FIRE DANGER RATING SYSTEM

Fire Danger Rating System (FDRS) Report

October 2021

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The risk of wildfires in Scotland and the UK as a whole is likely to increase due to changes in land use and climate. While significant wildfire seasons may still only occur intermittently in Scotland, there is a concern that we are unprepared to deal with this potential increasing risk of difficult wildfire seasons. Fire danger rating systems designed to predict potential fire risk can be a powerful tool in planning for and managing periods of increased wildfire activity and for supporting safe use of controlled burning as a land management practice. Currently, fire danger forecasts in Scotland rely heavily on modelled scenarios from the Canadian Fire Weather Index System sub-indices, which was originally designed for predicting fires in mature jack pine stands in Canada. Although this system has been widely adopted, it has not so far been adapted to the fire environment and fire regime in Scotland.

1.1 Scottish Fire Danger Rating System (SFDRS) project

The Scottish fire danger rating system project (February 2019 – June 2021) was a collaboration between the James Hutton Institute (Aberdeen) and the University of Edinburgh and had the primary aim of exploring how (if) the Canadian Fire Weather Index System could be adapted to the vegetation most frequently involved in wildfires in Scotland, namely moorland vegetation types dominated by heather and/or grass. The project was split into three work packages, each investigating different aspects of the applicability of the Canadian Fire Weather Index System to moorland vegetation.

Work package 1 produced a detailed literature review of existing data from vegetation in moorland, heaths and upland grasslands, which highlighted a paucity of detailed vegetation maps in upland Scotland. Even when data are available, how these translate to actual fuel loads is largely unknown. In general, very little is known about fuel loads and characteristics in upland vegetation types and there is a clear need for studies measuring fuel loads across a range of habitats with comparable methodology to improve our ability to map fuel loads and fuel characteristics for multiple habitats. *A comparison between identified fuel loads in heather moorland vegetation and those used in the Canadian Fire Weather Index System found limited overlap*. In particular, there is no fuel model in the Canadian Fire Weather Index System to account for any component of the shrub layer in moorlands. Where comparable physical structures could be identified, major differences in structural and response characteristics are present, which will negate the underlying assumptions built into the Canadian Fire Weather Index System models.

The investigations in work package 2 highlighted that a coupled laboratory and field experimental campaign represents an efficient way forward in calibrating a fire danger system in addition to allowing a holistic assessment of the different aspects of fire danger. Controlled field burns parameterised how fire behaviour is influenced by a wide range of environmental and fuel characteristic and determined that fire spread in heather is largely driven by the fuel moisture content of the fine parts of the vegetation. Field experiments also highlighted the importance of wind in driving the fire spread: the rate of fire spread in the field was much higher than observed in the laboratory. Laboratory fire spread experiments found significant relationships between spread rate and fuel consumption, and fine fuel moisture content. A robust and reliable fire danger rating system must be informed and underpinned by a thorough understanding of how fires spread in different fuel types: *there are no appropriate fuel models within the Canadian Fire Weather Index System that match the fuel structure of heather moorland and adequately capture the fire spread drivers in these systems.*

Work package 3 used real fire data obtained from the European Forest Fire Information System from 571 large fires in northern Europe to investigate fire occurrence and characteristics. We determined how effective the sub-indices of the Canadian Fire Weather Index System, and its final output – the Fire Weather Index, were at predicting the occurrence of fires in northern Europe, with a particular focus on the British Isles. In general, the Fire Weather Index worked well for fires occurring in forest vegetation types during summer months, probably due to the dominant fuel type (forest/trees) and the continental climatic conditions resembling the conditions used for initial model development in the Canadian boreal forest. However, *the Fire Weather Index failed to predict the majority of fires in Scotland and the rest of the UK which occur mainly in late winter and spring on shrublands (moorlands and heathlands) and peat bogs,* even though the initial sub-index - the Fine Fuel Moisture Code - gave satisfactory predictions of the fires. When fire danger ratings are based on solely on the Fire Weather Index or the sub-indices, a significant number of “false positive” or “false negative” situations occur. Fuel type and the seasonal phenological condition of fuels are key factors behind these errors. In general, the lack of close relationships between winter and spring fires in pasture, shrub and bog and the Canadian Fire Weather Index System fire behaviour indices means that the usefulness of the final output, the Fire Weather Index, for predicting fire danger early in the year is limited. However, the relationship found between the Fine Fuel Moisture Code and fire occurrence may support the use of this sub-index for fire danger intelligence purposes but not as a fully functional fire danger rating system.

1.2 Overall conclusion

The project was essentially an evaluation of the power of the Canadian Fire Weather Index System to predict potential ignition, fire spread and fire intensity of fires in moorland vegetation in Scotland. The system has provided an excellent structure with which to investigate the many elements involved in developing a fire danger rating system in Scotland. However, the fuel types and the fire behaviour of fires in Scottish moorlands appear to be very different from the original forest fire scenarios in which the system was developed. A detailed investigation of fire data from 571 fires in northern Europe showed that only some sub-indices of the Canadian Fire Weather Index System performed adequately for the prediction of fire occurrence. A robust and reliable Fire Danger Rating System must be informed and underpinned by a thorough understanding of the fuel structures involved and how fires spread in the different fuel types. There are no appropriate fuel models within the Canadian Fire Weather Index System that match the fuel structure of heather moorland and adequately capture the fire spread drivers in these systems. We therefore suggest that new approaches are supported to develop a Fire Danger Rating System that capture the variables inherent with the particular combination of fuel types, seasonal condition of vegetation and fire weather in Scotland.

1.3 Suggested future work

1.3.1 Immediate/Short-term (12 months):

- A workshop to share research results, stimulate conceptual thinking about fire danger rating system issues and develop a focused research and development programme.
- Optimise the current situation by creating a reliable wildfire intelligence decision support system for Scotland using existing evidence, infrastructure, and other capabilities.
- Further develop collaboration with related research and development work on similar fuel types in other countries and jurisdictions.
- Maintain fire-related field work to retain a core research skills base in Scotland

1.3.2 Medium term (1-5 years):

- Establish a dedicated Scottish wildfire research group within existing higher education and Scottish government infrastructure
- Application of existing landscape mapping tools for assessing fuel type and loads
- Development of relevant government policies for fire awareness and prevention
- Detailed investigations of the interactions between the different fuel layers and fire behaviours
- Determine moisture dynamics of different fuel layers.
- Model real-time effects of weather on fire behaviour.
- Develop fire behaviour models that allow fuel, weather and terrain conditions to be related to time-dependent assessments of fire intensity and fire severity
- Refinement of fire danger classes, that are related to the thresholds of control for fire suppression, and can be used as triggers for fire prevention activities and thresholds for prescribed fires
- Stimulate co-operation between fire management agencies, research institutions and programmes through the Scottish Wildfire Forum, to set common standards for the use of fire danger information and disseminate this through awareness raising, and training initiatives.
- Work with end-users in government agencies, third sector and private organisations on the standards, presentation, descriptors, and communication of fire danger information

1.3.3 Long term (5-10 years):

- Continue the development of cost-sharing agreements between interested agencies and interests that will support a long-term multi-purpose, multi-stakeholder fire danger information platform.
- Continue the development of a suite of fire danger guidance material for fire and land managers to support training and decision making on the ground for fire management and suppression purposes.
- Continue fire danger rating system development in view of changing land-uses, climate, policy development, economic and social change.

1.4 Funding Acknowledgment

Financial support for the Scottish Fire Danger Rating System Project from the Scottish Government is gratefully acknowledged.

2 Introduction to the project

The Canadian Fire Weather Index system (CFWIS) is one of the most widely used tools for the general assessment of wildfire danger around the World (Valentine, 1978; de Groot, 1987; Stocks *et al.*, 1989; Forestry Canada Fire Danger Group, 1992; Fogarty *et al.*, 1998; Legg et al, 2007).

Fire danger is a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control, and fire impact (Merrill & Alexander, 1987). The fire environment is the combination of the surrounding conditions, influences, and modifying forces of topography, fuel, and fire weather that determines fire behaviour (Merrill & Alexander, 1987).
Fire danger rating is the assessment and integration of the factors affecting fire danger, and is expressed in numerical indices (Chandler *et al.*, 1983; Stocks *et al.*, 1989).

Significant wildfire seasons only occur intermittently in Scotland and the UK. However, there is concern that we may be somewhat unprepared to deal with the potential increasing risk of difficult wildfire seasons due to climate change. There is a need to plan for increasing periods of significant wildfire activity and to safely conduct management burning by developing a Fire Danger Rating System (FDRS) for Scotland.

A Fire Weather Index System (FWIS) has been in use in the UK since 2005, as the main building block of the Met Office Fire Severity Index (MOFSI). The Scottish Government first investigated and evaluated this Canadian FWIS as part of the FireBeaters project 2006-08 (Legg & Davies, 2009). Both MOFSI and the FireBeaters project focussed on the use of the final product of the CFWIS, the Fire Weather Index (FWI). This has proved problematic because the CFWIS was simply adopted but not adapted to Scottish fuel types and conditions.

The major focus of current project was to establish approaches for the adaptation of the Canadian FWIS to Scottish vegetation types.

2.1 Background to the Canadian Fire Weather Index System

Research into fire danger in Canada has been going on for a century. It started in the mid-1920s and the system has been updated many times during development, with the recognizable current form of the CFWIS from the 1980's (Taylor & Alexander, 2006). The system started as a manual system with weather data collection at individual weather stations and the calculation of the fire weather indices done manually using look-up tables.

A video introduction to the CFWIS can be found at
https://www.youtube.com/watch?v=mdeM-cBCQJA .

The CFWIS was developed empirically on evidence of many thousands of fuel moisture readings, live fire tests and case studies of well documented fires. The environmental context under which it was developed is therefore highly relevant to any attempts at technology transfer (i.e. transfer of the system to a different environment, habitat, ecosystem). For example, the CFWIS system was designed for jack pine forests and to initiate after snow melt in the spring, run through the summer, which is the main fire season in Canada and shut down when snow cover happens in the autumn. There is a separate start-up procedure for areas with no snow.

The CFWIS uses a main reference fuel type of forest floor material on flat terrain under mature jack pine (*Pinus banksiana*) or lodgepole pine (*Pinus contorta*) (Anderson, 2005, 2009). The main fuels in these systems are the undecomposed surface litter and organic matter in the top layers of the soil (i.e. dead organic matter). A key component of these soils is the “F” fermentation layer, which is absent from Scottish moorland soils.

Although the final outputs of the CFWIS relate to fire behaviour, it was designed to be driven by only four simple weather inputs and hence the name, the Fire Weather Index system. This approach allowed it to be used across the whole continent of Canada. The complexities inherent in the fire environment that lead to the subsequent fire behaviour prediction were deliberately hidden in the models, tables and then computer software (Van Wagner, 1971).

However as also noted:

“Forest fire danger rating is a fascinating but exasperating branch of forest research. The goal is easily stated: Make an index such that any given index value will always represent the same fire behaviour, no matter what weather history leads up to it. The trouble is, one quickly outruns the available practical knowledge and theory” (Van Wagner, 1970).

And as also subsequently noted:

“The fact is that it’s difficult to portray all the aspects of fire danger in a single number… One number can’t be expected to cover the full range of fire management needs.” (Alexander, 1994).

The number, or index that these eminent Canadian fire researchers are referring to is the Fire Weather Index or FWI – the final output from the CFWIS. The endpoint FWI is only one of six component parts in the CFWIS, and each of these has a different purpose, with different inputs and models behind them. There are many examples around the world where only one or two components of the CFWIS are used for predicting fire danger instead of the whole system. Sometimes different fuel models are used to replace the reference fuel model. In other words, the system can be used flexibly to suit the fire management needs of the region it is being applied to.

2.2 Structure of the Canadian Fire Weather Index System

The six components of the FWI System consist of three fuel moisture codes and three fire behaviour indices (Figure 2.1). The soil moisture indices are:

- The Fine Fuel Moisture Code (FFMC)
- The Duff Moisture Code (DMC)
- The Drought Code (DC)

The fire behaviour indices are:

- The Initial Spread Index (ISI)
- The Build-up Index (BUI)
- The Fire Weather Index (FWI)

These numerical components are based on four weather observations: air temperature, rainfall in the previous 24 hours, relative humidity and wind speed for a reference fuel type.

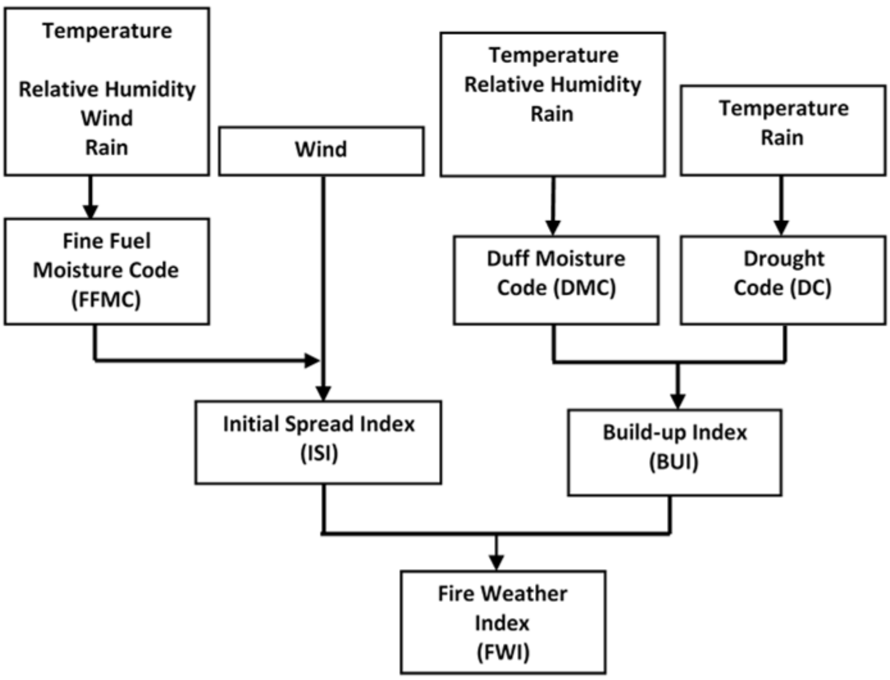

Figure 2.1 Inputs and outputs of the Canadian Fire Weather Index System (CFWIS)

The weather inputs are measured at 1200 local standard time and consist of air temperature, relative humidity, wind speed (measured in an open clearing at a height of 10 m), and total rainfall from the previous 24 hours. Although the data is collected and calculated at noon, the models behind the fuel moisture codes and indices are designed to represent peak fire danger conditions at about 16.00 hours. The codes and indices can also be calculated hourly (Alexander *et al.*, 1984; Van Wagner, 1987; Lawson & Armitage, 2008).

The three fuel moisture codes act like a book-keeping system. They are calculated by taking readings of the current day's weather, plus the value from the previous day's calculation (Stocks *et al.*, 1989). For example, if it has rained, moisture is added to the code-value, and if it is dry, moisture is subtracted. This means that the lower the fuel moisture content, the higher the moisture code index value will be. Also, the indices only go one way in that as an input value rises the related index value goes up.

Behind each soil moisture code is a drying curve. The drying curves are based on a set of assumptions. These are that air temperature is 21°C, relative humidity is 45%, wind speed is 13 km/hr, readings are taken at noon and day length is per July.

Although they are all linked together, each code has a different purpose. The FFMC represents the moisture content of dead fine litter and grasses 1 to 2 cm deep and gives an indication of ignition potential.

The DMC represents the moisture content of the duff layer, consisting of loosely compacted organic material 5 to 10 cm deep, and indicates the potential for combustion in this layer, contributing to fire intensity. The DMC has a big influence on the FWI index value and these fuels start to get involved in combustion at a DMC value of 20.

The Drought Code (DC) represents the moisture content of compacted organic material 10 to 20 cm deep, it does not really contribute to the FWI calculation of fire intensity but instead indicates the potential for deep-seated smouldering fire (Van Wagner, 1987).

Each moisture code has a time lag and a rainfall threshold (Table 2.1). If rainfall is lower than this threshold value, the code value does not decrease (Anderson, 2009).

Table 2.1 Characteristics of the fuel moisture code components of the FWI System (from Anderson, 2009; de Groot, 1987).

Fuel Moisture Code	Value Range	Rain Threshold (mm)	Time Lag (days)
FFMC	0 – 101	0.6	0.667
DMC	0 – 150	1.5	15
DC	0 – 800	2.8	53

The influence of the time lag is that it means that the dead fine surface fuels represented by the FFMC have lost 67% of their moisture in two thirds of a day and that the moisture content and the code will develop an equilibrium with relative humidity in 2 – 3 days.

For DMC, which dries more slowly and when fully saturated at 300% moisture content, it takes some 15 days of drying to reach 115% moisture content and a DMC index value of 45.

DC starts at 400% moisture content and takes some 53 days to lose all moisture, when the index value reaches 800. In Canada smouldering combustion in this fuel layer tends to start at DC values above 500.

The three fire behaviour indices (ISI, BUI and FWI) are broken down into two stages, an intermediary stage and the final fire weather index. They are formed by combinations of the moisture codes and wind speed (Stocks *et al.*, 1989; Anderson, 2005, 2009).

The Initial Spread Index (ISI) combines FFMC with wind speed and indicates fire spread potential without considering fuel quantity. The Buildup Index (BUI) combines the DMC and DC and indicates combustion potential of the available fuel. Finally, the FWI combines ISI and BUI to create an indirect representation of the potential fire intensity, usually expressed as kW/m. In the Canadian situation and, where validated in generally similar habitat types, the values of the three fire behaviour indices increase as the various elements of fire danger increase.

The fire behaviour index values range from zero to about 200 (de Groot, 1987) depending on the index (Table 2.2) and provide fire managers with a variety of information about potential fire behaviour.

