MC* of 150% reach temperatures between  
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47 417 100 and 500°C at 1 cm after the moisture ~~gradient~~transition. Some of these  
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49 418 temperatures are lower than typical oxidation temperatures 400-600°C reported for  
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51 419 *natural* peats  $\leq 100\%$  *MC* (Benscoter et al., 2011; Rein et al., 2008). Only temperatures  
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53 420 above 300°C indicate on-going peat oxidation (Chen et al., 2011). Between 100°C  
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55 421 and 300°C evaporation and pyrolysis processes dominate the smouldering and little  
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57 422 oxidation is expected (Huang and Rein, 2014). Compared to the infrared images, the  
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59 423 resolution of thermocouple data are limited and only providing data from fire  
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61 424 behaviour around the thermocouple. In some burns, the thermocouples registered  
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63 425 oscillations in combustion temperatures between 50 and 300°C (i.e. Fig. 3a and Fig.  
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65 426 3b), which could be caused by the local dynamics of the particles surrounding the

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3 427 thermocouple. The milled peat particle size was below 1 cm in diameter and had  
4 428 variable density due to differences in the degree of decomposition. Differences in the  
5 429 infiltration rates and hydrophobicity of the peat particles during the rewetting process  
6 430 (Kettridge et al., 2014) could cause short-term heterogeneity (~10 min) in the  
7 431 moisture content of a peat sample. This short-term heterogeneity was minimised by  
8 432 our protocol, which allowed samples to equilibrate for 24 h prior to an experiment.  
9 433 Any remaining variation in peat moisture will impact the fine-scale spread of the fire  
10 434 between particles (i.e. <1 cm), but have a minor effect on the average spread of the  
11 435 fire throughout a peat sample of 20 × 20 cm.

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18 436 The moisture gradient between *PRE* and *POST* peat could cause movement of the  
19 437 water through the transition boundary. ~~Higher peat~~ moisture content in *POST* peat  
20 438 could move to *PRE* peat, due to differences in ~~implies high unsaturated~~ hydraulic  
21 439 conductivity (capacity of water movement in unsaturated soil per unit volume)  
22 440 (Boelter, 1965; Hillel, 1980). ~~Milled p~~Peats below ~~200~~250% *MC* have a small  
23 441 unsaturated hydraulic conductivity and therefore very little water movement is  
24 442 expected for the duration of the experimental burns (~~Letts et al. 2000~~Holden and  
25 443 Ward, 1997). ~~Peat soils at 250% MC have a higher hydraulic conductivity, between~~  
26 444  ~~$10^{-8}$  and  $10^{-6}$  m s<sup>-1</sup> (Boelter 1968).~~ ~~Since~~The smouldering fronts reached *POST* peat  
27 445 ~~before less than 4 h after ignition implying minimal in all burns, we expected a~~ water  
28 446 movement ~~between 0.2 and 0.9 cm towards the *PRE* peat during that time.~~ Only peat  
29 447 samples with *PRE* of 125% and *POST* 250% and homogeneous 150% *MC* had a  
30 448 breakpoint in  $E_m$  ~~right~~ before the ~~transition~~ moisture gradient (Fig. S2). This  
31 449 breakpoint before the initial location of the gradient ~~that~~ could be caused by a weak  
32 450 smouldering spread due to the high moisture content in those *PRE* peat ~~the movement~~  
33 451 ~~of moisture content (ig. S2).~~ Even after several hours, little mMoisture evaporation is  
34 452 expected for peat moisture contents below 250% *MC* ~~may also be considered to alter~~  
35 453 ~~the moisture content of the peat after several hours~~(Kettridge et al., 2012)~~of burning.~~  
36 454 However, Our data (Prat-Guitart et al., in press) confirm that there is little in this  
37 455 study we quantified unsubstantial changes in peat moisture content after 12 h at  
38 456 ambient temperature. Movement of water is therefore mainly due to evaporation and  
39 457 condensation ahead of the smouldering front, which is driven by the oxidative  
40 458 combustion reactions (Rein, 2016).



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3 459 The spread distance into a wet peat is also affected by local changes in fire behaviour  
4  
5 460 caused by the moisture gradienttransition. The moisture content conditions of *PRE*  
6  
7 461 peat conditions control the fire spread during the first 10 cm into a wet peat (Table 3).  
8  
9 462 Only *PRE MC* of 25 or 50% combined with *POST MC* of 100 or 150% and few  
10  
11 463 homogeneous peats with 150% *MC* led to peat fires that could propagate more than 10  
12  
13 464 cm. The fire behaviour found for this moisture content combinations agrees with  
14  
15 465 results from previous studies indicating self-sustained spread for 10 cm or more in  
16  
17 466 similar moisture conditions (Frandsen, 1997; Prat-Guitart et al., 2015; Reardon et al.,  
18  
19 467 2007; Rein et al., 2008; Prat-Guitart et al 2015).

20  
21 468 Our simplified laboratory experiments enabled the effect of moisture content on the  
22  
23 469 spread of smouldering fires to be studied whilst controlling for mineral content, bulk  
24  
25 470 density and other artefacts in the peat (Belcher et al., 2010; Frandsen, 1987; Beleher  
26  
27 471 et al. 2010; Hadden et al., 2013; Zacccone et al., 2014). We note that studying  
28  
29 472 smouldering fire behaviour in field samples of peat soil would make the analysis more  
30  
31 473 complex and the results more difficult to interpret because of the multiple  
32  
33 474 uncontrolled factors (e.g. bulk density, organic composition, pore size) that vary  
34  
35 475 between field samples (McMahon et al., 1980). ~~However, o~~ Our results (Prat-Guitart  
36  
37 476 et al., in press) and those of others indicate that the ~~effect of a moisture transition on~~  
38  
39 477 ~~the~~ spread of smouldering fire in natural peats will also be ~~further~~ influenced by peat  
40  
41 478 bulk density (Frandsen, 1991; Lukenbach et al., 2015~~Prat-Guitart et al. PhD Thesis~~),  
42  
43 479 mineral content (Frandsen, 1987; Garlough and Keyes, 2011), depth (Benscoter et al.,  
44  
45 480 2011; Huang and Rein, 2015), as well ~~and other factors such~~ as the organic  
46  
47 481 composition, structure, pore size distribution and the degree of ~~peat~~ decomposition.  
48  
49 482 Future research should aim to further develop our experimental work to understand  
50  
51 483 how other peat properties contributing to the heterogeneity of moisture content of  
52  
53 484 peatlands affect the spread of peat fires.

54  
55 485

## 56 486 5.2. Application to peatland fires

57  
58 487 The results ~~Our~~ obtained in our milled peat experiments in the laboratory where a  
59  
60 488 moisture content gradient was implemented for the first time, give a first insight  
61  
62 489 results contribute to the understanding of the peat fire behaviour and interpretation of

1  
2  
3 490 post peat-fire landscapes. Often, post fire studies report irregular consumption of peat,  
4  
5 491 where wet *Sphagnum* hummocks are left unburnt (Benscoter and Wieder, 2004;  
6  
7 492 [Hudspith et al., 2014](#); Shetler et al., 2008; ~~Hudspith et al. 2014~~). Our results suggest  
8  
9 493 that ~~differences in peat moisture content could cause the~~ smouldering fire  
10  
11 494 consumption ~~in~~ the dry peat ~~in the surroundings of~~ *Sphagnum* hummocks and likely  
12  
13 495 reduced the size of the wet patches.

14  
15 496 ~~In peatlands, smouldering fires happen during extreme weather events, due to~~  
16  
17 497 ~~reductions of surface moisture content (Terrier et al., 2014; Turetsky et al., 2015).~~  
18  
19 498 ~~Peat fires in surface peat layers are part of the natural cycle of peatlands, often limited~~  
20  
21 499 ~~by the spatial heterogeneity of moisture content. These fires reduce peat~~  
22  
23 500 ~~accumulation, enhance biodiversity and facilitate the access of surface vegetation to~~  
24  
25 501 ~~the water table (Waddington et al., 2015).~~ The spatial distribution of moisture content  
26  
27 502 at a microtopographical scale has a strong influence on the smouldering fire spread  
28  
29 503 (Benscoter and Wieder, 2004). We predicted fire spread of less than 10 cm into a  
30  
31 504 wet patch for most of the moisture content combinations involving peat  $\geq 160\%$  MC  
32  
33 505 (Fig. 7). *Sphagnum* hummocks have a variable size, between 20 and 200 cm diameter  
34  
35 506 (Nungesser, 2003; Petrone et al., 2004), meaning that most of the hummock surface  
36  
37 507 can remain unburnt. Natural peatlands have high water table levels and heterogeneous  
38  
39 508 distributions of surface moisture (Waddington et al., 2014). ~~Our controlled peat~~  
40  
41 509 ~~experiments have only looked at surface horizontal spread. This is one kind of spread~~  
42  
43 510 ~~that, together with vertical spread, happens during peat fires due to the three-~~  
44  
45 511 ~~dimensional shape of the smouldering front (Ohlemiller, 2002). In these peatlands,~~  
46  
47 512 ~~smouldering fires happen during extreme weather events, due to reductions of surface~~  
48  
49 513 ~~moisture content (Terrier et al. 2014; Turetsky et al. 2014). Peat fires in surface peat~~  
50  
51 514 ~~layers are part of the natural cycle of peatlands, often limited by the spatial~~  
52  
53 515 ~~heterogeneity of moisture content. These fires reduce peat accumulation, enhance~~  
54  
55 516 ~~biodiversity and facilitate the access of surface vegetation to the water table~~  
56  
57 517 ~~(Waddington et al. 2014). Drained or harvested peatlands are likely to have drier~~  
58  
59 518 ~~surface layers and smaller *Sphagnum* hummocks (Cagampan and Waddington 2008).~~  
60  
61 519 ~~Under these circumstances smouldering fires can lead to extensive consumption of the~~  
62  
63 520 ~~topmost peat layers.~~

