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The effects of fuel moisture on fire spread in shrub vegetation typical of upland heath systems in northern latitudes

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Heathlands, Fire spread, Fuel moisture content, Energy release, Heat flux, Fuel structure

Abstract

Shrubs are the dominant fuel for wildfires which occur in heathland systems however, there are relatively few studies which explore the processes of flame spread in shrub fuels. A series of laboratory flame spread experiments are used to identify the relationships between the fuel moisture content of the fuel components of heather (Calluna vulgaris) shrubs and the resulting fire spread dynamics. Measurements of energy release, flame spread rate and mass loss are made to characterise the burning of 2 m × 0.75 m fuel beds, and heat flux measurements are made to record the magnitude of the propagating fluxes. Fuel moisture thresholds for fine and coarse fuel elements required for fire spread are identified, and the magnitude of the in-bed heat fluxes are reported. From the observations, it is suggested that the leading edge of the flame front is driven by the moisture content of the fine dead material suspended in the heather canopy while the trailing edge is dominated by the burning of coarser fuels which supports the burning of fine green fuels. These findings allow further targeted experimental study and can be used to aid determination of fire effects.

1. Introduction

Heathlands represent a major fire hazard in many parts of the world. For example, in the UK, 94% of wildfires fires occurred on heathlands (Taylor et al., 2021). The primary vegetation structures on UK heathlands are shrubs (e.g., *Calluna vulgaris*, *Ulex minor*), mosses and litter. There are also significant areas of upland heaths in the UK with underlying organic peat soils which, if ignited, can result in large release of carbon dioxide to the atmosphere. Despite the significance of these systems globally, there remains relatively little understanding of the drivers of fire spread in these systems. Fires are common in these systems through natural ignitions or through traditional land management practices (Davies et al., 2008). However, climate and land use changes are predicted to alter the intensity, and frequency of fires in these systems and therefore it is necessary to develop a detailed understanding of the mechanisms of fire spread in shrub fuels. This will allow improved fire risk prediction in these systems.

This work seeks to develop a process-based understanding of the fire spread in shrub fuels. Laboratory experiments are used to study the burning of *Calluna vulgaris*-dominated systems under quiescent conditions to identify the drivers of fire spread.

2. Methods

Experiments were carried out in the Rushbrook Fire Laboratory at the University of Edinburgh. Experiments were performed by constructing fuel beds with a nominal area of 2 m × 0.75 m using vegetation harvested locally.

2.1. Fuels: collection and conditioning

The structure of the *Calluna vulgaris* (heather) plant is given in Figure 1. There are three parts of note in the heather plant, older leafy growth which typically comprises fine dead (brown) leaves; younger growth which is characterised by green leafy growth and flowers; and coarse stems. In addition to the heather, heathlands have a moss and litter layer on the soils.

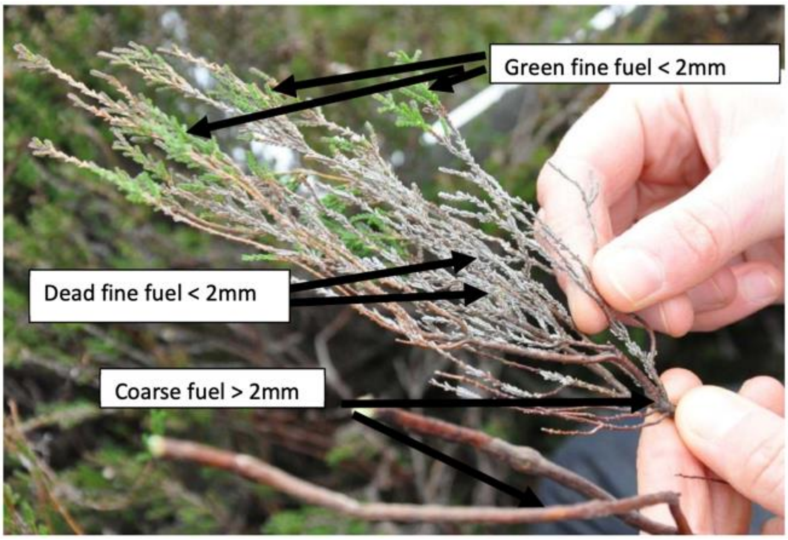

Figure 1 The different fuel types on heather (from Taylor et al., 2021)

