Fire Technology, 47, 421–436, 2011

DOI: 10.1007/s10694-010-0162-0

Fuel Moisture Thresholds in the Flammability of *Calluna vulgaris*

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Received: 19 January 2010/**Accepted:** 31 May 2010

Abstract. Managed and wild fires play a significant role in the ecology of heathlands in the UK but we currently have little ability to forecast fire behaviour or the likelihood of accidental wildfires. Like many shrubland fuel types, heathlands display significant structural complexity and the role of different fuel components in governing flammability has not been clear. Using a series of small, field-based ignition tests, we demonstrate the critical importance of the moisture content of dead fine fuels in the lower canopy for determining when sustaining fires in the vegetation canopy can develop. At moisture contents above c. 70% both spot and line ignitions failed but where moisture contents were less than c. 60% fires developed rapidly. The initial rate of spread of successful ignitions was primarily controlled by the moisture content of the lower canopy and the moss/litter layer. Models that predict the moisture content of elevated dead fuels and the moss litter layer are urgently needed in order to protect heathlands from wildfire and to allow forecasts of the suitability of conditions for prescribed burning to be developed.

Keywords: Fire behaviour, Fire sustainability, Heathland, Ignition, Logistic regression, Managed burning, Rate of spread, Wildfire

1. Introduction

Areas of moorland and heath dominated by the dwarf-shrub *Calluna vulgaris* (commonly known as heather, hereafter referred to as *Calluna*) are common throughout large areas of the British uplands. Their range extends across north-western Europe but a combination of changes in agricultural practice, poor fire management and nutrient deposition mean that in many areas they are under threat [1–4]. Fire has been an integral part of the management of heathlands for hundreds of years and is particularly important in the UK where carefully managed burning is used to improve productivity and diversity [5]. Uncontrolled wildfires are however a key threat to heathlands and can have devastating environmental impacts [3, 6]. Where fires occur on peat soils there is also growing

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debate about the impact of management burning on carbon dynamics [3, 7, 8]. Understanding the flammability of fuels is critical for predicting the risk of accidental and malicious wildfires and forecasting conditions when management burns can be lit safely and effectively. Although societal factors play an important role in governing where and when wildfire ignitions occur [9], these will only become major incidents when the vegetation is dry enough to burn. Fuel moisture content (FMC), along with weather conditions (particularly wind speed and direction), is important in determining how easily fires can be controlled in a given fuel type [10]. Both dead and live fuels contain water but they are often distinguished in studies of wildland fire behaviour due to significant differences in the amounts of moisture they typically contain and the speed with which this moisture content changes in relation to weather, climate and fuel particle morphology. Wales and England currently have a "Fire Danger Rating System" in the form of the Met Office Fire Severity Index [11–13]. Though this may be useful in forecasting conditions likely to allow particularly damaging wildfires, it does not predict when fires occur well and the fuel moisture indices on which it is based do not relate strongly to observed changes in live or dead *Calluna* fuel moisture [14, 15]. Key tasks for fire research on heathlands are therefore the development of robust fuel moisture models and understanding how *Calluna* fuel moisture relates to flammability.

Anderson, in his now classic study of forest fuel ignitibility [16], distinguished between three aspects of flammability: ignitibility, sustainability and combustibility. Ignitibility relates to the size of fuel particles and their ignition delay time, sustainability describes how well a fire will burn once the ignition source is removed and combustibility is the rate at which a fire burns. In the context of prescribed fires dead and live fine fuel ignitibility is likely to be less than 1-s [16]. Sustainability and combustibility are of more interest to fire managers as they relate to fire rate of spread and fireline intensity [16]. Fuel moisture content will affect all three aspects of flammability. Previous fire behaviour research on *Calluna* has failed to adequately identify the role of FMC on fire behaviour [14, 17], and though Davies et al. [18] advanced our knowledge somewhat, the relative importance of dead and live fuels and their respective moisture contents are still not well understood. The fact that *Calluna*-dominated fuels mostly comprise a live/green component that can display significant seasonal, intra-seasonal and diurnal variation [19–21] makes it particularly difficult to predict changes in their flammability. Management-scale experimental fires [18] are one way to try and discern the relationships between environmental variables and fire behaviour, but are labour and time intensive to set up and monitor and, by necessity, have focused on a restricted range of conditions when fires were likely to be self-sustaining. It has been demonstrated that the relationship between fire behaviour and FMC in shrub fuels is non-linear such that changes in moisture content can function as an "on/off" switch at the lower end of the fire behaviour spectrum [22]. A number of authors (e.g. [23–28]) have used field experiments to identify conditions necessary for sustained ignition whilst others (e.g. [29–31]) have demonstrated a significant relationship between fuel moisture and flammability in laboratory tests.