1  
2  
3 521 Future modelling of peatland fires needs to consider variations in the underlying  
4  
5 522 moisture content because of its effect on the smouldering propagation at a fine-scale  
6  
7 523 ~~in more complex smouldering spread scenarios~~. Modelling of peat fires incorporating  
8  
9 524 the effect of peat moisture changes will lead to more accurate estimates of carbon  
10  
11 525 emissions, fire perimeter and area burned (Benscoter and Wieder, ~~2001~~2003).  
12  
13 526 ~~Another studied variable, combustion temperatures, are often used as indicators of fire~~  
14  
15 527 ~~intensity (Keeley 2009; Hudspith et al. 2014). The transition between two moisture~~  
16  
17 528 ~~contents was reported to affect oxidation temperatures (fig. 3), suggesting that peat~~  
18  
19 529 ~~combustion temperatures are affected by fine scale variations of moisture content.~~  
20  
21 530 Finally, ecosystem management and fire management should also take into account  
22  
23 531 the spatial variation of peat moisture content to manage the fire risk, avoid large areas  
24  
25 532 of peat being consumed by fires and moisture maps may allow better estimates of fire  
26  
27 533 or burn severity to be made. It may be that peat fires can be managed by assuming  
28  
29 534 that extinction could be achieved by rising the moisture content of strategically  
30  
31 535 located peat areas above 200% MC. This technique may have a wider ranging of  
32  
33 536 ecological benefits than ~~of~~ flooding entire areas by blocking ditches or using  
34  
35 537 destructive techniques such as bull-dozing trenches ~~or soil compression~~ (Watts 2012;  
36  
37 538 Davies et al., 2013; Watts, 2012). ~~As such further work is required to assess the~~  
38  
39 539 ~~importance of moisture transitions in understanding the spread of smouldering~~  
40  
41 540 ~~peatland fires.~~

## 541 542 **Conclusions**

543 We studied the role of moisture content as a limiting factor of smouldering  
544 propagation in situations where peat moisture content is not homogeneous. Our  
545 approach presents a useful method toward building an understanding peatland  
546 smouldering fire behaviour that enable new information about the influence of  
547 moisture content transitions in peatland systems. We show that fire spread into wet  
548 peat patches is strongly affected by local transitions of moisture content. The moisture  
549 content of the peat before the transition governs the fire behaviour into a wet peat for  
550 the first centimetres of spread. After that distance it is likely that peat fires self-  
551 extinguish leaving unburnt patches of wet peat. Future research on peat fire behaviour

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2  
3 552 should consider local variation in moisture content to better understand the spread of  
4  
5 553 smouldering fronts through peat layers.

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9 555 **Acknowledgements**

10 556 The authors thank the School of Mechanical Engineering at University College  
11 557 Dublin, especially to David Timoney for the support and John Gahan for his help  
12 558 during the laboratory set up. [We thank M. Waddington and one anonymous reviewer](#)  
13 559 [that provided helpful comments on the manuscript.](#) This project is funded by the Irish  
14 560 Higher Education Authority PRLTI 5. Claire M. Belcher acknowledges a European  
15 561 Research Council Starter Grant ERC-2013-StG-335891-ECOFLAM.

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894 **Tables**

895 **Table 1. Peat moisture content and bulk density combinations of the**  
896 **experimental burns.**

897 *PRE* and *POST* are the moisture contents of the two peat blocks before and after the  
898 sharp moisture transition gradient, respectively; dry peat bulk density ( $\rho$ ) is the mass  
899 of dry peat per unit volume ~~bulk density of the dry peat mass~~ (median  $\pm$  median  
900 absolute deviation); ~~and wet peat density~~ wet peat density is the bulk density of mass of the moist  
901 peat per unit volume and volumetric moisture content is the volume of water per unit  
902 volume. Number of experimental burn replicates (*n*) for each combination of *PRE* and  
903 *POST* moisture contents.

<i>MC</i>	Dry peat $\rho$	Wet peat density $\rho$	Volumetric <i>MC</i>
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<i>PRE</i>	<i>POST</i>	<i>PRE</i>	<i>POST</i>	<i>PRE</i>	<i>POST</i>	<i>PRE</i>	<i>POST</i>	<i>n</i>
(%)	(%)	(kg m <sup>-3</sup> )	(kg m <sup>-3</sup> )	(kg m <sup>-3</sup> )	(kg m <sup>-3</sup> )	(m <sup>3</sup> m <sup>-3</sup> )	(m <sup>3</sup> m <sup>-3</sup> )	
25	150	123 ± 6	65 ± 6	154 ± 7	163 ± 16	3.1 ± 0.1	9.8 ± 0.9	4
25	200	121 ± 10	66 ± 2	152 ± 12	199 ± 6	3.0 ± 0.2	13.2 ± 0.4	4
25	250	121 ± 7	75 ± 9	151 ± 9	263 ± 33	3.0 ± 0.2	18.8 ± 2.3	4
50	100	100 ± 2	84 ± 2	149 ± 3	167 ± 4	5.0 ± 0.1	8.4 ± 0.2	4
50	150	101 ± 3	69 ± 7	152 ± 4	173 ± 16	5.0 ± 0.1	10.4 ± 1.0	4
50	200	100 ± 6	70 ± 1	149 ± 10	210 ± 3	5.0 ± 0.3	14.0 ± 0.2	4
50	250	99 ± 2	70 ± 7	148 ± 4	244 ± 26	5.0 ± 0.1	17.4 ± 1.8	4
100	125	63 ± 3	64 ± 1	127 ± 6	144 ± 1	6.3 ± 0.3	8.0 ± 0.1	4
100	150	77 ± 6	73 ± 4	154 ± 12	184 ± 2	7.7 ± 0.6	11.0 ± 0.1	4
100	200	84 ± 2	70 ± 2	167 ± 6	212 ± 2	8.3 ± 0.2	14.1 ± 0.2	4
100	250	78 ± 2	73 ± 8	157 ± 4	254 ± 29	7.8 ± 0.2	18.1 ± 2.1	4
125	150	63 ± 2	69 ± 5	143 ± 4	173 ± 11	7.9 ± 0.2	10.4 ± 0.7	4
125	250	59 ± 2	68 ± 8	134 ± 5	238 ± 29	7.4 ± 0.7	17.0 ± 2.0	4
150	150	62 ± 4	62 ± 4	154 ± 10	154 ± 10	9.3 ± 0.7	9.3 ± 0.7	4

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908 **Table 2. Location of the breakpoint and the median energy flux ( $E_m$ ) estimated**  
909 **before and after the breakpoint.**

910 All results are for a moisture content *POST* = 150% *MC*. Breakpoint is the location ( $C_i$ ,  
911 relative to the moisture ~~transition~~gradient) of a breakpoint in  $E_m$  estimated using  
912 piecewise linear regression (equation 1). CI is the breakpoint location's 95%  
913 confidence interval. ' $E_m$  before' is  $E_m$  before the breakpoint (mean ± standard error),  
914 ' $E_m$  after' is the  $E_m$  after the breakpoint.

<i>PRE</i>	Breakpoint	CI	$E_m$ before	$E_m$ after
(% <i>MC</i> )	(cm)	(cm)	(kW m <sup>-2</sup> )	(kW m <sup>-2</sup> )
25	1.5	1.0, 2.1	3.92 ± 0.05	2.89 ± 0.12
50	0.8	0.5, 1.1	3.03 ± 0.03	2.90 ± 0.07
100	1.5	1.0, 2.1	2.86 ± 0.08	2.13 ± 0.17
125	0.8	0.5, 1.1	2.78 ± 0.11	1.59 ± 0.26
150	-1.5	-2.0, -0.9	3.13 ± 0.09	2.33 ± 0.11

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917 **Table 3. Coefficient estimates from the model of spread distance ( $D_T$ ) after a peat**  
918 **moisture ~~transition~~gradient.**

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919 Dependent variable  $D_T$  was square-root transformed. Coefficients  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are  
920 parameter estimates for  $PRE$  and  $POST$  moisture ~~transition-gradient~~ and their  
921 interaction, respectively.  $R^2=0.92$ , residual standard error =0.21.

	<i>Coefficient</i> ( $\text{cm}^{0.5}$ )	<i>Standard error</i> ( $\text{cm}^{0.5}$ )	<i>p-value</i>
$\beta_0$ , Intercept	8.0	0.6	<0.0001
$\beta_1$ , $PRE_i$	-0.054	0.006	<0.0001
$\beta_2$ , $POST_i$	-0.026	0.003	<0.0001
$\beta_3$ , $PRE_i \times POST_i$	0.00018	0.00003	<0.0001

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## Figure Captions

**Fig. 1.** Image of an on-going experimental burn. A glowing coil ignites the peat at the ignition region. The fire spreads through a region of *PRE* peat (dry peat) and then through a region of *POST* peat (wet peat). Dashed line indicates the location of the sharp ~~transition~~gradient of moisture content between *PRE* and *POST* peat. Thermocouples monitor the temperatures inside the peat sample.

**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.

**Fig. 3.** Examples of temperature versus time profiles from five experiments (a-e). All experimental burns had *POST* peat moisture content of 150% and *PRE* peat moisture content of (a) 25%, (b) 50%, (c) 100%, (d) 125% and (e) 150%. Dot dash-black, solid red and double dash-blue lines correspond to thermocouples -4cm, +1cm and +6cm from the moisture ~~transition~~gradient, respectively. Profiles end when the fire self-extinguished.

**Fig 4.** Median radiation flux during smouldering combustion ( $E_m$ ) as a function of distance from the moisture ~~transition~~gradient. Data are for moisture contents of *POST*=150% *MC* and *PRE*s 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 equation 1.