Fuels were collected from the Pentland Hills Regional Park near Edinburgh, UK. Fuel samples comprised heather shrubs and the underlying moss and litter. Fuels were harvested in plots of approximate dimensions similar to those of the experimental fuel bed area (2 m × 0.75 m). After harvesting, fuels were stored under laboratory conditions until they were burnt. Prior to each experiment three samples of each of the fine green, fine brown, coarse stems and moss were collected. These were dried in an oven at 80°C for 48 hours to determine the fuel moisture content.

2.2. Experimental procedure

Immediately prior to burning, the fuel beds were assembled on a mineral wool substrate. The moss was distributed uniformly over the fuel bed area and the stems of the heather were pierced through the mineral wool. Care was taken to ensure consistent fuel bed heights and uniform distribution of stems across the area. A length of cotton rope (~0.8 m long) soaked in acetone and laid at the base of the heather was used as the ignition source. This is a strong, repeatable ignition source ensuring even ignition along the full 0.75 m short edge of the fuel bed. After ignition, the fire was allowed to spread (or not) and the test was terminated after flaming combustion had stopped or, if there was significant smouldering of course material, after this had stopped.

2.3. Measurements

Global and local fire behaviour measurements were made to characterise the flame spread and burning of the fuel bed. The whole fuel bed was supported on a load cell to obtain mass loss, total mass lost, and mass loss rate measurements. Heat release was measured by oxygen consumption calorimetry. Visual recordings of the flame spread were used to calculate the flame spread rate.

Local measurements of heat flux were made in three locations: at 2/3 fuel height facing the spreading flame; flush with the surface of the moss, and flush with the surface of the mineral wool substrate. Measurements were made using water cooled heat flux gauges (Huskeflux SBG01). These measurements allow analysis of the magnitude and duration of heating and help guide analysis of dominant heat transfer processes.

3. Results and discussion

An overview of the experimental conditions is given in Table 1. Sixteen experiments were conducted in total. These fall into two categories: experiments 2—7 with reduced measurement and instrumentation and variation in fuel loading and fuel moisture treatments. Experiments 8—17 were carried out with a more consistent fuel loading and fuel moisture treatment regime and also include the heat flux measurements. The fuel loadings are given on a wet basis.

Table 1 The experimental conditions, mass loss, and spread rate

	Fuel loading, kg/m²				Fuel moisture content, %				Mass consumed, %	Spread rate, cm/s
Exp.	**Moss**	**Heather**	**Total**	**Post burn**	**Fine green**	**Fine dead**	**Coarse**	**Moss/ Litter**		
1	--	--	--	--	--			--	--	--
2	1.22	2.24	3.46	1.96	1 day lab conditioned			Dry	43.43	--
3	1.31	3.59	4.90	0.71	2-day lab conditioned			Dry	85.48	1.295
4	0.27	4.97	5.24	0.10	3-day lab conditioned			Dry	98.17	1.622
5	0.75	6.18	6.93	4.80	5-day dry, then wetted (200 g water/kg heather)			Dry	30.79	--
6	0.22	1.84	2.06	--	5-day dry, then wetted (200 g water/kg heather)			Dry	--	--
7	2.57	4.20	6.77	1.78	6-day lab conditioned			Wetted	73.65	1.139
8	0.39	3.11	3.50	3.34	73.69	43.73	77.71	135.26	4.40	--
9	0.39	3.26	3.65	3.57	73.69	43.73	77.71	135.26	2.40	--
10	0.39	29.27	3.06	0.54	23.97	22.17	43.92	23.04	82.20	1.268
11	0.24	3.52	3.75	3.70	112.62	45.88	87.18	222.81	1.55	--
12	0.24	35.78	3.10	1.51	43.95	26.49	53.92	84.39	51.29	0.741
13	0.33	3.50	3.83	3.77	65.32	33.18	59.70	180.17	1.51	--
14	0.33	3.44	3.76	3.52	65.32	33.18	59.70	180.17	6.55	--
15	0.36	3.09	3.46	0.88	41.46	23.77	60.63	48.18	74.64	1.277
16	0.14	2.81	2.95	1.09	70.14	27.26	72.24	27.27	63.01	0.664
17	0.29	2.89	3.18	0.28	46.54	12.54	36.39	66.55	91.23	1.714