Table 2.2 Value range of fire behaviour indices:

Fire Behaviour Index	Value Range
ISI	0 ~ 100
BUI	0 ~ 200
FWI	0 ~ 150

This CFWIS information from soil moisture and fire behaviour indices (codes) can then be used by fire managers for a variety of purposes:

- Preparedness planning (primary aim)
- Fire prevention planning
- Detection planning
- Initial attack despatching
- Suppression tactics & strategies on wildfires
- Escaped fire situation analysis
- Prescribed Fire planning & execution
- Fire behaviour training

2.3 Initial comparison of the context of the CFWIS and Scottish scenarios

Some basic differences between the context of the CFWIS in Canada, the structure of the CFWIS and vegetation and fire scenarios in Scotland should be noted. Most wildfires in Scotland are known to occur on moorland. There is no above ground “shrub fuel moisture code” in the CFWIS. The fire behaviour of shrub fuels is acknowledged to be very different from the reference fuels (Alexander, 1994). The moorland (shrub) vegetation that burns in Scotland is also mostly alive and not dead. There is a strong seasonal influence on live fuel moisture content (Legg et al., 2007). Also, heather and other moorland fuels are known to dry out with frost (Davies et al., 2011; Log, 2020). Logically the cold weather drying means that while the index would be going down, the real state of nature would be doing the opposite, it would be getting drier and more flammable.

Weather inputs to the CFWIS are normally collected in a standardised way (Turner & Lawson, 1978). Wind speed data are collected in an open environment 10m above ground level. It is then applied in a forest environment (Van Wagner, 1987). An empirically based function has been applied to ISI to take this change of environment into account but when ISI is applied back onto open areas it is numerically set high and doubles with every 13kph increase in windspeed.

Other differences in terms of surface roughness between a forest environment compared to a more open shrub situation have also not been taken into account in the ISI model (Anderson et al., 2015) and it is designed to identify only the initial spread and not take account the impact of fuel quantity on rate of spread.

In Canada the FWI is used as an indirect indication of frontal fire intensity (van Wagner et al., 1987, after Byram, 1959), and from the original source this is defined as:

$I = HWR$

“Where in compatible units H is the heat of combustion. W is the weight of fuel consumed per unit area, R is the forward rate of spread, and I is the energy output rate per unit length of fire front.”

Bands or ranges of fire intensity are then used to create the levels of fire danger classes. The fire danger classes are split according to the upper threshold of fire suppression capability using a variety of tools, tactics and strategies (Table 2.3) based on fire intensity bands. These categories have been applied in a variety of contexts for example in Alaska (Alexander & Cole, 1994).

Table 2.3 Typical fireline intensity based fire danger classes for forest systems as applied to values from the Canadian Fire Weather Index. (FDR – Fire Danger Rating).

FWI Index values (kW/m)	FDR FWI class	Status	Description (Fire Danger Indicators)
< 10	2 – 4	Low	Fires likely to be self-extinguishing and new ignitions unlikely. Any existing fires limited to smoldering in deep, drier layers.
10 – 500	5 – 8	Moderate	Creeping or gentle surface fires. Fires easily contained by ground crews with pumps and hand tools.
500 – 2000	9 - 16	High	Moderate to vigorous surface fire with intermittent crown involvement. Challenging for ground crews to handle; heavy equipment (bulldozers, tanker trucks, aircraft) often required to contain fire.
2000 – 4000	17 - 29	Very High	High-intensity fire with partial to full crown involvement. Head fire conditions beyond the ability of ground crews; air attack with retardant required to effectively attack fire's head.
> 4000	30 +	Extreme	Fast-spreading, high-intensity crown fire. Very difficult to control. Suppression actions limited to flanks, with only indirect actions possible against the fire's head.

A key activity in the development of the CFWIS has been extensive efforts to identify Type 1 and Type 2 errors, which are respectively, false positives and false negatives (Taylor & Alexander, 2006). This is represented in Figure 2.2 and from the original source this is defined as:

- **“Type I errors** (errors of commission or false positives) occur when the system "sounds an alarm," but no real potential for serious fires exists: fire danger is over-estimated;
- **Type II errors** (errors of omission or false negatives) occur when serious fires take place prior to the system “sounding an alarm” or when the system "sounds no alarm at all": fire danger is underestimated.”

	Danger Rating	
True State of Nature	**Low Danger**	**High Danger**
Low Danger	**No error**	***Type I error—false positive***
High Danger	***Type II error—false negative***	**No error**

Figure 2.2 Potential type 1 (false positive) and type 2 (false negative) errors in relation to the true state of nature in fire danger predictions.

2.4 FireBeaters Research Project

As mentioned previously the Scottish Government sponsored research into the CFWIS in 2006-08. The purpose of this FireBeaters project was to look at the feasibility of extending the Met Office Fire Severity Index (MOFSI) to Scotland and to investigate heather fuel moisture and fire behaviour. The work was carried out by a combined team from Edinburgh University and the Met Office and was published as two reports (Legg *et al.*, 2007, Legg & Davies, 2009).

The project achieved a number of objectives but also found some significant problems. Conclusions from the Phase 1 report included:

- No relationship could be established between on-site ISI calculations and observed rate of spread.
- No relationship could be established between daily FWI and observed fire intensity
- There was no relationship between MOFSI values and either experimentally derived estimates of fire behaviour or practitioners perceived flammability of fuels and fire controllability
- A simple model for predicting rate of spread and fire intensity based on fuel characteristics and wind speed was better than FWI
- Ignition of building phase heather occurred when live fuel moisture was below 60%
- Critical ignition moisture content of dead fuels was between 20% - 30%
- Wildfires much more likely to occur when FFMC>70 and the majority of severe fires occurred when FFMC>80
- FWI performed poorly as an indicator of “difficulty of control” for wildfires. Fires did occur when MOFSI (FWI) was higher but fires of high magnitude also occurred at low MOFSI values
- Using the CFWIS the best correlation was between FFMC and ISI and wildfires occurring
- FFMC predicted the fuel moisture of the moss and litter layer

- *Molinia* leaf death more likely to be associated with changes in day length than by drought
- Spring fires were controlled by live fuel moisture while summer fires were controlled by dead fuel moisture

Conclusions from the Phase 2 report included:

- Heather fires were not sustaining when live stem FMC exceeded 80% of oven-dry weight, where the dead stem FMC exceeded 50% and where lower canopy exceeded about 75%.
- That for initial fire establishment the moisture content of the fine dead fuels is critical.
- Land managers generally avoided days with high FFMC / ISI when carrying our burning operations
- Moss ignition moisture <16%, which rises as wind speed increases

After the project finished a number of academic papers were published over time. One significant one is (Davies & Legg, 2016) which confirmed the relationship between FFMC and ISI for spring fires, in that fire danger was seen to rise significantly when FFMC>75 and ISI>2. It is significant that the FireBeaters analysis of fire behaviour found little correlation between heather fire behaviour the ISI and the FWI, which are at the core of the MOFSI system used to generate Daily Hazard Assessments for Wildfire for the Natural Hazards Partnership.

2.5 Developing a Fire Danger Rating System (FDRS) for Scotland

The process of successfully developing a FDRS is acknowledged to be long and complex with a need to engage many agencies and organisations, with technical research along with social and organisational inputs. Four main elements of a programme are recommended (Taylor & Alexander, 2006):

1. *A modular system of fire danger indicators or models of fire occurrence and behavior in important fire environments developed through a sustained program of scientific research and based on relationships between fire weather, fuels, topography, and ignition sources.*

2. *A reliable technical infrastructure to gather, process, disseminate, and archive fire weather data and forecasts (weather instruments/stations, standards, communication) and fire danger predictions (text and map displays) within operational agencies.*

3. *Guidelines, decision aids, and training for fire managers in the application of fire danger indicators appropriate to the needs and capabilities of operational agencies based on research and operational experience.*

4. *Cooperation between fire management agencies and with research agencies to foster communication, to share resources, and to set common standards for*

information, resources, and training (policies, cost-sharing agreements, national training courses, working groups).

2.6 Aims of current the project

The primary aim of the current project was to explore how the Canadian FWIS could be adapted to moorland vegetation types, primarily those dominated by heather and/or grass. The project was split into three work packages, each investigating different aspects of the relationship between the CFWIS and the fire environment and fire regime in Scotland.

Work packages

WP 1: Mapping and characterising fuel types in Scottish moorland habitats (Section 4, led by JHI)
WP 2: Ignition for Scottish fuel types (Section 5, led by University of Edinburgh)
WP 3: Calibration of FWI codes to fire incidence data (Section 6, led by JHI)

We hope our work in this project will significantly assist the development of a working FDRS for Scotland.

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3 Project Management

3.1 Introduction

The Fire Danger Rating System project began on 11th February 2019 with an initial completion date of 10th February 2021. Due to restrictions caused by COVID19 an extension was agreed with NatureScot and the Scottish Government until Monday 31st May 2021. A further extension was agreed on Thursday 13th May to extend the final reporting of the project until Wednesday, 30th June 2021. This enabled final field sampling of *Molinia* grasses by the James Hutton Institute during May 2021 and field sampling of material by staff from the University of Edinburgh to facilitate laboratory-based burns.

3.2 Principal Project Staffing

3.2.1 Principal Investigators

The Fire Danger Rating System (FDRS) project comprised two principal investigators:

i. Dr Rory Hadden, University of Edinburgh, Edinburgh
ii. Dr Andy Taylor, James Hutton Institute, Aberdeen

3.2.2 Technical Roles & Collaboration

Specific technical roles were provided by five research scientists:

i. Dr Andrea Britton, James Hutton Institute, Aberdeen
ii. Dr Ina Pohle, James Hutton Institute, Aberdeen
iii. Dr Zisis Gagkas James Hutton Institute, Aberdeen
iv. Dr Helaina Black, James Hutton Institute, Aberdeen
v. Debbie Fielding, James Hutton Institute, Aberdeen

Consultation on the project was provided by:

i. Dr Matt Davies, Ohio State University, Ohio
ii. Mr Michael Bruce, Firebreak Services, Glen Tanar Estate, Deeside, Aberdeenshire

3.2.3 Project Support

3.2.3.1 Project Management

Project management was provided by Dr Jason Owen, James Hutton Institute.

Table 3.1 Personnel involved in field-based activities not previously named.

Name	Company	Role
Colin McClean	Glen Tanar Estate	Fire Management
Colin Espie	Glen Tanar Estate	Fire Management
Fergus Cumming	Glen Tanar Estate	Fire Management
Duncan Leckie	Glen Tanar Estate	Fire Management
Ruari Wild Wood	Glen Tanar Estate	Fire Management
Paul Taylor	Glen Tanar Estate	Fire Management
Eric Baird	Glen Tanar Charitable Trust	Fire Management
Mike Martin	Glen Tanar Charitable Trust	Fire Management
José van Paassen	James Hutton Institute	Field Sampling
Sheila Reid	James Hutton Institute	Field Sampling
Donald Barrie	James Hutton Institute	Fire Management
Eric Mueller	University of Edinburgh	Fire Research
Zak Campbell-Lochrie	University of Edinburgh	Fire Research
Carlos Walker-Ravena	University of Edinburgh	Fire Research
Vasilis Koutsomarkos	University of Edinburgh	Fire Research
Peter Cairney	Fettercairn Estate	Fire Management

3.2.3.2 Field Team

Field support was provided by staff from James Hutton Institute, University of Edinburgh and Glen Tanar Estate, including personnel with experience of muirburn, field sampling and fire researchers (Table 3.1).

Responsibility for on-site ignition and fire suppression was provided by either Michael Bruce when burning took place at Glen Tanar or Donald Barrie when undertaken at Glensaugh Estate and Fettercairn Estate.

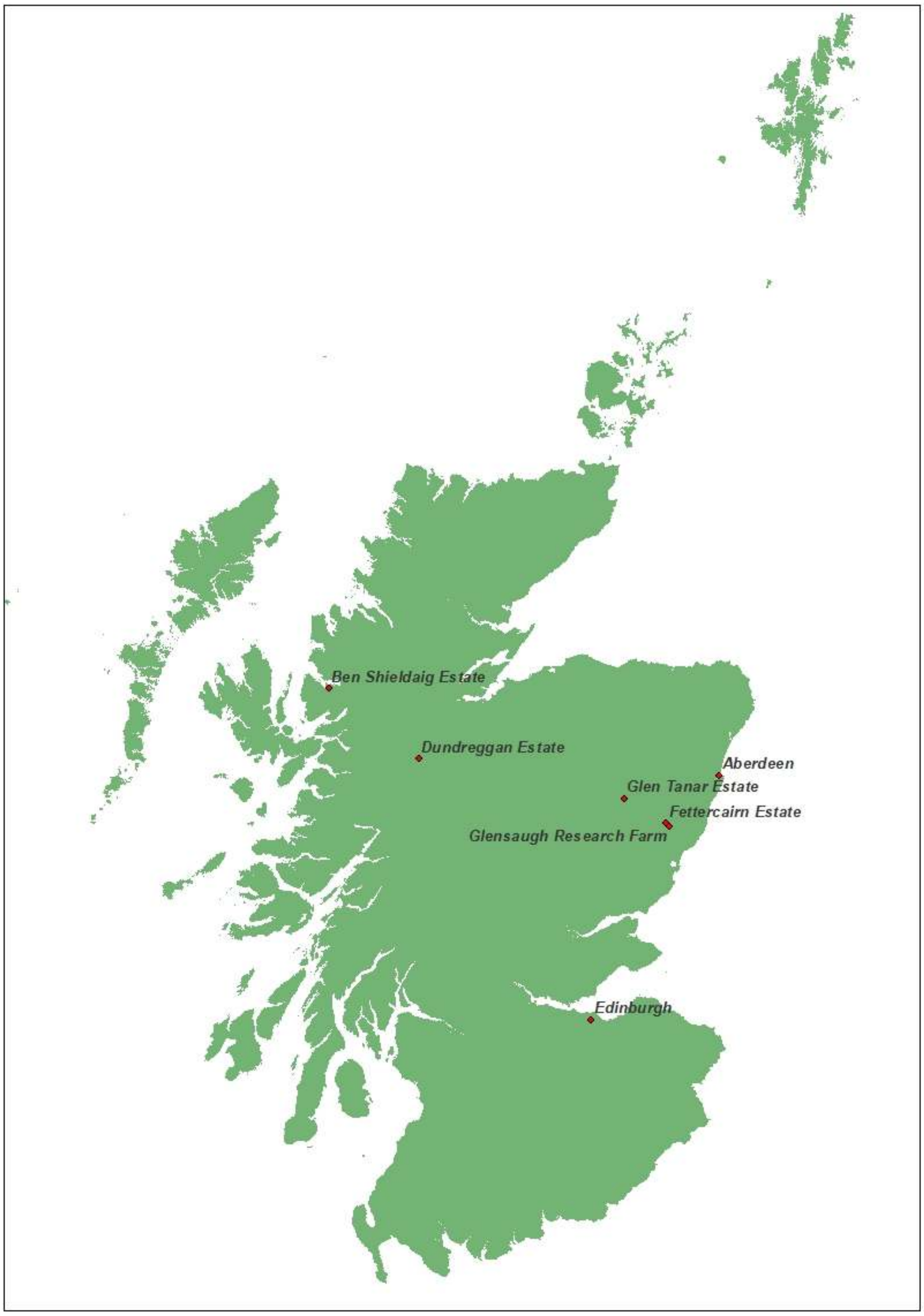

Figure 3.1 Locations of field sites in Scotland used for the collection of data on fuel loads and controlled burns.

3.3 Locations of field scale burning

The locations of field sites for field burns and fuel load determinations are shown in Figure 3.1. Field scale experimental burns took place with the permission of landowners, to which the project is indebted.

Glen Tanar Estate
Brooks House
Glen Tanar
Aboyne
Aberdeenshire
Scotland
AB34 5EU

Glensaugh Farm
Glensaugh
Laurencekirk
Aberdeenshire
AB30 1HB

Fettercairn Estate
Fettercairn House
Fettercairn
Kincardineshire

3.4 Training / H&S

Prior to undertaking field burns staff undertook a 'Basic Fire Training' course held at Glen Tanar Estate, Aboyne, Aberdeenshire on Tuesday 4th and Wednesday 5th February 2020. Course schedule shown in Appendix 8.1. The course was delivered by Michael Bruce, Firebreak Services.

Attendees were trained in the theory and practice of fighting wildfires with practical training on extinguishing fires using a range of equipment. Once considered competent the FDRS participants and staff from Glen Tanar Estate prepared ground and tested protocols to study fire behaviour.

Figure 3.2 Attendee practising fire suppression with beater during training provided by Firebreak Services at Glen Tanar Estate.

Figure 3.3 Attendee providing fire suppression using leaf blower during training given by Firebreak Services at Glen Tanar Estate.

3.5 Steering Group

Table 3.2 Contributors to the FDRS project Steering Group and roles.

Name	Company	Role
Andrew Coupar	NatureScot	Chair (Oct 19 – end)
Graham Sullivan	NatureScot	Chair (Mar 19 – Oct 19)
Bruce Farquharson	Scottish Fire and Rescue Service	Member
Ann McArdle	Scottish Government	Member (Mar 19 –Aug 20)
Amy Nicholson	Forestry Commission Scotland	Member
Kerstin Kinnaird	Forestry Commission Scotland	Member
Rob Stacey	Northumberland Fire and Rescue Service	Member
Karen Rentoul	Nature Scot	Member

3.5.1 Reporting – Steering Group

Prior to delivery of final report, formal reporting to the Steering Group was maintained by submitting regular reports:

June 2019
November 2019
June 2020
February 2021

3.6 Reporting – Scottish Government

Formal updates were provided to the Scottish Government, approximately fortnightly, between 1st March 2019 and 27th September 2019. Whereupon further fortnightly reporting was deemed unnecessary.

3.7 Meetings

Meetings were hosted for the Steering Group, stakeholders, and project participants regularly during the project.

3.7.1 Steering Group

- Steering Group Meeting – 9th April 2019, Battleby Centre
- Steering Group Chair, A Taylor & Jason Owen – 15th October 2019, Great Glen House, Inverness

3.7.2 Project Meetings

- Pre-Project Meeting – 11th January 2019
- Project Meeting - 9th April 2019, Battleby Centre
- Project Meeting – 30th April 2019, James Hutton Institute (JHI Staff)

- Project Meeting – 29th July 2019, James Hutton Institute (JHI Staff)
- Project Meeting – 27th September 2019, James Hutton Institute
- Project Meeting – 13th December 2019, James Hutton Institute – International speakers from 'fire research community' & related researchers / PhD student from JHI

  Project meeting held on 13th December 2019 included presentations from Anders Granström, Swedish University of Agricultural Sciences and Johan Sjöström, RISE Research Institute of Sweden.

  Matt Davies, Ohio State University, attended meeting in person and had opportunity to review work to date and advise accordingly.

