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Laboratory Flame Spread Experiments on Calluna Vulgaris Vegetation: Effect of Fuel Moisture Content and Fuel Load on Fire Behaviour

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International Master of Science in Fire Safety Engineering

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Abstract

Series of fifteen laboratory flame spread experiments were done on Calluna Vulgaris (also known as heather) vegetation, which commonly found in British Highlands and North-Western European coastal heathlands. The goal of the experiments were to evaluate the effect of fuel moisture content and fuel load on fire behaviour. In addition, impact of fuel layers in Calluna vegetation (fine dead, fine green and moss layers) with respect to their fuel moisture contents and fuel loads were observed. The FMC of the vegetation in experiments were varied between 10-32% for Calluna fine fuels and 12-79% for moss layer. Rate of spread, mass consumption, heat release rate, mass loss rate and local heat flux measurements were done and results were compared with the literature values, when available. An inverse relationship between fuel moisture content and fire intensity were observed for the measured values, while there were positive relationship between fuel load and fire intensity. Effect of moss layer on fire behaviour were clearly observed in rate of spread and heat release rate measurements, both in wet and dry moss layer cases and explanations were made.

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1. Introduction

Calluna Vulgaris (also known as heather and hereafter will be referred as Calluna) is a dwarf-shrub species that is commonly found in heathlands of North-western Europe and British Uplands. Fires occurring in these Calluna dominated heathlands are natural and part of the lifecycle of the vegetation [1]. While the correct way of managing these fires are debated, such as prescribed burning strategies [2]–[5], extinguishing wildfires or letting them burn [6], [7], etc.; there are concerns that the frequency of these fires will increase due to climate change or increasing urban-wildland interference [8]–[10]. Therefore, understanding the behaviour of these fires and how they spread are crucial and would benefit the authorities for the successful management of these fires.

Fire behaviour for a specific vegetation can depend on many factors and these factors can be grouped under two clusters: fuel particle properties; such as species, moisture content, thickness, etc., and fuel bed properties; such as bulk density, live – dead fuel ratio, porosity, etc. [11, p. 136]. While the impact of these properties can vary for different vegetations, some of these fuel properties usually have a higher influence on the fire behaviour.

For example fuel moisture content (can be referred as FMC hereafter) is one of the most critical properties which can directly affect the wildland fire attributes such as heat release rate, rate of spread [12] and ignition [13]. While effect of FMC on some of these attributes have been experimentally observed previously, understanding the complex dynamics behind these effects are highly challenging for the wildland fuels [14]. Unlike common construction materials in fire science, FMC of wildland fuels can vary greatly between different weather and season conditions. For example, in [15] it has been observed that FMC of Calluna vegetation in Scottish Highlands can highly fluctuate when exposed to specific winter conditions (relatively mild snow, low night temperatures and frozen ground), and cause fire hazards. Another experimental study from Norwegian coastal heathlands showed that severe wildfire hazards can occur when vegetation is exposed to 0 °C air with 50% relative humidity for two days only [9]. As these rapid changes in FMC occur, or can occur, throughout the entire year; prediction of fire behaviour and taking required precautions can become challenging.

Besides changes in environmental conditions, FMC of wildland fuels can vastly vary due to their heterogenous fuel properties as well. For example Calluna vegetation consists of 4 sub-fuel types which are:

- Fine green (live) fuels
- Fine dead fuels
- Coarse stem fuels
- Moss and litter layer

These four different fuel types can have different moisture content levels and FMC sensitivity to changing environmental conditions; so that their impact on Calluna fires can vary as well. Both in [16, Ch. 5.3], [17]; experiments pointed out that FMC of the fine dead fuels, and their share in overall fuel load, can be the major factor that controls the Calluna fire behaviour; such as flammability, rate of spread and HRR. On the other hand, despite their relatively low proportion on total vegetation load, there is evidence that FMC of moss layer can also influence the fire behaviour [18].

Another property that can affect the fire behaviour in Calluna fires can be the fuel load. In nature, Calluna stands are not homogeneously distributed so that burning behaviour can vary between patches or fields, as the available fuel that can burn differs. In [16, Ch. 4], the fuel loads, as in oven-dried mass, were measured in the field and the results were that: fine fuel (both live and dead) loads measured between $\sim 645 - 1615\ [g/m^2]$, the coarse fuel loads were between $\sim 148 - 1374\ [g/m^2]$ and; moss and litter loads were between $\sim 439 - 1251\ [g/m^2]$. Fuel loads, especially as varied as these, can significantly change the outcome of the fires in case of spread rates, burning rates (mass wise) and available energy (or heat release rates) [11, p. 136]. For example in [19], using controlled field experiments, a negative relationship between bulk density and rate of spread were observed. It should be noted that fuel load can be expressed in diverse ways such as dry fuel mass (oven dried) in kg, dry fuel loading in kg/m^2, bulk density kg/m^3, etc. Sampling, categorizing and measurements in shrub fuels, like Calluna, can be highly challenging due to its structural complexity in both axes and heterogeneous fuel combinations [11, pp. 276–278], [17]. Because of this reason, the fuel load expressions can vary depending on the controlled variables and availability.

Up to this point in a brief summary is that FMC of Calluna can affect the fire and flame spread behaviour significantly, as previous studies suggests. When evaluating the effect of FMC, heterogenous fuel type structure of Calluna should also be taken into account as there were various correlations between Calluna fuel types and fire behaviour. While these correlations were observed mostly for fine fuels (especially for fine dead), effect of moss can also not be neglected and should be examined further. Additionally, fuel loads should be considered too when talking about Calluna fire behaviour as it can alter significantly for different patches, while affecting the fire behaviour in case of available energy or rate of spread. Since fuel load measurements can be challenging and extremely labour demanding in field experiments, effect of the fuel load were studied relatively less. In this study, effect of the FMC will be evaluated, while also considering the effect of different fuel types and fuel loads. It should be noted that the focus on examining the effect of different fuel types were the fine fuels and moss layer, due to their potential being discovered in previous relevant studies and the effect of coarse fuels were relatively neglected.

While all these chosen properties are highly connected to each other, again due to the complexity and uncertainties of understanding the wildland fire problem, evaluating them together in field conditions can be extremely challenging. In order to decrease these uncertainties and have a more controlled environment, laboratory experiments were chosen instead of field experiments. In that way, additional dependent properties, such as wind or slope; can be eliminated; while also additional measurements can be done more precisely, such as heat release rate or mass loss rate. However, it should be strongly emphasized that the aim of this study is to give insights about how the fire behaves with respect to the properties mentioned for Calluna vegetation, using an artificial laboratory setup. Numerical results from these experiments will most probably not reflect real fire scenarios because of its idealized conditions (such as no wind or slope), which can significantly affect the results [20]). Additionally, due to static environment in the laboratory, fuels have higher possibility to reach equilibrium moisture content, which rarely happens in the nature, so that effect of FMC can be more consistent during experiments when compared with real fires. Nevertheless, fire behaviour in these experiments with respect to different FMC and fuel loading conditions can be greatly beneficial as the controlled environment in these experiments can illuminate some of the fire behaviours better. The feasibility of such laboratory experiments on studying flame spread in Calluna fires and the effect of FMC, were previously tested in [16, Ch. 5.3] and the results were seemed as encouraging.

1.1. Objectives

The objectives of this study are to:

- Study the effect of FMC on Calluna fire behaviour with respect to different fuel loads.
- Evaluate the impact of Calluna fuel types (fine green, fine dead and moss) on fire behaviour.
- Generate more data for the laboratory flame spread experiments in [16, Ch. 5.3], by following a similar methodology, and try to improve its feasibility for future studies.

2. Methodology

2.1. Sample Collection and Fuel Storage

For the laboratory experiments, vegetation samples have been collected from the field. Castlelaw Hill in the Pentland Hills (Edinburgh, UK) has been chosen for the collection. Location and date information of collected plots can be seen in Table 1 below.

Table 1. Location and date information of the collected 16 plots

Plot #	Collection Date	GPS Coordinates	what3words Address
1	31/01/2022	55.876738, -3.238188	///gangs.levels.sector
2	31/01/2022	55.876738, -3.23814	///output.misty.forms
3	31/01/2022	55.876658, -3.23814	///pans.smart.tricky
4	31/01/2022	55.876792, -3.23814	///slides.tune.maybe
5	01/02/2022	55.876846, -3.238236	///ending.defend.swim
6	01/02/2022	55.876792, -3.238284	///energy.salt.slide
7	01/02/2022	55.876792, -3.238188	///fantastic.launch.delay
8	14/02/2022	55.876846, -3.238284	///credit.broken.belts
9	14/02/2022	55.876819, -3.23814	///object.forks.civil
10	14/02/2022	55.876873, -3.238236	///love.activism.recent
11	14/02/2022	55.876873, -3.238188	///able.silver.ranch
12	14/02/2022	55.876954, -3.238236	///flies.thus.toast
13	24/03/2022	55.868383, -3.25137	///spud.situated.hunk
14	24/03/2022	55.86868, -3.251754	///mops.paradise.poetry
15	24/03/2022	55.86868, -3.251898	///beaker.display.crinkled
16	24/03/2022	55.868761, -3.251802	///detergent.giggles.names

A (2 x 1.2 m^2) area, which will be referred as plot from now on, has been selected randomly in the field and all the vegetation inside this plot were harvested. The Calluna samples were cut from the stems that are just above the ground level and the moss samples were collected afterwards from the ground in the designated plot. After harvesting several plots, moisture content samples were also collected from the field. Three samples were collected for each vegetation type, which are fine green, fine dead and moss, as introduced in the introduction section. The harvested vegetation was stored and let to be dried in the laboratory, which overall had 10-15°C and 40-60% RH conditions.

2.2. Moisture Content Measurement and Calculation

For the moisture content measurements, protocols from the previous similar studies on heather [16], [21], [22] were followed, which can be described as:

- Three vegetation samples were taken for each vegetation type (fine green, fine dead and moss, when applicable) from distinct parts of the designated plot / vegetation.
- The vegetation samples were placed in the small metal containers (Figure 1) and lid of these containers were closed tightly.
- Mass of the loaded containers were measured and noted.
- The containers, with open lid, were dried in an oven (60 °C) for 48 hours.
- After taking out the containers from the oven, lids were again closed and containers were let to be cool off.
- Mass of the containers, with dried vegetation, were again measured and noted.
- Fuel moisture content calculated for each sample and average of the samples were taken for each vegetation type.

Figure 1. Sample containers that were used for the FMC measurements.

It should be emphasized that moisture content of the vegetation can vary for the same plot even under laboratory circumstances, due to the storage conditions. For example, if moss is stored in a plastic container, part of the moss that is at the bottom of the container will contact air less so that it will be more wet than the moss located at the top of the container. Because of this reason, *sample standard deviation* should be checked when the average moisture content of the vegetation samples calculated.

The fuel moisture content can be calculated by [23]:

$$FMC = \frac{m_{wet} - m_{dry}}{(m_{dry} - m_{container})} \times 100 \qquad \textbf{(i)}$$

where:

- FMC is the fuel moisture content (%)
- m_{wet} is the mass of the sample and the drying container before drying (grams)
- m_{dry} is the mass of the sample and the drying container after drying (grams)
- $m_{container}$ is the mass of the empty drying container (grams)

And the *sample standard deviation* for fuel moisture content, s_{FMC}, can be calculated by [24]:

$$s_{FMC} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}((FMC)_i - \overline{FMC})^2} \qquad \textbf{(ii)}$$

where:

- n is the sample size, which is always 3 in this study
- $(FMC)_i$ is the fuel moisture content for data i
- $\overline{FMC}$ is the mean fuel moisture content

60 °C has been chosen for the oven drying temperature because volatile organic compounds (VOC) can be released from the vegetation during the standard oven drying process, which uses 105 °C, for moisture content measurements [25]. Since the lid of the sample containers are open in the oven, release of these VOC can affect the outcome of the measurements

negatively. Additionally, the sample masses in this study were under the recommended amount (300 gr) for the standard oven dry method [23], so that release of these VOC could affect the moisture content measurements significantly, if the temperature were higher than 60 °C.

It should also be noted that each of the sample containers had an identification number and the empty mass of these containers were checked regularly after each set of moisture content measurements to reduce empty mass uncertainties that can be caused by the leftover of the dried samples, such as small pieces of vegetation sticking inside the container after drying.

2.3. Experimental Setup

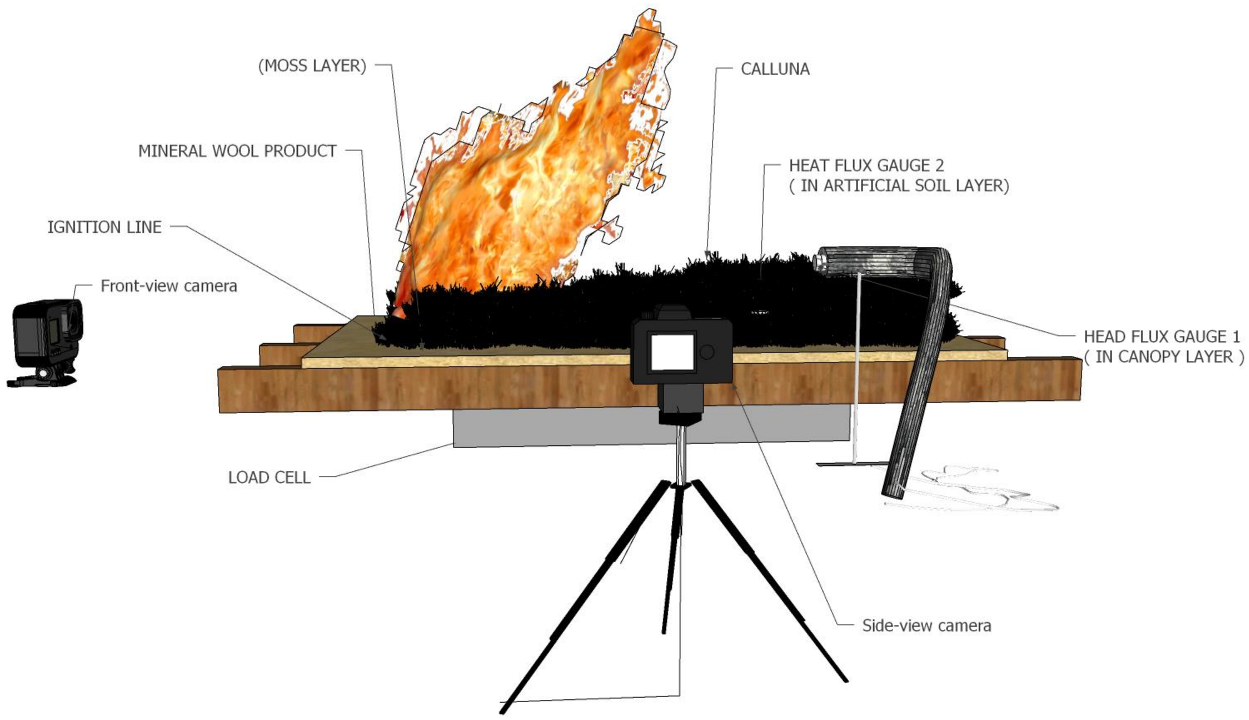

Figure 2. Illustration of the experimental setup.

2.3.1. Construction of the artificial fuel bed in the laboratory

Under the 2 x 2 m² calorimeter in the Rushbrook Fire Laboratory at the University of Edinburgh, artificial plots were reconstructed using the harvested vegetation samples. For constructing a base for the experiments, a load cell were placed centrally under the calorimeter for measuring the mass. Then three parallel wooden logs were placed on the load cell for supporting purposes and a mineral wool product were placed on them. The mineral wool product (1.2 x 2 m^2) can be seen as an artificial ground or soil, as it directly contacts with the Calluna and moss layer.

After building the base, the protocol for setting up the fuel beds can be explained as:

- If the experiment were aimed to have moss layer under Calluna; moss were placed uniformly on the mineral wool base, approximately covering 1.7 x 1 m^2 area on average. Mass of the system with the added moss layer were noted.
- Calluna were uniformly placed on top of the moss layer, perpendicularly or as it is in the nature, by stabbing the mineral wool base using its' relatively thick stems. Mass of the system with the added Calluna were noted.
- Moisture content samples of Calluna (fine live and fine dead) and moss were then taken before the ignition by following the steps in Section 2.2. Final mass of the experimental setup were noted.

Most of the tested vegetation had relatively low moisture content so that no slopes were necessary for the flame to spread. The illustration of the experimental setup can be seen in Figure 2, and a real representative example can be seen in Figure 3 below.

Figure 3. Example of an artificial fuel bed with moss layer.