Figure 2 shows a composite image of the 16 experiments taken 60 s after ignition to give an indication of the typical behaviours observed. The leading edge of the flame front in experiments 2, 3, 4, 7, 12, 15, 16 and 17 has propagated away from the ignition source and it is assumed that there is no longer an influence of this on the fire spread. Flame heights in these experiments are in excess of 2 m and the flame front has a depth approaching 1 m, indicating a significant degree of combustion behind the leading edge of the flame front. Experiments 5 and 6 remain in the location of the ignition source and flame heights in these cases are approximately 1.5 m. The flame in experiments 8, 9, and 14 are both discontinuous and less than 0.5 m in height. The flames in experiments 11 and 13 have quenched at this time with only residual burning near the ignition source apparent.

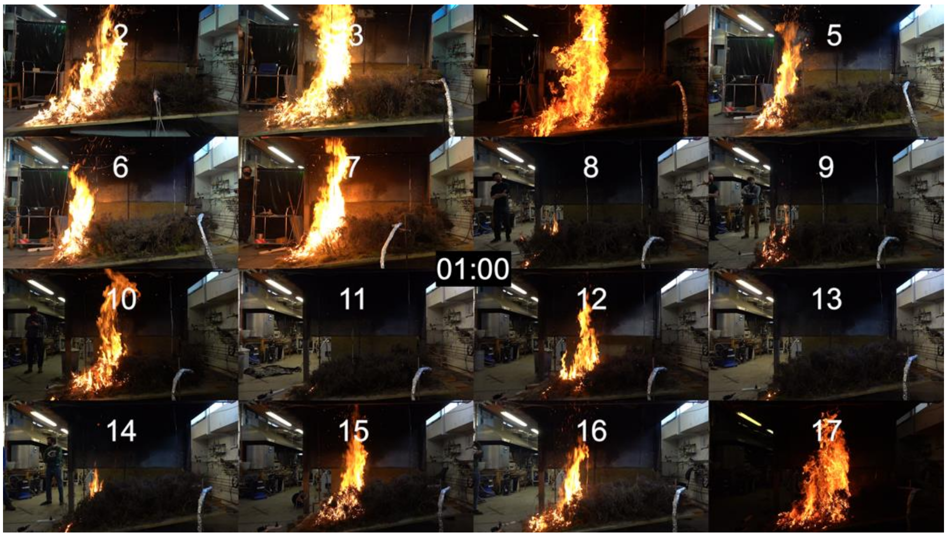

Figure 2 Composite image of laboratory flame spread experiments 60 s after ignition

3.1. Spread rate

The average rate of spread is measured by evaluating the time taken from ignition required for the flame to traverse the entire length of the fuel bed. Flame spread data are only reported when the flame traversed the entirety of the fuel bed. Flame spread rates ranging from 0.66 to 1.71 cm/s were recorded.