**Fig. 5.** Observations of spread distance ( $D_T$ ) into *POST* peat. Subplots are for *PRE* peats of (a) 25%, (b) 50%, (c) 100% and (d) 125% *MC*.

**Fig. 6.** Spread distance ( $D_T$ ) as function of *POST* moisture ~~transition~~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](#).

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1  
2 **1 Effects of spatial heterogeneity in moisture content on the horizontal spread of**  
3 **2 peat fires**  
4

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6  
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24  
25 13

26  
27 14 **Abstract (limit: 400 words)**

28  
29 15 The gravimetric moisture content of peat is the main factor limiting the ignition and  
30  
31 16 spread propagation of smouldering fires. Our aim is to use controlled laboratory  
32  
33 17 experiments to better understand how the spread of smouldering fires is influenced in  
34  
35 18 natural landscape conditions where the moisture content of the top peat layer is not  
36  
37 19 homogeneous. In this paper, we study for the first time the spread of peat fires across  
38  
39 20 a spatial matrix of two moisture contents (dry/wet) in the laboratory. The experiments  
40  
41 21 were undertaken using an open-top insulated box (22×18×6 cm) filled with milled  
42  
43 22 peat. The peat was ignited at one side of the box initiating smouldering and horizontal  
44  
45 23 spread. Measurements of the peak temperature inside the peat, fire duration and  
46  
47 24 longwave thermal radiation from the burning samples revealed important local  
48  
49 25 changes of the smouldering behaviour in response to sharp gradients in moisture  
50  
51 26 content. Both, peak temperatures and radiation in wetter peat (after the moisture  
52  
53 27 gradient) were sensitive to the drier moisture condition (preceding the moisture  
54  
55 28 gradient).

56  
57 29 Drier peat conditions before the moisture gradient led to higher temperatures and  
58  
59 30 higher radiation flux from the fire during the first 6 cm of horizontal spread into a wet  
60  
61 31 peat patch. The total spread distance into a wet peat patch was affected by the  
62  
63 32 moisture content gradient. We predicted that in most peat moisture gradients of  
64  
65

1  
2 33 relevance to natural ecosystems the fire self-extinguishes within the first 10 cm of  
3  
4 34 horizontal spread into a wet peat patch. Spread distances of more than 10 cm are  
5  
6 35 limited to wet peat patches below 160% moisture content (mass of water per mass of  
7  
8 36 dry peat). We found that spatial gradients of moisture content have important local  
9  
10 37 effects on the horizontal spread and should be considered in field and modelling  
11  
12 38 studies.

13 39 **Keywords:** peatland, smouldering, propagation, breakpoint analysis, step-change,  
14  
15 40 infrared image analysis.

## 16 41

### 17 42 **1. Introduction**

18  
19 43 Peatland soils are significant reservoirs of carbon, they cover less than 3% of the  
20  
21 44 Earth's land surface but they store 25% of the world's terrestrial carbon,  
22  
23 45 approximately ~560 Gt of carbon (Turetsky et al., 2015; Yu, 2012). The drainage of  
24  
25 46 peatlands for human activities combined with a lack of external water inputs (e.g.  
26  
27 47 rain) perturbs peatland hydrological feedbacks (Waddington et al., 2015), leading to a  
28  
29 48 suppression of the water table and drying of the surface peat. Enhanced drainage  
30  
31 49 makes peatlands highly vulnerable to drying and subsequently fires (Turetsky et al.,  
32  
33 50 2011). During flaming wildfires of the surface vegetation, part of the heat can be  
34  
35 51 transferred to the organic soil (e.g. duff, peat) and may ignite a smouldering fire  
36  
37 52 (Rein, 2013). These flameless fires are more difficult to detect and suppress than  
38  
39 53 flaming vegetation fires (Rein, 2013). Peat fires can spread both on the surface and in-  
40  
41 54 depth through the sub-surface of a peatland and can initiate new flaming fires well  
42  
43 55 away from the initial region of smouldering peat (Putzeys et al., 2007; Rein, 2016).  
44  
45 56 Very large amounts of peat can be consumed during smouldering fires, releasing  
46  
47 57 carbon gases (e.g. CO<sub>2</sub>, CO and CH<sub>4</sub>) and other greenhouse gases to the atmosphere  
48  
49 58 (Gorham, 1991; Turetsky et al., 2015). The 1997 Indonesian peat fires are estimated  
50  
51 59 to have consumed approximately 3% of the soil carbon stock from Indonesia, ~0.95  
52  
53 60 Gt of carbon, which is equivalent to 15% of the global fossil fuels emissions for that  
54  
55 61 year (Page et al., 2002). A 2007 peat fire event in the arctic tundra is estimated to  
56  
57 62 have reduced 30% of the soil depth in the whole area studied and consumed 19% of  
58  
59 63 the soil carbon stock of the region (Mack et al., 2011). The climate change projections  
60  
61 64 forecast an increase in drought frequency and severity in many peatlands worldwide

1  
2 65 (Roulet et al., 1992), suggesting that peatlands will become more vulnerable to peat  
3  
4 66 fires in the future (IPCC, 2013). This implies that larger amounts of carbon may be  
5  
6 67 released to the atmosphere further contributing to the climate change and turning  
7  
8 68 peatlands into carbon-sources rather than potential carbon sinks (Billett et al., 2010;  
9  
10 69 Flannigan et al., 2009; Turetsky et al., 2002, 2015).

11  
12 70 In peatlands, the physiochemical properties of the surface-unsaturated peat layers are  
13  
14 71 influenced by the position of the water table and its associated hydrological responses  
15  
16 72 (Waddington et al., 2015). Changes in water table position alter surface transpiration,  
17  
18 73 evaporation and peat decomposition, which contribute to the moisture variability of  
19  
20 74 the surface layers of peat (Waddington et al., 2015). The vegetation also plays a very  
21  
22 75 important role in determining the moisture content distribution of the topmost peat  
23  
24 76 layer. Hummock-forming *Sphagnum* mosses retain high levels of moisture in the  
25  
26 77 whole peat profile (Hayward and Clymo, 1982; McCarter and Price, 2014). Other  
27  
28 78 mosses (e.g. hollow *Sphagnum* species and feather mosses) do not have the same  
29  
30 79 capacity to uptake water from the water table, depending more on the regularity of  
31  
32 80 external water inputs (Thompson and Waddington, 2013). As a consequence, during  
33  
34 81 drought periods *Sphagnum* hummocks remain wet while the surrounding peat  
35  
36 82 becomes drier. The presence of vascular plants causes shading and interception of  
37  
38 83 precipitation also affecting the surface transpiration and evaporation (Waddington et  
39  
40 84 al., 2015). The rooting systems from trees are also a source of moisture spatial  
41  
42 85 heterogeneity in the topmost peat layers (Rein et al., 2008). The combination of all  
43  
44 86 these ecohydrological factors, specially during drought events, causes large moisture  
45  
46 87 heterogeneity on the topmost layers of peatlands (Nungesser, 2003; Petrone et al.,  
47  
48 88 2004).

49  
50 89 The main factors governing the ignition and spread of smouldering are peat moisture  
51  
52 90 content, organic content and bulk density (Frandsen, 1987, 1997; Reardon et al.,  
53  
54 91 2007; Rein et al., 2008; Watts, 2012). Once peat is ignited, the fire is sustained by the  
55  
56 92 energy released during the oxidation of the char (Hadden et al., 2013). This energy is  
57  
58 93 dissipated, some being lost to the surroundings and some being transferred to drive  
59  
60 94 the drying and pyrolysis of peat particles ahead of the oxidation front (Rein, 2016). If  
61  
62 95 the energy produced is enough to overcome heat losses to the environment and  
63  
64 96 preheat the surrounding peat, the smouldering front becomes self-propagating (Huang

1  
2 97 and Rein, 2014; Ohlemiller, 1985). The spread can be horizontal and vertical and the  
3  
4 98 extent of smouldering in each direction depends largely on the conditions of the peat  
5  
6 99 and the environment (Benscoter et al., 2011; Reardon et al., 2007; Rein, 2013). A  
7  
8 100 vertically spreading smouldering front can penetrate a few meters into the soil (Rein,  
9  
10 101 2013). However, more often tends to be extinguished after a few centimetres as  
11  
12 102 downward spread is limited by either the water table or the mineral soil layer  
13  
14 103 (Benscoter et al., 2011; Huang and Rein, 2015; Zacccone et al., 2014). A smouldering  
15  
16 104 front that spreads horizontally can contribute to consume a large area of dry peat soils  
17  
18 105 above the water table. This kind of spread coupled with the spread of vegetation  
19  
20 106 wildfires, often results in large surface areas being affected (Benscoter and Wieder,  
21  
22 107 2003; Shetler et al., 2008).

23  
24 108 Previous studies have highlighted the importance of peat moisture content on the  
25  
26 109 ignition and spread of peat fires (Frandsen, 1987; Huang and Rein, 2014, 2015;  
27  
28 110 Lawson et al., 1997; Reardon et al., 2007). A 50% probability of ignition and early  
29  
30 111 propagation has been estimated at 110-125%  $MC^1$  (Frandsen, 1987; Huang and Rein,  
31  
32 112 2015; Rein et al., 2008;). Recent experimental smouldering fires reveal horizontal  
33  
34 113 spread rates between 1 to 9 cm h<sup>-1</sup> in peats below 150%  $MC$  (Prat-Guitart et al., in  
35  
36 114 press). In peats with higher moisture content, between 150-200%  $MC$ , the  
37  
38 115 smouldering is weak and self-extinguishes within the first 10 cm of the sample  
39  
40 116 (Frandsen, 1997; Reardon et al., 2007).