3.7.3 Stakeholder Meetings

- Stakeholder Meeting – 30th March 2020 – Cancelled due to restrictions caused by Covid.
- Stakeholder Meeting – 19th October 2020

3.7.4 Webinar

- Scottish FDRS & UK NERC fire projects joint webinar - 26th April 2021

A joint webinar between the Scottish FDRS and UK NERC fire projects was hosted by James Hutton Institute during which speakers from both projects gave presentations. The presentations were recorded and are available on You Tube: [Webinar: Working towards a tailored UK fire danger rating system - YouTube]

3.7.5 External Meetings

Andy Taylor and Debbie Fielding attended the 'Preventing Wildfires, learning from experience', Highland Environment Forum, 6th March 2020 conference. The conference aimed to discuss past experience and good management practice of burning with the aim of preventing out of control burning.

3.7.6 Covid – Restrictions

From March 2020 restrictions placed by Covid curtailed formal project meetings and communication was maintained via video calls between project participants. Pressures of working from home and other responsibilities meant these were on a more ad hoc, as required basis and were not recorded as formal project meetings.

3.8 Support

The project received support from a range of parties to which we express our gratitude.

Letters of support to the project were provided by a range of parties: Association of Deer Management Groups, Urban Heaths Partnership, Confor, Ohio State University, European Forest Institute, Forest Research, Glen Tanar, The Heather Trust, University of Liverpool, Norwegian Metrological Society, Scottish Land & Estates and Scottish woodlands.

3.8.1 European Forest Fire Information System (EFFIS) Data

Significant data was provided by Jesus San Miguel, Director of the European Forest Fire Information System (EFFIS) and his team.

3.8.2 Scottish Rural College (SRUC)

James Marshal, Farm Manager, Easter Howgate Farm, Scottish Rural College (SRUC), provided invaluable samples of heather for laboratory scale burn trials during the project.

4 WP1: Mapping and characterisation of fuel type in Scottish habitats

4.1 Introduction

A key element of any Fire Danger Rating System (FDRS) is information on fuel type and behaviour which, when combined with associated fuel moisture contents, are integral for predicting fire risk. Currently, predictions of fire risk in Scotland are based on information supplied by the European Forest Fire Information System (EFFIS) which in turn is based on models designed to predict fire risk in the fuel types and fire behaviour of forested systems. Most fires in Scotland occur in heathlands and grasslands (see section 6, WP 3), and it has yet to be determined if the use of data on forest fuel types is appropriate for Scottish heathland and grassland systems. The need to gain a better understanding of characteristic Scottish fuel types was therefore identified as an essential aspect in the development of a Scottish-relevant FDRS.

Fuel type (including load and structure) is broadly associated with variation in vegetation type. Thus, it is necessary to develop a practical framework linking vegetation type/habitat with fuel load and structure. A crucial step in this process was determining what information is already available on fuel types in Scottish heathland and grassland habitats. This was achieved with a detailed literature review of existing data from vegetation in moorland, heaths and upland grasslands. The full review is given in Appendix 8.2, and a summary is provided here.

4.2 Literature review of Scottish vegetation and fuel loads

We examined, firstly, the current availability of vegetation mapping data for Scotland and the suitability of this data to inform on the spatial distribution of fuel loads. Secondly, we reviewed current knowledge of fuel loads in Scottish heathland and upland grassland habitats and the modifying effects of season, phenology, management and environmental factors (climate, nitrogen deposition). The scope of the review was limited to heathland and upland grassland types (especially *Molinia* dominated grassland) present in Scotland, but information from comparable systems in the UK, Europe and elsewhere was included where relevant.

4.2.1 Key unknowns

This review has highlighted several key gaps in our knowledge in relation to mapping fuel loads and understanding the relationships between vegetation types and fuel load characteristics in the UK. **Measurements of fuel load, which include characteristics such as the amount of biomass in different fuel size categories, or live: dead fuel ratios are scarce in the literature**. While methodologies for rapid assessment of fuel loads have been developed (Davies *et al.*, 2008) they have not yet been implemented to any degree for broad scale assessment of fuel load. Data describing standing biomass or annual biomass production are much more common, mostly deriving from studies of biomass production for grazing animals. These studies providing data on biomass are primarily focussed on a narrow range of community types (dry heathlands and grazed grasslands) and a limited number of geographical locations (east of Scotland, north Pennines and mid-Wales). **Biomass or fuel load data from wet heathlands, blanket bog, grassy heaths, semi-natural grasslands and habitats in the west of Scotland are lacking**.

Most studies to date focus on single plant species or communities; comparing across studies to assess relative fuel loads associated with different vegetation types is often difficult, due to differences in methodologies used, making comparisons uncertain. **More studies measuring fuel loads across a range of habitats in a comparable way are required** to improve our ability to map fuel load for multiple habitats.
Studies of heathland and grassland biomass to date indicate that climatic parameters such as growing season length, air/soil temperature and rainfall probably influence biomass production and standing biomass. Previous modelling exercises suggest, however, that the currently available pool of data is insufficient to allow robust relationships between climate and vegetation biomass/ fuel load to be derived. **Measurements of fuel load characteristics along latitudinal, altitude and climatic gradients in Scotland for a range of soil types and plant communities are required** to enable fuel loads to be better predicted over a wide geographic range.
Producing maps of fuel load or fuel characteristics for Scotland raises a number of issues. Before producing any map one key question arises which is **'at what spatial resolution do we need to map fuel loads to usefully inform on fire danger in Scotland'**. It is vitally important to determine the required mapping resolution before embarking on an attempt to map fuel loads in order to ensure both that the end product is useful and that unnecessary resources are not consumed in its production. Currently available vegetation mapping data would enable only very coarse mapping of fuel loads. If, as seems likely, NVC level data on community composition is required, **the current 'upland survey gap' and lack of detailed vegetation mapping for most upland areas in Scotland will be a major barrier to production of a fuel load map**. The 'upland survey gap' refers to approximately 2.7 million hectares (one third of Scotland) for which detailed habitat mapping is not available (Scobie, 2018).

Note: In addition to a lack of information on habitat distributions, there is a knowledge gap around what vegetation (and soil) components are actually consumed during fires. It is therefore important to recognise that even where habitat and biomass information is available, they need not directly relate to fuel that would be consumed in a fire. At present, except for heather, virtually nothing is known about what components are consumed during fires in Scotland. In addition, identifying what fuel characteristics need to be measured and in what way, are important for fire behaviour research, especially for model development.

4.3 Comparison of the fuel load categories in the Canadian Fire Weather Index and in Scottish heathland and grassland vegetation

The aim of the project was to investigate how (or if) the Canadian Fire Weather Index (CFWI) could be adapted to act as a Scottish Fire Weather Index. This involves taking a fire danger rating system that has been developed for the climate, weather, environment, vegetation and soil characteristics of forested land – primarily jack pine stands in Canada and adapting it to the Scottish climate and weather for predicting fires in treeless vegetation dominated primarily by dwarf shrubs, usually species in the genera *Calluna, Erica,* and *Vaccinium*, and by a range of grass species.

During the project, it became clear that adaptation was not simply a matter of collecting new data to parameterise Scottish fuel loads and flammability. We therefore investigated the primary input variables used in the CFWI in order to gain a greater understanding of the compatibility between jack pine systems and Scottish moorland and grasslands. The CFWI is modelled from weather data in a stepwise procedure using empirical relationships, where the primary step is the determination of three fuel moisture codes (Fine Fuel Moisture Code [FFMC], Duff Moisture Code [DMC], and Drought Code [DC]) (Table 4.1). These codes relate directly to physical aspects of forest systems and the following explanations of these are taken from Wagner (1974).

Fine Fuel Moisture Code (FFMC): based on the thick layer of litter (needles, fine and coarse branch material) under jack pine weighing ca. 210 g m^{-2} dry mass. This is a layer of dead material and the moisture content of this material closely tracks the prevailing weather conditions, making the FFMC the most responsive code. The 'equivalent' layer in heathlands would usually be a combined, deep moss and litter layer - which may be partially or fully enclosed by the shrub vegetation. The latter means that the moss and litter layer can have a considerable degree of insulation from changing weather conditions, which can seriously impact response time of the moisture contents. The proportion of moss in this layer can vary from 0-100% and, while mosses have limited capacity to control water loss, their moisture contents (water content relative to dry mass) can be extraordinarily high: 400-500% in feather mosses, and 1500-1600% in Sphagnum. This large reservoir of moisture will also influence the response time of the moss and litter layer to fluctuation weather conditions. The dry mass of the heathland moss and litter layer is ca. 1kg m^{-2}.

Duff Moisture Code (DMC), ca. 4.9 kg m^{-2}: Beneath the litter layer there is a 5-10cm layer of partly decomposed needles – this is termed the duff layer. This would equate with the fermentation in Scottish forest soils (see below Keith et al, 2010), but there is no equivalent layer in heather moorlands.

Drought Code (DC): this is based on organic layer between the duff layer and the mineral soil, where plant material is no longer recognisable. In jack pine, this would have ca. 49 kg m^{-2} dry mass. The organic layer under Heather moorlands varies form quite shallow (10 cm) to those with deep layers (soils with > 50cm of peat are classified as bogs). The median depth for the shallower layers is 19 cm (Aitkenhead and Coull, 2020; M. Coull pers. com.). The 49 kg m^{-2} dry mass from the jack pine stands would be equivalent to ca. 30 cm of organic matter in heather moorlands (M. Coull, pers. com.).

The responsiveness of the fuel components underlying these three codes to changing weather decreases in the following order: litter>duff layer>lower organic layer. It is the ecosystem components underlying these three codes FFMC, DMC, and DC, which are perhaps the least compatible with Scottish scenarios.

Keith et al. (2010) described the duff layer of forest soils as constituting all the organic layer between the litter and the mineral soil. The duff layer *sensu* the Canadian FWI would therefore refer only to the upper fermentation (F) layer where plant fragments are still recognisable, and the drought code would refer to all the amorphous humus material, the H layer, between the F and the mineral soil.

Table 4.1. The three fuel moisture codes that form the basis of the Canadian Fire Weather Index, and the fuel loads and characteristics which are included within each code. The possible Scottish equivalents are given for comparison (in heather dominated moorland).

Code	**Fuel description Canadian FWI** (Van Wagner, 1974, 1987)	**Possible Scottish vegetation equivalent** (mass data from this project)
Fine Fuel Moisture Code (FFMC)	Litter and other cured fine fuels in a forest stand, in a layer of dry weight about 0.05 lb/ft^2 (0.25 kg/m^2). Nominal depth (1.2cm)	Litter, moss and fibrous organic material down to amorphous organic material, dry mass of 0.4-1.2 kg/m^2
Duff Moisture code (DMC)	Loosely compacted, decomposing organic matter 2 to 4 inches deep (Nominal depth 7cm) and weighing about 1 lb/ft^2 (5 kg/m^2) when dry	
Drought code (DC)	Deep layer of compact organic (Nominal depth 18cm) matter weighing perhaps 10 lb/ft^2 (25 kg/m^2) when dry (10 – 20cm)	Amorphous organic layer with a highly variable depth (cms to ms in deep peats)

This non-concordance between heathland vegetation and the FWI parameters means that currently no account is taken of the major aboveground fuel type likely to be most involved in heathland fires i.e. the aerial shrub canopy components of vegetation. Forecasts of fire risk in Scotland supplied by the European Forest Fire Information System (EFFIS) are based on the Canadian FWI using parameters and therefore do not equate well with either heathland or grassland vegetation (the relationships between the model parameters and actual fire occurrence are explored in detail in Section 6, WP 3).

For the Canadian FWI to be adapted to be a more accurate reflection of Scottish scenarios on heathlands then it is likely that new parameters would have to be identified and parameterised for the intrinsic attributes which influence their characteristics as fuel. Ideally, the fine fuel fraction (i.e. the most responsive fraction) for heathlands would be readily identifiable, collectable and field data on field moisture content (FMC) would show good predictive power for the occurrence of fires. It is questionable whether the moss and litter layer would satisfy these requirements. The FMC and responsiveness of different fuel fractions are explored in section 5, WP 2.

The fuel fractions we have identified and have gathered information on in this project are, in part, based on the codes of the Canadian FWI, definitions used in the FireBeaters project (Legg and Davies, 2009), and on the interpretation of the physical structure of both the vegetation and soil characteristics. The latter was the main criterion applied in the collection of fuel data on *Molinia* dominated grassland, as no information was available on what is actually consumed during a fire in the grassland.

An important inherent quality of the fuel materials used to generate each code would be that the fuel components respond in a relatively uniform and predictable manner. The partitioning of the upper and lower organic layers in the Canadian system is a recognition of this. Keith et al (2010) investigated the moisture cycles of the F and H layers of forests, the organic layer of conifer forests and showed how the F and H layers had different responses to changing conditions during the summer season. Not surprisingly the upper layer was more responsive to changing conditions.

It is therefore important to consider what fuel categories of heather moorlands could be most suitable for generating the necessary codes in a FWI model. We have principally followed the FireBeaters project (Legg & Davies, 2009) for categories of above ground components of heather.

Fuel types used in this project (Figure 4.1 and Figure 4.2) include the following -

1. Fine live green shoots < 2mm diameter
2. Fine suspended dead material < 2mm diameter
3. Coarse stem material > 2mm diameter
4. Moss and litter – the combined moss and undecomposed plant litter material on top of the consolidated root mat.

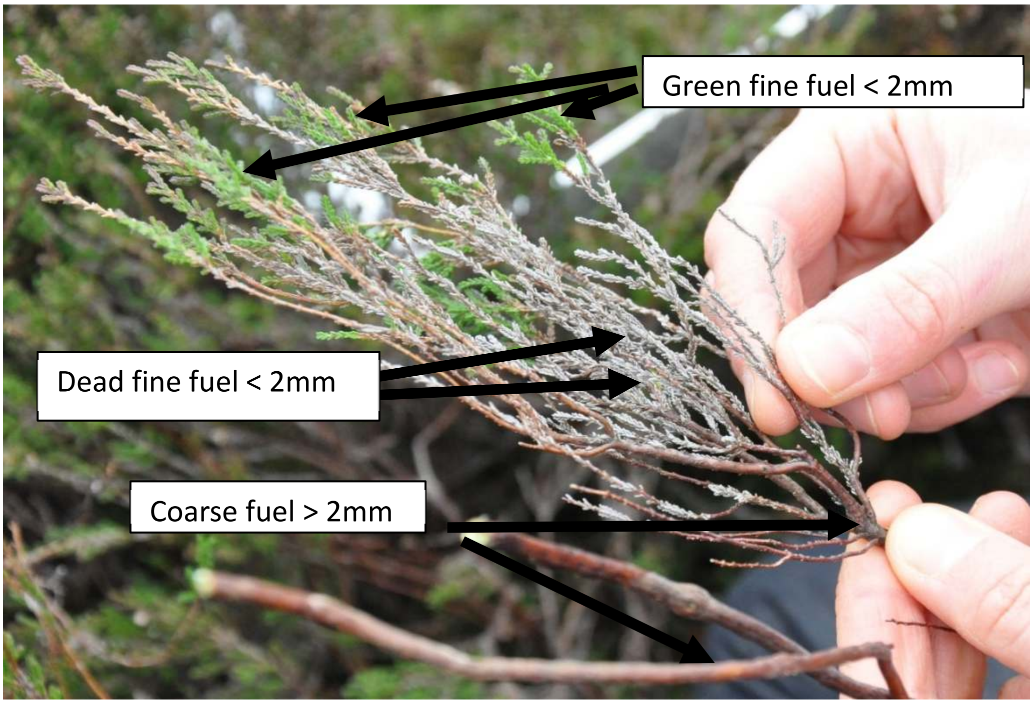

Figure 4.1 Above ground fuel categories used for determining field moisture contents and fuel loads in heather moorland.

Figure 4.2 The combined moss and litter category used for determining field moisture contents and fuel loads in heather moorland.

In addition, at each study site we also collected data on the top 10 cm of the organic layer and on the total depth of the organic layer. These data gave us information on the total fuel loads that could potentially be involved in a catastrophic fire.

The finer fractions were separated from the thicker stems in the heather canopy as the latter are likely to dry at a slower rate from the fine fraction, so including them with the fine fuels would decrease the usefulness of the data. In addition, they would most likely not be the fraction which determines the ignitability of the shoots in the canopy, although the thicker stems may dominate the energy available for fire spread once it became established (as shown in Section 5, WP2). The fine fraction is composed of live green shoots and dead suspended material. It was important to determine the fuel load and the FMC of both fractions to assess if they differ significantly as this could affect ignition properties of the fine fraction.

4.4 Determination of fuels and fuel consumption in *Calluna* heathland

To increase our understanding of the fuel components in heather moorlands and their fire characteristics, we investigated the different fractions described above at Glensaugh farm and Glen Tanar. We determined the mass of fuel loads, the proportions lost during fires, and how their field moisture contents influenced the latter. Fuel mass determinations, based on the FireBeaters protocol (Legg & Davies, 2009), used the following protocol:

1) All plant biomass was removed down to the top of the moss and litter layer and sealed in a plastic bag
2) The moss and litter layer was removed down to the consolidated root mat and bagged
3) In the laboratory, prior to drying, the relative proportions of the different fractions of the heather were determined by taking subsamples of approximately 30-40 *Calluna* shoots per quadrat and separating these into live green material, fine dead material (<2 mm) and stems (woody material >2 mm).
4) All material was dried at 80 °C for at least 48h, and then weighed.
5) The proportion of green material, fine dead material and stems in the subsamples were then used to calculate total biomass per fraction.

Initially fuel determinations were carried out on eight, 50 x 50cm quadrats. Figure 4.3 shows cross site comparisons of the fuel estimates at Glensaugh and Glen Tanar in heather of similar age structure. Both within and between site estimates are very comparable with this approach. However, collecting data from eight replicates was very time consuming and an acceptable degree of within site estimate could be garnered with 3-5 replications.