The spread rate is shown as a function of the fuel moisture content (FMC) of the different fuel elements in Figure 3. These data indicate that the flame spread rate has a strong dependence on the FMC of the fine dead fuels. The FMC of the fine green and coarse fuel elements also show an increasing trend in spread rate with decreasing FMC. The FMC of the moss does not appear to have a strong influence on the spread rate. It should be noted that in performing this analysis the assumption that the variations in fuel loading between experiments is not significant has to be made.

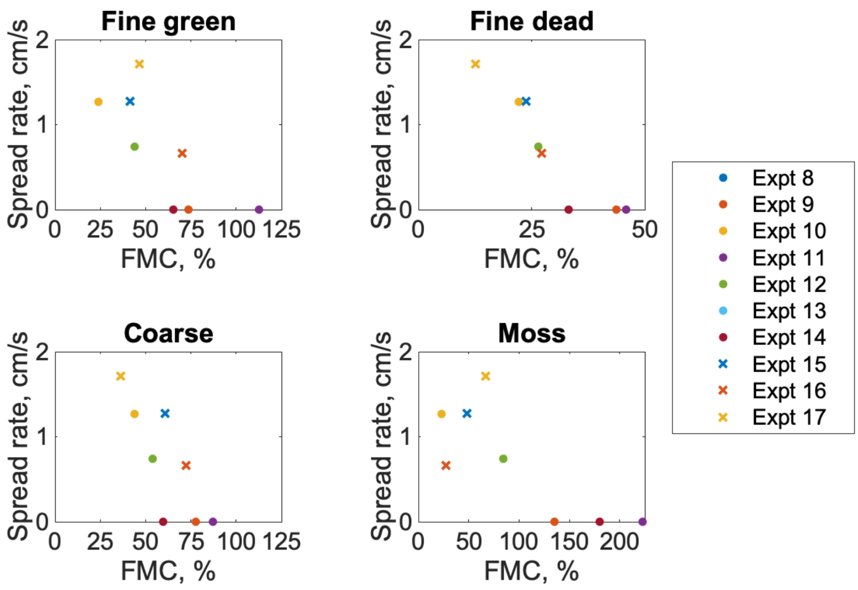

Figure 3 Flame spread rate as a function of the FMC of different fuel elements. Note the different ranges on the x axes.

These data also allow some thresholds for fire spread to be identified by evaluating the lowest FMC at which the fire did not spread and the highest FMC at which the fire did spread for each of the fuel classes to be identified. These are summarised in Table 2.

Table 2 Fuel element FMC thresholds for fire spread

Fuel element	**FMC threshold for spread, %**
Fine green	47—65
Fine dead	26—33
Coarse	54—60
Moss	84—135

3.2. Mass consumed

The total mass lost was recorded using measurements of the total mass of fuel in the fuel bed before ignition and at the end of the experiment. The mass loss ranged from 2 to 98%. Low mass losses were attributed to cases where the fire did not spread beyond the ignition source. For the cases which were identified as spreading through the whole fuel bed, the mass lost ranged from 51 to 98%.

The mass lost is shown as a function of the FMC of the different fuel elements in Figure 4. The total mass lost is again shown to be a function of the FMC for the different fuel elements. Again, there is a strong correlation with the FMC of the fine dead fuel. These data may suggest a stronger relationship between the FMC of the coarse fuels and the total mass lost compared to the spread rate, however this should be treated with caution due to the interactions between spread rate and heat release rate.