41  
42 117 Moisture content distributions of the topmost layer in peatlands are highly relevant to  
43  
44 118 determining the spread of smouldering fires. Post peat-fire landscapes are often  
45  
46 119 characterised by irregular peat consumption, were patches of peat associated with  
47  
48 120 *Sphagnum* hummocks remain unburnt (Hudspith et al., 2014; Shetler et al., 2008;  
49  
50 121 Terrier et al., 2014). Enhanced peat consumption has also been observed under trees,  
51  
52 122 suggesting that fires spread through the peat adjacent to the roots (Davies et al., 2013;  
53  
54 123 Miyanishi and Johnson, 2002). However, there is little understanding of how varying  
55  
56 124 the peat moisture content (e.g. transition from feather moss to *Sphagnum*) across a  
57  
58 125 spatial landscape affects the horizontal propagation of peat fires. This study  
59  
60 126 experimentally examines the behaviour of a smouldering front as it propagates

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<sup>1</sup> Gravimetric moisture content is the mass of water per mass of dry peat expressed as a percentage.

1  
2 127 through a gradient of peat moisture content in order to (1) identify local changes in  
3 128 the fire behaviour associated with a transition of moisture content and (2) test whether  
4 129 the contiguous drier moisture content ahead of a transition affects the fire behaviour  
5 130 into a wet peat.  
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9 131

## 10 132 **2. Materials and Methods**

### 11 133 *2.1. Experimental system*

12 134 In order to study the effect of a moisture content gradient on the smouldering spread  
13 135 behaviour we designed a simplified milled peat system that allows the natural sources  
14 136 of peat heterogeneity, such as moisture content, bulk density, mineral content and  
15 137 particle size to be controlled (Prat-Guitart et al., 2015). The smouldering experiments  
16 138 were conducted in an 18×22×6 cm open-top box (insulated fibreboard container) of  
17 139 similar thermal conductivity as peat (0.07-0.11 W m<sup>-1</sup> K<sup>-1</sup>) to minimise boundary  
18 140 effects (Benscoter et al., 2011; Frandsen, 1987; Garlough and Keyes, 2011; Rein et  
19 141 al., 2008). The peat samples were 5 cm in depth. The samples were kept shallow to  
20 142 facilitate the formation of a plane smouldering front spreading horizontally from one  
21 143 side of the box to the other. As a result, we focus solely on the horizontally spread and  
22 144 not on the vertical spread. The experiments were limited to 12 h to avoid day-and-  
23 145 night temperature fluctuations.  
24  
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33 146 The analysis of the spread inside the box was divided in three regions: (i) ignition  
34 147 region, (ii) region ahead of the moisture gradient (*PRE*) and (iii) region following the  
35 148 gradient (*POST*) (Fig. 1). The ignition region was at one side of the box where an 18-  
36 149 cm long electric igniter coil was buried in a 2-cm strip of peat at ~0% *MC*. The *PRE*  
37 150 region was adjacent to the ignition and consisted of a 10-cm strip of conditioned peat.  
38 151 The *POST* region was a peat sample of the same size as *PRE* but with higher moisture  
39 152 content. A clear straight boundary separated *PRE* and *POST* regions creating a sharp  
40 153 gradient in moisture content at approximately 10 cm from the ignition location.  
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54 154

55 155

[Figure 1]

56 156

1  
2 157 The milled peat samples were oven-dried at 80°C for 48 h and then rewetted in small  
3  
4 158 samples of less than 300 g of peat to achieve the desired moisture content. Since  
5  
6 159 oven-dried peats can become hydrophobic, rewetted peat samples were sealed in  
7  
8 160 plastic bags for at least 24 h prior to the experiment to reach moisture equilibrium.  
9  
10 161 One day is more than an order of magnitude longer than the typical infiltration time of  
11  
12 162 severely hydrophobic soil (Kettridge et al., 2014). This protocol therefore minimises  
13  
14 163 heterogeneity within the moisture content of the peat samples. We used 14 *PRE-*  
15  
16 164 *POST* moisture content combinations in our experiment (Table 1). The *PRE* samples  
17  
18 165 never exceeded 150% *MC* in order to be below the threshold of 125-150% *MC* for  
19  
20 166 self-sustained spread for more than 10 cm (Frandsen, 1997; Prat-Guitart et al., in  
21  
22 167 press; Reardon et al., 2007). The moisture content of *POST* peats (between 125% and  
23  
24 168 250% *MC*) represents wet peats around the threshold of self-sustained spread. All  
25  
26 169 peats had a mineral content<sup>2</sup> of  $2.6 \pm 0.2\%$ . Within the box volume, peat bulk density  
27  
28 170 (mass of dry peat per unit volume) varied between 55 and 140 kg m<sup>-3</sup>. The variation  
29  
30 171 in density was in part due to the expansion of peat when water was added (Table 1).  
31  
32 172 Bulk densities were representative of peat soils from temperate and boreal peatlands  
33  
34 173 (Davies et al., 2013; Lukenbach et al., 2015; Thompson and Waddington, 2013;  
35  
36 174 Wellock et al., 2011).

37  
38 [Table 1]  
39

40 177  
41  
42 178 The ignition protocol consisted in powering the ignition region with 100 W for 30  
43  
44 179 minutes using the electric igniter coil (Rein et al., 2008). This energy input is strong  
45  
46 180 and similar to a burning tree stump and is enough to ignite dry peat (Rein et al., 2008).  
47  
48 181 After 30 minutes the igniter coil was turned off and a linear smouldering combustion  
49  
50 182 front spread through the samples of peat. A visual and infrared cameras imaged the  
51  
52 183 surface of the smouldering every minute (Prat-Guitart et al., 2015). The infrared  
53  
54 184 camera (SC640, FLIR Systems, US) captured the radiated energy flux from the peat at  
55  
56 185 a resolution of 0.05×0.05 cm (i.e. one pixel equated to 0.25 mm<sup>2</sup>). The images were  
57  
58 186 corrected for the angle of the infrared and webcam cameras and processed to extract

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60 <sup>2</sup> Mass of mineral particles per mass of dry organic peat.

1  
2 187 the values of radiated energy flux at a pixel scale. Details of the methods are given in  
3  
4 188 Prat-Guitart et al. (2015). An array of seven K-type thermocouples (1.5 mm diameter)  
5  
6 189 monitored the smouldering temperatures inside the peat samples at 1 cm from the  
7  
8 190 bottom of the box. One thermocouple was situated in the ignition region and the other  
9  
10 191 six were distributed to capture the temperature 4 cm before the moisture gradient and  
11  
12 192 then at 1 and 6 cm after the moisture increase (Fig. 1).

13 193

## 14 15 194 2.2. Behaviour of the smouldering front

16  
17  
18 195 Smouldering temperatures have often been analysed to study the peat combustion and  
19  
20 196 fire spread (Benscoter et al., 2011; Rein et al., 2008; Zaccone et al., 2014). We  
21  
22 197 analysed the thermocouple data to identify changes in the combustion temperatures  
23  
24 198 due to the sharp transition of peat moisture. For each thermocouple, we estimated the  
25  
26 199 combustion duration, as the time taken since the start of the combustion (increase  
27  
28 200 above 100°C) and until the peat burnout (decreased below 200°C for the last time).  
29  
30 201 We also estimated the peak temperature as the 90<sup>th</sup> percentile of the thermocouple  
31  
32 202 temperature profile. To demonstrate the effect of *PRE* moisture content on the spread  
33  
34 203 into *POST* peats, we statistically compared the temperatures of 22 experiments with  
35  
36 204 the same *POST* moisture content (150% *MC*) but different *PRE* moisture contents  
37  
38 205 (25% - 150% *MC*). The effects of moisture content treatment and distance from the  
39  
40 206 moisture gradient on peak temperature and combustion duration were estimated using  
41  
42 207 one-way ANOVAs. The differences between treatment levels were estimated using  
43  
44 208 Tukey's Honesty Significant Difference (HSD) post-hoc test with a significance level  
45  
46 209 of  $p=0.05$ . Temperature profiles from all the *PRE-POST* combinations are provided in  
47  
48 210 the [supplementary materials \(Fig. S1\)](#).

49  
50 211 We also analysed the radiation flux from the smouldering of peat in order to identify  
51  
52 212 changes in the smouldering behaviour due to the transition of moisture content. Even  
53  
54 213 though the information from infrared imagery was limited to spread on the peat's  
55  
56 214 surface, it allowed the smouldering spread to be monitored at a finer resolution than  
57  
58 215 any array of thermocouples. We built a time-profile of each pixel's radiation flux ( $\text{kW}$   
59  
60 216  $\text{m}^{-2}$ ) and the radiation flux rate ( $\text{kW m}^{-2} \text{min}^{-1}$ ) (Fig. 2). The start of the smouldering  
61  
62 217 fire is defined by a peak in the radiation flux rate (Prat-Guitart et al., 2015). The last



1  
2 218 occurrence of a similar radiation flux value is used to define the end of the  
3  
4 219 smouldering fire. From our defined start and end times of combustion we calculated  
5  
6 220 the median radiated energy flux during combustion ( $E$ ). Repeating this procedure for  
7  
8 221 each pixel of the infrared box image gave a matrix of median radiation fluxes  $E$   
9  
10 222 during combustion.

11 223

12  
13  
14 224 [\[Figure 2\]](#)

15 225

16  
17  
18 226 We analysed the spatial autocorrelation of  $E$  by computing the data's semivariance  
19  
20 227 (half average squared difference between pairs of pixels) (Bivand et al., 2008). The  
21  
22 228 semivariogram was produced using a subset of  $E$  from each experimental burn.  
23  
24 229 Subsets of  $E$  were selected from a central area of *PRE* peat away from any boundary.  
25  
26 230 We then fitted a theoretical spherical model to the semivariogram. The spatial range  
27  
28 231 of the semivariogram indicated the distance where the data exhibited no spatial  
29  
30 232 autocorrelation. To avoid statistical issues of spatial autocorrelation we considered 48  
31  
32 233 sub-regions (2×1 cm) from each box and ensured that sub-regions were separated by  
33  
34 234 at least 1 cm. This separation is greater than the scale of autocorrelation in the data for  
35  
36 235  $E$ . We estimated the median  $E$  in each sub-region ( $E_m$ ) and the median absolute  
37  
38 236 deviation.