2.3.2. Ignition

A one-meter acetone-soaked rope was used for igniting the fuel in the experiments. The rope was placed parallelly along the same short edge of the fuel bed for all experiments and aimed to start simultaneous ignition along the line.

2.3.3. Measurements

2.3.3.1. Mass

Using the load cell that has been placed under the experimental setup, mass measurements have been made before and during the experiments. Steady state mass of the moss and Calluna layers have been measured while constructing the fuel bed, as described in the previous section, for determining the fuel mass load for each vegetation layer. In addition, mass of the experimental setup has been recorded, with ≈2.6 s timesteps, throughout the flame spread experiments so that mass loss rate and the mass consumed by the burn can be calculated.

2.3.3.2. Heat Release Rate (HRR)

Using the calorimeter and measuring the concentration of O_2, CO_2 and CO in the combustion products[26], heat release rate has been calculated using MATLAB, with ≈2.6 s timesteps.

2.3.3.3. Heat Flux

Heat flux measurements have been made, using water cooled heat flux gauges in two separate locations: one in the mineral wool, under the moss layer; and the other one 27 cm over the first one, aimed to be located around the middle height of the Calluna. Data from the heat flux gauges have been recorded again with ≈2.6 s timesteps. Approximate location of the heat fluxes can be seen in Figure 2.

2.3.3.4. Visual Measurements

Two video cameras have been used for recording the experiments. First one has been positioned to capture side view angle for determining the flame spread rate afterwards. Second one has been positioned to capture front view (located at the ignition side) for observing the fuel behaviour (ignition and spread) from another angle.

2.4. Experimental Matrix

Over the course of 2 months, 15 experiments were completed in total. For the first nine experiments, various combinations of fuels were evaluated around three parameters:

1) ***Fuel moisture content*** of the vegetation (both Calluna and moss)
2) ***Presence of moss layer,*** which means constructing fuel beds with and without moss layer
3) ***Fuel load***, or (dry) mass of the vegetation in other words

Using the information obtained from the first nine experiments, the experiments 10-15 were conducted using vegetation that has same fuel moisture content levels; and the relationship between the remaining two constraints were aimed to be observed better.

The dry mass of the vegetation, $m_{dry,vegetation}$, has been simply calculated by:

$$m_{dry,vegetation} = m_{wet,vegetation} \times \frac{100 - FMC}{100} \quad \text{(iii)}$$

where:

- $m_{wet,vegetation}$ is the wet mass of the vegetation (grams)
- FMC is the fuel moisture content of the vegetation (%)

Table 2. Experimental matrix, which also includes the mass consumption and fire spread rates of the experiments.

Experiment #	Plot #	Vegetation Area [m2]	Moisture Content [%]				Dry Mass [kg]		Mass consumed [%]	Spread Rate [m/min]
			Fine Green	Fine Dead	Calluna Average	Moss	Moss	Heather		
1	1	1.75	19%	21%	20%	64%	0.6	4.0	56%	-----
2	2	1.70	11%	9%	10%	0%	0.0	5.6	98%	0.62
3	3	1.62	13%	10%	11%	58%	0.6	4.2	79%	0.43
4	4&7	1.62	14%	9%	12%	49%	0.6	5.6	79%	0.31
5	5	1.62	10%	11%	10%	14%	0.3	4.5	-----	0.63
6	6	1.49	10%	11%	10%	75%	0.2	4.6	97%	0.60
7	11	1.66	39%	23%	31%	68%	0.1	3.1	33%	-----
8	10&12	1.70	30%	15%	22%	0%	0.0	4.8	65%	0.28
9	9	1.62	12%	13%	12%	79%	0.3	4.3	88%	0.45
10	14	1.70	11%	10%	10%	12%	0.3	5.4	98%	1.13
11	13	1.70	11%	10%	10%	0%	0.0	6.7	97%	0.70
12	15	1.70	11%	10%	10%	12%	0.3	3.1	93%	0.95
13	15&16	1.70	11%	10%	10%	0%	0.0	3.1	76%	0.54
14	16	1.70	11%	11%	11%	12%	0.3	1.7	85%	1.21
15	16	1.70	11%	11%	11%	0%	0.0	1.9	52%	0.45

3. Results and Discussions

Vegetation has been ignited successfully and fire were spread in all fifteen experiments. Only for the experiments 7 and 15; the fire has spread for some distance but not been spread fully (until the end of the mineral wool product).

Due to the experiments having various independent variables (FMC, fuel load, presence of moss layer) and this were resulted in considerable amounts of measured data; presenting the results were slightly challenging in this section. In order to overcome this; similar patterns and experimental groups were used for presenting the data for some of the variables. Readers guide for the presentation of the data in this section can be as follows:

- For static or average variables such as FMC, peak HRR, 1D rate of spread, etc.; the overall data for all experiments were presented in single figures.
- For continuous measurements, such as heat release rate (HRR), mass loss rate (MLR) and heat fluxes:
  - Firstly, the data were presented for the last six experiments (Experiments 10-15), as all had same FMC, and relatively more controlled fuel load conditions; so that the effect of the FMC were neglected. These six experiments had tree colour palettes where the fuel load in blue colour were $\sim 5 - 6$ kg, while the fuel load in green colour were $\sim 3\ kg$ and the green colour represents fuel loads of $\sim 2\ kg$.
  - Secondly, the data were presented for different fuel loading groups, which were mostly divided as $\sim 3\ kg, \sim 4\ kg$ and $\sim 5\ kg$ fuel loads (oven dried mass), in order to eliminate the effect of the fuel loads and focus the influence of FMC.
- Each experiment had its unique plotting colour so that comparison of the data can be easier between different variables. Additionally:
  - For plots: experiments with moss layer were demonstrated as regular lines in figures while experiments without moss layer were presented with dashed lines.
  - For scatter graphs: experiments with moss layer were scattered using ‘filled’ circles, while the experiments without moss layer were demonstrated with ‘empty’ circles. Also, the experiments 10,12 and 14 with dry moss layer were presented with star sign.

- Finally, detailed information about the presented experiments can always be found in Table 2 (Page 16).

3.1. Fuel Moisture Content

3.1.1. FMC Measurements

Fuel moisture content in the fuel bed were measured for the three different types of vegetation: Fine Dead, Fine Green and Moss, as explained in the Methodology section; and the results can be seen in Figure 4 below.

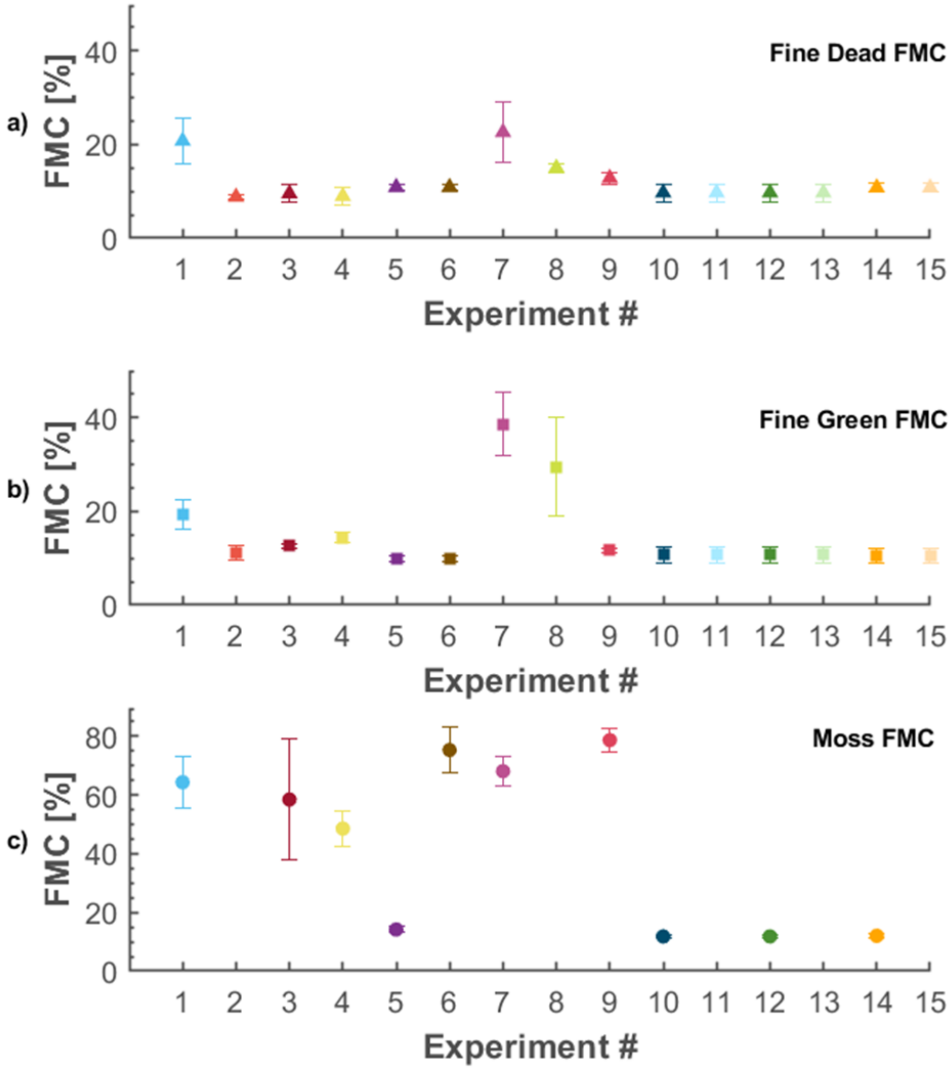

Figure 4. Fuel moisture content [%] of the Fine Dead, Fine Green and Moss for each set of experiments, with standard deviations: a) Fine Dead Fuels, b) Fine Green Fuels, c) Moss

In Figure 4 parts a and b; it can be seen that the standard deviations of the fuels were mostly negligible in the experiments, especially for the fuels with low moisture contents. Experiment 7 can be the only exception with its relatively high standard deviation (~7%) for fine dead and fine green fuels, as it had the highest FMC for both of the fuel types. However, since the fire were not fully spread in Experiment 7, the output data of it has been excluded for most of the variable comparisons in the following sections so that it did not have a major effect on the concluding remarks of this report.

Experiment 8 also had a high deviation for the fine green FMC (~11%); where the three measured fuel moisture contents were 38%, 33% and 18%, with a 30% FMC average overall. As the distinction between fine dead and fine green fuels were visually made, it can be argued that some of the fine dead fuels were mixed with fine green fuels for the third FMC sample with 18%, so that a lower FMC value were obtained.

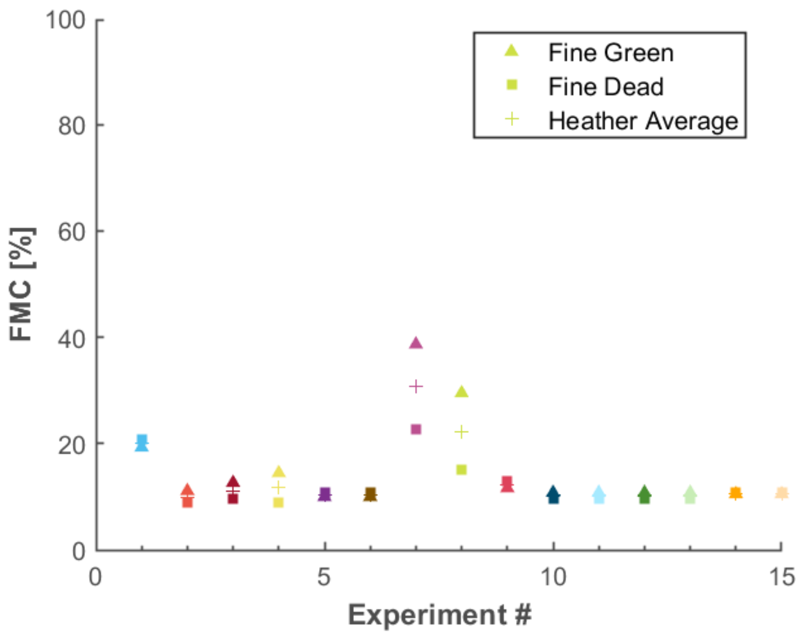

Figure 5. Calluna FMC measurements for experiments 1-15. Average of fine green and fine dead fuels were presented as Heather Average (or Calluna Average) for simplification purposes.

In some of the previous studies [16, p. 92], [17], it has been asserted that the ignition and flame spread of Calluna wildfires were considerably associated with the FMC of the Fine Dead fuels. On the other hand, since the distinction of fine dead and fine green parts of the vegetation were practically challenging, in both field and laboratory conditions, it can be argued that making this separation when presenting the data, such as HRR, MLR, etc., with respect to the FMC can be misleading. While making such a separation imposes an additional data load, it may also confuse the reader, as there is already much data to evaluate. Because of these reasons, a simplification has been done by taking the average FMC of fine green and fine dead fuels; and defining this average as ***Calluna Average*** *FMC* (or ***Heather Average*** *FMC*).

In Figure 5, both of the FMC values for fine dead and fine green fuels can be seen for the experiments 1-15. It can be seen that except for the Experiments 7 and 8; fine dead and fine green FMC values were remarkably similar for most of the experiments. The explanation for the exception of the Experiments 7 and 8 were discussed above. Besides those, the Calluna Average concept seems to be a good fit for the experiments in this study, most probably due to the low variability in Calluna FMC. Because of this reason, Calluna Average (Heather Average) values were used as a single FMC variable for Calluna, for most of the presented data in this report.

For the moss, it can be seen in Figure 4 that the fluctuations in FMC measurements were relatively higher when compared with parts a and b. However, since it had higher fuel moisture contents overall, higher standard deviations were expected for the moss layer in experiments. As the fuel load of moss were significantly lower than the Calluna, these fluctuations can be neglected. As a side note, high fluctuations in moss FMC were most probably caused by the storage conditions of the moss vegetation. Due to its small particle size, moss were stored either in plastic containers or in plastic bags. Because of this reason some of the moss were contacted air with less and these parts of the moss were did not dried as well as the parts, or the vice versa. In future studies, a better way of storing moss can be considered because of this reason.

3.1.2. Fuel Moisture Content Thresholds

During the experiments, almost all fuel beds, except the Experiment 7, were ignited at first try and sustained a successful spread as the fuel moisture content of the Calluna were relatively low. The fuel moisture content threshold of the Calluna for a successful fire spread were $\sim 39 \pm 7\%$ for fine green fuels and $\sim 23 \pm 6\%$ for fine dead fuels in the experiments. While the variation in the Calluna FMC should be increased by doing more experiments for examining further these thresholds; it can be strongly argued that the obtained threshold values in controlled laboratory environment will be lower than the real fires, as there was no slope or wind that affected the fire behaviour. In reference [16, p. 92], this threshold was around $\sim 52 \pm 4\%$ for fine green and $\sim 30 \pm 3\%$ for fine dead fuels, for a very similar experimental setup. The difference between the thresholds can be explained by the fact that the reference study had

5-10% slope under the fuel bed, so that the flame spread were induced more with verticality [27]. Furthermore, for the field experiments in reference [16, p. 110], the FMC thresholds were ~75% for fine green and ~20% for fine dead fuels while in reference [17]; the FMC threshold for a successful spread for 2x2 m^2 fuel beds in the field were 75% for the lower (dead) canopy layer. An overall comparison of the FMC thresholds mentioned above can be seen on Table 3 below. Besides the constraints in the table, there can be several other factors that might affect the FMC thresholds in Calluna fires such as the Calluna maturity, live-dead ratio of the fuel, weather, seasons, etc. Therefore it should be highlighted that the FMC thresholds obtained in this study are only a representation of some conditions and they should not be seen as absolute values.

Table 3. Comparison of FMC thresholds for several different studies on Calluna fires. * For Reference [17], the threshold given was for the 'lower canopy layer', which aimed to be consisted mostly of fine dead fuels.

Experiment	Setup	Slope / Wind?	Fine Green	Fine Dead
This Study	Laboratory	No	$39 \pm 7\%$	$23 \pm 6\%$
Reference [16, p. 92]	Laboratory	5% Slope	$52 \pm 4\%$	$30 \pm 3\%$
Reference [16, p. 110]	Field	Yes	~75%	~20%
Reference [17]	Field (2x2 m^2)	Yes	75%*	

3.2. Visual Observations

A series of images have been taken from the side view videos of the experiments for simultaneous timesteps and they will be presented in this section in order to visualize the flame spread in the experiments. As there was no available video material for the Experiment 1, it has not been presented.