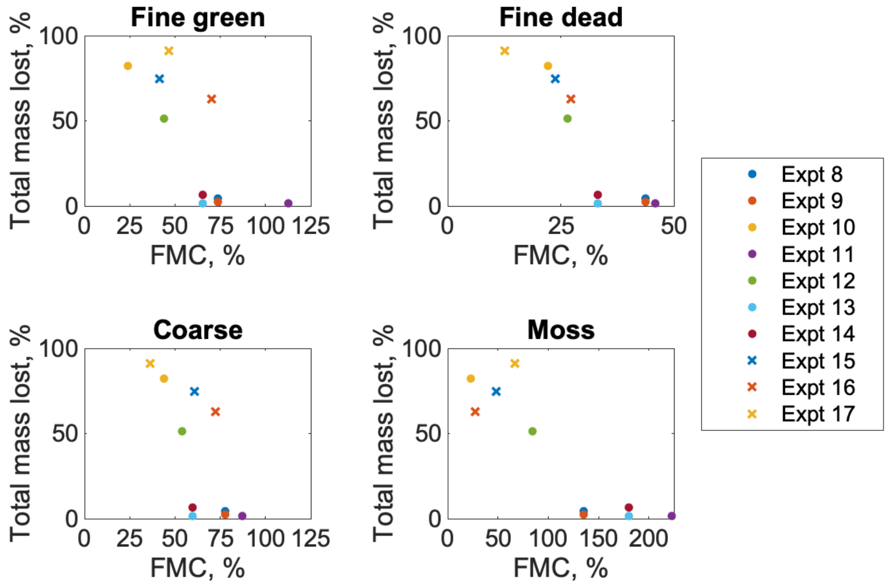

Figure 4 Total mass lost as a function of the FMC of different fuel elements. Note the different values on the x axes.

3.3. Energy release

The observations made until now can be subjected to independent verification using the energy release as measured by oxygen consumption calorimetry. This is shown for experiments 2—7 in Figure 5. The highest energy release exceeded 600 kW for experiment 4. This experiment also had the highest mass consumption (98%). This is due to these fuels having been dried for 3 days in the laboratory. Experiment 3 which also had a high mass consumption (85%) and had been dried for 2 days showed a lower peak energy release with a maximum in the range 400 kW. Similarly experiment 7 with 6 days conditioned dry heather and wetted moss, had a similar peak heat release rate (400 kW). However, this experiment took longer to reach the peak compared to experiment 3 indicating that the combustion of the moss layer, while not significant in determining the overall energy (due to the relatively small mass), may play a role in determining the total energy release under some conditions.

In experiments 2, 5 and 6, the flame did not spread on the full length of the fuel bed. In experiment 2 and 5, 43 and 31% of the mass was consumed indicating partial spread. No measurements of mass lost are available for experiment 6. Consequently, the measured energy release is low for these experiments. The peak in energy release in experiment 6 at around 120 s is attributed to uneven application of water while wetting the heather. These interpretations are confirmed by visual observations.

The energy release data for experiments 10, 12, 15, 16, 17 are shown in Figure 6 (data for experiments 8, 9, 11, 13 and 14 are omitted as no fire spread beyond the point of ignition was observed). These data indicate that there are two clusters: a high energy release cluster with experiments 10, 15 and 17 and a lower energy release grouping with experiments 12 and 16. This is reflected in the spread rate measurements where the spread rates in experiments 10, 15 and 17 were in excess of 1.20 cm/s but for experiments 12 and 16 the rates of spread were 0.74 and 0.66 cm/s, respectively. The higher spread rate in experiment 12 is attributed to the combination of lower moisture content of the coarse and fine green fuel elements compared to experiment 16. The coarse FMC was between 36 and 61% in experiments 10, 15 and 17 meanwhile for experiments 12 and 16 the coarse FMC was 54 and 72%. Likewise, the fine green FMC was between 24 and 47% for experiments 10, 15 and 17 and between 44 and 70% for experiments 12 and 16. For context, should be noted that in field experiments the FMC of the live coarse fuels was approximately 70—80% (Taylor et al., 2021).