39 237 Piecewise linear regression was used to identify a step-change in  $E_m$  as a function of  
40  
41 238 distance from the moisture gradient (Crawley, 2013). The analysis was performed on  
42  
43 239 data from each moisture combination ( $i$ ) separately as

44  
45 240

46  
47 241 
$$E_{mi} = \beta_{d1}(x_i < c_i) + \beta_{d2}(x_i > c_i) \quad \text{Eq. (1)}$$
  
48  
49

50 242

51  
52 243 where  $x_i$  is the distance (cm) from the moisture gradient,  $c_i$  is the position of the  
53  
54 244 breakpoint,  $\beta_{d1}$  and  $\beta_{d2}$  are the estimated intercepts before and after the breakpoint. To  
55  
56 245 estimate the position of the breakpoint, equation 1 was fitted for values of  $c_i$  ranging  
57  
58 246 from -4cm to +8cm in steps of 0.1 cm, and the values of  $c_i$  that produced the  
59  
60 247 minimum residual standard error was selected.

1  
2 248

3  
4 249 *2.3. Spread distance after a moisture gradient*

5  
6 250 The spread distance was estimated from the first visual image taken after the fire had  
7  
8 251 extinguished (assessed with the infrared images). We used the visual images to  
9  
10 252 distinguish by eye between the burnt and unburnt peat based on the colour; white and  
11  
12 253 grey for the char and ash and brown for the unburnt peat (Fig. 1). We estimated the  
13  
14 254 final position of the smouldering front into *POST* peat using the boundary between  
15  
16 255 burnt and unburnt peat regions (often of irregular shape). The median spread distance  
17  
18 256 after the moisture gradient ( $D_T$ ) was estimated by manually removing the areas where  
19  
20 257 fresh peat had collapsed. We associated  $D_T$  with the moisture content of *PRE* and  
21  
22 258 *POST* peats using the following statistical model

23  
24 259

25  
26 260 
$$\sqrt{(D_T)_i} = \beta_0 + \beta_1 PRE_i + \beta_2 POST_i + \beta_3 PRE_i \cdot POST_i + \varepsilon_i \quad \text{Eq. (2)}$$

27  
28 261

29  
30  
31 262 where  $\beta_0$ ,  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are regression coefficients and  $\varepsilon_i$  are normally distributed  
32  
33 263 residuals of the  $i^{\text{th}}$  experimental replicate of each *PRE* and *POST* combination. The  
34  
35 264 dependent variable ( $D_T$ ) was square root transformed to normalise the distribution of  
36  
37 265 the residuals. Experiments where the smouldering front completely consumed the  
38  
39 266 *POST* sample (i.e. extinguished due to the box wall) were discarded since it was not  
40  
41 267 possible to quantify  $D_T$ .

42  
43 268 The image processing was done in Matlab with the *Image Processing Toolbox*  
44  
45 269 (*Mathworks, version R2012b 8.0.0.783*). The data analysis was done with *R project*  
46  
47 270 statistical software (Development Core Team, 2013). The spatial autocorrelation  
48  
49 271 analysis was done with packages *automap* (Hiemstra et al., 2009) and *gstat* (Pebesma,  
50  
51 272 2004).

52  
53 273

54 274 **4. Results**

55  
56  
57 275 *4.1. Smouldering behaviour*

1  
2 276 In experiments combining *PRE MC* of 25% and *POST* of 150% a breakpoint in  $E_m$   
3  
4 277 was identified at  $c_i = 1.5$  cm after the moisture gradient (Table 2). The  $E_m$  before the  
5  
6 278 breakpoint was  $3.92 \pm 0.05$  kW m<sup>-2</sup> (mean  $\pm$  standard error), whereas after the  
7  
8 279 breakpoint it decreased to  $2.89 \pm 0.12$  kW m<sup>-2</sup>. In the experiments with *PRE MC* of  
9  
10 280 25% and *POST* of 150%, we found that the distance from the moisture content  
11  
12 281 gradient was associated with differences in the peak temperature (one-way ANOVA  
13  
14 282  $F_{2,16}=11.1$ ,  $p<0.001$ ). Before the  $E_m$  breakpoint (at -4 cm and +1 cm from the  
15  
16 283 moisture gradient) no difference in the peak temperatures was found ( $384 \pm 25^\circ\text{C}$  and  
17  
18 284  $349 \pm 24^\circ\text{C}$ , respectively; Fig. 3a). However, the peak temperature at +6 cm from the  
19  
20 285 moisture gradient ( $155 \pm 93^\circ\text{C}$ ) was less than peak temperatures before the breakpoint  
21  
22 286 (Tukey's HSD  $p<0.05$ ). The combustion durations ( $113 \pm 11$  min,  $107 \pm 10$  min and  
23  
24 287  $56$  min at -4 cm, +1 and +6 cm, respectively) were not associated with the distance  
25  
26 288 from the moisture gradient (one-way ANOVA  $F_{2,16}=1.6$ ,  $p=0.2$ ).

27  
28 289 At +1 cm from the moisture gradient both combustion duration and peak temperatures  
29  
30 290 were affected by the *PRE* moisture contents (red lines in Fig. 3). We found that *PRE*  
31  
32 291 *MC* was associated with peak temperatures at +1 cm (one-way ANOVA  $F_{4,25}=6.6$   
33  
34 292  $p<0.001$ ). Peak temperatures did not differ between *PRE MC* of 25% and 50%, ( $349 \pm$   
35  
36 293  $24^\circ\text{C}$ ,  $329 \pm 21^\circ\text{C}$ , respectively), but a higher *PRE* moisture content significantly  
37  
38 294 decreased the peak temperatures (e.g.  $137 \pm 27^\circ\text{C}$  in *PRE=150% MC*) (Tukey's HSD  
39  
40 295  $p<0.05$ ). The combustion duration differed across *PRE MC* treatments (one-way  
41  
42 296 ANOVA  $F_{3,19}=4.3$   $p=0.02$ ). The combustion duration was similar for *PRE MC* of  
43  
44 297 25% and 50%, ( $107 \pm 10$  min and  $99 \pm 18$  min, respectively) but at higher *PRE*  
45  
46 298 moisture contents (100%, 125% and 150% *MC*) the combustion duration decreased to  
47  
48 299  $43 \pm 5$  min,  $81 \pm 9$  min and  $78 \pm 9$  min respectively (Tukey's HSD  $p<0.05$ ). At +6 cm  
49  
50 300 from the moisture gradient (blue lines in Fig. 3) the combustion duration and peak  
51  
52 301 temperatures were not different from to the ones reported for *PRE MC* of 150% (one-  
53  
54 302 way ANOVAs  $F_{3,7}=1.1$   $p=0.4$ ,  $F_{2,3}=0.65$   $p=0.5$ , respectively).

55 303

56 304

57 305

[Figure 3]

1  
2 306 The finer resolution of the radiated energy flux data ( $E_m$ ) added information on the  
3  
4 307 location where the changes in fire behaviour took place (Table 2, Fig 4, Fig. S2). The  
5  
6 308 majority of breakpoints in  $E_m$  were located after the increase of moisture content,  
7  
8 309 indicating a continuation of *PRE*-moisture gradient behaviour for up to 6 cm into the  
9  
10 310 *POST* peat. Two moisture content combinations (*PRE*=150%, *POST*=150% and  
11  
12 311 *PRE*=125%, *POST*=250%) had breakpoints in  $E_m$  before the moisture gradient (Table  
13  
14 312 2, Fig. S2).

15 313  
16  
17 314 [Figure 4]

18  
19 315  
20  
21  
22 316 [Table 2]

#### 23 317 24 25 318 4.2. Spread distance into wet peat

26  
27 319 The spread distance ( $D_T$ ) showed no difference between *PRE* of 25% and 50% *MC*  
28  
29 320 (ANOVA  $F_{1,22}=0.067$   $p=0.8$ ) (Fig. 5). For all other peat combinations, the  
30  
31 321 smouldering front spread no further than 5 cm into the wetter peat ( $D_T < 5$  cm).  
32  
33 322 Experiments that combined *PRE MC* of 125% or *POST MC* of 250% *MC* always had  
34  
35 323 self-extinction less than 1 cm after the moisture transition.

36  
37 324  
38  
39 325 [Figure 5]

40  
41 326  
42  
43 327 The spread distance into wet peat was well described by *PRE* and *POST* moisture  
44  
45 328 content conditions (Table 3, Fig. 6). Increasing either *PRE* or *POST* moisture contents  
46  
47 329 decreased the spread distance. The coefficient  $\beta_1$  was higher ( $-0.06$ ,  $-0.04$ , 95%  
48  
49 330 confidence interval) than  $\beta_2$  ( $-0.03$ ,  $-0.02$ ), indicating a bigger effect of *PRE* moisture  
50  
51 331 content on  $D_T$  than *POST* moisture content. The interaction term *PRE*×*POST* showed  
52  
53 332 that the effect of *PRE* on reducing the spread distance was larger when *POST* peats  
54  
55 333 had lower moisture content.

1  
2 335 [Table 3]

3  
4 336

5  
6 337 [Figure 6]

7  
8 338

9  
10  
11 339 *PRE MC* above 125% lead to smouldering self-extinction immediately after the  
12 340 transition (<1 cm) for any *POST MC* (Fig. 7). Similarly, high *POST MC* (greater than  
13 341 260% *MC*) spreads for less than 1 cm for any *PRE MC*. Equation 2 predicts that  
14 342 spread for more than 10 cm can be achieved when most *PRE MC* is below 50%  
15 343 combined with *POST MC* below 160%.