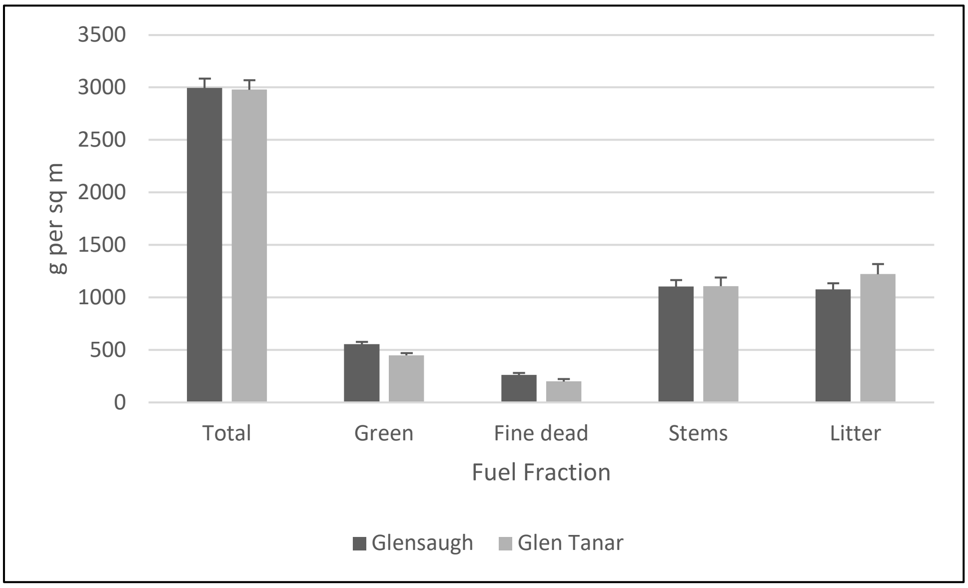

Figure 4.3 Fuel loads (g m^{-2}) in different fractions of heather-dominated moorland determined at Glensaugh farm and Glen Tanar. Green and fine dead are < 2mm diameter. Litter includes undecomposed dead plant material and the moss layer. The age of the heather at both sites was ca. 10 years old.

4.4.1 Variation in the mass of fuel loads

The amount of biomass associated with heather moorlands has been investigated on many occasions form a range of perspectives: biomass production (e.g. Aerts, 1989, Egan and Smith 2000) and life cycle and ecology (e.g. Gimingham, 1989).

Here, we focussed on dry mass in the fuel categories outlined above and the range of values we obtained lie within those reported from younger stands (ca. 20 cm in height) to greatest biomass of old growth stands where the heather is > 50 cm (Table 4.2).

Table 4.2 Summary of fuel load data (grams per square metre) for different fractions of fuel on heather moorlands.

Fuel Fraction	Number of observations	Mean (gm sq m)	Min	Max
Green fine	17	515.2	449.1	553
Dead fine	17	217.6	191.6	261
Combined fine	32	929.7	645.2	1614.8
Coarse	32	860.5	147.6	1373.5
Moss and litter	32	842.9	439.4	1250.7

The adopted protocols allowed us to take accurate assessments of fuel consumptions by determining pre- and post-fire fuel loads (reported in section 5, WP2).

4.5 Determination of fuels in *Molinia* dominated grassland

A major knowledge gap identified in the review is the lack of information of fuel loads in grassland systems in Scotland. Grasslands dominated by *Molinia caerulea* have been identified in particular as a vegetation type where large wildfires can and do occur. For example, in May 2011, a large wildfire covering nine square miles occurred in the Torridon area with much of the area burnt being grassland dominated by *Molinia*. Increasing our understanding of *Molinia* fuel characteristics would therefore enhance our ability to predict the potential for fires in these systems. *Molinia caerulea* is of particular importance because it is deciduous and dies back each autumn to the basal meristems with the green biomass produced during the growing season senescing and becoming brown, a process known as curing. This creates a pool of rapidly drying dead material. This transition of grass fuels from alive to dead state, is normally quantified by the degree of curing (i.e. the proportion of dead material in a grass sward or in a grassland as a percentage of the total fuel). The moisture content of the dead grass components is a function of atmospheric conditions and the material becomes flammable as the moisture content decreases. As in other vegetation systems subject to wildfires, availability of fuel quantity and moisture content have a significant effect on the ease of grassfire ignition and ensuing fire behaviour.

There is currently a lack of basic wildfire-related information about many aspects of *Molinia* dominated grasslands in Scotland. This includes field assessments of the fuel loads within the system, what components are actually consumed during wildfires, and which fuel components are the most sensitive to environment conditions (e.g. which dry down the quickest) and hence are most relevant with respect to wildfires starting and establishing. It would have been greatly beneficial to carry out controlled burns in *Molinia* grasslands to determine fire behaviour characteristics and fuel loss using a similar approach as that taken in *Calluna* heathlands. Discussions were initiated in early 2020 with NatureScot staff on sampling *Molinia* grasslands and possible controlled burns on the Beinn Eighe Reserve, but the Covid restrictions curtailed any possibility of developing this further.

An initial field sampling trip was made in January 2020 by Andy Taylor and Debbie Fielding to Dundreggan Conservation Estate, Inverness, which is owned Trees for Life, to develop the methodology to capture the data from *Molinia*-dominated grasslands. The following approach is based primarily on experience gained in this scoping trip and subsequent adaptation with knowledge gained in the full-scale sampling at Ben Shieldaig, Northwest Highlands in March 2020, and April 2021.

Data was collected on the following components:

1. the mass of aerial dead grass (grass shoots held above the litter and moss layer) – this was cured grass from the previous growing season which was not yet incorporated into the litter layer,
2. the mass of live vegetation (split into graminoids/forbs and shrubs – mainly ericaceous),
3. the mass of moss and litter layer (this would include old dead stems incorporated into the moss layer),
4. the mass of the top 10cm of the organic layer (termed the duff layer in the CFWI),
5. the total depth of the organic layer.

Each component was considered to represent a separate fuel types with different drying, ignition and burning characteristics.
Data was collected within eight quadrats, each 50 x 50 cm, at three areas at each locality, giving 24 plots per locality. Each sampled quadrat was GPS located and a photo taken before harvest. Within each quadrat, all vegetation was removed and separated into the defined components. The mass of the litter and moss was determined for the whole quadrat. The amount (depth) and characteristic of the organic layer is important information for developing a fuel model of the vegetation. This was determined by taking a 10 x 10 x 10 block of the upper organic layer and by using a soil auger to measure the full depth of the organic layer to the nearest cm. All samples were stored in the cold room (4°C) until processed for drying (within 48 hours of return). Prior to drying, any further sorting of the vegetation was carried out. All samples were dried at 85°C for a minimum of 48 hours and then weighed. All dried material was stored for use in determining the fuel characteristics of the different components by Rory Hadden at the University of Edinburgh (WP2).

A series of sampling trips were planned in February and March 2020 to generate new field data on different aspect of *Molinia* dominated vegetation and to collect organic material for further work in the lab. However, due to inclement weather condition (the sampling areas were covered in snow) the first sampling trip was rescheduled. Data on fuel loads were obtained during a four-day sampling trip to Ben Shieldaig (3-6th March, 2020). Areas on Ben Shieldaig have been identified using vegetation maps provided by Donnie Chisholm, Woodland Trust site manager at Ben Shieldaig.

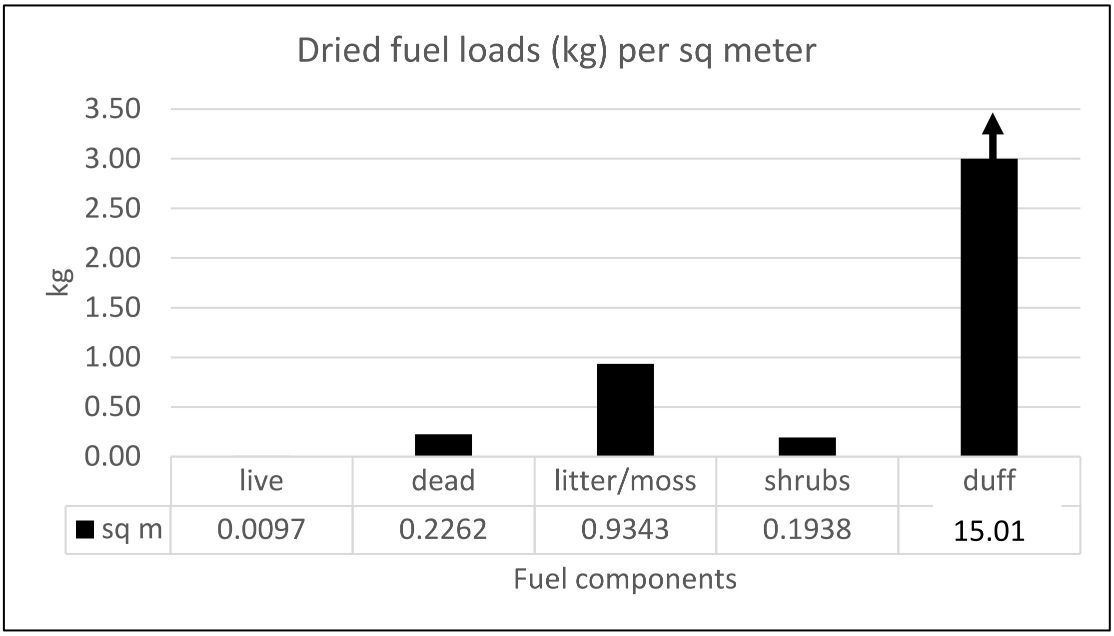

Figure 4.4 Mean values (kg per square metre) of fuel categories in *Molinia* dominated grasslands on Ben Shieldaig, March 2020. Means based on values from 24 plots. Duff in this case is the top 10 cm of the organic layer.

The data obtained from the field sampling at Ben Shieldaig highlighted the large differences in the relative quantities of each fuel (Figure 4.4). In March, the quantities of live fuel are negligible. The dead grass fraction is less than 250 grams per sq metre dry mass, which is just slightly more than the shrub component (when it is present). The moss and litter are four times more plentiful than either the dead grass or the shrubs. These figures translate to 2.2 tonnes of dead grass per ha and 9.3 tonnes moss/litter dry mass per ha. All these figures are very small compared to the amount of organic matter in the duff layer (the upper 10 cm), with ca. 14.5 kg per sq metre and 143.8 tonne per ha. This is just in the top 10 cm of the soil profile. The depth of the organic layers under the sampled plots ranged from 35-100 cm, which means that the amount of organic material available to burn ranges from 503 – 1438 tonnes per ha. However, due to the wet ground conditions which are prevalent under this type of vegetation, it would be very rare drought event when this organic material would be available for burning. However, this is a very important gap in our knowledge of these systems – we do not currently know the moisture dynamics of these ecosystems.

The actual release of carbon dioxide (CO_2) during a wildfire involving *Molinia* grassland is presently unknown, but we can estimate this if the different fuel components were consumed during a wildfire. Actual consumption would depend on the conditions of the fuel and fire intensity. The carbon (C) content of the organic material will range from 45-50% C, (Ma et al., 2018) which means consumption of just the dead grass would release around 1 tonne of CO_2 per hectare, and the moss and litter, would release around 5.5 tonnes of CO_2 per hectare. A much more severe fire which included the upper 10 cm of the organic layer would result in the release of a very significant quantity of carbon dioxide into the atmosphere, ca. 70 tonnes of CO_2 per hectare – 7 tonnes of CO_2 per hectare for every cm of organic layer lost!
A second sampling trip was made to Ben Shieldaig in May 2021, to capture late spring data on the process of greening-up of the *Molinia* grasslands (Figure 4.5). The sampling protocols used were those described above, with the exception that the eight samples per area were reduced to six.

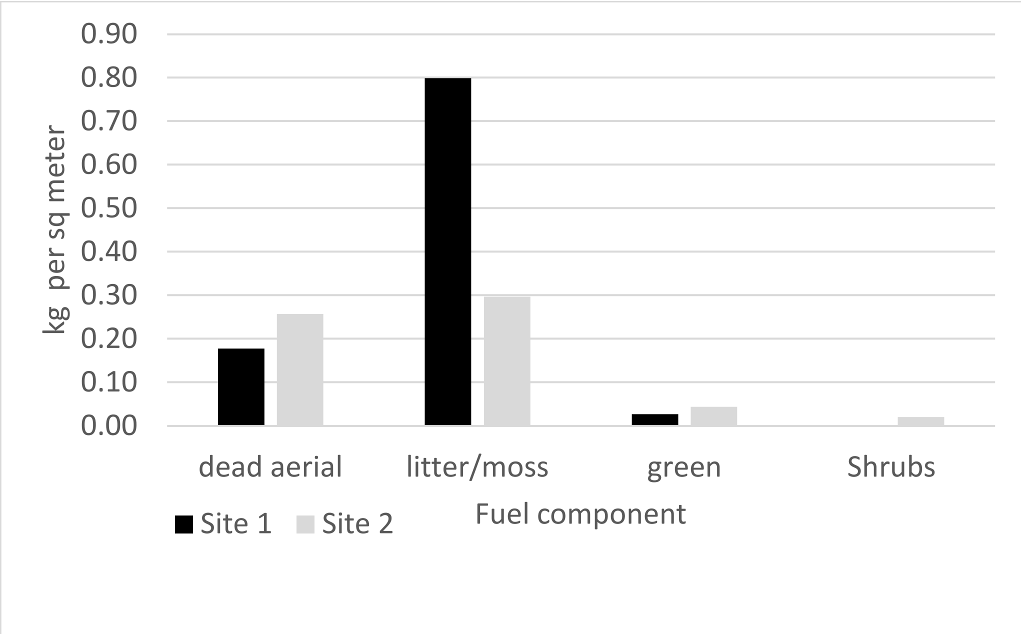

Figure 4.5 Mean dry mass (kg per square metre) of above ground fuel categories in *Molinia*-dominated grasslands on Ben Shieldaig, May 2021. Means based on values from six plots at each site. (Green refers to new growth of *Molinia*)

The data from May 2021 for the dead aerial and moss and litter were comparable with the data from March 2020, although the amount of moss and litter was quite variable across the sites. Surprisingly the amount of greening up of the *Molinia* was still limited, with the components only representing around 10% of the *Molinia* biomass. This is likely to be a reflection of the long cold spring period of 2021. However, it is also a reflection of the phenology of *Molinia* as it is considered to be a species which greens up later than many other graminoid species (Taylor et al., 2001). This has the consequence that the amount of dead material exposed remains high into the potentially drier condition of late spring and early summer and hence this potentially prolongs the fire danger season.

We have compared the fuel loads found in *Molinia* grasslands with the grass fuel model O1b in the Canadian Fire Behaviour Prediction system which has a reference fuel load of 300 g m^{-2} (Van Wagner et al., 1992). Due to presence of significant amounts of moss / litter and undecomposed organic matter, the fuel loads in *Molinia* areas are significantly higher (500 -1200 g m^{-2}) and it is unlikely that fuel model O1b can be used.

4.6 Conclusions

- Measurements of fuel load, which include characteristics such as the amount of biomass in different fuel size categories, or live: dead fuel ratios are scarce in the literature.
- Biomass or fuel load data from wet heathlands, blanket bog, grassy heaths, semi-natural grasslands and habitats in the west of Scotland are also lacking.
- The existence of the ‘upland survey gap’ of approximately 2.7 million hectares (one third of Scotland) of unmapped land area is a major barrier to production of a fuel load map.
- At present, with the exception for heather, very little is known about what vegetation and soil components constitute fuel that would be consumed during fires in Scotland.
- The jack pine litter and fine debris of the fine fuel fraction of the CFWIS can be related to the moss and litter beneath heather shrubs, but there are important distinctions.
- The moss and litter layers are often sheltered by the overstorey of the shrub layer, which will significantly impact on response times to the changing environmental conditions.
- The moss and litter layers are mixtures of living and dead material, whereas the CFWIS fine fuel relates only to dead material.
- Mosses can hold proportionally very large volumes of moisture (5-20 times dry mass), which will significantly influence drying responses and timelags.
- The fuel categories used in the project in heather dominated moorland were live green, dead fine (<2mm), coarse (>2mm) and moss and litter. For the *Molinia* dominated grasslands, fuel categories were green grass, dead aerial grass, moss and litter, shrubs, and ‘duff’ top 10 cm of the organic. Total depth of the organic layer was also recorded at each study site.
- Use of the sampling protocols established in the FireBeaters project showed highly comparable fuel mass determinations across field sites of heather in similar lifecycle stages.
- Protocols allowed accurate determinations of pre- and post-fire fuel mass during field controlled burns.
- In general, fuel mass in heather increased in the following order: dead fine < green fine <coarse = moss litter. Ratios among fractions changed during the life cycle of the heather.

4.7 References

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5 WP2: Ignition for Scottish Fuel Types

Fuel moisture content (FMC, expressed on a dry basis) is recognised as being a key driver in the fire hazard posed by vegetation (Davies et al., 2010; Davies & Legg, 2011; Log, 2020; McAllister, 2018; Rossa, 2017; Rossa & Fernandes, 2018), and modelling changes in FMC must take into account both long- and short-term meteorological conditions and the fuel type. Previous works on the issue have attempted to quantify the flammability of wildland fuels as a function of their moisture content (Davies & Legg, 2011) which is defined as the proportion of water content over the dry mass of the fuel. Live and dead fuel are likely to respond differently to changing environmental conditions and are often reported separately. Local investigations into factors influencing FMC and consequences for fire behaviour can help adapt the CFWIS for use in other regions of the world, with very different climatic, topology, and fuel type conditions (Dimitrakopoulos et al., 2011; Taylor & Alexander, 2003). Within the UK, this was previously investigated by the FireBeaters projects (Legg et al., 2007; Legg & Davies, 2009). Here, we have expanded upon this work in the field but particularly in the lab under controlled conditions. Investigations were carried out at the Rushbrook Fire Laboratory at the University of Edinburgh, which has the only Fire Propagation Apparatus in the UK, and a demonstrated track record in assessing fuel flammability.

The Canadian system has embedded within it several assumptions about the drivers of fire behaviour and the relative importance (and relationship between) of the different sub-indices. To evaluate the similarities (or otherwise) between these metrics and to develop an evidence base to identify the most relevant drivers of fire behaviour in Scottish fuels, it is necessary to evaluate the processes which drive fire spread in these fuel types.

Four distinct packages of experimental work were undertaken to understand the burning behaviour of Scottish fuels. These are: flammability assessments, small flame ignition propensity, laboratory flame spread studies, and field-based fire spread studies. Each of these packages focusses on different angles of understanding the fire problem in the context of Scottish fuels. Natural fuels introduce a large degree of complexity when studying the processes which control fire spread, and which define the hazards they present in a fire – this ranges from the ease of ignition of individual fuel types through to how these different fuels contribute to the overall hazard of a wildfire. Breaking the problem into tractable parts is an established method to developing an understanding of the different factors which define a fire hazard. Laboratory studies are well suited to the investigation of variables around the fuel, fuel structures, fuel moisture and the interaction between fuel layers. This is because they allow tight control of the environmental variables. This allows identification of the fuel elements and their role in the fire spread process. This information can be used to evaluate whether the fuel elements which drive fire spread are adequately represented in a fire danger system.