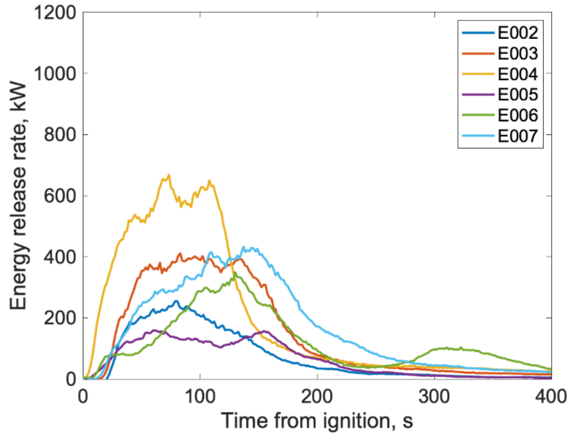

Figure 5 Energy release as a function of time for experiments 2—7.

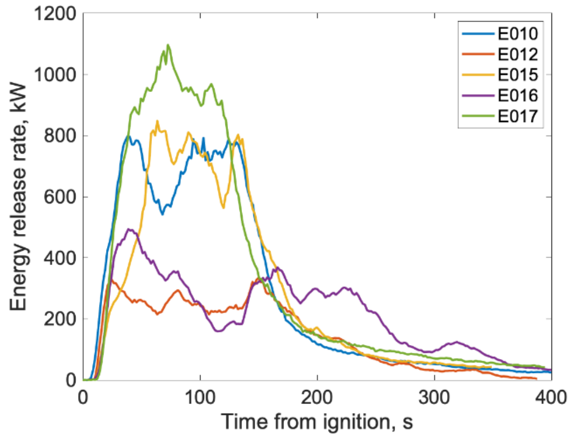

Figure 6 Energy release as a function of time for experiments 10, 12 15, 16, 17.

3.4. Heat fluxes.

The heat fluxes to the mid height of the heather canopy are shown in Figure 7. Only data for experiments in which flame spread was observed to occur on the whole length of the fuel bed are reported. The data show that the heat fluxes through the heather canopy exceed 100 kW/m^2 where there are large flames and significant burning behind the leading edge of the flame e.g., experiments 4, 10 and 17. For experiments with smaller flames with less burning behind the leading edge (e.g., experiment 16), lower heat fluxes are recorded but for extended durations. In cases where the flame thickness is lower (e.g., experiments 7 and 12), the heat flux was between 50 and 100 kW/m^2. Finally, in cases where the flame spread is characterised by a thin flame front, the heat fluxes is around 30kW/m^2. This highlights the importance of the burning behind the leading edge of the flame front in driving the fire spread processes.

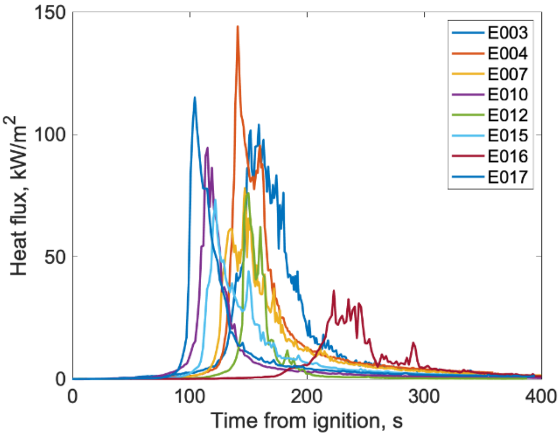

Figure 7 Heat fluxes to the heather canopy as a function of time from ignition.

4. Conclusions

Using laboratory scale experiments, we have observed the effects of different fuel elements on the likelihood for fire spread in *Calluna vulgaris*-dominated systems. These results apply only to laboratory conditions and should not be applied directly to fire danger assessments. The results indicate that the fire spread in heather under these conditions is a complex process in which the interaction between the different components of the fuel structure determines the fire spread characteristics. It seems that the fine brown fuels dominate the leading edge of the fire spread and that radiation from the trailing edge where the coarse fuels are burning supports combustion of fine green fuels. Heat fluxes greater than 100 kW/m^2 are measured from the combustion zone to the heather ahead however the heating lengths are very short. These insights will help develop models for flame spread in shrub fuels, in the development of fire danger systems and in the evaluation of fire impacts.

5. References

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