16  
17 344

18  
19 345 [Figure 7]

20  
21 346

22  
23 347

## 24 348 **5. Discussion**

### 25 349 *5.1. Effects of peat moisture content heterogeneity on the propagation dynamics*

26 350 We have analysed the behaviour of smouldering fires through a gradient in peat  
27 351 moisture. We find that the peat moisture before the gradient influences the fire spread  
28 352 into the wet peat beyond. The smouldering ignition and spread in peats with  
29 353 homogeneous moisture conditions are primarily limited by the moisture content of the  
30 354 peat (Frandsen, 1987, 1997; Garlough and Keyes, 2011; Lawson et al., 1997; Reardon  
31 355 et al., 2007). However, we show that fire spread in milled peats with heterogeneous  
32 356 moisture conditions is strongly influenced by the moisture conditions of adjacent peat  
33 357 as well as the immediate moisture content of the peat.

34 358 Whilst, this study reports limited spread distances of 10 cm into a more moist peat,  
35 359 the scale of the experiment was enough to examine local changes in fire behaviour  
36 360 during the spread through a moisture gradient. Our analysis of radiation flux suggests  
37 361 two main effects of the *PRE* peat conditions on the fire behaviour after a moisture  
38 362 gradient. First, the strongest effect of *PRE* peat conditions happens within the first  
39 363 centimetres (<7 cm) after the moisture gradient (Fig. 4, Fig. S2). In this region the  
40 364 combustion duration and the peak smouldering temperatures have similar behaviour

1  
2 365 to the adjacent drier peat. The smouldering front spreading close to the moisture  
3  
4 366 gradient evaporates part of the water from the wet peat (Ohlemiller, 1985).  
5  
6 367 Consequently, a few centimetres ahead of the moisture gradient are already drier  
7  
8 368 when the smouldering front reaches the wetter *POST* peat. Second, the location of the  
9  
10 369 breakpoint could be interpreted as a new moisture gradient created by the dynamics of  
11  
12 370 the smouldering fire. After the breakpoint the smouldering fire continues spreading  
13  
14 371 but is less affected by the *PRE MC* conditions (Fig. 4). Experiments with *PRE*=50%  
15  
16 372 and *POST*=150% did not have a substantial change in  $E_m$  after the breakpoint but an  
17  
18 373 increase of the standard error of the  $E_m$  after (Table 2). We tested the sensitivity of the  
19  
20 374 results obtained to changes in the methods used to analyse the infrared images.  
21  
22 375 Variation of the thresholds used to determine  $E$  produced different  $E$  and  $E_m$  outputs,  
23  
24 376 although the results did not change qualitatively.

25  
26 377 The analysis of thermocouple temperature data also supports the effect of *PRE* peat  
27  
28 378 conditions on the smouldering spread into *POST* peat. While the temperatures  
29  
30 379 measured at 1 cm after the moisture gradient correspond to the region of *POST* peat  
31  
32 380 more affected by the *PRE MC* conditions, the temperatures recorded at 6 cm after the  
33  
34 381 moisture gradient were less affected by the *PRE* peat conditions (Fig. 4). We found  
35  
36 382 that *POST MC* of 150% reach temperatures between 100 and 500°C at 1 cm after the  
37  
38 383 moisture gradient. Some of these temperatures are lower than typical oxidation  
39  
40 384 temperatures 400-600°C reported for natural peats  $\leq 100\%$  *MC* (Benscoter et al., 2011;  
41  
42 385 Rein et al., 2008). Only temperatures above 300°C indicate on-going peat oxidation  
43  
44 386 (Chen et al., 2011). Between 100°C and 300°C evaporation and pyrolysis processes  
45  
46 387 dominate the smouldering and little oxidation is expected (Huang and Rein, 2014).  
47  
48 388 Compared to the infrared images, the resolution of thermocouple data are limited and  
49  
50 389 only providing data from fire behaviour around the thermocouple. In some burns, the  
51  
52 390 thermocouples registered oscillations in combustion temperatures between 50 and  
53  
54 391 300°C (i.e. Fig. 3a and Fig. 3b), which could be caused by the local dynamics of the  
55  
56 392 particles surrounding the thermocouple. The milled peat particle size was below 1 cm  
57  
58 393 in diameter and had variable density due to differences in the degree of  
59  
60 394 decomposition. Differences in the infiltration rates and hydrophobicity of the peat  
61  
62 395 particles during the rewetting process (Kettridge et al., 2014) could cause short-term  
63  
64 396 heterogeneity (~10 min) in the moisture content of a peat sample. This short-term

1  
2 397 heterogeneity was minimised by our protocol, which allowed samples to equilibrate  
3  
4 398 for 24 h prior to an experiment. Any remaining variation in peat moisture will impact  
5  
6 399 the fine-scale spread of the fire between particles (i.e. <1 cm), but have a minor effect  
7  
8 400 on the average spread of the fire throughout a peat sample of 20 × 20 cm.

9  
10 401 The moisture gradient between *PRE* and *POST* peat could cause movement of the  
11  
12 402 water through the transition boundary. Higher moisture content in *POST* peat could  
13  
14 403 move to *PRE* peat, due to differences in unsaturated hydraulic conductivity (capacity  
15  
16 404 of water movement in unsaturated soil per unit volume) (Boelter, 1965; Hillel, 1980).  
17  
18 405 Milled peats below 250% *MC* have a small unsaturated hydraulic conductivity and  
19  
20 406 therefore very little water movement is expected for the duration of the experimental  
21  
22 407 burns (Holden and Ward, 1997). The smouldering fronts reached *POST* peat less than  
23  
24 408 4 h after ignition implying minimal water movement during that time. Only peat  
25  
26 409 samples with *PRE* of 125% and *POST* 250% and homogeneous 150% *MC* had a  
27  
28 410 breakpoint in  $E_m$  before the moisture gradient (Fig. S2). This breakpoint before the  
29  
30 411 initial location of the gradient could be caused by a weak smouldering spread due to  
31  
32 412 the high moisture content in those *PRE* peat. Even after several hours, little moisture  
33  
34 413 evaporation is expected for peat moisture contents below 250% *MC* (Kettridge et al.,  
35  
36 414 2012). Our data (Prat-Guitart et al., in press) confirm that there is little change in peat  
37  
38 415 moisture content after 12 h at ambient temperature. Movement of water is therefore  
39  
40 416 mainly due to evaporation and condensation ahead of the smouldering front, which is  
41  
42 417 driven by the oxidative combustion reactions (Rein, 2016).

43  
44 418 The spread distance into a wet peat is also affected by local changes in fire behaviour  
45  
46 419 caused by the moisture gradient. The moisture content conditions of *PRE* peat  
47  
48 420 conditions control the fire spread during the first 10 cm into a wet peat (Table 3).  
49  
50 421 Only *PRE MC* of 25 or 50% combined with *POST MC* of 100 or 150% and few  
51  
52 422 homogeneous peats with 150% *MC* led to peat fires that could propagate more than 10  
53  
54 423 cm. The fire behaviour found for this moisture content combinations agrees with  
55  
56 424 results from previous studies indicating self-sustained spread for 10 cm or more in  
57  
58 425 similar moisture conditions (Frandsen, 1997; Prat-Guitart et al., 2015; Reardon et al.,  
59  
60 426 2007; Rein et al., 2008).

61  
62 427 Our simplified laboratory experiments enabled the effect of moisture content on the  
63  
64 428 spread of smouldering fires to be studied whilst controlling for mineral content, bulk

1  
2 429 density and other artefacts in the peat (Belcher et al., 2010; Frandsen, 1987; Hadden  
3  
4 430 et al., 2013; Zaccone et al., 2014). We note that studying smouldering fire behaviour  
5  
6 431 in field samples of peat soil would make the analysis more complex and the results  
7  
8 432 more difficult to interpret because of the multiple uncontrolled factors (e.g. bulk  
9  
10 433 density, organic composition, pore size) that vary between field samples (McMahon  
11  
12 434 et al., 1980). Our results (Prat-Guitart et al., in press) and those of others indicate that  
13  
14 435 the spread of smouldering fire in natural peats will also be influenced by peat bulk  
15  
16 436 density (Frandsen, 1991; Lukenbach et al., 2015), mineral content (Frandsen, 1987;  
17  
18 437 Garlough and Keyes, 2011), depth (Benscoter et al., 2011; Huang and Rein, 2015), as  
19  
20 438 well as the organic composition, structure, pore size distribution and the degree of  
21  
22 439 decomposition. Future research should aim to further develop our experimental work  
23  
24 440 to understand how other peat properties contributing to the heterogeneity of moisture  
25  
26 441 content of peatlands affect the spread of peat fires.

27 442

## 28 443 *5.2. Application to peatland fires*

29  
30 444 The results obtained in our milled peat experiments in the laboratory where a moisture  
31  
32 445 content gradient was implemented for the first time, give a first insight to the  
33  
34 446 understanding of the peat fire behaviour and interpretation of post peat-fire  
35  
36 447 landscapes. Often, post fire studies report irregular consumption of peat, where wet  
37  
38 448 *Sphagnum* hummocks are left unburnt (Benscoter and Wieder, 2003; Hudspith et al.,  
39  
40 449 2014; Shetler et al., 2008). Our results suggest that differences in peat moisture  
41  
42 450 content could cause smouldering consumption in the dry peat surrounding *Sphagnum*  
43  
44 451 hummocks and likely reduced the size of the wet patches.