Conditions during the legal burning period in the UK uplands (1st October until the middle of April, or mid-May in certain circumstances, see SEERAD [32] for exact dates) are extremely variable with weather ranging from sub-zero temperatures with deep snow cover to extended warm, dry spells. Early spring constitutes one of the major periods of high fire risk on heather moorlands when over-winter damage to leaf cuticles, and both frozen ground and sunny days with low humidity can lead to low moisture contents of both live and dead fuel [20, 33, 34]. Periods of rain often interrupt burning periods, whilst fires may easily escape control in dry conditions. Limited man-power, on top of such variable conditions, means that time spent trying to burn in conditions when fire is non-sustaining is an unnecessary cost to the land manager. The spate of wildfires in the spring of 2003, some attributable to escaped management fires, has been linked to a period of extended dry weather combined with a cold but largely snow-free winter that froze ground and allowed live *Calluna* to become exceptionally dry [17].

Shrubland fuels, such as those formed by *Calluna*, show significant structural complexity in both horizontal and vertical space [35]. Modelling fire behaviour, both empirically and mathematically, in such fuels is generally acknowledged to be extremely challenging [27]. Dense stands of *Calluna* often form clearly definable layers with a number of long shoots sticking out above the surrounding canopy, the top half of which is green and mostly live, whilst the bottom is grey and predominantly composed of live and dead stems bearing dead foliage (Figure 1). Below this self-thinning creates a layer of dead and live stems of various sizes but

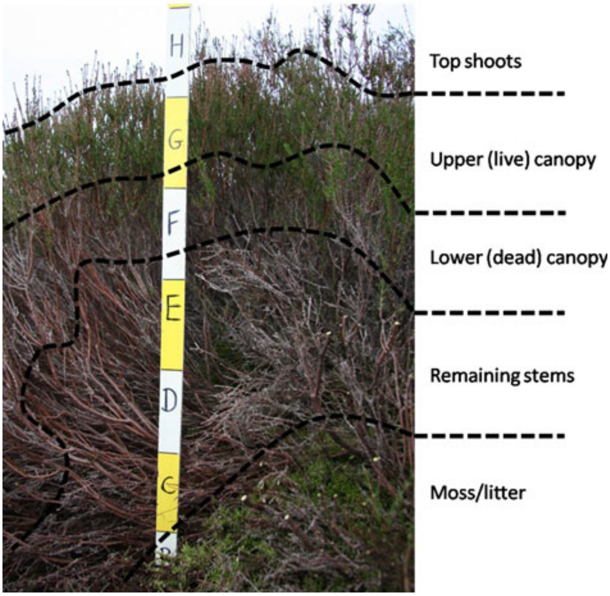

Figure 1. Cross-section through a closed *Calluna* stand illustrating the five layers harvested during FMC quadrat collection. For the 'remaining stems' layer dead and live stems 2 mm or less in diameter were collected separately. The scale is a 'FuelRule' [35] with 10 cm bands.

with little foliage. A layer of moss and litter lies beneath this. In order to determine the influence of fuel moisture and other variables on potential fire risk and behaviour a field experiment was designed that combined ignition attempts with fine-scale dead and live fuel moisture monitoring, information on fuel structure and on-site weather data. We sampled all the layers of *Calluna* fuel beds (Figure 1) individually and also took samples of purely dead material. Fires were small (2 m × 2 m) ignition tests as these allowed rapid set-up and monitoring in response to changing weather conditions. Such small tests also allowed us to burn safely in a wider range of conditions than would be possible with larger fires typical of accidental wildfires or those used by managers [18]. Our objectives focused on quantifying variation in fire sustainability. We sought to, (i) determine the role of weather and fuel moisture in governing ignition and sustained combustion of *Calluna* fires, (ii) model the probability of ignition based on fuel moisture content, fuel characteristics and weather conditions and, (iii) model the rate of spread of small, developing fires.

2. Methods

2.1. Experimental Areas

Experiments were completed at two different locations. The first site was located on Castlelaw Hill in the Pentland Hills outside Edinburgh (UK O.S. Grid Ref: NT2265; Lat 55°52′N, Long 3°14′W) and the second site within Crubenmore Estate, near Dalwhinnie, on the edge of the Cairngorms National Park in N.E. Scotland (UK O.S. Grid Ref. NN 6386; Lat 04°15′W, Long 56°57′N). All fires were carried out on flat ground. The vegetation at both sites was classified as belonging to a "Late-building" type fuel load (15–20 years old, with a somewhat open but generally uniform canopy, few stems >2 mm in diameter, continuous bryophyte layer) [18] though it was generally taller and sparser at Crubenmore than at Castlelaw Hill. This fuel is that typically burnt by managers. Species composition was dominated by *Calluna*, generally underlain by a deep mat of pleurocarpous mosses. In some dense patches of *Calluna* mosses were replaced by a layer of litter. Areas locally dominated by *Vaccinium myrtillus* or *Empetrum nigrum* were avoided. Grasses, mainly moor matt grass (*Nardus stricta*) and wavy hair grass (*Deschampsia flexuosa*) were a regular occurrence but formed only a tiny fraction of the total fuel load (<1%). The experimental areas were both protected by cut firebreaks.