Flammability assessments allow the study of the ease of ignition and the energy release during the burning of specimens under highly controlled conditions. This allows comparison to be made between different fuel types under well-defined, repeatable conditions. The data used in this study are time to ignition and heat release rate. These allow assessment of the ease of ignition and the energy released while burning, respectively.

Small flame ignition studies allowed the likelihood of ignition of a fuel when subjected to small ignition sources to be determined. In this study, the probability of ignition is determined as a function of the fuel moisture content. This approach gives an indication of the relationship between fuel moisture content and ignition and can be used to evaluate when different fuels are susceptible to ignition by small sources.

Laboratory flame spread studies are designed to explore the mechanisms of flame spread in the reconstructed fuel beds. This approach has been long-established in the literature and, although it does not capture all the dimensions of field studies, the greater control of variables, and ability to make more measurements (type and resolution), allows greater insights into the processes that drive the flame spread.

Field experiments allow the effect of environmental variables (weather) and spatial characteristics of the fuel on fire behaviours to be identified. They also provide the input data required to calibrate the systems. In addition, these experiments serve as ground truth data for the observations made in the laboratory.

5.1 Laboratory-based flammability assessments

5.1.1 Introduction

Flammability is a key variable in fire science to describe the hazard posed by a fuel. The concept of flammability encompasses the ease of ignition, and the energy released when a fuel is burning. These are measured using the time to ignition and heat release rate, respectively. Flammability assessments require that the fuel is exposed to a well-defined heat source in a controlled environment. Evaluating the flammability of wildland fuels is a challenge as the fuel properties, structure and fuel moisture content challenge many of the underlying assumptions built into the theoretical development of the flammability framework. Nevertheless, a comparative assessment can be made using these approaches to understand the relative contributions of different fuel types to the rate of fire spread and the energy release.

In this project the Global Fire Propagation Apparatus (FPA) (ASTM International, 2013) was used to determine the time to ignition and heat release rate from a range of relevant fuels. These included samples of live heather, dead heather, heather stems, live grass, dead grass, moss and dead bracken.

5.1.2 Methods

Flammability assessments were made using the Fire Propagation Apparatus (FPA) to develop a relative ranking of the ease of ignition and the energy released from burning vegetation. This technique has been long-established as an appropriate tool allowing controlled and repeatable exposure to an ignition source and a well-defined combustion environment (e.g. Schemel *et al.*, 2008; Bartoli *et al.*, 2011; Hadden, Rein and Belcher, 2013; Houssami *et al.*, 2016; Thomas, Hadden and Simeoni, 2017). The technique allows the flammability of samples to be quantified using time to ignition and heat release measurements.

Samples are placed in a porous sample holder (Figure 5.1) to allow adequate supply of oxygen and are exposed to a radiant heat flux generated by 4 tungsten lamps on the top surface of the sample. In this study a heat flux of 25 kW/m2 was used. A small pilot flame (ethylene/air) is used to promote ignition of the pyrolysis gases. Time to ignition data are recorded manually; heat release is calculated by oxygen consumption calorimetry (Janssens, 2016a).

5.1.3 Fuels

The fuels for which flammability assessments are made are shown in Figure 5.1. Fuels were filled in sample holders in a way to preserve the density when collected. The exception is thick heather stems which were filled to approximately cover the whole area of the sample holder. When a sample was prepared, a small subsample was taken to measure fuel moisture content.

Figure 5.1 The fuels tested (clockwise from top left) Heather, heather stems, thick heather stems, bracken, moss and grass.

5.1.4 Time to ignition

The time to ignition was evaluated when samples were exposed to an incident heat flux of 25 kW/m^2. The time to ignition for fuels typical of those present in moorland and grass-dominated systems are presented in Table 5.1. The results indicate that the fuels which are easiest to ignite are those of a low fuel moisture content and, those which are fine. These data can be used to inform the most relevant fuels to select when calibrating a FDRS and they suggested that dead litter, and dead, suspended material in the heather plant are significant contributors to the ignition hazard. The grass tested in these conditions presents a somewhat anomalous result. Grass is a fine fuel, and these samples have a low measured FMC, however under these condition, it has the longest time to ignition. This is attributed to the structure of the fuel which formed a tightly packed sample when placed in the sample holder. The effects of reduced air flow through the sample and increased bulk density resulted in a long time to ignition.

Table 5.1 The time to ignition in relation to fuel moisture content (FMC) for a range of fuel types exposed to an incident heat flux of 25 kW/m^2.

Fuel (FMC)	Time to ignition, s
Moss (11%)	25
Bracken (11%)	50
Heather (9%)	52
Heather fine stems (11%)	73
Grass (40%)	129
Heather thick stems (23%)	168
Heather live (104%)	205
Grass (9%)	220

Given the significance of heather moorlands as the most common vegetation type involved in fires in Scotland, the flammability was assessed in considerable detail as a function of the FMC. The time to ignition data are presented in Figure 5.2. These data indicate that FMC has a strong influence on the time to ignition at low heat fluxes with the time to ignition increasing from approximately 60 s at 0% FMC to more than 200 s at 100% FMC. The time to ignition dependence is less significant at higher heat fluxes. For example, at 45 kW/m^2 the time to ignition increases from around 25 s to 50 s over the FMC range 11-93%. These data indicate that the FMC will be significant in determining the ignition hazard posed by vegetation of differing FMC, but also that the relationship between FMC and fire spread, where heat fluxes are likely to be higher than tested here (see section 5.3), may not be straightforward.

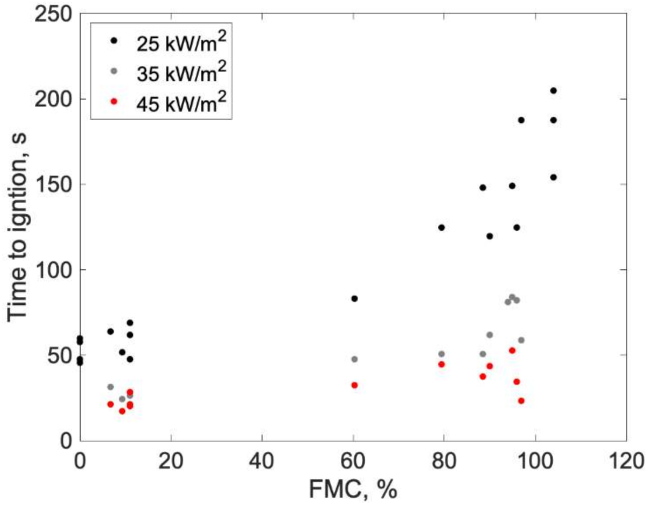

Figure 5.2 The time to ignition as a function of fuel moisture content (FMC) for fine heather fuels exposed to three different heat fluxes

5.1.5 Energy release

The energy release gives an indication of the nature of the hazard presented by a fuel as it burns. The hazard is quantified by both the rate of energy release (the heat release rate) and the duration of burning. Some fuels may release a large amount of energy over a short period of time – these fuels are likely to contribute to the leading edge of the fire – and others may release energy over a longer duration and are likely to contribute more to the trailing edge of the fire.

The energy release for the different fuels studied is presented in Figure 5.3. These data show that the largest (and longest) contribution to burning is from the thick heather stems with a peak heat release rate in these conditions of more than 6 kW and a burning duration of more than 200 s. The dry (11% FMC) fine dead heather stems have a similar peak but a much shorter burning duration of approximately 60s. Fine green (9% FMC) heather stems have a heat release rate around half that of the fine brown heather. It is assumed that this is due to the higher FMC which delays the time to ignition (seeTable 5.1). The energy release rate of grass (40% and 9% FMC), live heather (104% FMC) and bracken (11% FMC) have a peak heat release rate of 2.5 kW and a burning duration of 60 s. Dry moss has the lowest heat release rate with a peak of only 1 kW but burns with a mixture of flaming and smouldering for an extended duration (greater than 200s under the conditions tested.

These data are helpful in understanding the likely contributions to fire behaviours. For example, the long burning duration of the thicker fuels suggests that, while these are relatively difficult to ignite, they will release a significant quantity of energy to promote forward fire spread. Meanwhile fine, dry fuels such as dead heather and dry moss are relatively easy to ignite but release relatively little energy over a short period of time. This suggests that the interaction between the different fuel classes may be significant in understanding the fire spread processes.

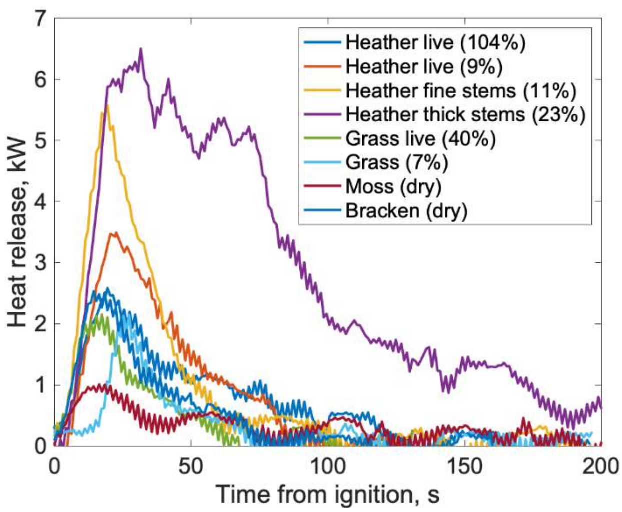

Figure 5.3 The heat release rate of the fuels studied

The peak heat release rate for fine heather is shown in in Figure 5.4. These data indicate that for FMC ranges likely to be encountered in living vegetation, FMC does not significantly affect the rate of energy release with an average of approximately 200 kW/m^2 (note data are presented per unit area of exposed sample). At low FMC, such as might be encountered in dead heather, the heat release rate ranges from 250 to more than 500 kW/m^2. This information is useful as it allows insights into the contribution of different parts of the vegetation structure to the fire spread. Fine dead fuels are expected to contribute up to twice as much energy to the fire as the living vegetation with higher FMC.

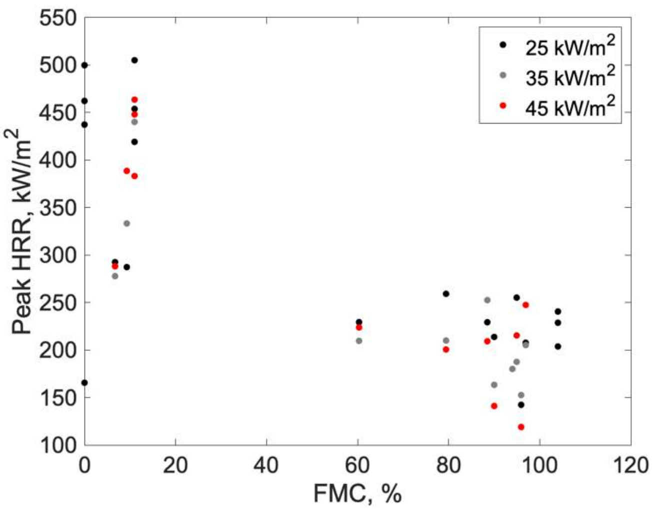

Figure 5.4 Energy heat release rate as a function of fine fuel moisture (FMC) for fine heather fuels exposed to three different heat fluxes

5.2 Laboratory-based ignition assessments

Previous studies have identified that the moisture content of "thin" or "fine" fuel elements respond more rapidly to changes in the environmental conditions than thicker fuel elements. Therefore, this study aimed to provide an experimental methodology to determine the effect of FMC on the ignition probability for two fuel types: *Molinia* grass and moss. This study seeks to develop an understanding of the hazard of two ground fuels which, given their location and characteristics may be the first fuel ignited. Understanding the drying dynamics, and the resulting ignition potential (as a function of FMC) allows an assessment of the ignition potential of a fuel.

The steps followed throughout this process and the reasoning behind them is presented to ensure clarity, transparency, and highlight the approach's limitations. The methodology section outlines the tools and equipment used to carry out the experimental procedure. Then the results of that procedure are presented, followed by a discussion on the findings. This last section is supplemented by an explicit declaration on the limitations of this approach along with possible future avenues for additional research

5.2.1 Methodology

The preparation and testing methodologies developed and followed in this work are separate for the grass and moss samples. Given the differing nature of the materials, the process of drying and handling them needed to be different in each case, hence they will be explained in their respective sub-sections.

An illustration is presented in Figure 5.5 that visualises the process followed in steps. Blue boxes indicate a process, and green boxes indicate an outcome of the linked process.

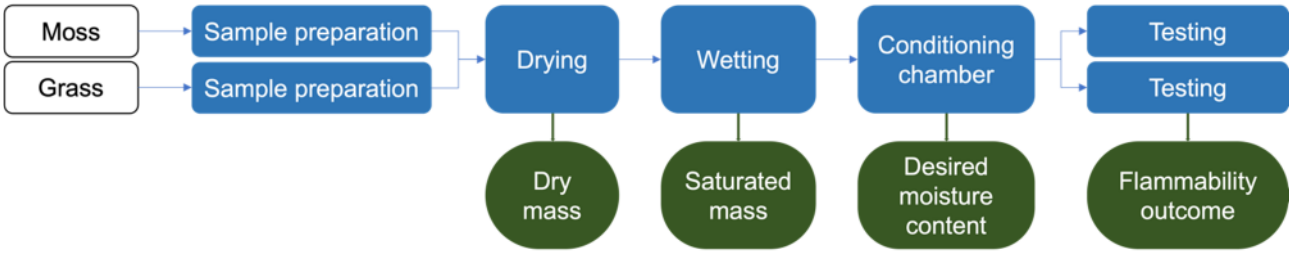

Figure 5.5 An outline of the process followed for examining relationships between fine fuel moisture (FMC) and flammability

5.2.1.1 *Molinia* grass samples

Molinia samples were provided to the University of Edinburgh by the James Hutton Institute. Samples were received in a cured dry condition and required rewetting and drying down to obtain the FMC of interest. Sample preparation was essential to ensure consistent results and homogenous conditioning of the samples.

Samples were prepared by attaching a fixed mass of grass to electrical tape to allow for consistency in rewetting and drying (Figure 5.6).

Figure 5.6 *Molinia* grass sample prior to testing fixed with electrical tape

5.2.1.2 Moss sample preparation

Every moss sample was extracted from the bag of origin and weighed beforehand to reach an approximation of the desirable sample weight. As it was placed in the sample holder, the moss was handpicked to ensure the purity of the sample in terms of possible litter or grass, affecting their water absorbing capability and hence, burning behaviour.

A set size of 10 x 10 x 5 cm was chosen for the moss sample holders because this enabled consistency amongst the sample sizes and weights, and a stable sample holder weight (approximately 30 g) which could be subtracted from the calculations per sample (Figure 5.7).

Figure 5.7 Moss sample preparation prior to testing

5.2.2 Calculations

5.2.2.1 Moisture content

The dry basis moisture was used for the calculation of the samples' moisture content, which is defined as the amount of water over the dry sample. This is calculated through the formula

$$MC = 100\frac{m_w}{m_{ds}}$$

where:

- MC is the sample's moisture content in percentage form
- m_w is the mass of the water contained in the sample
- m_{ds} is the mass of the dry sample.

5.2.2.2 Drying rate (water loss rate per dry sample mass)

The drying curves were based on the drying rate normalised per each sample's dry mass, calculated as follows:

$$DR = \frac{m_{i+1} - m_i}{t_{i+1} - t_i}\frac{1}{m_{di}}$$

where:

- DR is the sample's drying rate normalised to its dry mass
- m_i is the mass of the sample at a given time t_i,
- t_i is the time of the measurement.

5.2.3 Sample drying

Both *Molinia* and moss samples were dried straight after preparation in an oven at 60°C (Figure 5.8 and Figure 5.9). The samples remained in the drying oven until their mass remained stable over 4 consecutive hourly measurements. This typically took less than 24 hours. This temperature was chosen to avoid the loss of any volatile organic compounds which can occur in organic fuels when dried at higher temperatures (Samuelsson, Nilsson and Burvall, 2006).

Figure 5.8 *Molinia* samples in the oven until complete drying.

Figure 5.9 Moss samples in the oven until complete drying.

5.2.4 Sample wetting

This section outlines how the samples were saturated in order to reach their maximum moisture content.

5.2.4.1 Grass

After the grass samples were prepared and totally dried, they were placed in groups (for practical reasons) in a glass beaker full of tap water and were left submerged overnight to saturate, covered with aluminium foil. This is shown in Figure 5.10.

Figure 5.10 Wetting of grass sample by submerging in water

5.2.4.2 Moss

After the moss samples were prepared and totally dried, they were placed in large tank with tap water and were left submerged overnight to saturate, covered with aluminium foil. This is shown in Figure 5.11.

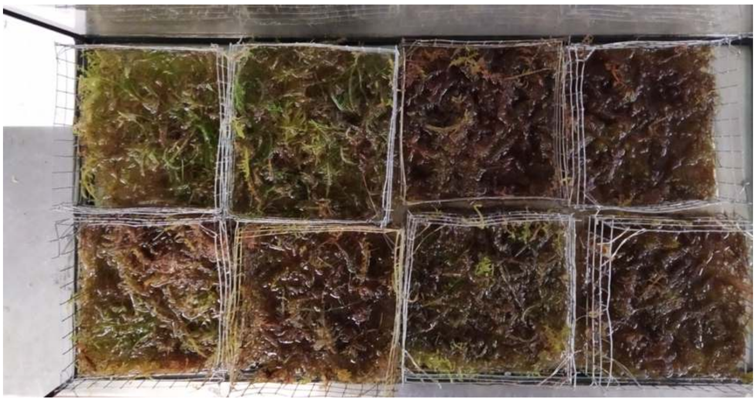

Figure 5.11 Wetting of moss samples by submerging in water.

5.2.5 Drying for moisture content control

An environmental chamber (TAS ECO MTCL400) was used for the controlled drying of the samples before every experiment. The conditions in the chamber were set at 30°C and 90% relative humidity (RH). These conditions were chosen as suitable for providing a manageable rate of sample drying while maintaining a manageable timeframe of every experimental run.

5.2.5.1 Grass

After the grass samples were left to saturate overnight, they were extracted from the beaker and placed atop absorptive paper to remove the excess water attached to the surface. This was found to accelerate and improve the consistency of the drying procedure, by removing any droplet on the surface of the grass and ensuring their homogenous drying in the conditioning chamber. This is shown in Figure 5.12 and Figure 5.13.