45  
46 452 In peatlands, smouldering fires happen during extreme weather events, due to  
47  
48 453 reductions of surface moisture content (Terrier et al., 2014; Turetsky et al., 2015).  
49  
50 454 Peat fires in surface peat layers are part of the natural cycle of peatlands, often limited  
51  
52 455 by the spatial heterogeneity of moisture content. These fires reduce peat  
53  
54 456 accumulation, enhance biodiversity and facilitate the access of surface vegetation to  
55  
56 457 the water table (Waddington et al., 2015). The spatial distribution of moisture content  
57  
58 458 at a microtopographical scale has a strong influence on the smouldering fire spread  
59  
60 459 (Benscoter and Wieder, 2003). We predicted fire spread of less than 10 cm into a wet



1  
2 460 patch for most of the moisture content combinations involving peat  $\geq 160\%$  MC (Fig.  
3  
4 461 7). *Sphagnum* hummocks have a variable size, between 20 and 200 cm diameter  
5  
6 462 (Nungesser, 2003; Petrone et al., 2004), meaning than most of the hummock surface  
7  
8 463 can remain unburnt. Natural peatlands have high water table levels and heterogeneous  
9  
10 464 distributions of surface moisture (Waddington et al., 2015). Our controlled peat  
11  
12 465 experiments have only looked at surface horizontal spread. This is one kind of spread  
13  
14 466 that, together with vertical spread, happens during peat fires due to the three-  
15  
16 467 dimensional shape of the smouldering front (Ohlemiller, 2002). Future modelling of  
17  
18 468 peatland fires needs to consider variations in the underlying moisture content because  
19  
20 469 of its effect on the smouldering propagation at a fine-scale in more complex  
21  
22 470 smouldering spread scenarios. Modelling of peat fires incorporating the effect of peat  
23  
24 471 moisture changes will lead to more accurate estimates of carbon emissions, fire  
25  
26 472 perimeter and area burned (Benscoter and Wieder, 2003). Finally, ecosystem  
27  
28 473 management and fire management should also take into account the spatial variation  
29  
30 474 of peat moisture content to manage the fire risk, avoid large areas of peat being  
31  
32 475 consumed by fires and moisture maps may allow better estimates of fire or burn  
33  
34 476 severity to be made. It may be that peat fires can be managed by assuming that  
35  
36 477 extinction could be achieved by rising the moisture content of strategically located  
37  
38 478 peat areas above 200% MC. This technique may have a wider range of ecological  
39  
40 479 benefits than flooding entire areas by blocking ditches or using destructive techniques  
41  
42 480 such as bull-dozing trenches ( Davies et al., 2013; Watts, 2012).

43 481

## 44 482 **Conclusions**

45 483 We studied the role of moisture content as a limiting factor of smouldering  
46  
47 484 propagation in situations where peat moisture content is not homogeneous. Our  
48  
49 485 approach presents a useful method toward building an understanding peatland  
50  
51 486 smouldering fire behaviour that enable new information about the influence of  
52  
53 487 moisture content transitions in peatland systems. We show that fire spread into wet  
54  
55 488 peat patches is strongly affected by local transitions of moisture content. The moisture  
56  
57 489 content of the peat before the transition governs the fire behaviour into a wet peat for  
58  
59 490 the first centimetres of spread. After that distance it is likely that peat fires self-  
60  
61 491 extinguish leaving unburnt patches of wet peat. Future research on peat fire behaviour

1  
2 492 should consider local variation in moisture content to better understand the spread of  
3  
4 493 smouldering fronts through peat layers.

5  
6 494

7  
8 495 **Acknowledgements**

9  
10 496 The authors thank the School of Mechanical Engineering at University College  
11  
12 497 Dublin, especially to David Timoney for the support and John Gahan for his help  
13  
14 498 during the laboratory set up. We thank M. Waddington and one anonymous reviewer  
15  
16 499 that provided helpful comments on the manuscript. This project is funded by the Irish  
17  
18 500 Higher Education Authority PRLTI 5. Claire M. Belcher acknowledges a European  
19  
20 501 Research Council Starter Grant ERC-2013-StG-335891-ECOFLAM.

21 502

22  
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### Tables

676 **Table 1. Peat moisture content and bulk density combinations of the**  
677 **experimental burns.**

678 *PRE* and *POST* are the moisture contents of the two peat blocks before and after the  
679 sharp moisture gradient, respectively; peat bulk density ( $\rho$ ) is the mass of dry peat per  
680 unit volume (median  $\pm$  median absolute deviation); wet density is the mass of moist  
681 peat per unit volume and volumetric moisture content is the volume of water per unit  
682 volume. Number of experimental burn replicates ( $n$ ) for each combination of *PRE* and  
683 *POST* moisture contents.

<i>MC</i>		$\rho$		Wet density		Volumetric <i>MC</i>		<i>n</i>
<i>PRE</i>	<i>POST</i>	<i>PRE</i>	<i>POST</i>	<i>PRE</i>	<i>POST</i>	<i>PRE</i>	<i>POST</i>	
(%)	(%)	(kg m <sup>-3</sup> )	(kg m <sup>-3</sup> )	(kg m <sup>-3</sup> )	(kg m <sup>-3</sup> )	(m <sup>3</sup> m <sup>-3</sup> )	(m <sup>3</sup> m <sup>-3</sup> )	
25	150	123±6	65±6	154±7	163±16	3.1±0.1	9.8±0.9	4
25	200	121±10	66±2	152±12	199±6	3.0±0.2	13.2±0.4	4
25	250	121±7	75±9	151±9	263±33	3.0±0.2	18.8±2.3	4
50	100	100±2	84±2	149±3	167±4	5.0±0.1	8.4±0.2	4
50	150	101±3	69±7	152±4	173±16	5.0±0.1	10.4±1.0	4
50	200	100±6	70±1	149±10	210±3	5.0±0.3	14.0±0.2	4
50	250	99±2	70±7	148±4	244±26	5.0±0.1	17.4±1.8	4
100	125	63±3	64±1	127±6	144±1	6.3±0.3	8.0±0.1	4
100	150	77±6	73±4	154±12	184±2	7.7±0.6	11.0±0.1	4
100	200	84±2	70±2	167±6	212±2	8.3±0.2	14.1±0.2	4
100	250	78±2	73±8	157±4	254±29	7.8±0.2	18.1±2.1	4
125	150	63±2	69±5	143±4	173±11	7.9±0.2	10.4±0.7	4
125	250	59±2	68±8	134±5	238±29	7.4±0.7	17.0±2.0	4
150	150	62±4	62±4	154±10	154±10	9.3±0.7	9.3±0.7	4

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688 **Table 2. Location of the breakpoint and the median energy flux ( $E_m$ ) estimated**  
689 **before and after the breakpoint.**

690 All results are for a moisture content *POST* =150% *MC*. Breakpoint is the location ( $c_i$ ,  
691 relative to the moisture gradient) of a breakpoint in  $E_m$  estimated using piecewise  
692 linear regression (equation 1). CI is the breakpoint location's 95% confidence  
693 interval. ' $E_m$  before' is  $E_m$  before the breakpoint (mean ± standard error), ' $E_m$  after' is  
694 the  $E_m$  after the breakpoint.

<i>PRE</i>	Breakpoint	CI	$E_m$ before	$E_m$ after
(% <i>MC</i> )	(cm)	(cm)	(kW m <sup>-2</sup> )	(kW m <sup>-2</sup> )
25	1.5	1.0, 2.1	3.92 ± 0.05	2.89 ± 0.12
50	0.8	0.5, 1.1	3.03 ± 0.03	2.90 ± 0.07
100	1.5	1.0, 2.1	2.86 ± 0.08	2.13 ± 0.17
125	0.8	0.5, 1.1	2.78 ± 0.11	1.59 ± 0.26
150	-1.5	-2.0, -0.9	3.13 ± 0.09	2.33 ± 0.11

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697 **Table 3. Coefficient estimates from the model of spread distance ( $D_T$ ) after a peat**  
698 **moisture gradient.**



699 Dependent variable  $D_T$  was square-root transformed. Coefficients  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are  
700 parameter estimates for  $PRE$  and  $POST$  moisture gradient and their interaction,  
701 respectively.  $R^2=0.92$ , residual standard error =0.21.

	<i>Coefficient</i> (cm <sup>0.5</sup> )	<i>Standard error</i> (cm <sup>0.5</sup> )	<i>p-value</i>
$\beta_0$ , Intercept	8.0	0.6	<0.0001
$\beta_1$ , $PRE_i$	-0.054	0.006	<0.0001
$\beta_2$ , $POST_i$	-0.026	0.003	<0.0001
$\beta_3$ , $PRE_i \times POST_i$	0.00018	0.00003	<0.0001

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## Figure Captions

**Fig. 1.** Image of an on-going experimental burn. A glowing coil ignites the peat at the ignition region. The fire spreads through a region of *PRE* peat (dry peat) and then through a region of *POST* peat (wet peat). Dashed line indicates the location of the sharp gradient of moisture content between *PRE* and *POST* peat. Thermocouples monitor the temperatures inside the peat sample.

**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.

**Fig. 3.** Examples of temperature versus time profiles from five experiments (a-e). All experimental burns had *POST* peat moisture content of 150% and *PRE* peat moisture content of (a) 25%, (b) 50%, (c) 100%, (d) 125% and (e) 150%. Dot dash-black, solid red and double dash-blue lines correspond to thermocouples  $-4\text{cm}$ ,  $+1\text{cm}$  and  $+6\text{cm}$  from the moisture gradient, respectively. Profiles end when the fire self-extinguished.