2.2. Pre-Fire Monitoring

On each day, prior to the ignitions, a portable weather station was set up to record wind speed and direction (2 m above ground level), temperature, humidity and solar radiation at 5 s intervals. Following this two 2 m × 2 m plots were marked out (Figure 2). Fuel load and structure were estimated using both the FuelRule technique [35] and the destructive harvesting of a single 25 cm × 25 cm, fuel sub-quadrat. This was separated into the following fuel components: live

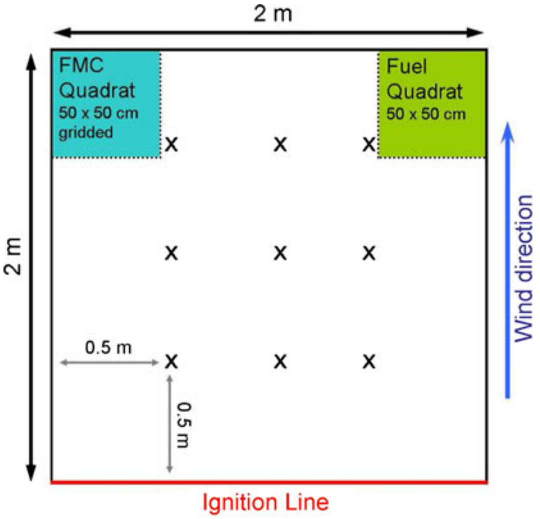

Figure 2. Layout of an ignition experiment. X represents the nine FuelRule measurement locations spaced 0.5 m from the plot edge and 0.5 m apart. Fuel load was also estimated by destructive harvesting a randomly selected quarter of the 'fuel quadrat'.

stems with foliage, live stems <2 mm in diameter, live stems 2–5 mm in diameter, live stems >5 mm in diameter, dead stems bearing dead foliage, and dead stems without foliage. Species other than *Calluna* were analysed separately but represented a very small (mean 3.7 ± 0.6%) proportion of the available fuel.

Fuel moisture monitoring was completed immediately prior to each ignition attempt using a 50 cm × 50 cm gridded quadrat (25 sub-quadrats, each 100 cm^2). Five sub-quadrats were randomly selected for harvesting. Within each sub-quadrat all *Calluna* was harvested in the following order: green shoots projecting above the top of the main canopy, the top half of the *Calluna* canopy then the bottom half of the canopy; each stratum comprising small stems <2 mm in diameter bearing a mixture of live and dead foliage. Remaining live stems less than 2 mm in diameter, but without foliage, and dead stems were also harvested as was the top 2 cm of the moss/litter layer. Five samples of dead *Calluna* shoots were collected from the area within and around the quadrat. Samples were sealed in air-tight containers, weighed and dried (48 h at 80°C) to allow calculation of FMC on a dry weight basis.

2.3. Ignition and Fire Behaviour

On each day two ignitions were attempted, one in the morning, normally around 11 am, and another in the afternoon around 3 pm. Fires were ignited using a mini drip-torch (500 ml) filled with a 3:1 diesel/petrol mix. First a single spot ignition was made by holding the lit torch in the heather canopy for 30 s. If three attempts using this procedure all failed then a 2 m line ignition was attempted. All ignitions were made along the up-wind edge of the plot. A stopwatch was started when each ignition attempt was made. Fires that failed to spread were recorded as non-sustaining. For established fires, the time taken for them to spread across the 2 m plot was recorded. Fires that took more than 5 min to spread across the plot were recorded as sub-sustaining.

During the fire we visually estimated the maximum and average length of the flames and noted whether the fire seemed to be spreading primarily through the upper or lower canopy (Figure 3) or equally through both. Qualitative descriptions of patterns in fire spread and fuel consumption were also noted.

2.4. Data Analysis

All data were analysed using Minitab 15. A preliminary investigation of data distributions was made, after which associations between predictor variables were tested using correlation analysis. A General Linear Model was used to determine whether significant differences existed in the moisture content of the FMC variables for sustaining and non-sustaining (including sub-sustaining) fires.