3.2.1. Effect of fuel load and the presence of moss layer

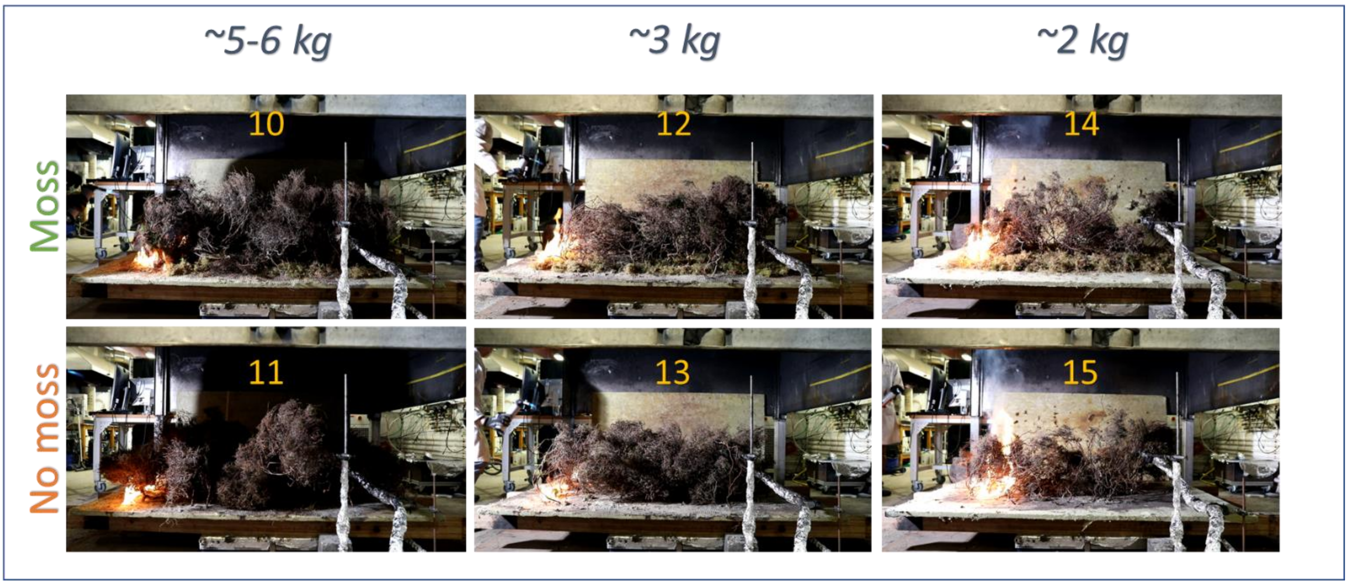

Figure 6. Images taken just after the ignition, for reference purposes, for the experiments 10-15. The top line indicates the dry fuel mass of the experiments below, while the left side indicates the presence of the moss layer.

The experiments 10-15 will be discussed firstly, as they all had similar fuel moisture contents for the Calluna and moss layer; so that the effect of fuel load and the effect of the presence of moss layer can be observed better by eliminating the variation in the FMC of the fuels. While they had different fuel loads for Calluna; the moss fuel load in experiments 10,12 and 14 were all 0.3 kg. In Figure 6, the images taken right after the ignition can be seen for reference. The relative fuel load difference between the pairs of experiments, 10-11; 12-13 and 14-15, can be seen in the figure.

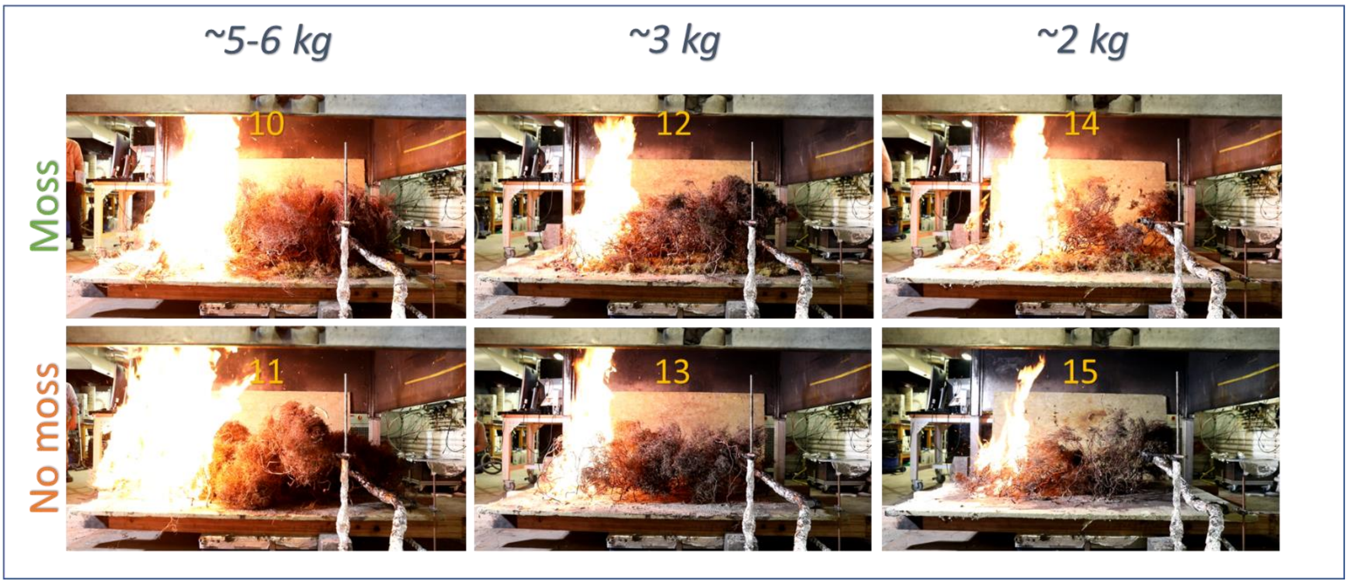

Figure 7. Experiments 10-15; images taken 30 s after the ignition.

The images taken after 30 seconds from the ignition for the experiments 10-15 can be seen in Figure 7 above. It can be seen that the fire were successfully spread in all experiments while there is a significant difference between the flame size for Experiments 10-11 and the rest, due to the higher fuel load.

Figure 8. Experiments 10-15; images taken 60 seconds after the ignition.

In Figure 8, it can be seen that the flame spread rate differences between the experiments with moss layer and the experiments without moss became more significant. While the front fire line in all experiments seems to be tilted towards right (as "/"), fire spreading through the moss layer can also be seen for the experiments 10, 12 and 14, when the burning at the bottom of the fuel bed examined. The fire were spread faster in these experiments when compared with the experiments without the moss layer.

Figure 9. Experiments 10-15; images taken 75 seconds after the ignition.

The difference between the front fire line shape can be seen more apparently in the figure above, especially for the pairs Experiments 10-11 and Experiments 14-15. The fire in the experiments with moss layer seemed to spread through bottom, while the no moss experiments still only have the "/" shape. While the fire fronts of the Experiments 10 and 11 are closer; the difference is more significant for the Experiments 14 and 15.

As the flame fronts are in similar locations for the Experiments 10, 12 and 14; and all these experiments had same amount of moss layer, it can be said that the flame spread in moss layer completely dominates the fire spread mechanisms in speed wise. On the other hand, for the experiments without moss layer; there seems to be positive and possibly linear correlation between the rate of spread and Calluna fuel load; as the experiments 11, 13 and 15 had rate of spreads in a decreasing order, similar to their fuel loads.

Figure 10. Experiments 10-15; 90 seconds after the ignition

In Figure 10 above, it can be seen that the fire in almost all experiments with the moss layer were reached at the end of the fuel bed in 90 seconds. The possible linear correlation between rate of spread and fuel load still seems to be present for the experiments without moss layer.

The explanation for the faster spread rates in experiments with moss layer can be simply explained by the fact that the ignition time being lower for the moss layer than the Calluna layer, when exposed to same amount of heat flux. For example, in flammability assessment experiments in [16, p. 55], moss with 11% FMC and Calluna with 9% FMC were exposed to 25 kW/m^2 heat flux; and the ignition times were 25 s for moss and 52 s for the Calluna. Using this information, rate of spread rates for the experiments with moss layer can be expected to be nearly the twice rate of the experiments without moss layer, for the FMC between 9-11%. Rate of spread for the experiments with moss layer (experiments 10, 12 and 14) were ∼1.1, ∼1, ∼1.2 [m/min]; while the experiments without moss layer (experiments 11, 13 and 15) had ∼0.7, ∼0.5 and ∼0.4 [m/min], respectively. In this case the relationship between the moss and Calluna ignition time seems to be consistent for the experiments 10-15 in this study.

3.2.2. Effect of moss on Calluna with similar FMC and fuel load

Until now, the experiments 10-15 were examined as they had more controlled variables in case of the fuel load, presence of the moss layer and the fuel moisture contents. In the following figures, the experiments with similar fuel loads will be categorized based on their dry Calluna masses, or fuel loads, in order to eliminate the effect of fuel load; and the effect of the moss layer and it's FMC will try to be observed better.

Figure 11. Experiments 10, 2 and 4; images taken right after the ignition, 30 seconds after the ignition and 90 seconds after the ignition. All the experiments had ~5 kg of Calluna fuel load.

In Figure 11, images taken at ignition, 30 and 90 seconds after the ignition can be seen for the Experiments 10, 2 and 4; where they all had similar fuel loads between $\sim 5.3 - 5.6\ kg$. While there is dry moss layer in Experiment 10, there is no moss layer in Experiment 2 and relatively wet moss layer for the Experiment 4. Again as there is dry moss layer burning in the Experiment 10, the flame spread seems to be relatively faster than the Experiments 2 and 4. Additionally, it seems that the variety in the moss layer affected the shape of the flame and the burning regions. The moss layer or the base of the fuel bed seems to be burning for the Experiment 10, and despite there is no moss layer in Experiment 2; there are still flames at the bottom of the vegetation. However, for the Experiment 4 there seems to be no flames at the bottom of the fuel bed, or in moss layer, which can be explained by the presence of the wet moss layer.

While the rate of spread in experiments will be discussed further in the next section, it is notable to mention that the rate of spread for the Experiments 10, 2 and 4 were $\sim 1.1\ [m/min]$,

$\sim$0.6 $[m/min]$ and $\sim$0.3 $[m/min]$, respectively. To explain these differences in the rate of spreads, the flame spread can be accepted as the ignition that occurs continuously within the fuel bed and the ignition time concept can be used [28]. If the Calluna and moss vegetation can be simply accepted as thermally thin fuels due to their smaller diameters, the ignition time can be found by the equation (21.32) from [28]:

$$t_{ig} = \frac{\left(\rho_s c_s d\left(T_{ig} - T_i\right)\right)}{\dot{q}''_s} \quad \textbf{(iv)}$$

where:

- t_{ig} is the ignition time,
- ρ_s is the density of the fuel,
- c_s is the specific heat of the fuel,
- d is the thickness of the fuel,
- T_{ig} is the ignition temperature of the fuel,
- T_i is the initial temperature of the fuel,
- $\dot{q}''_s$ is the external heat flux that is occurring on the fuel surface.

As the fuel loads and fuel moisture content of Calluna layers were similar for these experiments, it can be argued that the variety in the moss layer were the major cause for this difference in spread rates. Also, it has been assumed that the thickness of the Calluna and initial temperatures were same for simplification.

Firstly, the difference in burned regions (fire at the bottom vs no fire at the bottom) might have affected the heat transfer mechanisms so that the external heat flux, $\dot{q}''_s$, can be different for all the experiments. For example, as the fire was not present at the base of the fuel bed for Experiment 4, the effect of convective cooling from the surrounding air might have been occurred more. Secondly, as the moisture content can affect the density, specific heat and ignition temperature properties of the fuel [11, pp. 122–125], [29]–[32], it can be said that the moisture content difference in moss layer might have affected the ignition time, t_{ig}, in the experiments 10, 2 and 4. As the ignition time changes due to these properties, the ignition in a single fuel particle occurs more slow or fast so that the rate of spread in the fuel bed changes accordingly.

3.3. Spread Rate

Using the available side-view videos of the experiments, one dimensional flame spread rates were obtained. The flame spread rate calculations were done manually by dividing the length of the fuel bed with the time it takes flame front to reach at the end of the fuel bed. Experiment 7 and Experiment 1 were excluded from the calculations, as the fire was not fully spread for Experiment 7 and the video material was not available for the Experiment 1. Also for the Experiment 15, the fire self-extinguished $\sim 10\ cm$ before the end of the fuel bed so that the required adjustments in calculations were done for it.

For the experiments, fire spread rates were varied between ~ 0.3 and $\sim 1.2\ m/min$. This interval seems reasonable as some of the previous studies on Calluna had similar intervals such as; $0.35 - 1.36\ m/min$ for field experiments in [33] or $0.4 - 1.03\ m/min$ for laboratory experiments in [16, Sec. 5.3]. Since fire spread rates of the experiments were already given in experimental matrix, the relationship between spread rates and some other constraints, such as fuel load, FMC, etc.; will be discussed in this section.

3.3.1. Spread Rate and Fuel Load

From the previous sections, it has already seen and explained that the experiments with dry moss layer behaved differently and the flame spread, or flame front, were driven by the burning of moss layer in these experiments. This phenomenon can again be seen in Figure 12 below, for the experiments 10, 12 and 14, where all had significantly higher flame spread rates when compared with the rest. For these three experiments, it seems that there is no correlation between the fuel load and rate of spread. Since the flame spread mechanisms were relatively different for these experiments, they were excluded from the arguments discussed below.

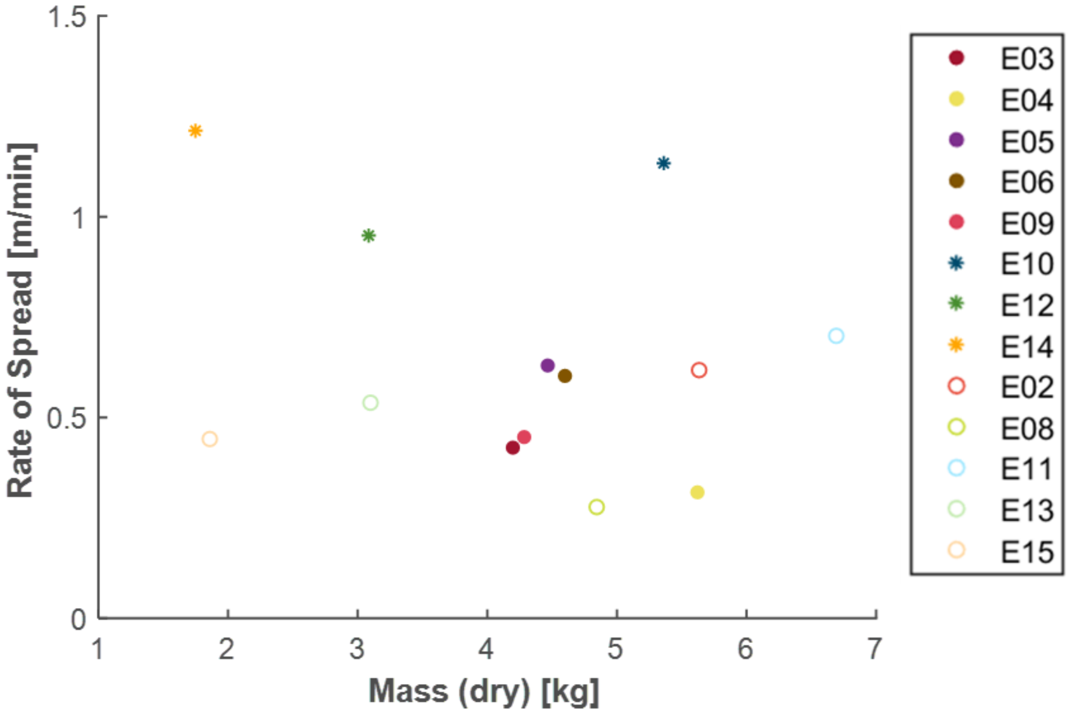

Figure 12. Rate of Spread with respect to the fuel load of the experiments. While the filled circles are the experiments with moss layer, empty circles are the experiments without moss. For the flame spreads driven by dry moss layer, star marker has been used.