Figure 5.12 *Molinia* samples placed on absorptive paper.

Figure 5.13 Covering the grass samples with absorptive paper to remove any excess water from both sides.

The sample mass was then measured to calculate their saturation moisture content, and subsequently placed in the conditioning chamber. A batch is shown in the conditioning chamber in Figure 5.14.

Figure 5.14 Samples drying in the conditioning chamber

5.2.5.2 Moss

After the moss samples were left to saturate overnight, they were extracted from the water tank and placed atop absorptive paper to remove the excess water attached to the surface. This was found to accelerate and improve the consistency of the drying procedure. Then the samples' mass was measured to calculate their saturation moisture content, and subsequently placed in the conditioning chamber. A batch is shown in the conditioning chamber in Figure 5.15. It should be noted that moss samples were never allowed to be completely dry while monitored.

Figure 5.15 Moss drying in the conditioning chamber

5.2.6 Ignition source

The ignition source was chosen to be a commercially available wax candle to represent a small ignition source. The flame was approximately 15 mm high. This was chosen to give a consistent ignition source both in terms of size and burning duration and seeks to represent a small ignition source. The results presented in this section are strongly dependent on this choice of ignition source.

5.2.6.1 *Molinia* apparatus

For the grass samples, the developed and used apparatus is shown in Figure 5.16. The sample and sample holder remained in a fixed position while the ignition source could be positioned manually. The vertical orientation of the apparatus was chosen to provide conservative results given the intensity of vertical fire spread.

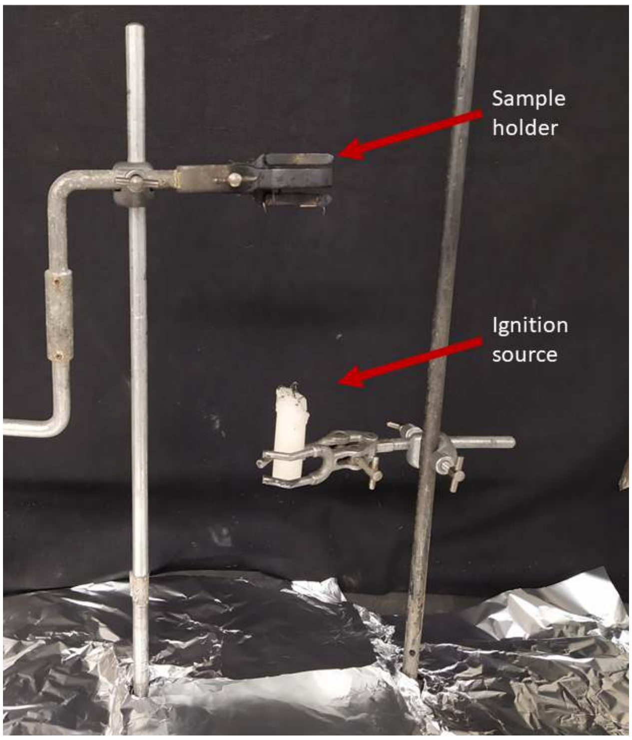

Figure 5.16 The *Molinia* grass ignition testing apparatus.

5.2.6.2 *Molinia* procedure

Once a sample reached the desired moisture content, it was rolled into shape and placed in the sample holder. The ignition source was placed just below the sample for 5 seconds to ensure consistency. Then the ignition source was removed and the resultant burning (or otherwise) of the sample observed.

Subjective probabilities were used for the assessment of flammability. This is a type of probability that expresses the observer's belief on a system or outcome, derived from their personal judgment or experience. The rationale behind assigning the subjective probabilities of ignition are outlined in Table 5.2.

Table 5.2. Assignment of subjective probabilities of ignition after testing *Molinia* grass.

Value	Assessment
0.00	The flame does not consume strands of the grass. No flaming occurs apart from the ignition source. The sample does not burn more in consecutive attempts at ignition.
0.25	The strands of grass are consumed by the ignition source, but once it is removed then any combustion processes cease and there is no spread. The sample does not burn more in consecutive attempts at ignition.
0.50	The strands of grass are consumed by the ignition source; once it is removed then there is only smouldering combustion that consumes some portion of the sample strands but eventually quenches. The sample might burn more in consecutive attempts at ignition.
0.75	The strands of grass are consumed by the ignition source; once it is removed then there is still some flaming combustion and a significant portion of the sample strands are consumed. Fire spread is slow and ceased towards the top of the sample. The sample might burn more in consecutive attempts at ignition.
1.00	The sample is easily ignited and flaming occurs. The flame spreads and the sample is consumed. There is no sample left to burn in consecutive attempts at ignition.

This assignment of subjective probabilities of burning produced the flammability graphs for grass in the Results section.

5.2.6.3 Moss apparatus

For the moss samples, the developed and used apparatus is shown in Figure 5.17. The wire mesh was assembled to place the sample holder and ignition source in position. The horizontal orientation of the apparatus was chosen to emulate realistic conditions.

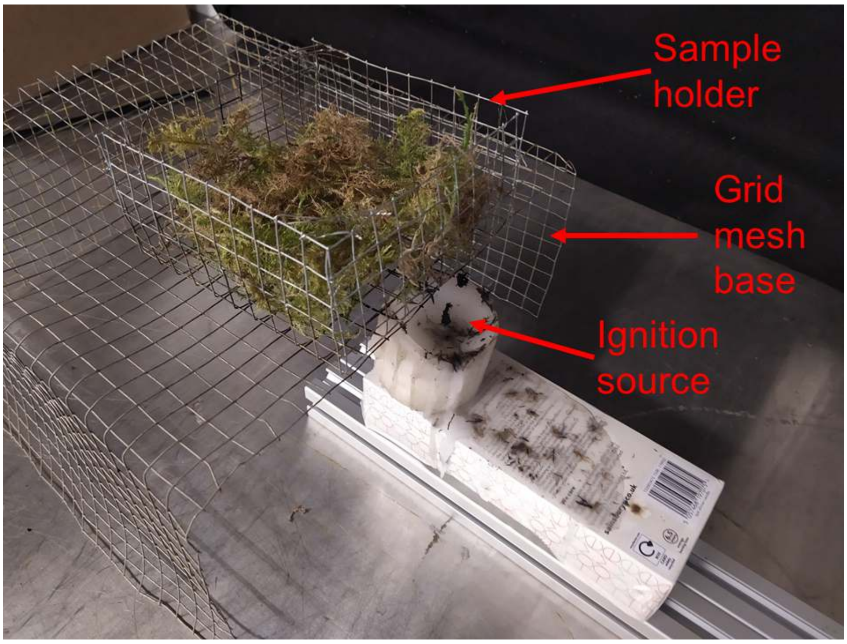

Figure 5.17 The moss testing apparatus: sample holder, base mesh grid, and ignition source are indicated.

5.2.6.4 Procedure for testing flammability of moss samples

Once a sample reached the desired moisture content, it was placed upon a metal grid and the ignition source was placed just below the sample until the estimation flammability was definitive; either established burning or combustion extinction. The ignition source was then removed and the impact on the sample observed. The rationale behind assigning the subjective probabilities of ignition is outlined in Table 5.3.

Table 5.3. Assignment of subjective probabilities of ignition after testing moss.

Value	Assessment
0.00	The flame does not consume the moss. No flaming occurs apart from the ignition source. The sample does not burn more in consecutive attempts at ignition.
0.25	The moss is consumed locally by the ignition source, but once it is removed then any combustion processes cease and there is no spread. The sample does not burn more in consecutive attempts at ignition.
0.50	The moss is consumed by the ignition source; once it is removed then there is only smouldering combustion that consumes some portion of the sample but eventually quenches. The sample might burn more but not completely in consecutive attempts at ignition.
0.75	The moss is consumed by the ignition source; once it is removed then there is still some flaming combustion and a significant portion of the sample is consumed. The sample might burn more or completely in consecutive attempts at ignition.
1.00	The sample is easily ignited and flaming occurs. The fire spreads and the sample almost totally consumed. There is no sample left to burn in consecutive attempts at ignition.

This assignment of subjective probabilities of burning produced the flammability graphs for moss in the Results section.

5.2.7 Recording of data and analysis

5.2.7.1 Mass and time readings

The mass and time were recorded manually. For the mass readings, an advanced laboratory precision balance (Mettler Toledo NewClassic MS) was used, with readability of 0.01 g. These readings provided the input for the graphs in the Results section.

5.2.7.2 Video recording and analysis.

Every experimental run was captured using an optical video camera (Panasonic HC-V770). The recordings were also calibrated in case further image analysis needed to be undertaken. The shutter speed was fixed at 1/500 to ensure the same brightness and sensitivity in all experimental runs. The videos served as documentation of each experiment and to allow future interpretation of the subjective probabilities.

5.2.8 Results

In this section the results from the measurements and experimental procedure are presented. Initially the indicative moisture loss graphs and the drying curves are presented for *Molinia* grass and moss, respectively. Following that, the moisture loss graphs up to ignition, and the flammability graphs linking the moisture content with the probability of ignition are provided.

5.2.8.1 Moisture loss graphs and drying curves: *Molinia*

The findings from the 20 indicative samples of grass that were dried from saturation to dryness are presented in the figures below. Figure 5.18 presents the loss of moisture over time. The rapid drying rates are not unusual for fine fuels and are in agreement with field data (see Section 5.4).

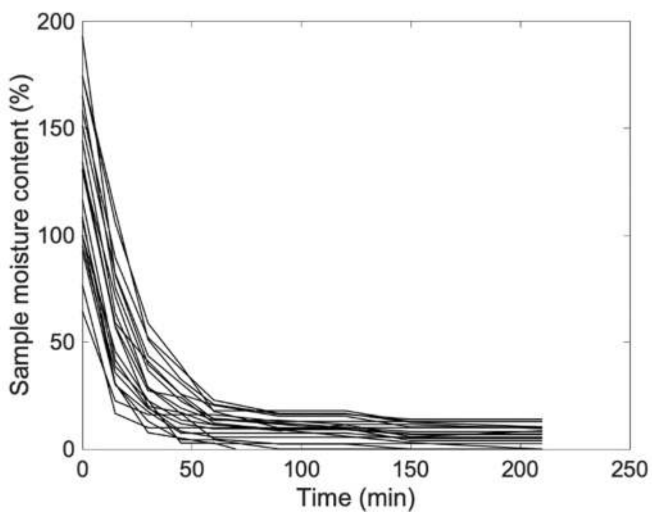

Figure 5.18 Moisture loss curves for *Molinia* grass samples.

Figure 5.19 below shows the drying curve for these grass samples, which as was presented in the Calculations sub-section, is the drying rate normalised by dry sample mass. The drying curve is characterised by a decreasing drying rate as a function of time. After 60 minutes, the drying rate approaches zero and the samples reach equilibrium with the environmental conditions in the chamber.

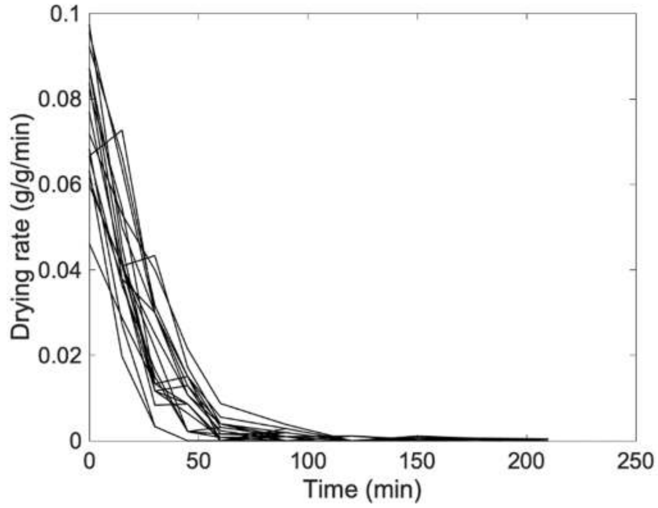

Figure 5.19 Drying curves for *Molinia* grass samples.

Change in FMC as a function of time from the 13 indicative samples of moss that were dried from saturation over a period of seven hours are presented in Figure 5.20. Compared to the *Molinia* samples the characteristic time of the drying is much longer with none of the samples reaching a stable FMC over the time period available.

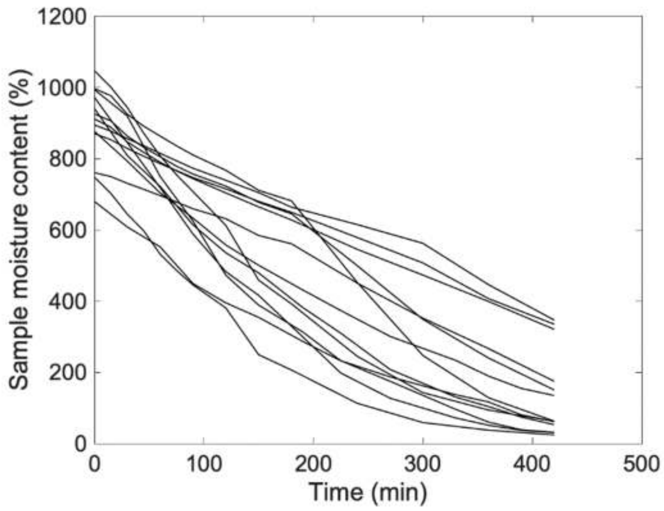

Figure 5.20 Moisture loss curve for moss samples.

There is some variability in these results. This is attributed to the differing thickness of the samples, which was not controlled in this experimental series. Additionally, the structure of the moss is more complicated than the strands of grass in the previous sub-section, so such variability is expected.

Figure 5.21 below shows the drying curve for these moss samples, which as was presented in the Calculations sub-section, is the drying rate normalised by dry sample mass. Again, given the nature of the fuel structure there is some scatter in the results but for moss sample in this condition, the drying rate appears to be on the order of 0.01—0.03 g/g/min.

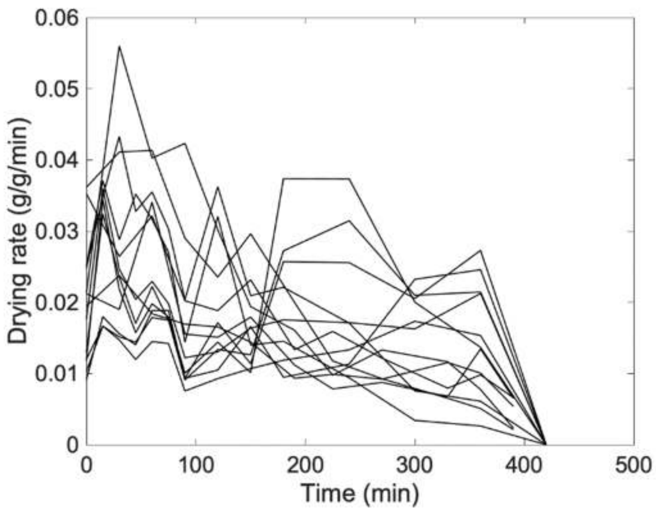

Figure 5.21 Drying curves for moss samples

5.2.8.2 Flammability graphs

Characterising the drying times allows for target moisture contents to be reached for testing. New samples were prepared, wetted, and dried for a duration required to achieve the desired FMC for testing.

All the sample FMCs as a function of drying time for every sample tested are presented, to showcase how the process was relatively repeatable and consistent, taking into consideration the natural variability of the fuel studied.

Figure 5.22 shows the moisture loss curves for all the grass samples tested. Figure 5.23 shows the resulting probability of ignition as a function of FMC.

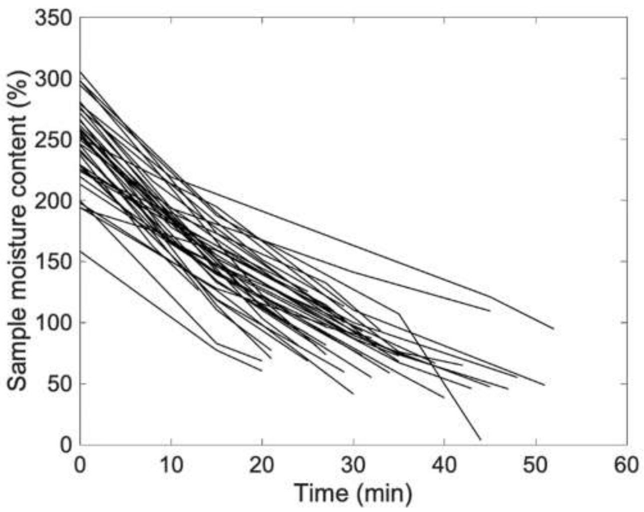

Figure 5.22. Moisture loss curve for all grass samples tested.

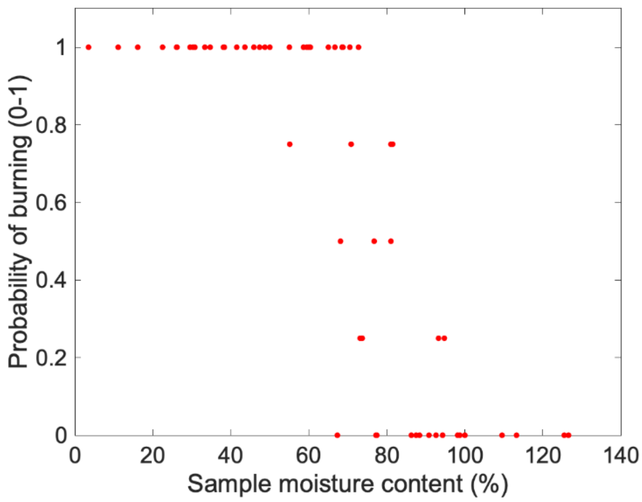

Figure 5.23 Ignition probability as a function of fine fuel moisture (FMC) for *Molinia* grass.

From Figure 5.23 it can be inferred that there is not a critical FMC at which the behaviour of the fuel changes. Instead, the ignition probability increases from 0 to 1 in the range 85—65% FMC. FMC lower than 65% are almost certain to ignite and burn to completion.

Figure 5.24 shows the moisture loss curves for all the moss samples tested and Figure 5.25 shows the resulting probability of ignition as a function of FMC.

Similar to the behaviour of Molinia grass, for this graph too it can be inferred that there is not one point where the behaviour of the fuel immediately changes, but it is rather defined as a region in between 10 and 20% FMC.