2.4.1. Data Transformation. Initial exploration of the data using Anderson–Darling tests for normality revealed that several of the predictor variables did not follow a normal distribution. The FMC of dead shoots, the lower canopy and live stems, and dead fuel load estimated destructively were transformed by taking the reciprocal and multiplying by −1 to aid interpretation. Time since last rain was square-root transformed.

2.4.2. Relationships Between Fuel Structure Variables. There was little agreement in fine fuel load estimated using the destructive and FuelRule techniques

Figure 3. Fire spreading through the lower canopy of building phase *Calluna* during marginal burning conditions. The live-fuel dominated upper layers burnt after the predominantly dead material below.

($r = 0.29$) due to the patchiness of the fuel at the scale of the harvested plots. The FuelRule technique has proven reliable in this fuel type in the past [35] and we therefore used FuelRule estimates of fuel load and structure in subsequent logistic regression modelling but included the dead:live ratio (not provided by the FuelRule) calculated from the quadrat analysis of fuel load.

2.4.3. Patterns in Fuel Moisture Content. There was highly significant correlation ($P < 0.001$) amongst nearly all the FMC predictor variables (Table 1). Factor Analysis with varimax rotation was therefore used to reduce the dimensionality of the fuel moisture data to four orthogonal (uncorrelated) factors: the first factor related strongly to the moisture content of the upper, live part of the *Calluna* canopy; the second to moisture contents in the lower canopy and the moss layer; factor three represents the moisture content of dead stems; and four the FMC of dead shoots (Table 2). These four factors together explained 96% of the variation in the data set.

Table 1
Correlation Coefficients Between Fuel Moisture Content of the Different Components of the Vegetation in the Small Ignition Experiments

	Dead shoots	Dead stems	Live stems	Lower canopy	Moss/litter	Top shoots	Upper canopy
Dead shoots	–						
Dead stems	0.14	–					
Live stems	0.76	0.13	–				
Lower canopy	0.76	0.32	0.86	–			
Moss/Litter	0.72	−0.03	0.81	0.82	–		
Top shoots	0.72	0.34	0.77	0.80	0.54	–	
Upper canopy	0.77	0.26	0.82	0.86	0.59	0.89	–

All the correlations, except all those with dead stems, are statistically significant

Table 2
Rotated (Varimax) Loadings for Factor Analysis on FMC Variables

Variable	Factor 1	Factor 2	Factor 3	Factor 4
Dead shoots*	0.473	0.451	0.046	**−0.754**
Top shoots	**0.876**	0.273	0.208	−0.232
Upper canopy	**0.859**	0.350	0.123	−0.270
Lower canopy*	0.598	**0.700**	0.235	−0.208
Live stems*	**0.638**	**0.689**	0.015	−0.177
Dead stems	0.156	−0.003	**0.986**	−0.028
Moss/litter	0.246	**0.916**	**−0.073**	−0.268

Variables marked with an asterisk (*) were transformed by taking their reciprocal and multiplying by −1. Values in bold indicate variables that relate strongly to a given factor

2.4.4. Ignition Models. Stepwise binary logistic regression was used to model the probability of line-ignition success (Sustaining/Non-sustaining) based on the FMC factors, fuel structural characteristics and weather conditions. Sub-sustaining fires were treated as non-sustaining. Each variable was tested and model fit assessed by examining the significance of the b coefficient, the value and significance of the G-statistic, the number of concordant and discordant pairs and Pearson, deviance, and Hosmer–Lemeshow goodness-of-fit tests. Only variables that were statistically significant ($P < 0.05$) were retained.

We modelled the probability of sustaining fires from successful spot ignitions and line ignitions (assuming that a successful spot ignition indicated that a line ignition would also be successful). The decision to focus on a 'strong' ignition technique is well justified by the observation that spot ignitions were highly susceptible to small-scale spatial variation in fuel structure and fuel moisture rather than larger-scale day-to-day variability in FMC. Best subsets regression was used to model the rate of spread of sustaining and sub-sustaining fires.

3. Results

Twenty ignition attempts were made with six successes and fourteen failures (two sub-sustaining) from spot ignitions and nine successes and eleven failures (three sub-sustaining) from line ignitions.

Plot FMC characteristics and weather conditions are shown in Table 3. Fuel structure data is shown in Table 4. Upper canopy FMC varied widely from a low of 29.7% of oven-dry weight during a sunny period when the ground was frozen, to as high as 163% in periods immediately following rain. The lower canopy often exhibited lower FMC values than the upper but this was dependent on how much time had passed since the last precipitation event. With the exception of live stems, which showed relatively low variability, lower-canopy strata and dead fuels showed greater variability than upper, live fuel layers (Table 3). Greatest variability was seen in the moss layer where FMC varied from less than 25% to more than 400%. The moss and litter layer was not consumed where the moisture content was 140% or higher, but at FMCs less than 70% significant amounts burnt and smouldering often continued after flaming combustion was extinguished.