The ignition time were given as follows in the previous section as [28]:

$$t_{ig} = \frac{\rho_s c_s d(T_{ig} - T_i)}{\dot{q}"_s} \qquad \text{(iv)}$$

If the fuel distribution and particle geometries were assumed to be homogeneous and the effect of FMC on the numerator variables neglected, external heat flux on the surface, $\dot{q}"_s$, lefts as the only constraint that can influence the ignition time. For a Calluna fire, this external heat flux will be representing the heat transfer occurring between the flame and fuel particles and this heat transfer mechanisms can be influenced by the fuel load, or bulk density in another perspective. Bulk density can be used instead of fuel load in order to represent the physical characteristics of the fuel bed better. While the fuel load only gives information about the mass of the fuel, bulk density also considers the volume of the fuel so that the representation of fuel becomes 3D. Also the height of the Calluna depends on the age of the vegetation or even seasons [33], [34] and it can vary between $20\ cm -> 50\ cm$ depending on these conditions, so that having this 3D aspect seems essential. In this study, while the fuel mass and fuel area were known, the fuel heights were not measured strictly. Most of the fuel beds had overall heights around $\sim 40 - 50\ cm$ and because of this reason $0.45\ m$ homogeneous heights were assumed for the fuel beds in all experiments.

In reference [19], 'bulk density of fuel burnt' concept was used in order to take account of the enthalpy change for a burning fuel bed, empirically. Without going into much detail, Thomas used the equation:

$$q" = R * \rho'_b * \Delta H \qquad (v)$$

where

- $q"$ is the heat flux,
- R is the rate of spread,
- ρ'_b is the bulk density of burned fuel,
- ΔH is the enthalpy rise of fuel between initial and ignition conditions.

Using the bulk density of burned fuel, which is basically the bulk density multiplied by the mass consumption rate, enthalpy change of the whole fuel bed were aimed to be taken into account, instead of an individual fuel particle. Same burned bulk density concept have been used in this study to generalize the rate of spread for the whole fuel bed, and the results can be seen in Figure 13 below.

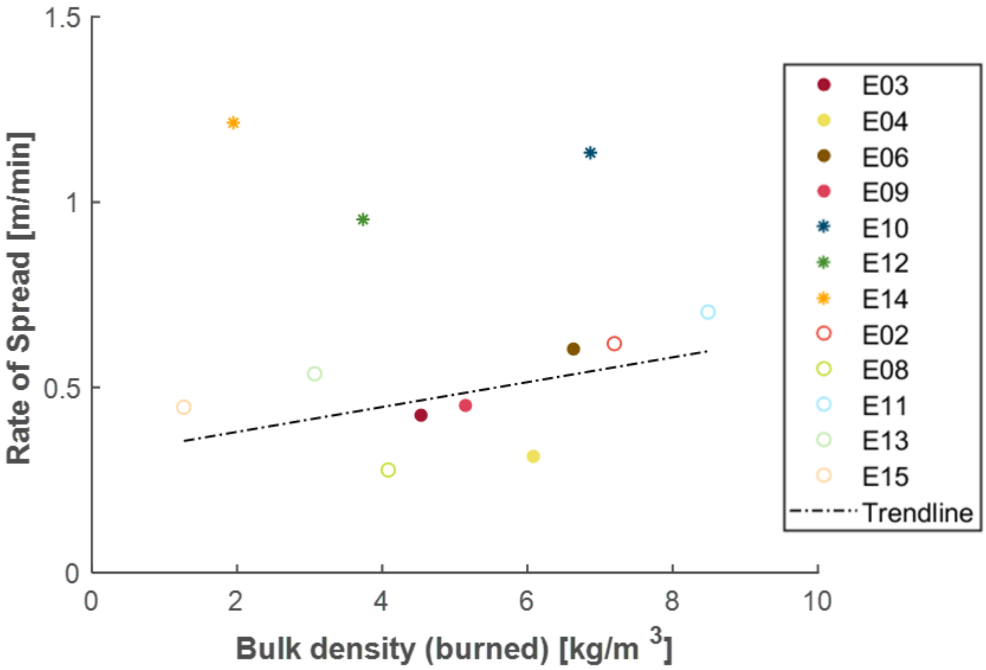

Figure 13. Rate of Spread with respect to the burned bulk density of the experiments. While the filled circles are the experiments with moss layer, empty circles are the

experiments without moss. For the flame spreads driven by dry moss layer, star marker has been used. It should be noted that the trendline doesn't cover the experiments 10,12,14 (flame spread through dry moss) and 8 (relatively wet heather).

As fuel heights were assumed to be same for all the experiments and the vegetation areas were similar, Figure 13 looked much alike with the Figure 12. Again the experiments 10,12 and 14 had higher spread rates as the fire were spread through the dry burning moss in these experiments. Most of the experiments seemed to have a positive relationship between the rate of spread and burned bulk density. All the experiments that had FMC between $\sim 10 - 12\%$ for the Calluna seemed to follow a positive trendline between the spread rates and burned bulk density, especially this was the case for the experiments without moss layer. While the trendline had some outliers, it also contradicts with the previous fire spread experiments on Calluna [19], [33]; as they had concluded that there is a negative correlation between the flame spread rate and bulk density, similar to other references on other wildland fuel types [11, Ch. 6], [20]. The reason for this contradiction can be complex, especially when the fine structure and air gaps of the Calluna were considered. The heat transfer mechanisms are very complex for wildland fires; and the relationship between convective cooling, dominant heating mechanism(s) and bulk density are not defined well yet [14]. While the exact reason for this contradiction cannot be explained, a small portion of it can be explained in the figure below.

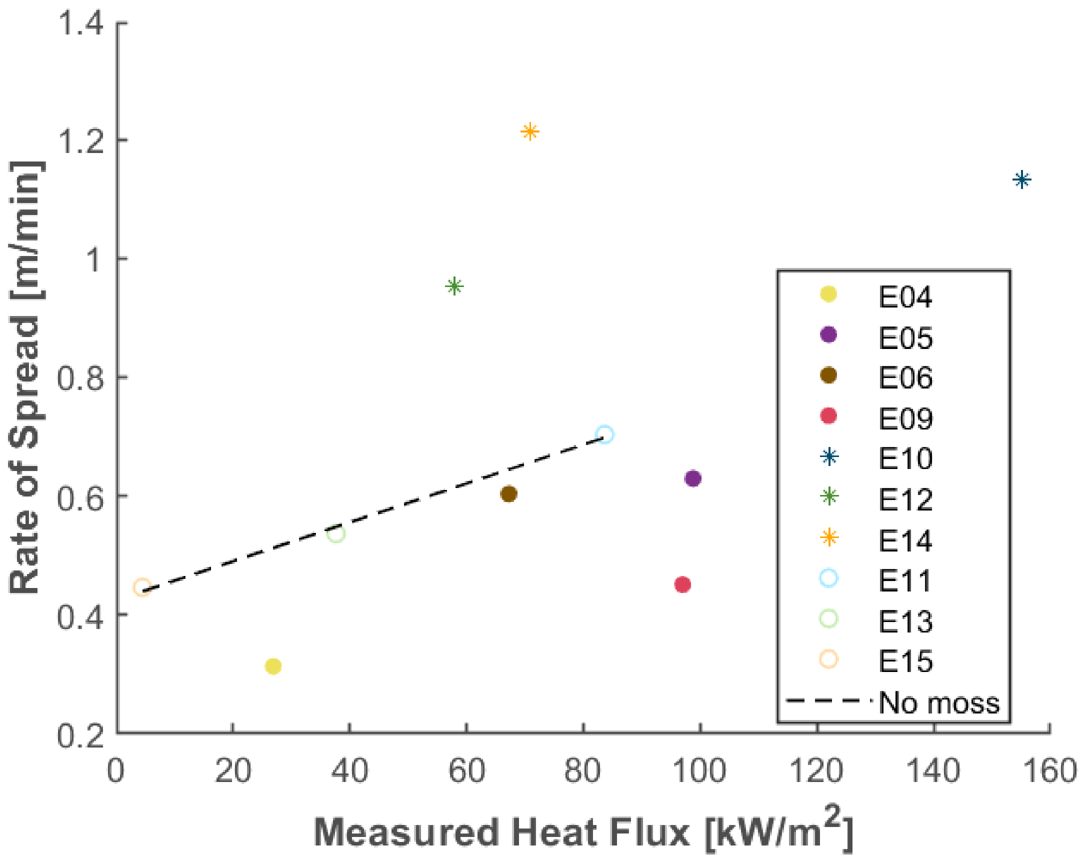

Figure 14. Rate of spread with respect to the measured heat flux in mid-height canopy layer. "No moss" trendline is just for the experiments 11, 13 and 15, which had ~6 kg, ~3 kg and ~2 kg fuel load, respectively, with no moss.

In Figure 14 above, the rate of spread with respect to the measured heat flux in canopy layer can be seen. For the experiments with no moss layer (11, 13 and 15), it seems there is positive linear relationship between rate of spread and measured heat flux. It should be highlighted that all these three experiments had same FMC content, so that the ρ_s, c_s, d and T_{ig} in the numerator of the ignition time, t_{ig}, equation (iv) were more or less the same. That only leaves the external heat flux, $\dot{q}"_s$, for manipulation, which we can accept as the measured heat flux that can be seen in the figure above. When the heat flux increases, the ignition time decreases so the vegetation burns quicker and the rate of spread increases. The "No moss" positive trendline is the indication of this increase. However, these three experiments had no moss layer so that the heat transfer mechanisms were relatively less complex. The effect of moss layer, in this aspect, can examined further in future studies. It should also be noted that these heat flux measurements were local point measurements so that their reliability is debatable.

3.3.2. Spread Rate and FMC

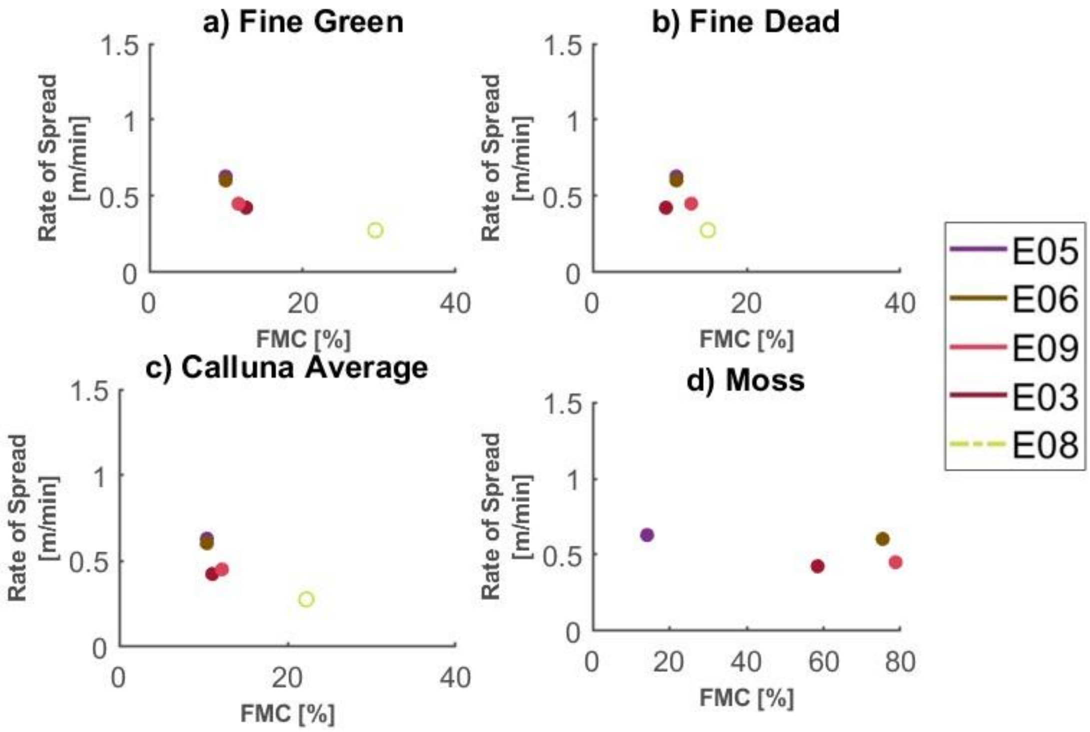

Figure 15. Rate of Spread with respect to the Calluna Average FMC for the experiments with ~4 kg fuel load: Experiments 3, 5, 6, 8, 9.

Rate of spread with respect to the vegetation FMC for the experiments with $\sim 4\ kg$ fuel load, can be seen in Figure 15 above. There seems to be a negative correlation between Calluna FMC and rate of spread for the fuels with similar fuel loads, as expected. In some of the previous studies [16, Sec. 5.3.7], [17], [33], [35], it has been observed that the fine dead FMC is the primary factor that influences the fire behaviour and it affects the rate of spread in Calluna fires. This assertion can be seen in Figure 15, where the negative correlation between FMC and rate of spread behaves more linearly for the part b) Fine Dead fuels, if the Experiment 3 is excluded. The Experiment 3 had a dryer fine dead fuel but it had relatively higher wet moss fuel load ($\sim 0.6\ kg$); while the experiments 5, 6, 8, and 9 had $\sim 0.3, \sim 0.2, no\ moss$, and ~ 0.3, respectively. The eccentricity of Experiment 3 for the linear trendline can be explained with this higher wet moss fuel load, which acts like a heat sink and increases the ignition time so that the rate of spread decreases. While the slopes can vary, Fine Green and Calluna Average FMC values seems to follow the negative trendline as well for the experiments plotted above.

Due to the low FMC variability, differences in fuel loads and the variable presence of the moss layer; there were no reasonable correlation observed between FMC and rate of spread when the data for all the experiments plotted together (Figure 16 below).

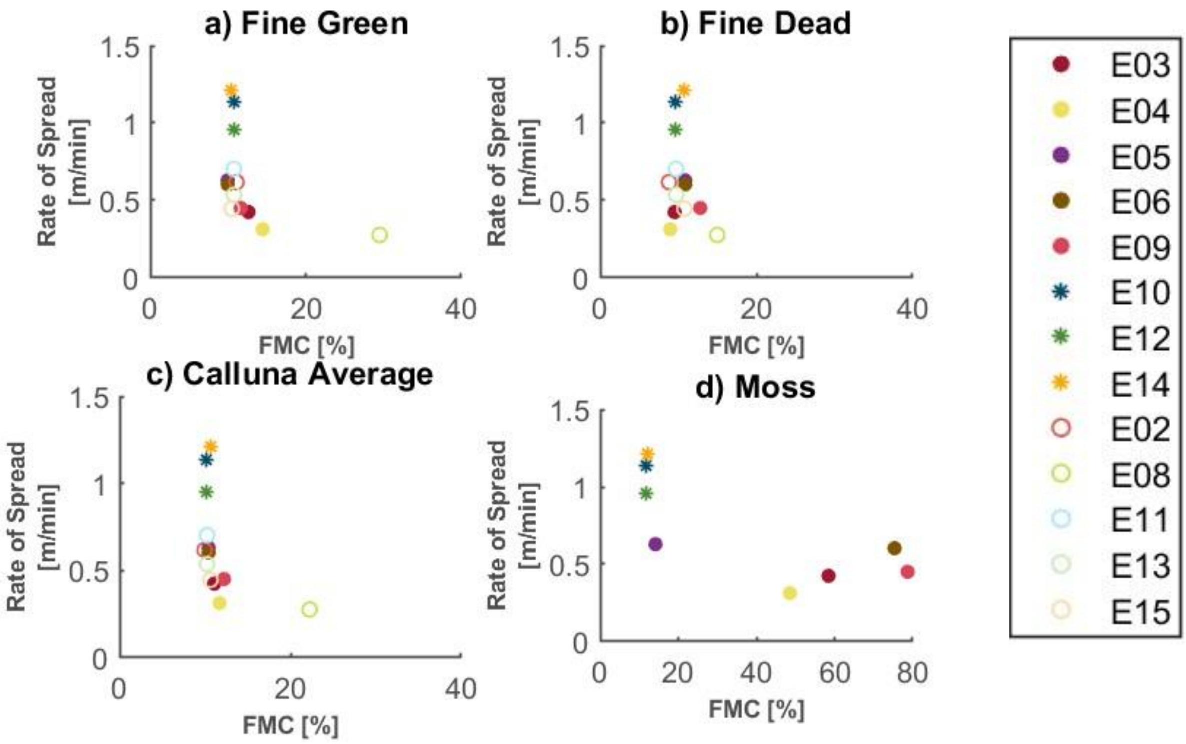

Figure 16. Rate of Spread [m/min] with respect to the FMC [%]. Star markers are for experiments with dry moss, empty circles are for experiments with no moss experiments and the filled circles are for the rest of the experiments. For obtaining more information about a particular experiment, please refer to Table 2.

3.4. Fuel Consumed

As explained in the Methodology section, static mass measurements were made before and after the experiments and the fuel consumption rates were found. The consumption rates were between 31% and 98%. Lowest consumption rates were from the experiments 7 and 15, which were 31% and 52% respectively, where the fire were not fully spread along the fuel bed. Experiment 7 were not fully spread fully due to the high Calluna moisture content, while the cause was low fuel density for the uncomplete burn in Experiment 15. Also, post-burn mass data from the experiment 5 is not available due to an error in the load cell so that it has been excluded from the final results below.