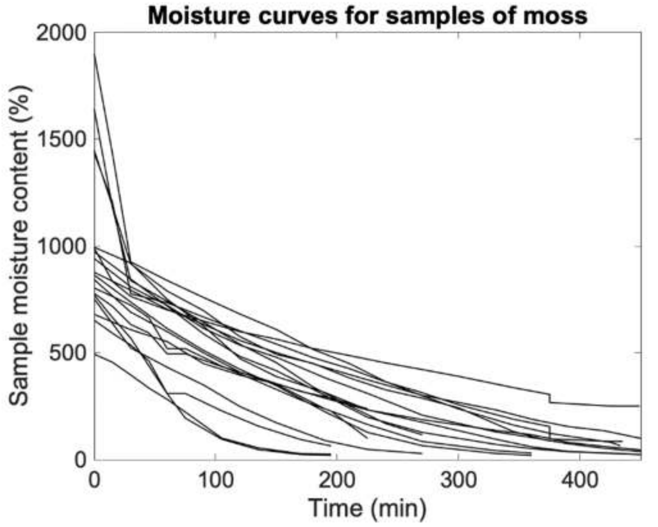

Figure 5.24 Fuel moisture content as a function of time for all moss samples tested.

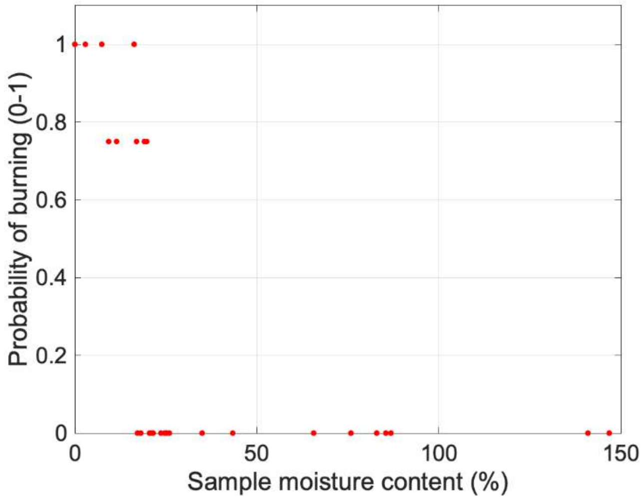

Figure 5.25 Ignition probability as a function of fine fuel moisture (FMC) for moss

5.2.9 Conclusions and future work

- This study has highlighted the ignition probability for *Molinia* and moss subject to a small flame source. These fuels were chosen as they are found on the ground where small ignitions sources may arise accidentally e.g. dropped matches, discarded cigarettes.
- The FMC for ignition of *Molinia* grass was found to be in the range below 85%. With a high probability for samples with less than 65% FMC. The ignition of moss was found to occur at FMC below 20% with a high probability at FMC less than 10%. These results serve to calibrate ignition thresholds and to evaluate the relative hazards posed by different fuels.
- Combining the drying rate data and the ignition probabilities in this section allow an estimation of the timescales required for the different fuels to become ignitable. For Molinia this is on the order of 30 minutes. For the moss, this on the order of 5 hours. These differing timescales are strong indicators that the hazard associated with different fuel elements requires careful consideration.
- When interpreting these results, the following limitations should be considered:

  - The nature of the ignition source and the duration of the application will have an impact on the results. Particularly it may be possible to ignite samples with FMC outside the ranges quoted here with larger heat sources or longer durations. For example, these results would not be appropriate for determining the ignition arising from discarded barbeques.
  - Natural structure of the fuel.
  - Qualitative observations suggest that the FMC of the samples after drying was not uniform.
  - The extent of burning used to derive probabilities was subjective.

A number of factors could be included in this study to increase the realm of applicability of the results:

- Use of dead and live vegetation – this is known to affect flammability through means other than FMC alone.
- Sensitivity to the ignition source. The size and duration of the ignition source could be optimised to reduce the sensitivity of the results to this factor.
- Drying rate curves could be determined under different temperature and relative humidity combinations.
- The propagation is dependent on the arrangement of the fuel. It is possible that other arrangements may result in different relationships between FMC and ignition probability.

5.3 Laboratory flame spread

A series of sixteen laboratory scale fire spread experiments have been undertaken to complement the fieldwork components of the project. Fuels were harvested from the Pentland Hills Regional Park in an area north of Castlelaw. Ten fuel plots of approximate area 2.4 x 1.2 m were collected. Fuels were conditioned to explore the effects of moisture content on the flame spread dynamics. After conditioning, the plots were reconstructed in the fire calorimeter at the University of Edinburgh.

These flame spread experiments have given insights into aspects of fire behaviour and impacts that are not available in the field including: energy release, carbon emissions, burning rate, and thermal impacts to soils. These measurements allow further insights into the interaction between fuel layers to be observed through the selective conditioning of the reconstructed elements.

These insights need to be interpreted with care as they represent an idealised system with respect to the boundary conditions of a fire which we know to be significant. For example the absence of wind, and the use slope will influence the results. Nevertheless, the higher degree of control and repeatability of this system will allow insights into the interactions of the different fuel elements. This evidence base will be helpful in understanding which elements of the fuel could be representative inputs to the FDRS.

5.3.1 Objectives

The objectives of this study are to:

- Determine the feasibility of reduced, laboratory scale investigation of flame spread in heather-dominated systems.
- Evaluate the effect of fuel moisture content on the flame spread.
- Explore the effects of different fuel layers on the flame spread.

5.3.2 Materials and methods

Samples were harvested from sites in the Pentland hills. Eleven plots were harvested around the area of Castlelaw. The locations can be identified using the What3Words addresses in Table 5.4. Fuel sampling was undertaken between February and April 2021.

Table 5.4 Locations from which the fuel was harvested.

Plot ID	What3Words address	Latitude, Longitude	Grid refernece
Plot 1	///cascaded.baroness.fracture	55.872992,-3.237192	NT 22685 65117
Plot 2	///other.splashes.roofer	55.873181,-3.236664	NT 22718 65138
Plot 3	///bracelet.equipment.soaps	55.872965,-3.23724	NT 22681 65114
Plot 4	///unstated.conductor.local	55.872884,-3.23724	NT 22681 65105
Plot 5	///they.twist.cubs	55.876765,-3.238188	NT 22630 65538
Plot 6	///second.rises.holly	55.876819,-3.238188	NT 22630 65544
Plot 8	///pure.paused.enter	55.876604,-3.237899	NT 22647 65520
Plot 9	///twice.punch.stored	55.87655,-3.237803	NT 22653 65514
Plot 10	///supplied.besotted.focus	55.872507,-3.236279	NT 22741 65062
Plot 11	///stubble.ranches.revamped	55.87248,-3.236183	NT 22747 65059
Plot 12	///vies.maker.smudges	55.872426,-3.236135	NT 22750 65053

Heather was harvested by cutting stems at ground level. Moss and litter were harvested from within the plots by lifting from the soil layer. There were variations in the fuel loading at each site. Images of the fuels collected are shown in Figure 5.26 Samples of heather (left) and moss (right) after collection

Figure 5.26 Samples of heather (left) and moss (right) after collection

It should be noted that fuels harvested from some field plots were used in more than one laboratory experiment (where it did not burn and ignition did not result in significant local changes to the fuel structure).

5.3.3 Fuel treatment

Fuels were dried under laboratory conditions (10-15°C, 40-60% RH). The duration of the conditioning was used to create different moisture contents. In some cases, a convective air flow provided by a fan was used to dry the moss layer using laboratory air. Fuel moisture measurements were made following the procedure and classifications set out in Section 5.4.

The moisture contents for each experiment are reported in the experimental matrix in Table 5.5

5.3.4 Construction of fuel beds

Lab plots were reconstructed in the Rushbrook Fire Laboratory at the University of Edinburgh under the intermediate scale calorimeter which has a maximum usable area of 2 x 2 m^2. Lab plots were supported using a mineral wool product. An exception is experiment 002 in which a rigid polyisocyanurate board was used. The moss and litter were laid on the substrate to create a uniformly distributed layer covering an area of approximately 1.8 x 1.0 m^2. The heather was then pierced into the substrate such that it was held in close to the original orientation. The substrate was angled with a slope of 5° to promote flame spread. The fuel loading sought to reproduce that present in the field plot from which it was harvested and these are reported in the experimental matrix Table 5.5.

Images of the fuel bed under construction are shown in
Figure 5.27. The total mass of the substrate materials was recorded before addition of the moss and litter and then the heather was pierced through the fibrous structure of the substrate and arranged in a fuel loading as found in the field. The fuel load of each layer was calculated, and the samples were harvested before ignition to measure the fuel moisture content (Table 5.5).

Figure 5.27 Laboratory-scale flame spread apparatus. Left: support materials including mineral wool product positioned on load cell. Centre: with moss layer. Right: with heather.

5.3.5 Measurements

The following measurements were made to characterise the burning of the fuel.

5.3.5.1 Energy release rate (heat release rate)

Oxygen consumption calorimetry and carbon dioxide generation calorimetry were used to measure the heat release from the burning fuel (Janssens, 2016b). These techniques allow for the energy release to be measured with a temporal resolution of approximately 0.7 Hz.

5.3.5.2 Mass

The mass of the sample was recorded during the experiments with a frequency of 0.7 Hz. Steady state mass was recorded for each fuel layer during construction of the fuel layer and at the end of the experiment. The derivative of the sample mass with respect to time is used to calculate the mass loss rate. The mass loss rate was smoothed with using a Savitsky-Golay filter with a frame length of 51 and an order two polynomial.

5.3.5.3 Carbon emissions

The concentrations of CO_2 and CO are measured in the exhaust duct. The flow of combustion products is known and therefore the mass flow of CO and CO_2 can be determined. The total mass emitted can be used, in conjunction with the total mass lost, to estimate the total carbon flux from the burning vegetation.

5.3.5.4 Visual measurements

Video cameras are used to record the progression of the flame front. Cameras are positioned to capture overhead, side and front (looking towards the sample from the ignition) view angles. Video analysis is used to determine the duration of the flame spread and hence the flame spread rate.

5.3.5.5 Heat fluxes

Heat fluxes in the fuel beds are measured in three locations: 1) at the mid height of the heather canopy, 2) at the surface of the moss layer, and 3) at the surface of the substrate beneath the moss. In each case heat flux is measured using a water-cooled heat flux gauge. These are point measurements so are highly sensitive to the local fire behaviour therefore these should be interpreted in conjunction with the visual evidence.

These data are helpful in identifying the drivers for fire spread and also for assessing the impacts that a fire will have on the vegetation. It should be noted that both the magnitude and duration of the heat flux measurements are relevant quantities in this regard.

5.3.5.6 Ignition

Ignition of the vegetation was by a 1 m long heptane-soaked rope. This allowed for instantaneous ignition along the entire short edge of the fuel layer. The fuel was always ignited at the lowest part of the slope.

5.3.6 Experimental matrix

The experimental matrix is presented below. Sixteen experiments were conducted in total. These fall into three categories: experiments 2—7 were calibration experiments 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. These experiments also included additional heat flux measurements.

The approach used in these experiments is based on previous work on the development of flame spread models including that of Byram (1959) and Rothermel (1972).

Table 5.5 The experimental matrix including details of the fuel moisture content prior to testing. Note no data were recorded for experiment 1.

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

5.3.7 Results

This section presents the results from the laboratory flame spread studies. These studies were aimed at delivering 1) insights into the effects of FMC in different fuel layers on the flame spread processes; and 2) evaluation of the parameters which control flame spread. In addition, carrying out these experiments in the laboratory has allowed measurement of the carbon emissions from the burning vegetation. These are explored in more detail below.

5.3.7.1 Qualitative observations

A series of still images taken at regular intervals are used to describe the visual observations from these experiments.

An image taken 10 seconds after ignition is shown in Figure 5.28. In all cases, the flame is still in the location of the ignition source and, since this is still burning, it is likely to be supporting the burning of the vegetation in some cases. Heating from the ignition source has resulted in the ignition of heather locally in all samples but to different degrees. Experiments 2, 3, 4, 6, 7, 10, 12, 14, 15, 16, and 17 display a strong ignition with flame heights in excess of 1 m. Ignition of the heather in experiments 5, 8, 9, and 11 is more marginal with lower flame heights. This is attributed to the higher FMC of the heather in these experiments.

Figure 5.28 Composite image of laboratory flame spread experiments 10 s after ignition

Figure 5.29 shows a composite image taken 30 s after ignition. At this time although the flame is still in the location of the ignition source, this has almost burnt out and is no longer supporting the burning of the vegetation significantly (see e.g. experiment 13 which shows residual burning on the ignition source). Flame heights in experiments 2, 3, 4, 7, 10 and 17 are greater than 2 m indicating a high burning and energy release rate. Flame heights in experiments 5, 6, 12, 14, 15 and 16 are all greater than 1 m indicating a degree of self-sustained burning. Experiments 8, 9, have flame heights less than 1 m suggesting these may not spread independently of the ignition source. Experiments 11 and 13 have low, discontinuous flame heights in the location of the ignition location suggesting the burning is not sustained in the absence of the heating from the ignition source.

Figure 5.29 Composite image of laboratory flame spread experiments 30 s after ignition

Figure 5.30 shows a composite image taken 60 s after ignition. The leading edge of the flame front in experiments 2, 3, 4, 7, 12, 15, 16 and 17 is now far 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 remain 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 5.30 Composite image of laboratory flame spread experiments 60 s after ignition

The flame fronts 120 seconds after ignition are shown in Figure 5.31. Experiments 3, 4, 7, and 15 continue to have flame heights in excess of 2 m and significant flame depths with a large degree of burning behind the leading edge of the flame front. Experiments 4 and 17 have already reached the end of the fuel bed and the flame height is beginning to decrease. Experiments 2, 5, 6, 10, 12 and 16 all have flame heights less than 2 m and have less burning behind the leading edge of the flame front. Experiments 8, 9, 11, 13 and 14 have not spread significantly beyond the ignition source and have effectively quenched by this time, with only some localised burning continuing.

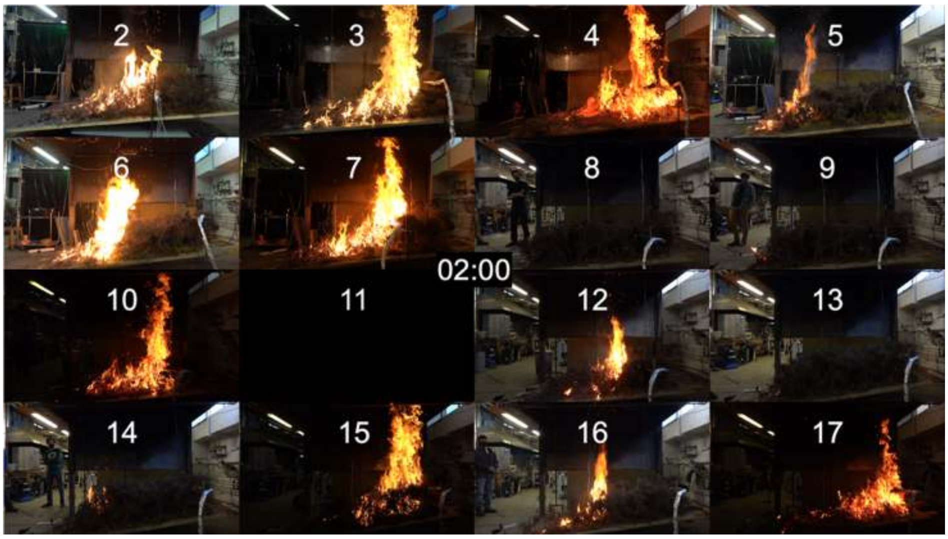

Figure 5.31 Composite image of laboratory flame spread experiments 120 s after ignition

Figure 5.32 shows a composite image taken 150 s after ignition. By this time experiments 3, 4, 7, 10, 15, 16 and 17 have reached the end of the fuel bed and the flame heights are decreasing as the fuel has been consumed. Experiments 3, 4 and 15 display a flame depth of close to 1 m indicating significant combustion behind the leading edge of the flame. Experiments 5, 6 and 12 have flame lengths less than 2 m and relatively little burning behind the leading edge of the flame. Experiment 2 has a discontinuous flame structure with isolated pockets of burning. Experiments 8, 9, 11 and 14 have all quenched at this time.

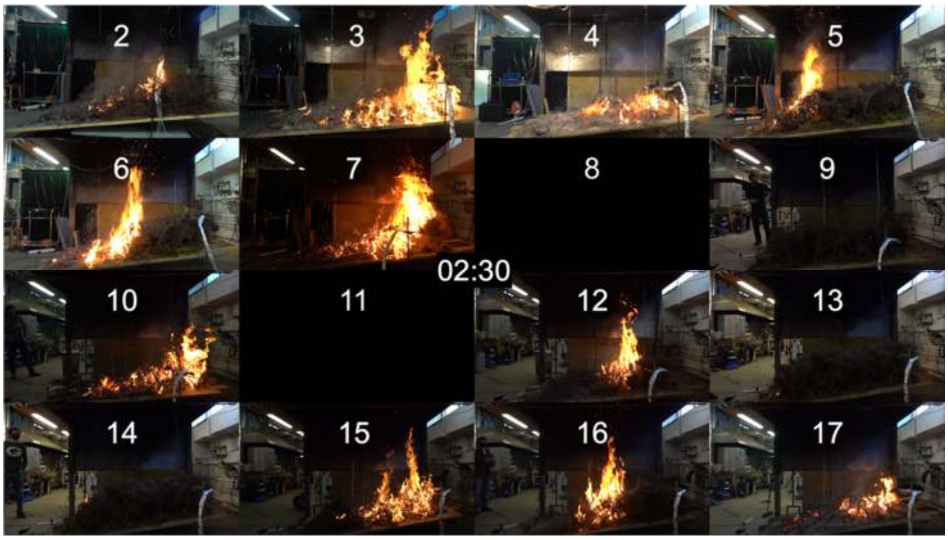

Figure 5.32 Composite image of laboratory flame spread experiments 150 s after ignition

In summary:

- Flame spread through the whole fuel bed occurred for experiments 3, 4, 7, 10, 12, 15, 16, 17.
- Flame spread and flame height was largest in experiments 3, 4, and 17. These fuel beds were characterised by the low FMC in the fine dead and fine green fuels suggesting that these drive the flame spread. It should be noted that the lowest fine dead FMC was measured in experiment 17 which had a fine green FMC greater than that of some experiments in which flame spread was not sustained suggesting that this may be the dominant factor in driving the leading edge of the flame subject to sufficient supporting combustion behind the leading edge of the flame front.
- Experiments which only partially spread through the fuel bed e.g. 5 and 6, were characterised by narrow combustion regions suggesting that burning of vegetation behind the flame front is an important aspect to promote fire spread.
- Experiments 12 and 16 took the longest duration to reach the end of the fuel bed (hence lowest spread rates). The fuels in these experiments had relatively high fine green and moss FMC, respectively. This highlights the importance of the interactions between fuel layers in determining the flame spread rate.