3.1. Modelling Ignition Probability and Rate of Spread

A GLM comparing successful and unsuccessful ignitions demonstrated that there were significant differences in the moisture contents of the upper canopy, lower canopy, live stems, dead shoots and the moss/litter layer (Table 5).

The lower canopy moisture content was highly variable with the clearest threshold at which both spot and line-ignition fires will sustain (Figure 4). Binary logistic regression analysis showed that FMC Factor 2 (FMC of lower canopy and moss layer) alone was a powerful predictor of ignition success (Equation 1, Table 6). The slight improvement of fit with additional predictor variables did not justify the increased model complexity. The rate of spread of sustaining and sub-sustaining fires was also best predicted by FMC Factor 2 (Equation 2,

Table 3
Results of the Ignition Experiment Showing the Mean FMC of Each of the Fuel Strata, Weather Conditions and Fire Behaviour

ID	Dead shoots (%)	Top shoots (%)	Upper canopy (%)	Lower canopy (%)	Live stems (%)	Dead stems (%)	Moss/ litter (%)	Last rain (h)	Temp. (°C)	RH (%)	Wind speed ($m\ s^{-1}$)	Solar radiation ($W\ m^{-2}$)	Sustaining		Flame length (m)	RoS ($m\ min^{-1}$)
													Spot	Line		
13	49.6	119.8	155.8	200.8	151.7	–	436.5	12	3.0	75.9	9.0	305.3	No	No	0.00	0.00
14	31.9	85.4	86.7	86.0	99.6	–	385.8	16	2.7	69.1	4.8	116.1	No	No	0.00	0.00
15	31.3	88.3	105.3	90.1	82.1	–	355.6	12	3.4	75.6	6.3	388.2	No	No	0.00	0.00
16	24.0	73.7	71.0	98.4	84.1	78.1	301.8	18	5.5	68.7	5.3	225.3	No	No	0.00	0.00
17	24.3	80.2	75.0	67.1	71.3	34.5	279.2	60	6.6	73.1	8.3	460.0	No	Sub	0.25	0.35
18	22.2	66.8	72.0	57.1	68.6	–	250.3	72	7.5	68.0	9.7	136.3	No	Sub	0.25	0.38
19	25.8	102.0	67.8	55.6	75.1	46.1	216.2	40	7.7	77.9	6.9	415.8	Sub	Yes	0.30	0.54
20	24.4	91.1	73.5	52.0	75.4	29.8	190.1	43	7.7	79.3	9.7	93.9	Sub	Yes	0.30	0.64
22	14.6	46.0	41.1	39.6	62.4	26.8	69.8	48	2.5	48.8	4.2	596.3	Yes	Yes	0.50	0.72
23	16.2	28.4	29.7	34.4	58.6	21.7	54.3	51	2.4	61.8	6.2	141.6	Yes	Yes	0.75	1.36
24	22.7	67.9	64.3	44.0	71.1	21.5	28.9	120	7.7	60.6	4.9	176.1	Yes	Yes	0.75	0.91
25	17.3	66.7	57.7	37.4	70.8	33.9	23.6	120	10.0	51.7	7.0	557.9	Yes	Yes	0.80	1.03
26	50.8	131.6	163.1	164.4	95.8	111.3	238.9	6	3.7	80.3	5.3	431.1	No	No	0.15	0.00
27	22.4	72.3	82.8	66.9	73.9	42.6	143.6	10	5.1	77.3	2.5	253.2	No	No	0.20	0.00
28	33.8	97.6	117.4	144.7	92.7	54.7	315.0	6	3.9	73.4	2.4	822.3	No	No	0.15	0.00
29	19.8	91.2	84.2	101.6	87.2	70.6	254.6	0	3.8	64.4	4.9	218.0	No	No	0.20	0.00
30	12.5	82.9	74.1	50.0	67.2	31.5	45.6	120	8.8	63.8	1.8	237.1	Yes	Yes	0.40	0.79
31	18.0	81.1	81.0	54.3	68.5	18.7	45.6	120	10.7	50.1	6.7	440.3	Yes	Yes	0.50	1.36
32	35.2	101.6	109.4	75.8	74.1	37.7	134.4	1	7.7	82.9	2.8	202.1	No	Sub	0.10	0.57
33	25.5	88.5	83.3	65.4	74.7	26.8	159.7	0	8.6	80.0	6.6	154.9	No	Yes	0.10	1.24
C.V.	39.4	27.8	38.6	56.2	24.9	58.1	64.7									

There are some missing values for the category "Dead stems" as not all quadrats contained this fuel component. C.V. is the coefficient of variation of the mean FMC for each of the fuel strata