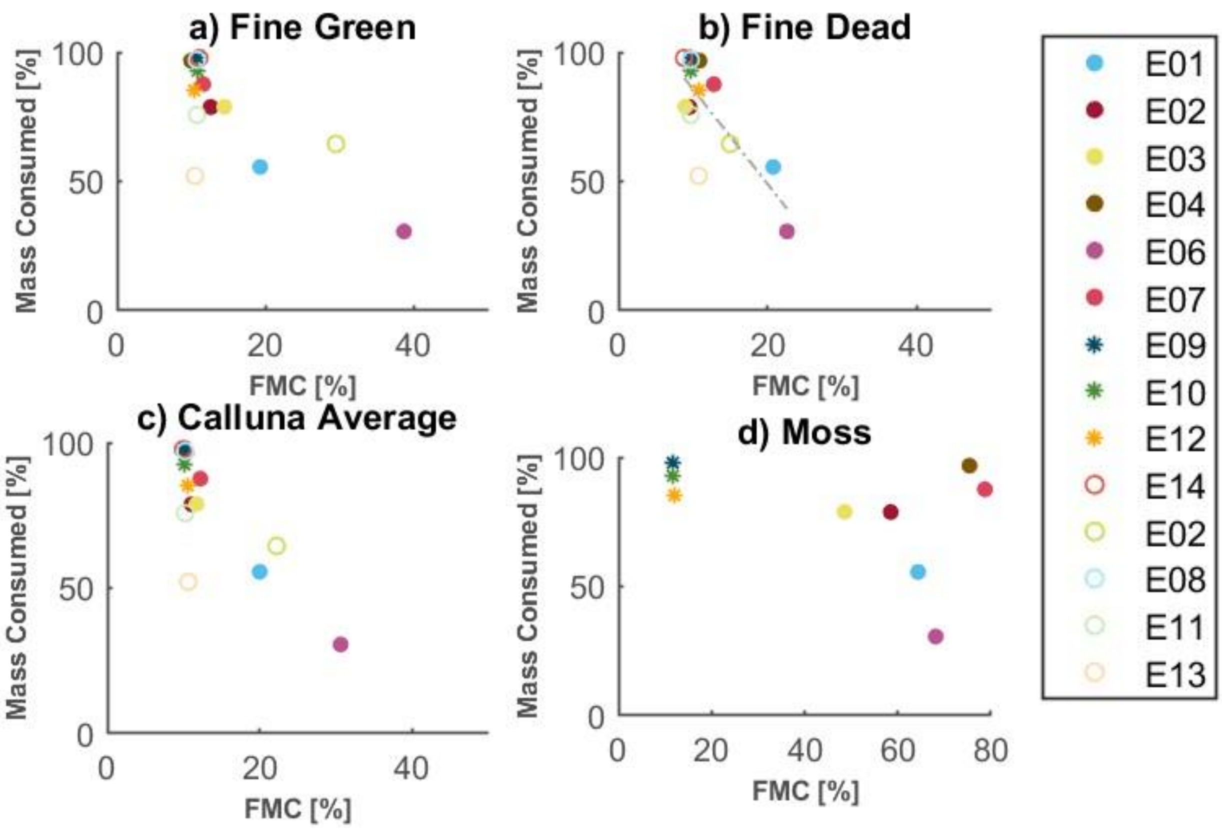

Figure 17. Mass consumption rates (%) for the experiments with respect to the FMC (%) of different vegetation types: a) Fine Green, b) Fine Dead, c) Calluna Average (mean FMC of a and b), d) Moss FMC.

In Figure 17, the mass consumption rates for the experiments, excluding 5,7 and 15; can be seen with respect to the fuel moisture content for different vegetation types. As Calluna fuel moisture contents were low for most of the experiments, mass consumption rates are relatively high. There seems to be no correlation between the moss FMC and mass consumption rates as there are many outliers. This was due to the low fuel load of the moss when compared with the Calluna fuel load. For Calluna, fine dead and Calluna average seems to have a linearity between the mass consumption and FMC. However, as the variety for Calluna FMC were low in the experiments, the verification of this linearity is challenging for the data available.

Another representation for the mass consumption can be the total fuel consumption ($kg\ m^{-2}$), which were calculated as follows:

$$Total\ Fuel\ Consumption = \frac{m_{pre-burn\ fuel} - m_{post-burn\ fuel}}{Area_{fuel}} \qquad (\text{vi})$$

where:

- $m_{pre-burn\,fuel}$ is the wet mass of the pre-burn fuel (kg)
- $m_{post-burn\,fuel}$ is the mass of the remaining material, such as fuel, char and ash (kg)
- $Area_{fuel}$ is the area of the vegetation layer, which were $\sim 1.7\,m^2$ for most of the experiments in this study.

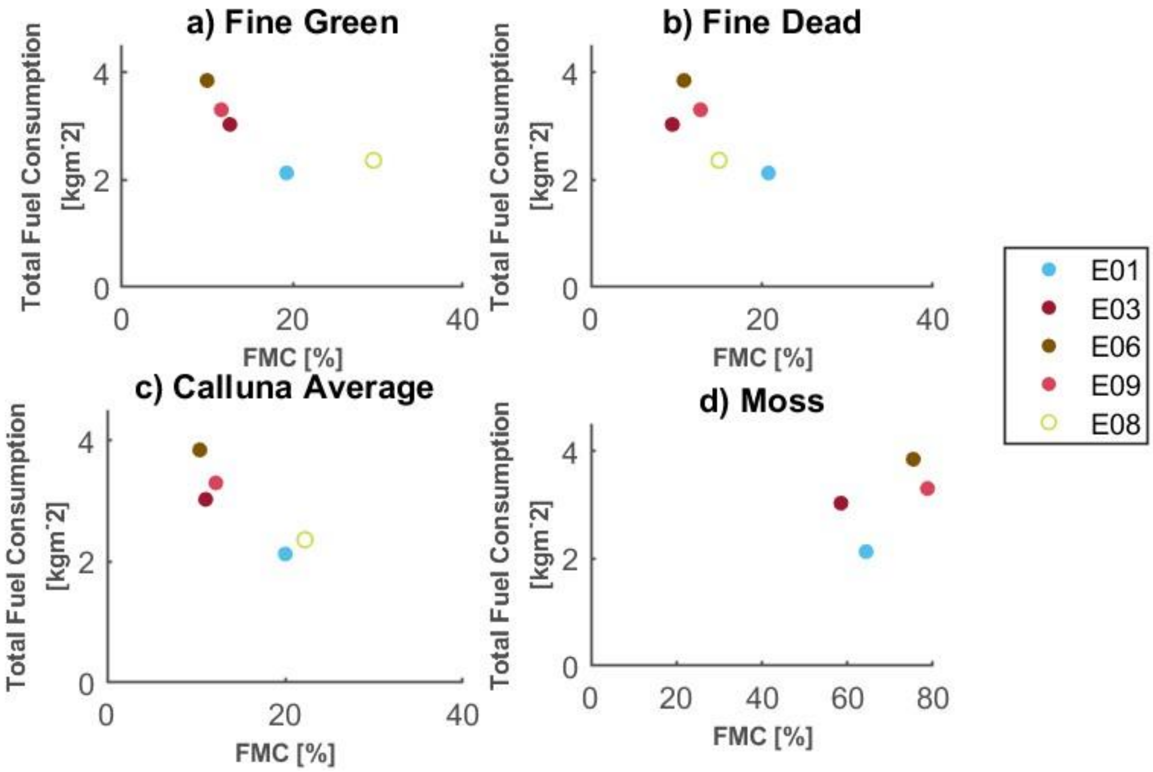

Figure 18. Total Fuel Consumption [kg/m²] for the experiments 1, 3, 6, 8 and 9 with respect to the FMC (%) of different vegetation types: a) Fine Green, b) Fine Dead, c) Calluna Average (mean FMC of a and b), d) Moss FMC.

The total fuel consumption for the experiments that had similar Calluna fuel load (dry mass), $\sim 4 - 4.8\,kg$, with respect to the FMC can be seen in Figure 18 above. It can be said that for both fine green and fine dead parts, the FMC affects the fuel consumption as expected. For example, the fuel consumption difference between Experiment 6 and Experiment 1 were nearly double rate, while they had ~10% and ~20% FMC, respectively. Due to all experiments having similar areas ($\sim 1.7\,m^2$); total fuel consumption rates seems remarkably similar to the mass consumed (%) figure (Figure 17). However in field experiments or real fires, expressing the fuel consumption rates by considering the area and using the total fuel consumption rates would be more beneficial.

3.5. Heat Release Rate (HRR)

3.5.1. Maximum Heat Release Rate – Fuel Moisture Content

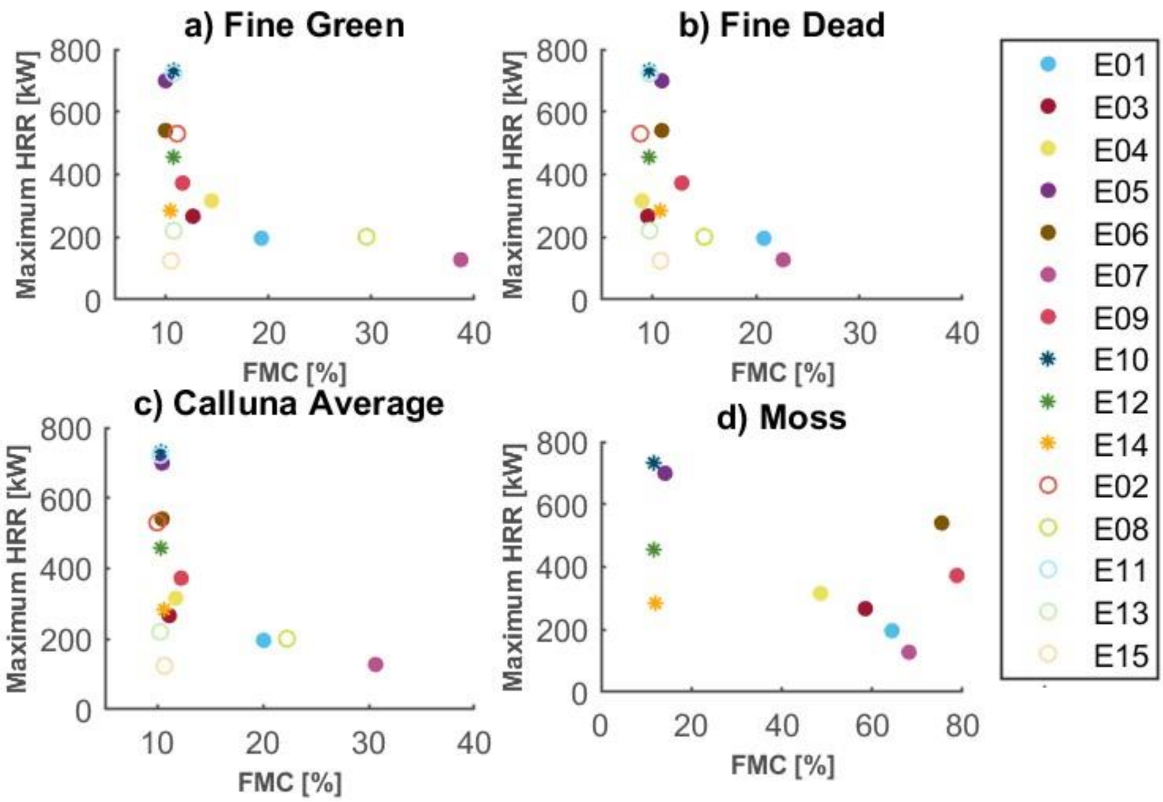

Figure 19. Maximum heat release rate [kW] as a function of fuel moisture content [%] for the experiments 1-15

Maximum heat release rate values between $124 - 730\,kW$ were observed during the experiments. The maximum heat release rate with respect to the vegetation fuel moisture content can be seen in Figure 19. From the figure, there seems to be a threshold, for lower HRR values, around 10% FMC and after this threshold, the HRR seems to be constant at minimum. This was slightly anticipated as the FMC of the Calluna in different set of experiments were not varied enough (mostly between 10-12%). In order to examine this FMC threshold further and eliminate the effect of fuel loads, the maximum heat release rate / dry mass ratio has been presented as a function of fuel moisture content in Figure 20 below. The converging pattern for higher FMC still seems to be exists, especially for the Fine Green Calluna.

For moss, there seems to be no clear relationship between Maximum HRR and FMC for the experiments. Since the moss fuel load were significantly lower than the Calluna fuel load, which is also true for the moss in natural environment [16, p. 46] this was expected.

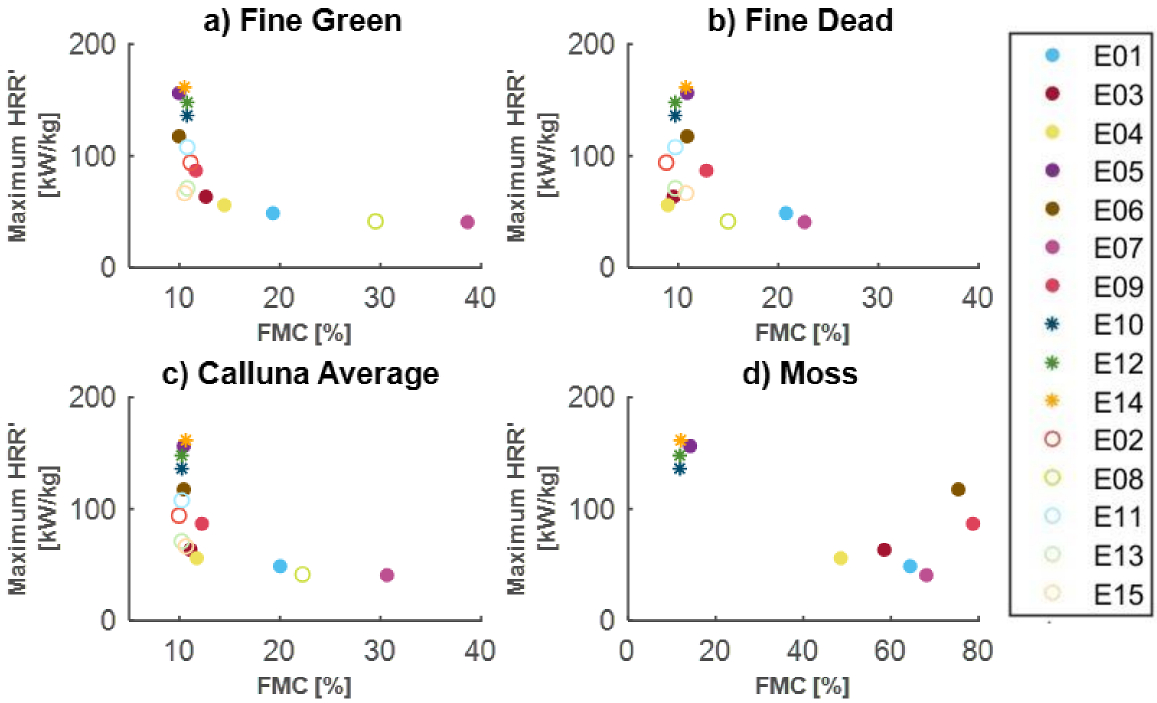

Figure 20. Maximum Heat Release Rate / dry mass ratio for various Calluna and moss FMC% values.