**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 equation 1.

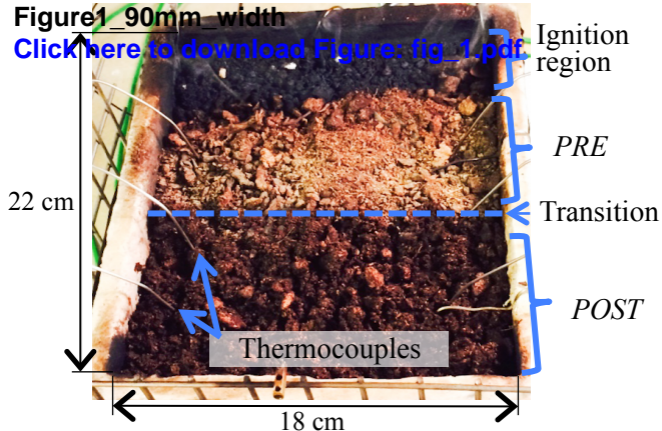
**Fig. 5.** Observations of spread distance ( $D_T$ ) into *POST* peat. Subplots are for *PRE* peats of (a) 25%, (b) 50%, (c) 100% and (d) 125% *MC*.

**Fig. 6.** Spread distance ( $D_T$ ) 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.

Figure1\_90mm\_width

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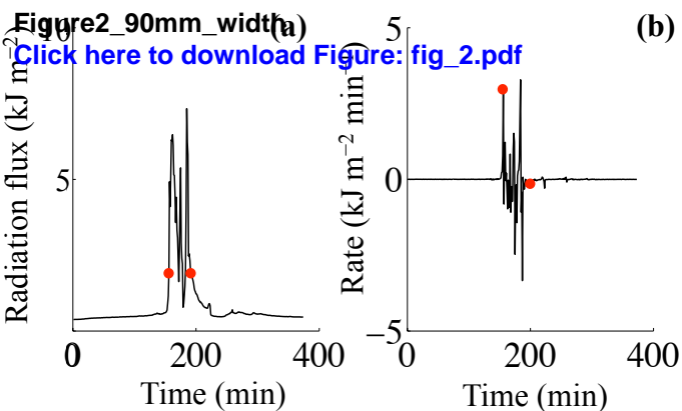


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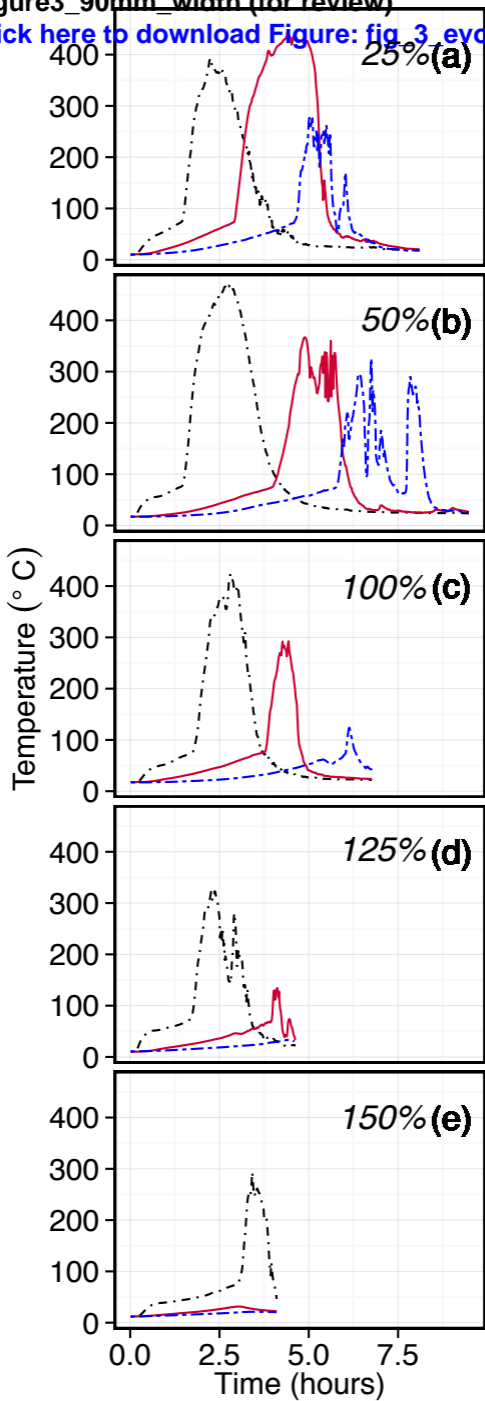


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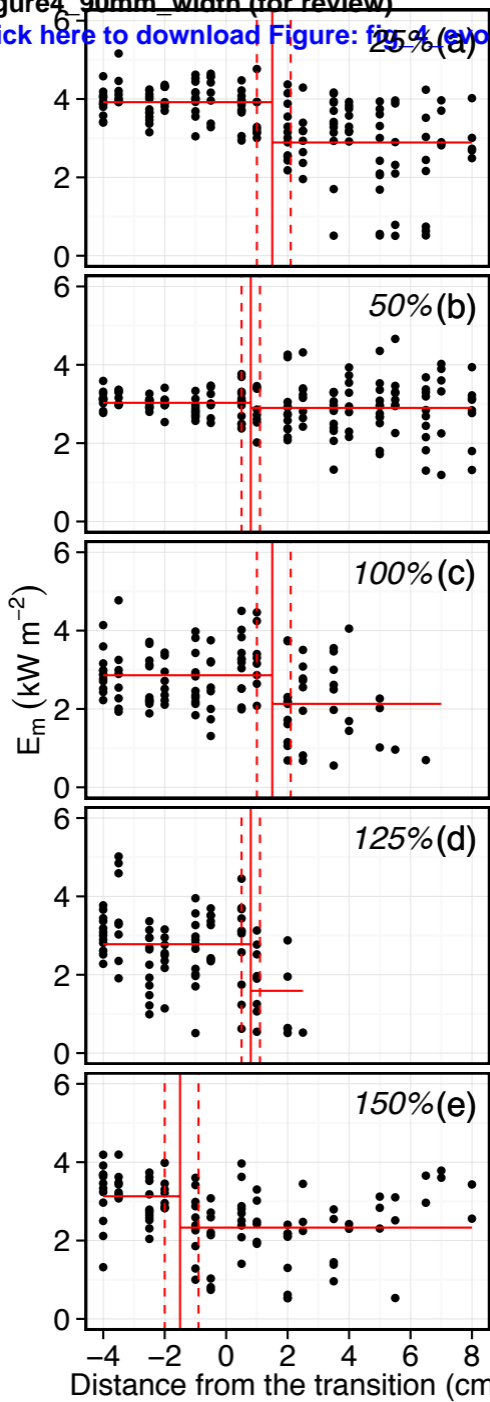


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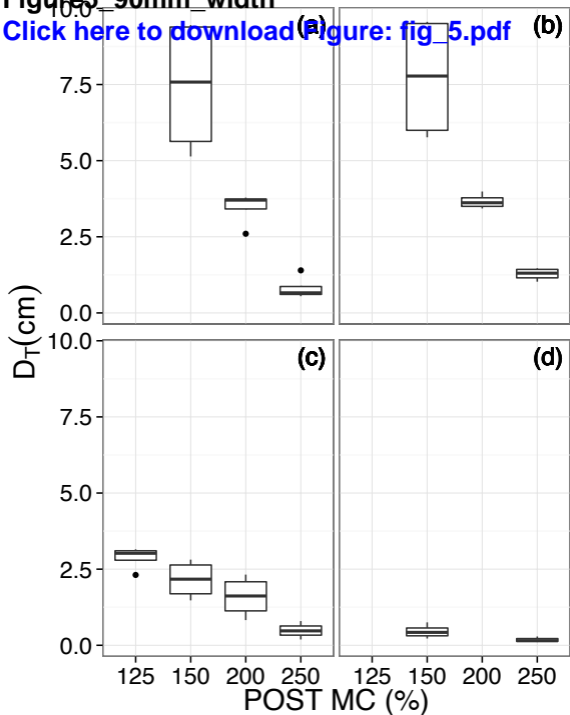
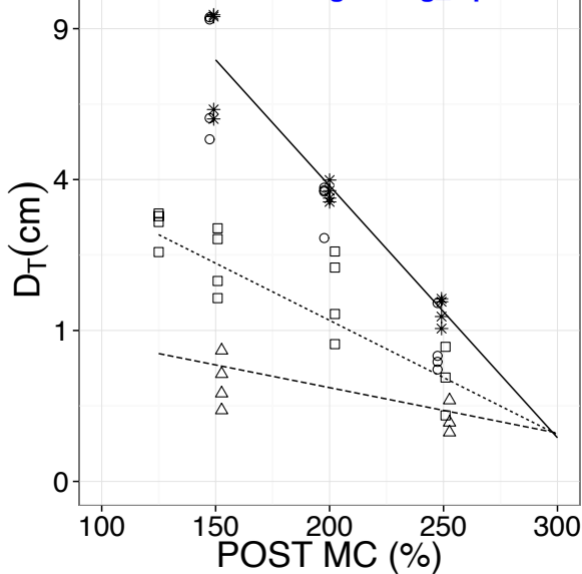


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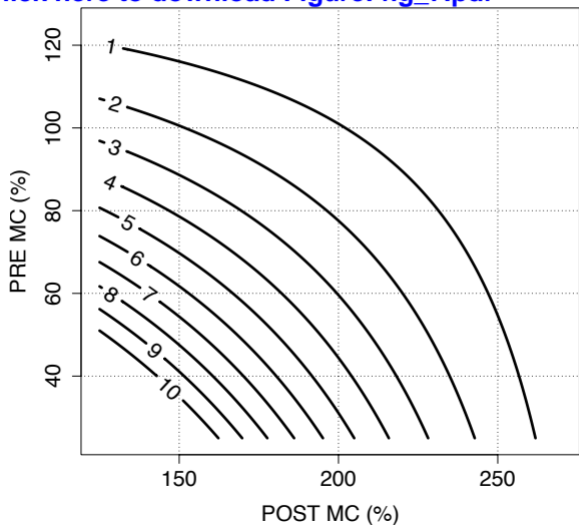
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