Table 4
Fuel Structure of the Ignition Experiment Plots

ID	Destructive total (kg m^{-2})	Destructive fine (kg m^{-2})	Destructive dead (kg m^{-2})	FuelRule total (kg m^{-2})	FuelRule fine (kg m^{-2})	Bulk density (kg m^{-3})	*Calluna* height (cm)	CDI	S
13	0.61	0.39	0.11	0.77 ± 0.14	–	4.04 ± 1.06	19.4 ± 3.0	−0.71 ± 0.40	1.18
14	0.43	0.29	0.10	0.91 ± 0.28	–	4.38 ± 0.93	20.8 ± 4.4	−0.84 ± 0.48	2.12
15	0.56	0.34	0.19	0.89 ± 0.30	–	4.71 ± 1.03	18.8 ± 4.2	−1.14 ± 0.25	1.08
16	0.64	0.34	0.14	0.92 ± 0.28	–	4.59 ± 0.89	20.0 ± 3.5	−1.22 ± 0.45	1.54
17	0.94	0.31	0.23	1.00 ± 0.20	–	5.35 ± 0.48	18.9 ± 4.3	−0.91 ± 0.39	1.69
18	0.52	0.29	0.11	0.86 ± 0.14	–	4.26 ± 0.73	20.3 ± 3.3	−0.86 ± 0.42	1.38
19	0.58	0.23	0.26	0.98 ± 0.27	–	5.34 ± 1.00	18.2 ± 3.3	−1.30 ± 0.54	1.78
20	0.74	0.41	0.27	1.17 ± 0.18	–	5.62 ± 0.57	21.0 ± 3.6	−1.25 ± 0.71	2.58
22	0.38	0.26	0.06	0.99 ± 0.37	0.71 ± 0.26	5.29 ± 0.98	18.4 ± 5.3	−0.97 ± 0.53	2.84
23	0.52	0.28	0.14	0.90 ± 0.17	0.75 ± 0.33	4.46 ± 0.92	20.4 ± 3.6	−1.00 ± 0.36	1.28
24	0.37	0.22	0.07	1.19 ± 0.37	–	5.43 ± 1.58	22.0 ± 4.6	−0.72 ± 0.27	1.22
25	0.57	0.37	0.11	1.33 ± 0.34	0.96 ± 0.23	5.46 ± 1.00	24.6 ± 4.5	−0.69 ± 0.18	0.82
26	0.33	0.19	0.09	0.97 ± 0.30	0.77 ± 0.31	4.14 ± 1.07	23.2 ± 2.5	−0.89 ± 0.18	0.46
27	0.54	0.28	0.19	0.81 ± 0.22	0.57 ± 0.12	5.00 ± 1.70	16.9 ± 4.5	−0.87 ± 0.38	1.70
28	0.44	0.24	0.14	0.99 ± 0.26	0.69 ± 0.46	4.86 ± 0.81	20.3 ± 4.5	−0.76 ± 0.18	0.81
29	0.60	0.28	0.11	0.90 ± 0.36	0.60 ± 0.30	4.27 ± 1.35	20.8 ± 2.9	−0.61 ± 0.23	0.66
30	0.56	0.39	0.06	1.06 ± 0.20	0.71 ± 0.10	4.59 ± 1.09	23.8 ± 5.0	−0.43 ± 0.20	1.00
31	0.34	0.26	0.06	0.84 ± 0.32	0.59 ± 0.16	4.18 ± 0.80	20.1 ± 7.2	−0.43 ± 0.18	1.31
32	0.38	0.28	0.07	0.86 ± 0.25	0.51 ± 0.15	3.95 ± 0.80	21.7 ± 4.3	−0.44 ± 0.26	1.11
33	0.41	0.31	0.05	1.00 ± 0.38	0.63 ± 0.28	5.90 ± 4.58	21.0 ± 6.8	−0.44 ± 0.17	1.16

Fuel loads estimated using both destructive harvesting and the FuelRule. It was not possible to estimate fine fuel load with the FuelRule for a number of plots as data on % cover were missing. *Calluna* height is essentially a measure of the depth of the fuel bed. CDI = Canopy Density Index. S is the product of the standard deviations of height and CDI and has previously been shown to relate strongly to fire behaviour [17]

Table 5
Results of General Linear Models Testing the Difference in the FMC Between Successful and Failed Ignitions for the Sampled Fuel Components

	F	d.f. num	d.f. denom	*P*
Top shoots	3.82	1	19	0.066
Upper canopy	10.09	1	19	0.005
Lower canopy	30.81	1	19	<0.001
Live stems	10.57	1	19	0.004
Dead stems	0.67	1	19	0.424
Moss/litter	24.32	1	19	<0.001
Dead shoots	11.86	1	19	0.003

d.f. num and d.f. denom are the numerator and denominator degrees of freedom respectively