3.5.2. Maximum Heat Release Rate – Fuel Load

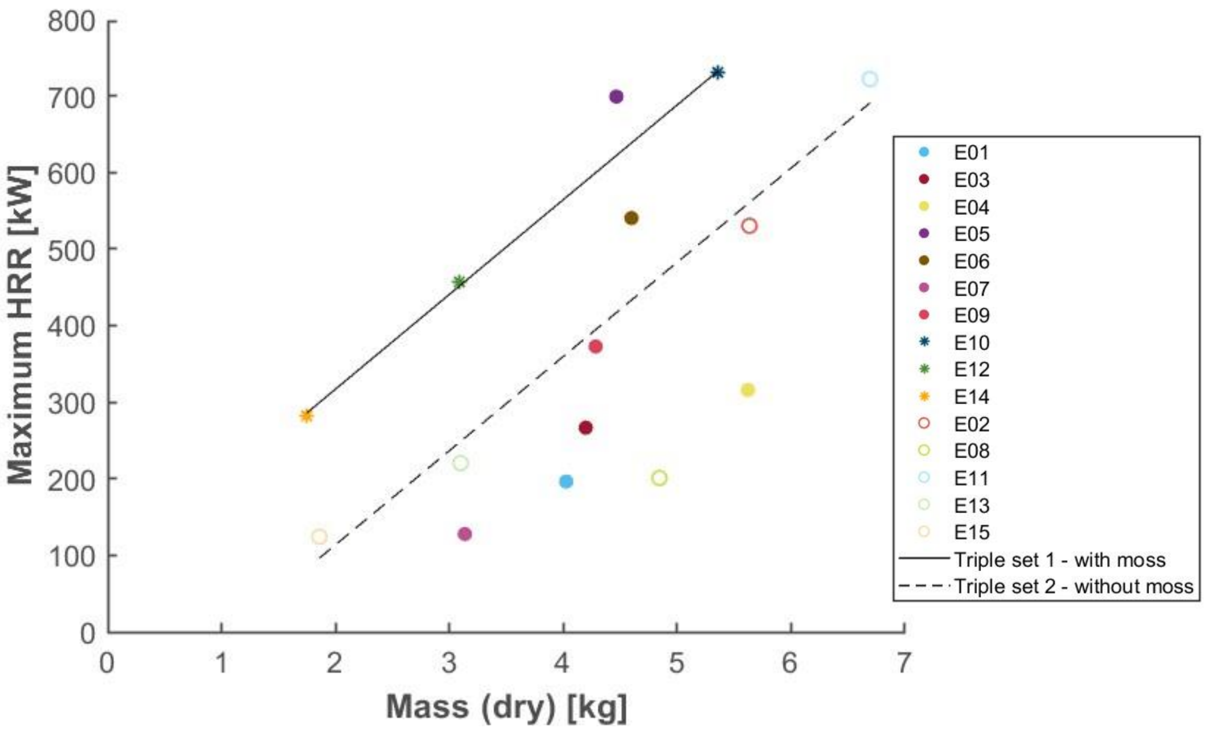

Figure 21. Maximum Heat Release Rate [kW] as a function of dry Calluna mass (in kg); Triple set 1: Experiments 10,12,14; Triple set 2: Experiments 11,13,15. All experiments in triple sets had similar FMC (~12%) and similar moss masses (if exists).

The maximum heat release rate with respect to the fuel load, dry Calluna mass, can be seen in Figure 21 above. An overall positive trend between fuel load and peak HRR can be seen for the Calluna as expected. Additionally, two triple sets has been defined in Figure 21 for analysing further the last six experiments (#10-15), which had 3 fuel load patterns as 2,3 and ~5-6 kg of dry Calluna while having similar FMC for the vegetation. The only difference between triple set 1 and triple set 2 is that the triple set 1 had $\sim 300\ grams$ of moss for all experiments, while triple set 2 had no moss. Despite the presence of moss layer, the two triple sets have remarkably similar trendlines. In fact, the ratio between the slope of the two trendlines are ~ 0.97. Based on this similarity, it can be said that a similar linear relationship between the dry mass and peak HRR have been observed for the vegetation, whether it has moss layer or not, that has the same fuel moisture content.

3.5.3. Heat Release Rate over time

3.5.3.1. Effect of Fuel Load and Moss Layer

The heat release rates over time for the experiments #10-15 can be seen in the Figure 22 below, where all experiments have nearly the same fuel moisture contents for both vegetation layers. The experiments that had moss layer were plotted using regular lines while the experiments that had no moss layer demonstrated by using dashed lines for easy comparison. The vegetation for these experiments were collected at the same day, from the same field and all six experiments have occurred in a 24-hour period to minimize the effect of fuel moisture content. In the figure, similar colour palettes were used to indicate similar fuel loadings; where the experiments 10-11 had ~5-6 kg of fuel load (blue); while the experiments 12-13 had ~3 kg (green) and experiments 14-15 had ~2 kg of fuel loads (orange). Additionally, the moss layer for all the experiments had same FMC and same fuel load, which was ~0.3 kg. The fuel bed of the experiment 10 and 11 were constructed using distinct plots (plot 14 and 13, respectively) from the field to simulate a real plot, while the fuel bed of experiments 12-15 had lower mass individually when compared with the mass of average collected plots, which were usually between ~4-7 kg.

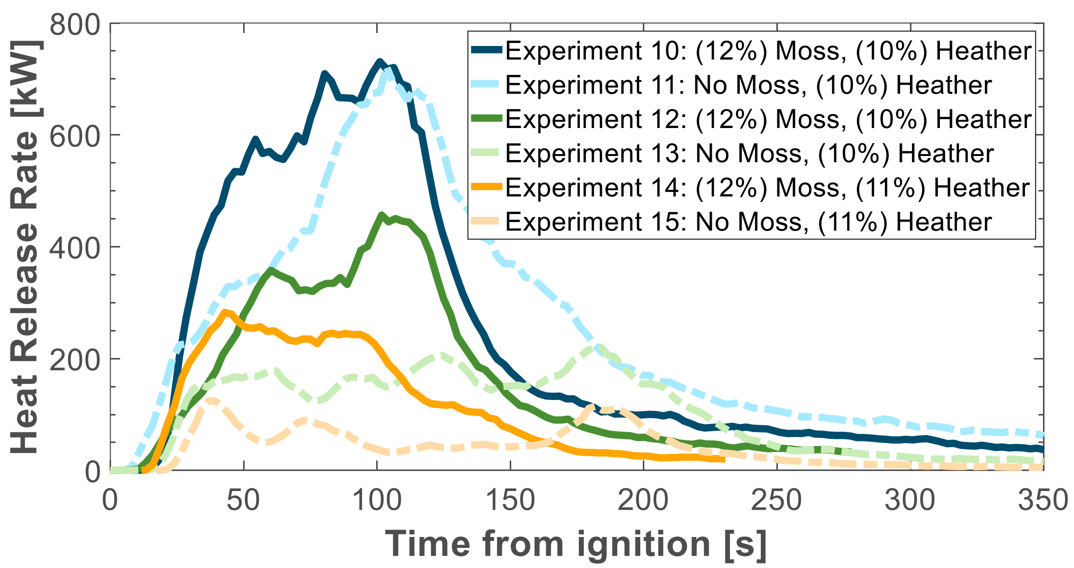

Figure 22. Heat Release Rate [kW] for the experiments #10-15, which had similar FMC and similar fuel load patterns; E10-E11 = ~5-6 [kg], E12-13 = ~3 [kg], E14-E15 = ~2 [kg] of dry Calluna mass. The dry moss layer mass was ~0.3 [kg] for the E10-E12-E14.

The positive trend between the peak HRR and the dry Calluna mass can be seen in the Figure 22. The experiments with the highest fuel loading, E10 and E11, have the highest HRR, ~730 kW, while the experiments, #12-15, with 3 kg and 2 kg fuel loadings have lower heat release rates: ~450, ~220, ~280 and ~120 as peak HRR, respectively. It should be noted that since the FMC of moss layer in these experiments were significantly low, ~12%; the moss layers were also burned well and contributed the fire spread. The contribution of the moss layers on HRR can be clearly seen as increased overall HRR for the experiments 12 and 14, when compared with the no moss ones (E13 and E15). Whereas a similar contribution cannot be seen for the comparison between experiments 10 and 11. The reason for this can be the extra ~1 kg of dry Calluna mass that the experiment 11 has. Luckily, the experiment 2 has similar Calluna FMC, ~10%, and similar fuel load, only ~0.3 kg higher, when compared with the experiment 10; so that it was exchanged with the experiment 11 to double check this anomaly. The results can be seen in Figure 23 below, where the effect of the moss layer can be seen between experiment 10 and 2 as a HRR difference, ~200 kW difference for peak values. Therefore, it can be said that the presence of ~0.3 kg moss layer with 12% FMC in these experiments, have increased the peak HRR values by ~200 kW on average.

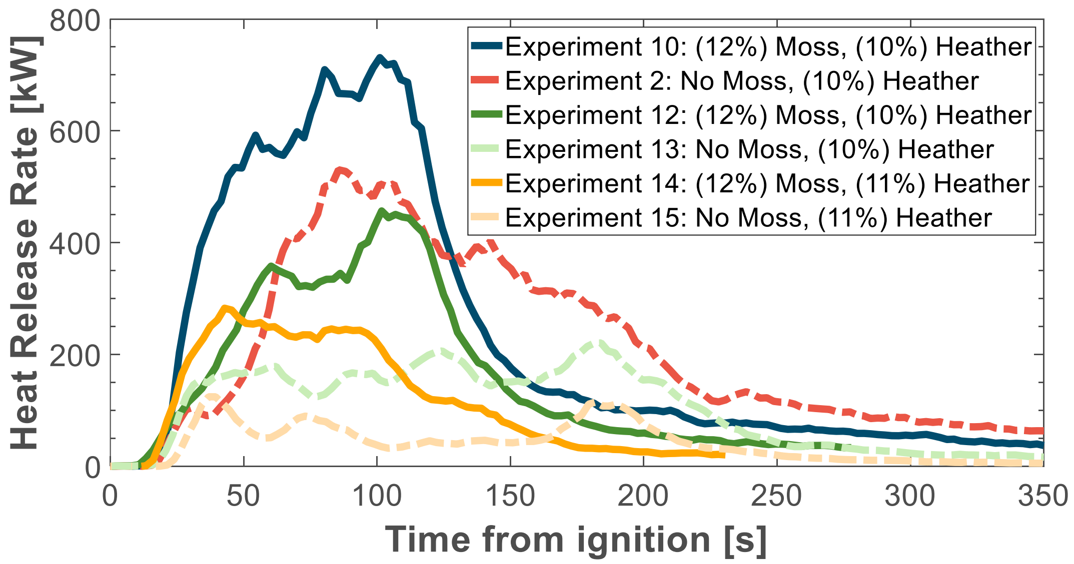

Figure 23. Heat Release Rate [kW] for the experiments #2,10,12-15, which had similar FMC and similar fuel load patterns; E10-E2 = ~5 [kg], E12-13 = ~3 [kg], E14-E15 = ~2 [kg] of dry Calluna mass. The dry moss layer mass was ~0.3 [kg] for the E10-E12-E14.

3.5.3.2. Effect of FMC on HRR

In order to evaluate the effect of the FMC on Calluna fires better, the HRR over time figures were divided into categories with respect to the fuel loadings, such as 2, 3, 4 and 5 kg of dry Calluna mass. Also similar to the Figure 22, the experiments that had moss layer will be plotted using regular lines while the experiments that had no moss layer will be demonstrated by using dashed lines for easy comparison.

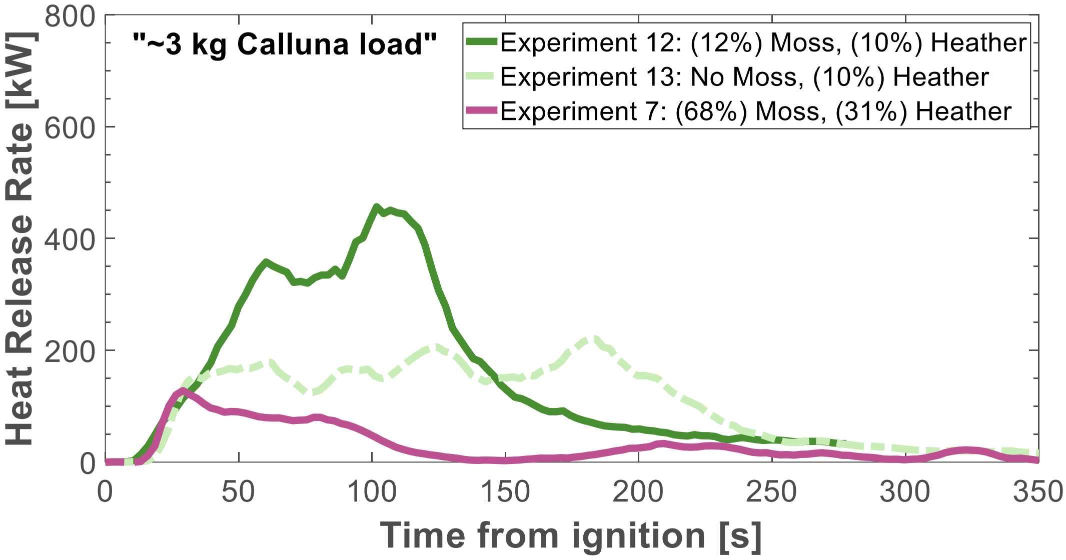

Figure 24. HRR over time for experiments with ~3 kg Calluna load (dry mass); Experiment 7, Experiment 12 and Experiment 13.

Over 15 experiments, 3 of them had 3 kg of Calluna load and their heat release rates over time can be seen in Figure 24 above. The experiment 12 has the highest energy release as it had the driest Calluna and moss, where moss also burned and contributed to the energy released. The experiment 7, on the other hand, had the highest fuel moisture content, 31%, for Calluna so that it had the second lowest heat release rate, ~128 kW at peak, among all the experiments. In fact, the fire has not spread fully during the experiment 7 as the heather FMC was relatively higher. The mass consumption for the experiments 7, 12 and 13 were 33%, 93% and 76%, respectively.

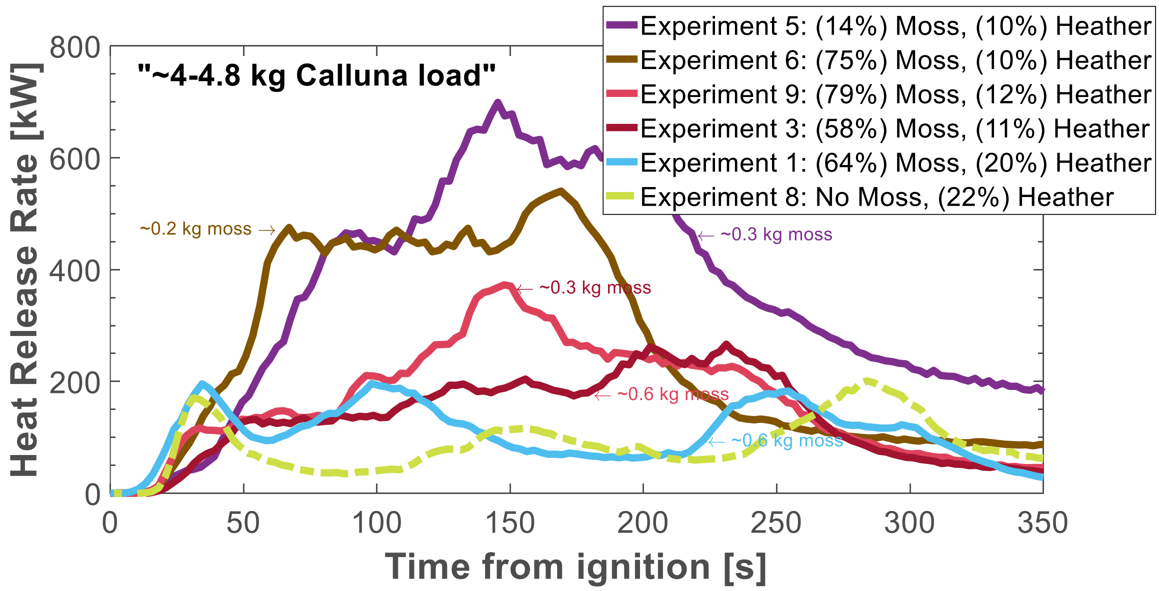

Figure 25. HRR over time for experiments with ~4-4.8 kg Calluna load (dry mass); Experiment 1, 3, 5, 6, 8, 9. The moss layer masses also indicated on the graph in (kg) for comparison.

The experiments that had dry Calluna mass around ~4-4.8 kg can be seen in Figure 25 above, where this time moss masses were also indicated for comparison. As it can be seen from the graph, the FMC of the Calluna is the major factor here that affects the heat release rate. The experiments 1 and 8 that had the highest Calluna FMC, ~20-22%, have the lowest overall heat release rates over time. For the experiments 3, 5, 6, 9 that had low Calluna FMC, ~10-12%; there seems to be a significant variation between each other as the peak HRR for these varies between ~267 and ~700 kW. The experiment 5 had the lowest FMC for moss and using the recorded video material, it can be said that the moss slightly contributed to the burn so that the HRR is higher than the other ones. The standard deviation for the moss moisture content measurement of experiment 3 was around 20%. If this has been taken to account; it can be said that the experiments 3, 6 and 9 have similar FMC contents for moss; with 58%, 75% and 79%, respectively. As the FMC of these three experiments, for both Calluna and moss, have been accepted as relatively similar; the HRR variation among them might be explained by the fuel load of the moss; which were ~0.2 kg, ~0.6 kg and ~0.3 kg for experiments 3, 6 and 9, respectively. Since the moss in these experiments were wet and functioned as a heat sink, it can be concluded that the increasing fuel load of moss had decreased the overall HRR in these experiments.