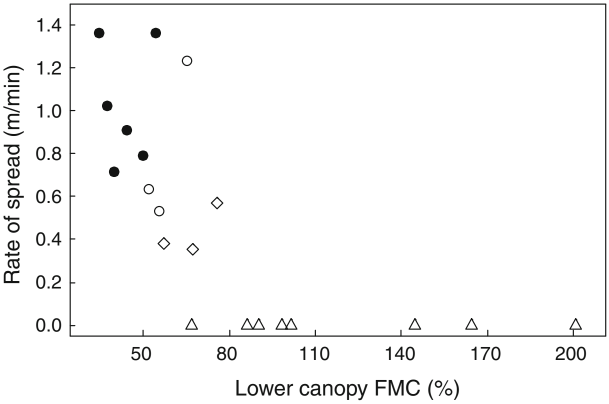

Figure 4. Mean rate of spread of fire across 2 m × 2 m plots following ignition along the windward edge plotted against the fuel moisture content of the lower canopy (% oven-dry weight). Solid circles represent successful spot fires, open symbols are subsequent line-fires. Circles: successful ignitions; diamonds: sub-sustaining fires; triangles: failed ignitions.

Table 6
Details of Model Performance for Equation 1

Predictor	SE_c	SE_p	G	Odds R	Con	Dis	Pearson	H–L
FMC Factor 2	0.84	1.36	13.67	0.05	91	8	0.48	0.49

The table shows the standard errors of the constant (SE_c) and predictors (SE_p). The value G tests the hypothesis that all the coefficients are different from zero and is significant at $P < 0.001$. Odds R is the odds ratio and compares the odds of each level of a categorical response variable to quantify how the predictor affects the probabilities of each response level. Con and Dis are the number of concordant and discordant pairs calculated by pairing observations with different response values and comparing predicted versus observed success. Pearson and H–L (Hosmer–Lemeshow) are *P* values for goodness of fit tests

Table 7
The Correlation Between *Calluna* Fuel Moisture Variables and Initial Rate of Spread in 20 Small (2 m × 2 m) Ignition Test Fires

	Dead shoots	Top shoots	Upper canopy	Lower canopy	Live stems	Dead stems	Moss/litter
r	−0.58**	−0.51*	−0.58**	−0.79***	−0.71***	−0.28	−0.81***

r = Pearson's correlation coefficient, asterisks indicate the level of significance (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$)

R^2(adj) = 0.48). The addition of FMC Factor 1 marginally improved the fit. Rate of spread was significantly correlated with all the raw FMC variables except for dead stems (Table 7) and correlated most strongly with the moisture content of the moss/litter layer.

$$P_{\text{ignition}} = \mathrm{e}^{-0.824-2.907\times \text{FMC2}} / \left(1 + \mathrm{e}^{-0.824-2.907\times \text{FMC2}}\right) \tag{1}$$

$$R_{\text{sustaining}} = \mathrm{e}^{-0.598-0.546\times \text{FMC2}} \tag{2}$$

where P_{ignition} is the probability of sustaining combustion, $R_{\text{sustaining}}$ is the rate of spread of those fires that are self-sustaining (m min^{-1}) and FMC2 is fuel moisture Factor 2, representing the moisture content of the lower canopy and moss/litter layer.

4. Discussion

Qualitative observations of behaviour indicated extremely patchy behaviour for many of the fires. Variation in fuel structure at the scale of these small (2 m × 2 m) test fires, even within relatively homogenous stands of *Calluna*, means moisture is retained in dense areas of fuel when sparser areas have dried to a much greater extent. It is possible that a longer ignition front, or applying the ignition source for a longer time, would generate a greater heat output to pre-heat fuel ahead of the fire front and allow sustained burning in situations where small ignitions such as ours self-extinguish. There were several occasions when the spot ignition failed to establish a self-sustaining fire, but line ignitions were successful demonstrating the importance of the physical size and energy input of the ignition source. Not only do longer ignition lines provide more energy to ignite the fuel but they also have a higher probability of contact with areas of drier, more flammable vegetation. These experiments give a good indication of conditions when a fire will be easy to ignite and show the relationships between FMC and initial fire behaviour. However, the rates of spread reported here should not be taken as an indication of potential behaviour of management fires as significant differences may exist between the initial and "steady-state" rates of spread [20]. An understanding of the balance between initial energy input from burning lighter-fuel that is required to dry and heat the *Calluna* to ignition temperature and the amount of energy released by the burning vegetation is key to developing a better understanding of the mechanisms driving go/no-go conditions in heathland fuels (e.g. [36]). Further tests should therefore examine the influence of ignition strength.

Our results are strikingly similar to those of Anderson and Anderson [37] who reported that thresholds for ignition and sustained fire spread in gorse (*Ulex europaeus*) related strongly to the moisture content of elevated dead fuels (i.e. dead fuel contained in the gorse canopy). The results of our work suggest fires are unlikely to be sustaining where the FMC of the lower canopy exceeds approximately 75%. It should be noted that this fuel layer contains a mixture of dead foliage and twigs as well as live stems, the critical moisture of the dead fuel is likely to be somewhat lower than the value reported here. For *Calluna*, separating the intimate mixture of live and dead fuels is extremely difficult in the field. Flammability tests in a laboratory would be required to allow better separation of fuel components and reliable estimation of the true moisture of extinction. Although the FMC of moss/litter was strongly related to FMC Factor 2, we suggest that this is not a primary control on when *Calluna* will and will not burn: our results here, and those of Davies et al. [18], demonstrate that fires will often burn in the *Calluna* canopy independently of these ground-layer fuels.

Once the fires had established, the initial rate of spread was influenced primarily by the FMC of the dead foliage in the lower canopy and the moss/litter layer. Fires spread primarily through the dead foliage within the lower part of the *Calluna* canopy and the FMC of these fuels determined the rate of energy release which drives the preheating of other fuel layers to ignition temperature. Where the moss layer was very dry and available for ignition this significantly added to the fuel available for consumption by flaming combustion and greatly increased fire spread. Davies et al. [17, 18] showed that for larger, established fires live (i.e. upper canopy) FMC content can also be a significant control of rate of spread. The FMC of fine dead fuels is critical for initial fire establishment. If this fuel is available for combustion and a fire establishes then the FMC of the live fuel may exert a significant control on established spread. Where live fuels are relatively dry, as seen in early spring, fire spread may be fast and intense [18]. It is likely that the balance between the relative amounts and moisture contents of live and dead fuels is critical for fire behaviour. Future fire experiments should examine the effect of a weighted mean moisture content based on the FMC of different fuel components and their relative loadings.

Previous, similar research [24] has shown that wind speed is an important control on the development of sustaining fires; although the addition of this to our models did improve their predictive ability, the additional variance explained after inclusion of lower-canopy fuel moisture (FMC2) was not statistically significant. The majority of our tests were, however, completed at rather high wind speeds (Table 3) and we anticipate that tests in a wider range of conditions would lead to it having a significant effect.

Our results suggest that the development of a fuel moisture model that incroporates the FMC of live and dead canopy material and the moss/litter layer is needed to adequately capture moorland fire hazard. From the point of view of forecasting conditions when a fire can occur in *Calluna* (as opposed to subsequent levels of fire behaviour) it may be sufficient to focus on the behaviour of dead canopy fuels. Anderson and Anderson [38] demonstrated that such fuels respond extremely rapidly to changing weather conditions but that it is possible to develop working models of their FMC. Legg and Davies [16] have suggested that in order to understand the likelihood of accidental moorland wildfires from ignition sources such as cigarette ends and embers it is necessary to understand the flammability of the moss/litter layer as this is the medium in which ignition is most likely to occur. Tanskanen et al. [25] suggested that fires are unlikely to establish in pleurocarpous moss mats with FMCs above 30%. Such work requires confirmation for heathlands as does the ability of flaming combustion in the moss/litter layer to ignite the *Calluna* canopy. The current study is based on a limited number of fires in a single *Calluna* fuel type. Further ignition tests in a wider range of conditions, especially during summer and in a wider range of fuel structures, will allow us to evaluate the importance of fuel structural characteristics and other factors such as wind speed and slope and to identify robust critical thresholds in fuel moisture content. Priorities for the development of a UK fire danger rating system are therefore: ignition tests on moss/litter fuels, the development or ground-truthing of FMC models for moss/litter and elevated dead fuels and further ignition tests of *Calluna* to determine sensitivity to differences in fuel structure and wind speed.

Acknowledgements

We wish to express our thanks to the landowners and managers that allowed us access to their property for our research: the Ministry of Defence, the Scottish Agricultural College and Ralia Enterprises. The Game and Wildlife Conservation Trust kindly provided us with field logistical support. Teresa Valor-Ivars assisted with the fieldwork. This project forms part of the FireBeaters project (http://firebeaters.org.uk) and was funded by the Scottish Government through the Scottish Wildfire Forum and by Scottish Natural Heritage. We are grateful to Wendy Anderson for her advice and to Michael Bruce, the chairman, and the other members of the FireBeaters Scottish Wildfire Forum steering group.

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