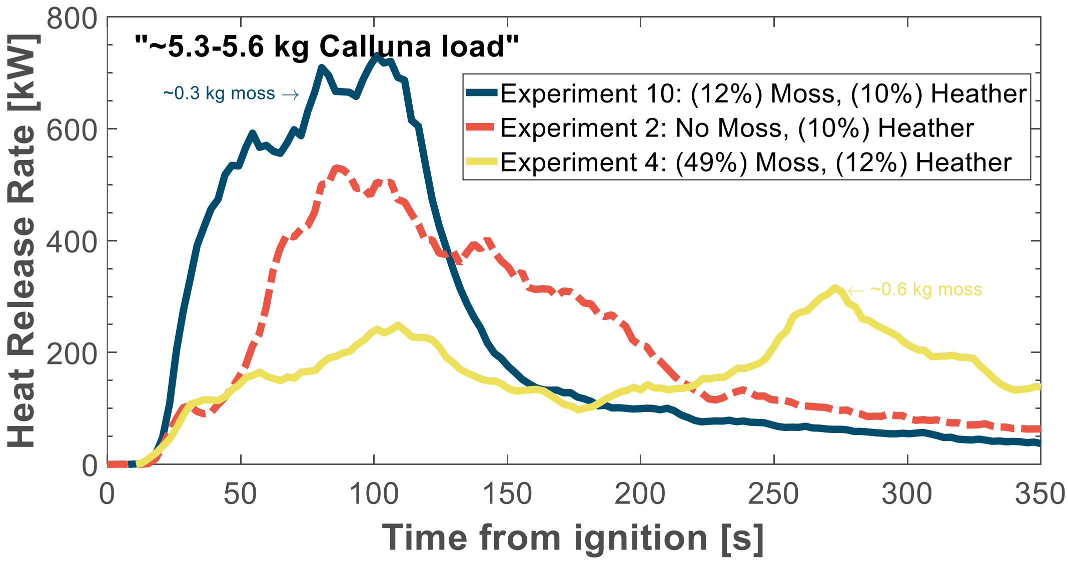

Figure 26. HRR over time for experiments with ~5.3-5.6 kg Calluna load (dry mass); Experiment 2, 4, 10. The moss layer masses also indicated on the graph in (kg) for comparison.

Finally, the HRR over time for the ~5.3-5.6 kg Calluna load experiments, 2, 4 and 4; can be seen in Figure 26 above. These three experiments had similar Calluna FMC and fuel loads, while having variety in the moss layer. The experiment 10 had dry moss layer that contributed the burning, while the experiment 4 had relatively wet moss with a higher fuel load, which acted again as a heat sink so caused a decrease in the HRR. The peak HRR for experiments 10, 2 and 4 are 731 kW, 530 kW and 316 kW, respectively. It can be said that the presence of moss layer and FMC of it can affect the heat release rate in Calluna fires, for similar fuel loads.

3.6. Mass Loss Rate

3.6.1. Effect of Fuel Load and Moss Layer on Mass Loss Rate

Using the continuous mass readings, the mass loss rate has been calculated for the experiments by taking the derivative of the mass measurements over time. Savitzky Golay finite impulse response filter has been applied to the mass loss rate calculations; using polynomial order of 2 and frame length of 11 properties, which have been suggested in reference [36] for mass loss rate calculations.

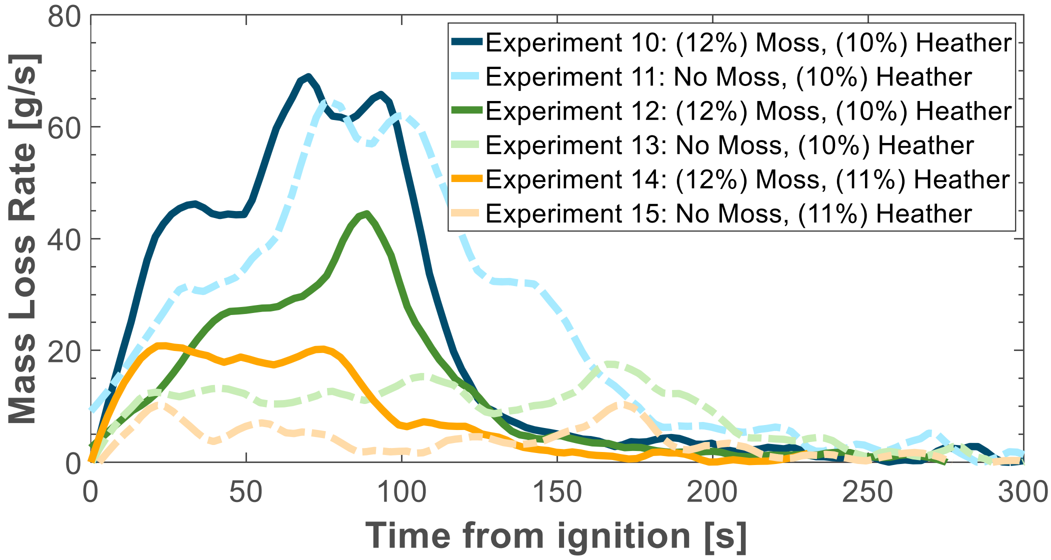

Figure 27. Mass loss rate over time for the experiments 10-15; fuel loads were: ~5.4, ~6.7, ~3.1, ~3.1, ~1.7 and ~1.9 kg as dry Calluna mass, respectively. FMC of the experiments were approximately same and the moss fuel load in experiments 10, 12, 14 were ~0.3 kg.

The mass loss rate over time figure for the experiments 10-15 can be seen in Figure 27 above, where all the experiments had similar fuel moisture contents. The difference between these experiments were the fuel loadings and the presence of the moss layer. It can be said that there is a positive correlation between the mass loss rate and the fuel load, as expected. For the experiments with moss layer, experiments 10, 12 and 14, the positive correlation between mass loss rate and fuel load seems to have a more gradual behaviour than the experiments without moss, when the peak mass loss rate values were considered. Moreover, experiments 10, 12 and 14 seems to have relatively shorter steady burning durations, which indicates faster spread rates due to the presence of the moss layer. As the FMC of the moss layer was low in these experiments, the moss burned well and in fact the moss layer lead the fire spread in these fires, as discussed in the fire spread section.

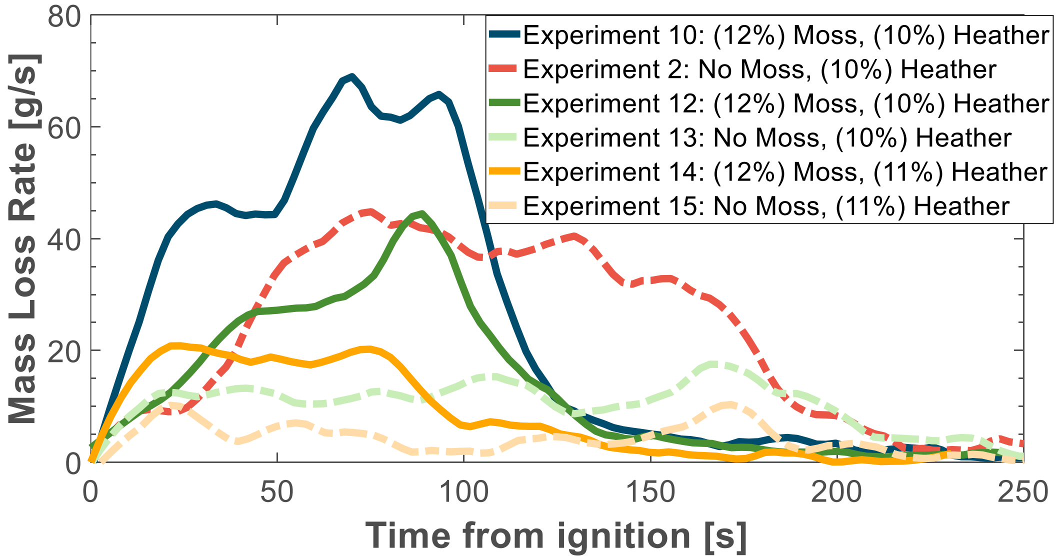

Figure 28. Mass loss rate over time for the experiments 2, 10, 12, 13 and 15; fuel loads were: ~5.6, ~5.4, ~3.1, ~3.1, ~1.7 and ~1.9 kg as dry Calluna mass, respectively. FMC of the experiments were approximately same and the moss fuel load in experiments 10, 12, 14 were ~0.3 k

An almost identical graph to the Figure 27 can be seen above, as Figure 28. As distinct from Figure 27, the Experiment 2 has been switched with Experiment 11 as it has a more similar fuel load with Experiment 10 for comparison purposes. The observation of longer steady burn periods for the experiments without moss layer seems to be more noticeable. Additionally, the positive correlation between mass loss rate and fuel load seems gradual for both of the cases, with and without moss layer.

3.6.2. Effect of FMC on Mass Loss Rate

Similar to the HRR over time figures, the mass loss rate over time graphs can be presented for different fuel load categories, for example: ~3 kg, ~4 kg, etc. Most of these mass loss rate figures had similar patterns with the HRR graphs but here, only the ~4 kg fuel load graph will be given as it had some differences with its HRR figure.

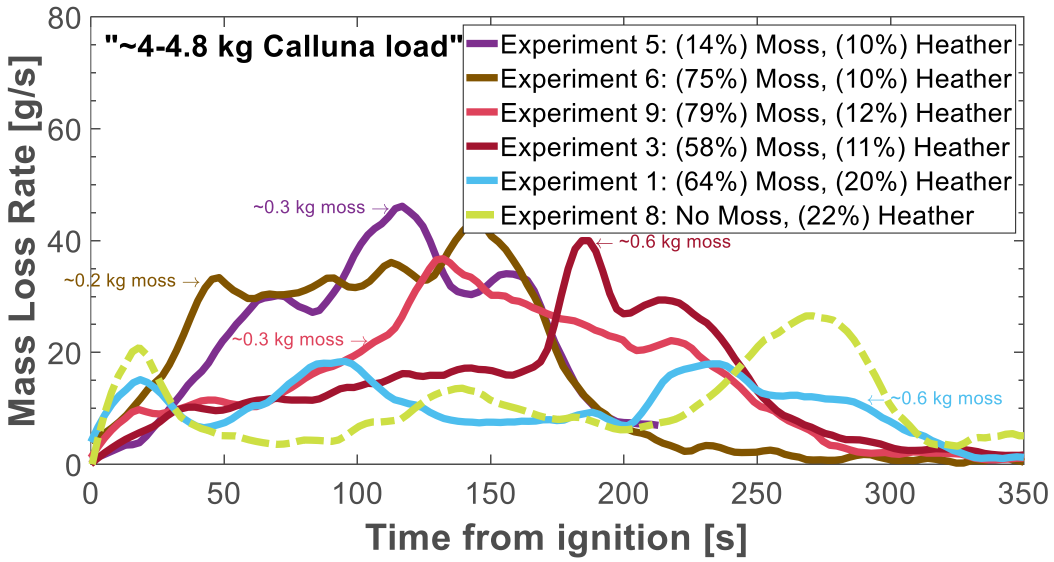

Figure 29. Mass loss rate (g/s) over time for the ~4-4.8 kg Calluna fuel load experiments: Experiments 1, 3, 5, 6, 8 and 9. The moss fuel loads were also presented in the figure.

The mass loss rate over time for the experiments with $\sim 4 - 4.8\ kg$ fuel load experiments can be seen in Figure 29 above. While there was significant differences between peak heat release rates of experiments 5, 6, 9 and 3 in Figure 25; they have similar mass loss rates as it can be seen from Figure 29. The biggest pattern difference is for the Experiment 3 as it made a big jump around 180 seconds after ignition. Recorded video material were double checked in order to check for an error or a vegetation fallen out from the experimental setup, but this wasn't the case. Explanation for these differences can be the high moisture content in moss layer that vaporized during the burning. Because of this reason the effect of FMC were seen relatively less on mass loss rates when compared with HRR.

3.7. Heat Fluxes

As stated in the methodology section, two water cooled heat flux gauges were placed in the experimental setup in order to observe the heating during the Calluna fires. One of these heat flux gauges were located in the Canopy layer (~27 cm above the moss layer), while the other one located in or under the moss layer. It should be highlighted that these measurements were local point measurements and the fuel beds constructed during the experiments had variations, such as different densities, different moss layer conditions, etc.; so that the outcome of these measurements might vary greatly.

3.7.1. Heat flux gauge in canopy layer

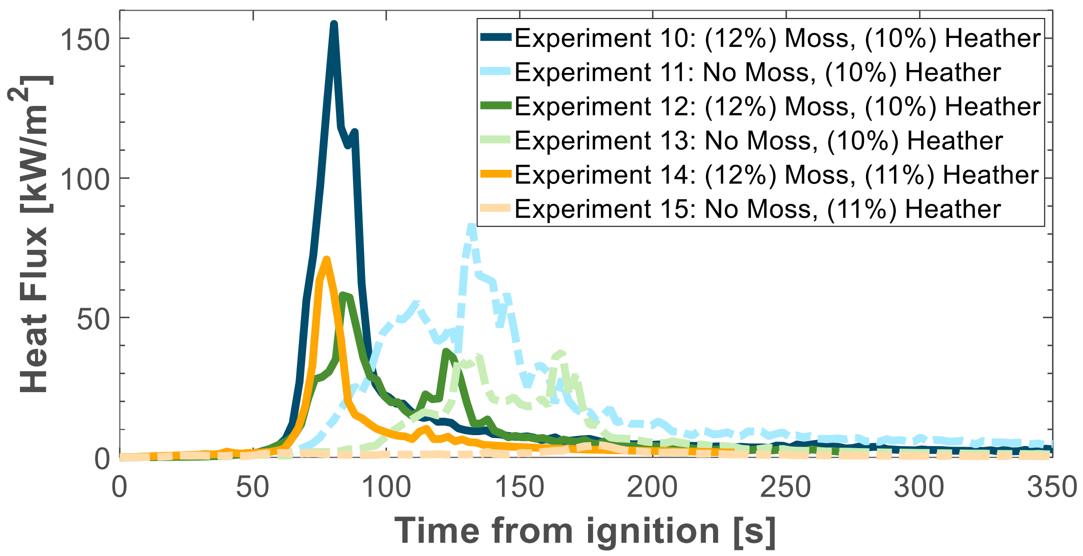

Figure 30. Heat flux readings in the canopy layer (at mid-height of Calluna) for the Experiments 10, 11, 12, 13, 14 and 15. Fuel load of the experiments as dry Calluna mass (kg) were: ~5.4 kg, ~6.7 kg, ~3.1 kg, ~3.1 kg, ~1.8 kg and ~1.9 kg, respectively.

Heat flux in the canopy layer gauge over time can be seen in Figure 30 above. The faster spread rates can be observed for the experiments 10, 12 and 14 as they had quicker sharp rises in the measured heat flux. As these experiments had a dry moss layer, the fire spread through the moss layer and burned faster. Also, the experiments 10 and 12, that had moss layer, seems to have higher heat fluxes than the experiments 11 and 13, that had similar Calluna fuel load but without moss layer. The reason for this higher heat fluxes, in experiments with moss, can be the radiation coming from the burning moss layer below. Another reason can be that the air gaps were larger around and below the canopy layer in no moss experiments, so that it might helped the surrounding air cooling the heat flux gauge more by the convection. As the fire were not fully spread for experiment 15, the heat flux readings were not very significant.

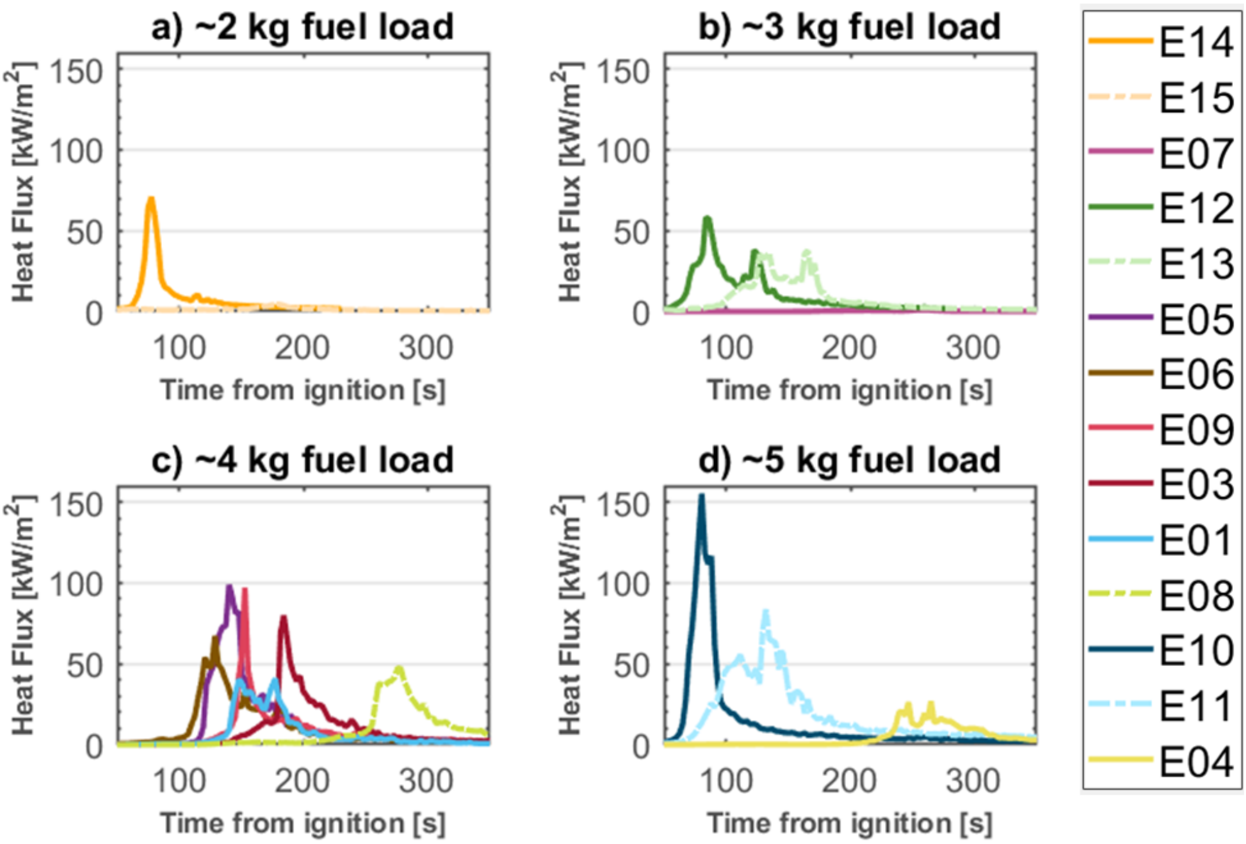

Figure 31. Heat flux measurements in mid-Calluna height over time for the experiments 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15.

The heat flux measurements in canopy layer over time for different fuel loads can be seen in Figure 31 above. The peak heat fluxes for the experiments were varied between $\sim 1\ kW/m^2 - \sim 155\ kW/m^2$ while the average of all was around $\sim 60\ kW/m^2$. In experiments 7 and 15 the readings were $\sim 1\ kW/m^2$ and $4.5\ kW/m^2$, respectively, as the fire were not fully spread in the fuel bed in these experiments. If these experiments excluded, the new average becomes $\sim 71\ kW/m^2$.

As expressed in the HRR results section, there seems to be a positive correlation between the energy released and the fuel load. As a consequence, higher heat fluxes were mostly seen for the higher fuel loads. However, due to the locality of the measurements this correlations were not observed for all the experiments. For example while the Experiment 12 had higher heat release rates overall than the Experiment 14, the measured heat flux in canopy layer are higher for the Experiment 14.

3.7.2. Heat flux gauge in soil (under the moss layer when applicable)

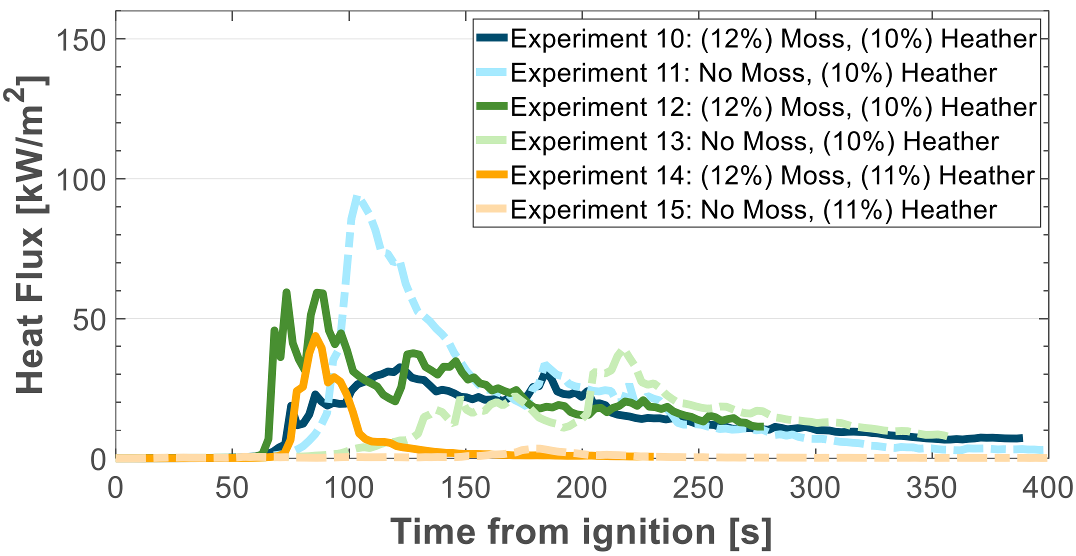

Figure 32. Heat flux readings in the soil (under the moss when applicable) for the experiments 10, 11, 12, 13, 14 and 15. Fuel load of the experiments as dry Calluna mass (kg) were: ~5.4 kg, ~6.7 kg, ~3.1 kg, ~3.1 kg, ~1.8 kg and ~1.9 kg, respectively.

The second heat flux gauge in the experimental setup were located in the soil layer. The randomness of the fuel bed construction have affected the heat flux measurements in soil more than the heat flux measurements in the canopy layer. In Figure 32, measurements from the heat flux gauge in the soil for the experiments 10-15 can be seen. Again the faster spread rates of the experiments with moss layer, (experiments 10, 12 and 14) can be seen from the earlier sharp increases in flux measurements. The measured peak heat fluxes for the experiments 10, 12 and 14 were $\sim 33\ kW/m^2$, $\sim 59\ kW/m^2$ and $\sim 44\ kW/m^2$, respectively. While the measured heat flux was similar for the experiment 12, it was significantly lower for the experiments 10 and 14 when compared with the measurements in the canopy layer (Figure 30). For the no moss experiments (experiments 11, 13 and 15), the measured heat fluxes were matching with the heat flux in the canopy layer.

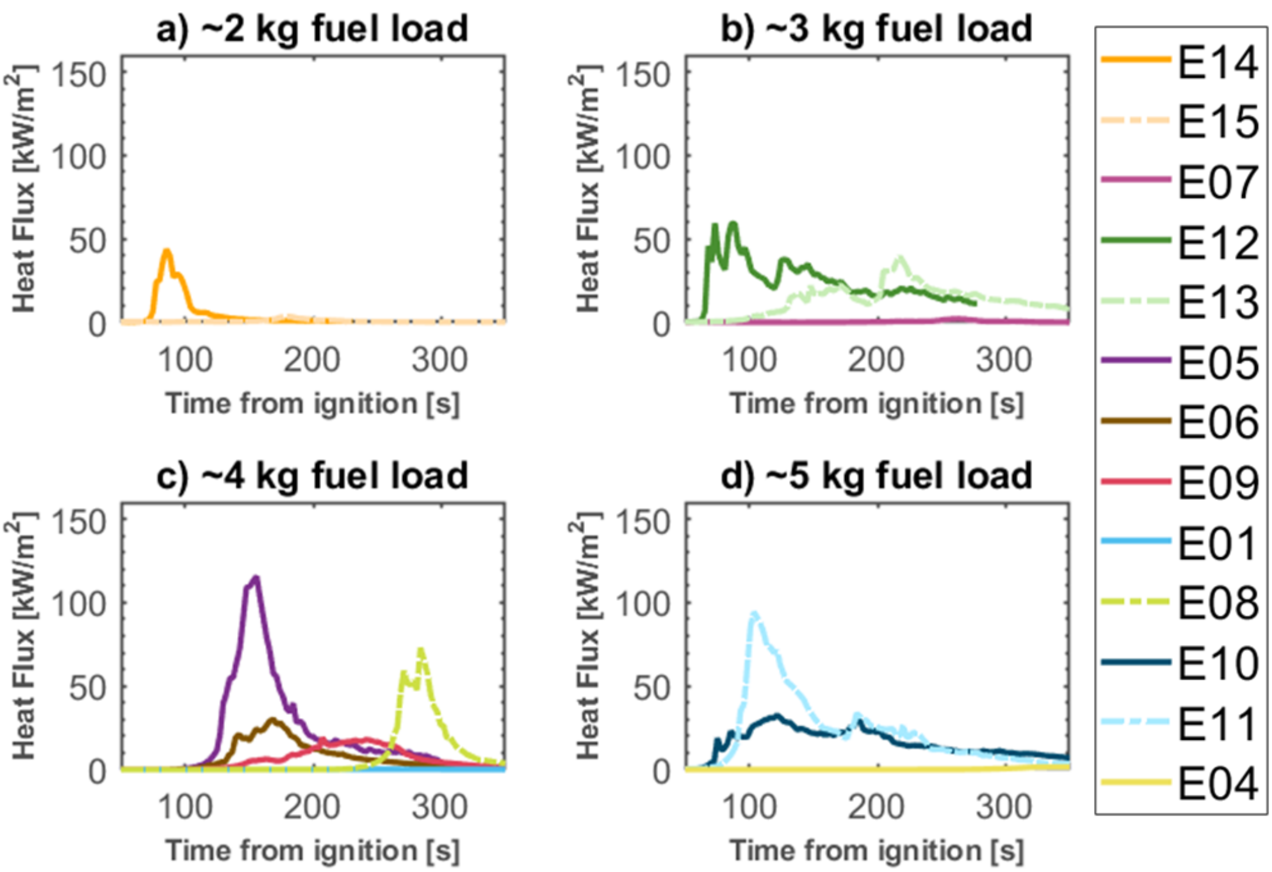

Figure 33. Heat flux measurements in mid-Calluna height over time for the experiments 1, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15.

The heat fluxes measured in soil layer over time for all the experiments can be seen in Figure 33 above. Due to an error in the readings of experiments 2 and 3, they were not included in the figure. The readings for the experiments 7 and 15 were also not significant because of the omission of the spread in those experiments. The peak heat fluxes vary greatly between $\sim 1\ kW/m^2$ and $\sim 116\ kW/m^2$. The reason for this great variation is the randomness in the fuel bed construction, as mentioned previously in this section. However, when the experiments 1, 4, 6 and 9 examined, which had 64%, 49%, 75% and 79% FMC respectively for the moss layer; there seems to be a negative correlation between the FMC of the moss layer and peak heat fluxes measured in the soil layer. These four experiments with the wet moss layer had the four lowest heat fluxes. In addition to this correlation, the highest four peak heat fluxes measured in the soil layer among all the experiments were the experiments 5, 11, 8 and 12 where they all either have a dry moss layer (FMC <14%) or no moss layer at all. The only exception can be the Experiment 10, where despite it had 12% FMC moss layer and one of the highest Calluna fuel loads (~5 kg); the peak heat flux measured in the soil layer was only $\sim 33\ kW/m^2$.

Besides the maximum heat flux rates, the exposure time is important as well to predict the damage to the ground, where some of the seeds or natural life might be laying down. Assessing the damage to this layer can be helpful to predict the regeneration of the vegetation and natural life, after the fire passes. Because of this reason 20 kW/m^2 was chosen as a threshold value and the time that heat fluxes observed over this threshold were obtained. The results with respect to the peak heat fluxes observed in soil layer can be seen in Figure 34 below. For the experiments plotted, there seems to be no correlation between the peak HRR and exposure time over 20 kW/m^2. However, again it should be highlighted that due to the locality of these measurements, their reliability can be argued.

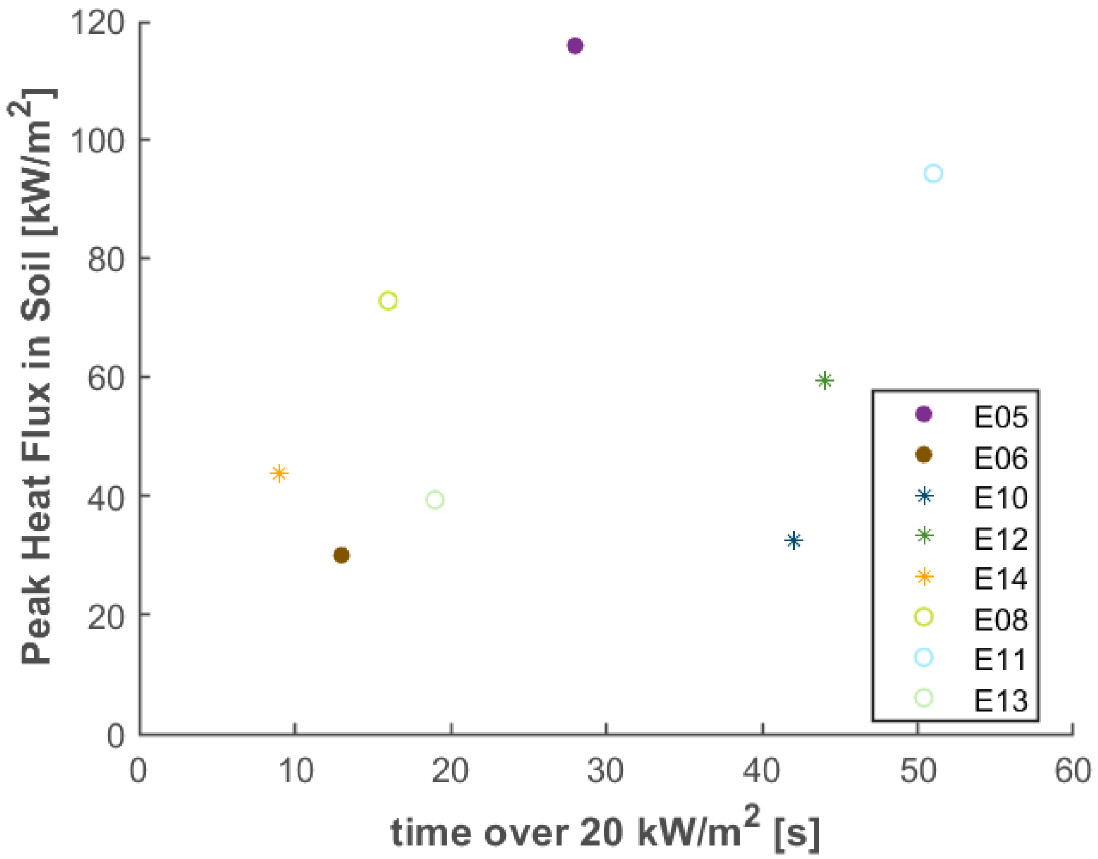

Figure 34. Peak Heat Flux observed in soil layer with respect to time that vegetation exposed for heat flux over 20 kW/m².

4. Conclusions

- An inverse relationship between FMC and fire intensity were observed for the following values: rate of spread, mass consumption, HRR and MLR. While there were similar indications for heat fluxes, it was not as certain as the others. However, the variety of FMC in experiments were low so it should be increased in the future laboratory experiments.
- Positive relationship between fuel load and fire intensity were observed. While this was expected as the available fuel increases with fuel load, the positive relationship between rate of spread and fuel load contradicts some of literature findings. This contradiction should be examined further as the fuel load can vary greatly in Calluna fields for a specific area. Measuring fuel heights and calculating the bulk density more accurately can be highly beneficial in the future studies.
- Moss layer in Calluna certainly has an effect on fire behaviour and this effect depends on the FMC and fuel load of the moss layer. While moss layer with low FMC changes the flame spread mechanisms and increase the rate of spread values; moss layer with high FMC does the vice versa.
- For low fuel moisture contents (<14%), using the average FMC of fine green and fine dead layers for expressing Calluna FMC seems reasonable as the effect of these separate layers were undistinguishable for low FMC.
- Laboratory experiments can be beneficial as it allows for more detailed measurements and offers the opportunity to control the environmental variables more. However, it must be highlighted that the data obtained from laboratory experiments might be misleading and possibly lower than the real fire scenarios, due to the scale difference with real fires. An example for this can be the lower FMC thresholds for successful fire spread, when compared with real fires from the literature.
- More experiments can be done using a similar experimental setup and generate more data by increasing FMC variability, adding slope or wind, etc. However, to understand the fire behaviour in Calluna fires better, fundamental studies on heat transfer mechanisms can be done. The effect of moss layer on heat transfer mechanisms can be a good starting point for this.

5. References

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