5.3.7.2 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. The flame spread data are only reported when the flame traversed the entirety of the fuel bed. Flame spread rates ranging from 0.664 to 1.714 cm/s were recorded.

The spread rate is shown as a function of the FMC of the different fuel elements in Figure 5.33. 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 making this analysis the assumption that the variations in fuel loading between experiments is not significant has to be made.

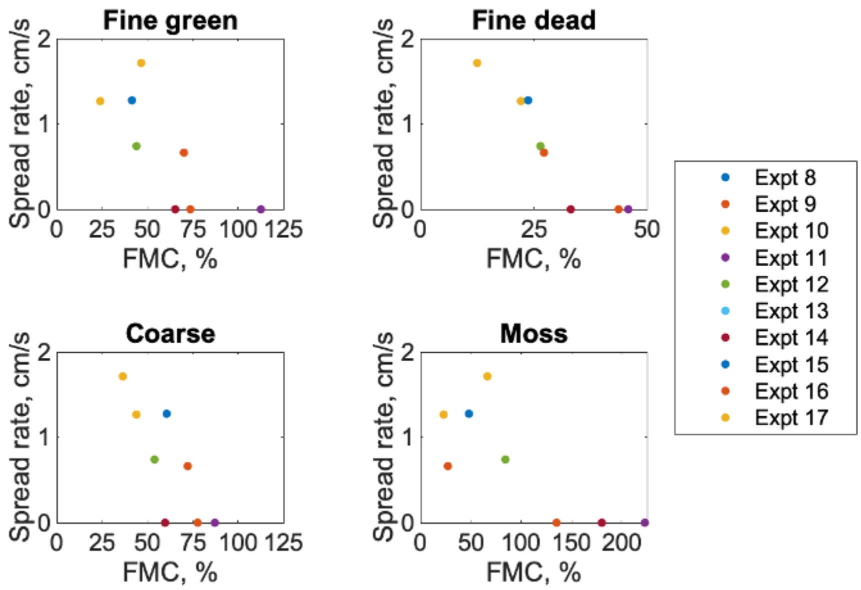

Figure 5.33 Flame spread rate as a function of the fine fuel moisture (FMC) of different fuel elements. Note the different values on the x axes.

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 5.6.

Table 5.6 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

These data highlight the complex interactions associated with the study of fire spread in these systems. Although the fine dead fuel elements require a lower FMC to permit flame spread, these are the strongest driver of flame spread (as illustrated in Figure 5.33) i.e. the ignition and burning of the fine dead fuels is the major contributor to the energy release at the leading edge of the flame. This apparent contradiction is explained by the comparatively faster drying response of the dead fine material and the characteristically lower FMC measured in the field.

Visual observations suggest that the moss and litter and coarse fuels did not significantly contribute to the leading edge of the flame spread under these conditions (see Section

5.3.7.1 Qualitative observations) as the leading edge appears to be close to the top of the heather canopy.

5.3.7.3 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 lab plot, the mass lost ranged from 51 to 98%.

The mass lost rate is shown as a function of the FMC of the different fuel elements in Figure 5.34. 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.

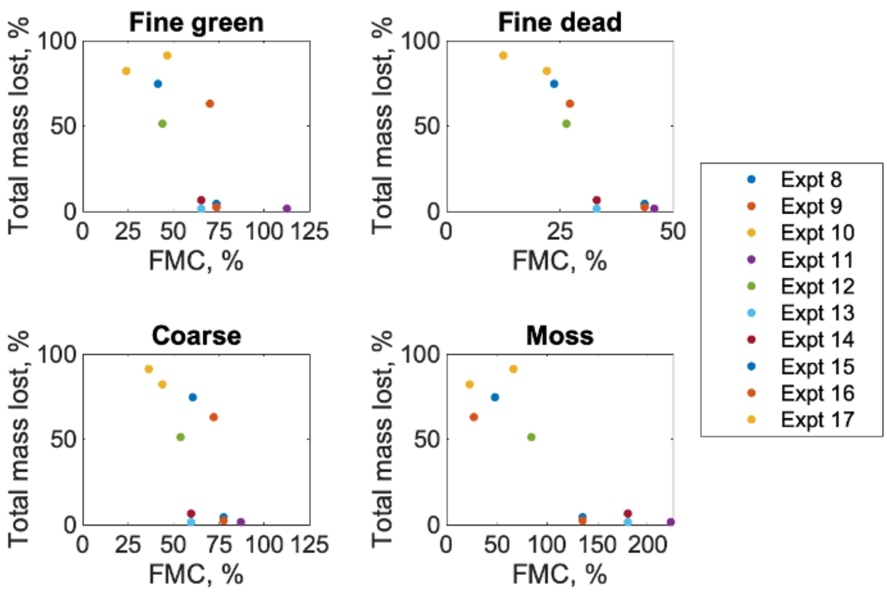

Figure 5.34 Total mass lost as a function of the fine fuel moisture (FMC) of different fuel elements. Note the different values on the x axes.

5.3.7.4 Mass loss rate

The mass loss rate of the experiments 8, 10, 12, 15, 16, and 17 which resulted in flame spread on the full length of the fuel bed are presented in Figure 5.35. Although experiments 3, 4, and 7 also spread to the end of the fuel bed they are not discussed here as the variation in fuel loads does not allow meaningful comparison.

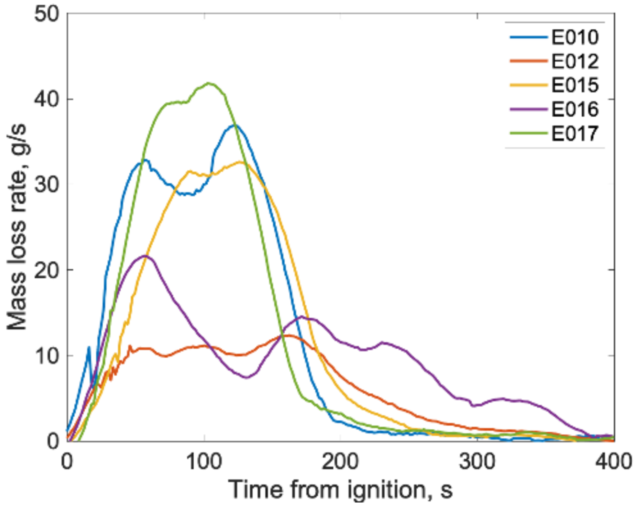

Figure 5.35 Mass loss rate for experiments in which the flame spread the full length of the fuel bed

The mass loss rate for experiments 10, 15 and 17 is characteristically higher than for experiments 12 and 16. This is in agreement with the spread rate data which shows faster spread for experiments 10, 15 and 17 compared to experiments 12 and 16 (Table 5.5). The burning rates of experiments 10, 15 and 17 are characterised by an initial growth to a peak, a short quasi-steady period and a decay. This indicates that a steady state flame spread was only reached for a short duration in these experiments. A peak burning rate of 30-40 g/s was recorded.

The burning rate of experiments 12 and 16 are characterised by a lower values and longer durations. The quasi-steady burning rates in these experiments is approximately 10 g/s. Note at that a higher burning rate peak is recorded in experiment 16 near the beginning of the experiment. It is assumed this is due to the influence of the ignition source. The lower burning rate results in lower energy release (see Section 5.3.7.5) and hence a lower spread rate. Visual observations of experiments 12 and 16 indicated little burning behind the leading edge of the flame front and as measurements indicate relatively high residual mass (Table 5.5).

5.3.7.5 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 5.36. The highest energy release exceeded 600 kW for experiment 004. This experiment also had the highest mass consumption (98%) and represented fuels that had been dried for 3 days in the laboratory. Experiment 003 which also had a high mass consumption (85%) and represented 2 days of drying showed a lower peak energy release with a maximum in the range 400 kW. Similarly experiment 007 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 003 indicating that the combustion of the moss layer, while not significant in determining the overall energy (due to the relatively small mass), this layer may play a role in determining the total energy release and under some conditions.

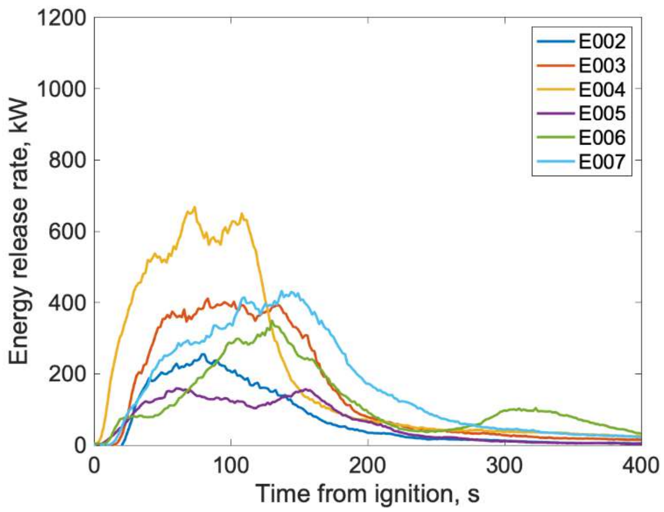

Figure 5.36 Energy release as a function of time for experiments 2—7.

In experiments 2, 5 and 6, the flame did not spread on the full length of the lab plot. 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 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 5.37 (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 1.2 cm/s but for experiments 12 and 16 the rate of spread were 0.74 and 0.66 cm/s, respectively. This difference in energy release is attributed to the combination of higher moisture content of the coarse and fine green fuel elements. 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 the field experiments the FMC of the live coarse fuels was approximately 70—80%.

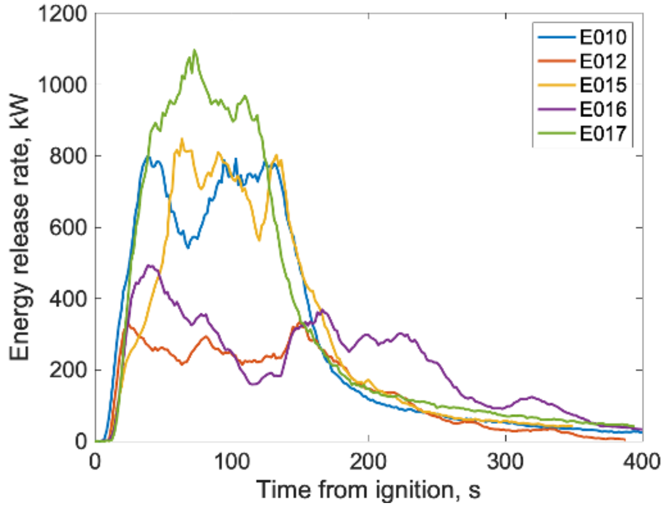

Figure 5.37 Energy release as a function of time for experiments 10, 12 15, 16, 17.

5.3.7.6 Peak energy release

The peak energy release is shown as a function of the FMC of the different fuel elements in Figure 5.38. Again, this shows that FMC has a significant role in determining the rate of energy release. Experiments with low FMC in both the fine fuels and the coarse fuel elements give the highest rate of energy release e.g., experiments 10, 15 and 17. It is expected that the contributions of the fine green and coarse fuels are more significant because these will contribute to the total energy release as they burn after the passing of the leading edge of the flame front.

The average spread rate is shown as a function of the peak heat release rate in Figure 5.39. The peak is used as a proxy to differentiate between experiments with general higher and generally lower energy release rates. These data show that in general there is a positive correlation between the energy release and the flame spread (as expected). However, the small number of experiments precludes a definitive statement regarding the nature of the relationship.

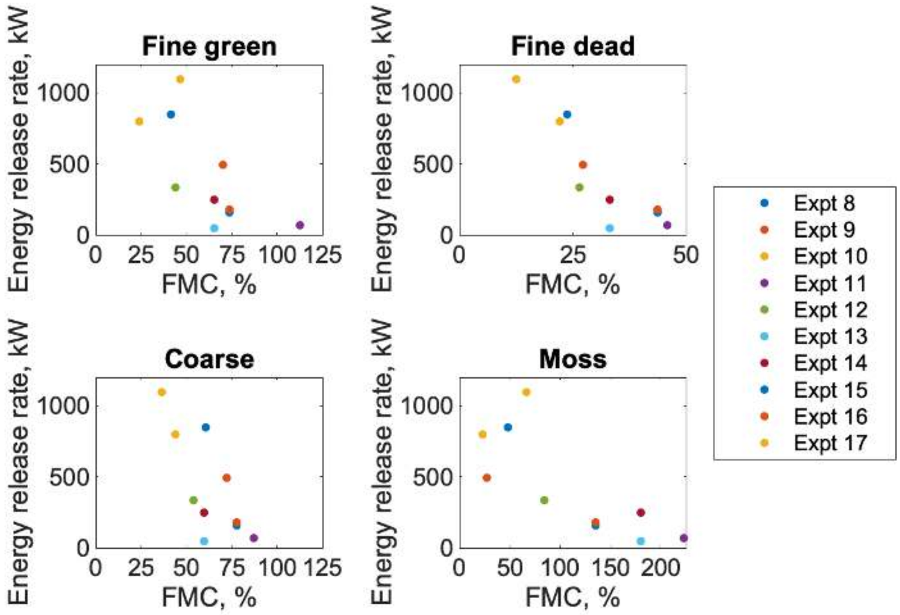

Figure 5.38 Peak heat release rate as a function of the fine fuel moisture (FMC) of different fuel elements. Note the different values on the x axes.

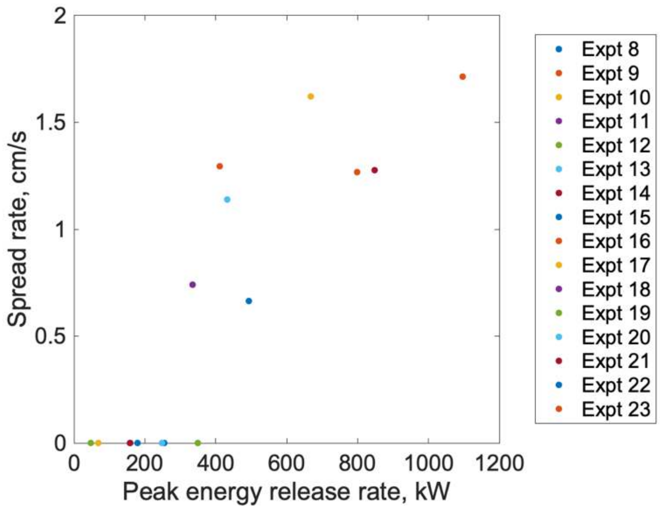

Figure 5.39 The spread rate as a function of the peak energy release rate

5.3.7.7 Heat fluxes

Measurement of the heat fluxes at three locations within the fuel bed were made. These were positioned to characterise the heating of: 1) the heather ahead of the flame front, 2) the moss layer and 3) the 'soil' (i.e., under the moss). These are point measurements and as such are dependent on the local fire/fuel conditions so comparisons should be considered in this context. As a result, only data for experiments in which flame spread was observed to occur on the whole length of the lab plot are reported.

The heat fluxes to the mid height of the heather canopy are shown in Figure 5.40. 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 (see Table 5.5). 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.

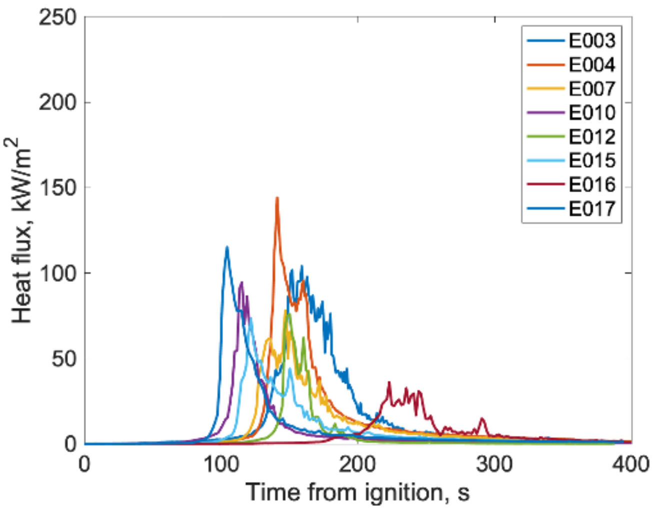

Figure 5.40 Heat fluxes to the heather canopy as a function of time from ignition.

Heat fluxes to the moss layer are shown in Figure 5.41. The peak heat flux recoded is over 200 kW/m2. It should be noted that this is outside the calibrated range of the gauge, however the data are not likely to show significant error. There is no strong correlation between the magnitude of the heat flux and the flame spread dynamics. This may be due to the high sensitivity on the positioning of the gauge relative to the surrounding vegetation e.g. if a smouldering stem is near the gauge, a large value of heat flux would be expected. In all cases the characteristic time of the thermal exposure of the mosses was approximately 100 s. These data are useful in quantifying the impact of the fire on the moss layer.

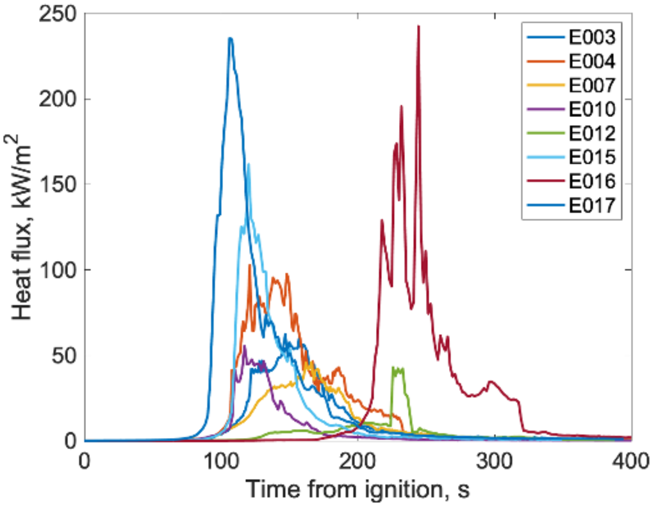

Figure 5.41 Heat fluxes to the moss layer as a function of time from ignition.

Measurements of heat fluxes to the soil layer were made from experiments 11 onwards. These are shown in Figure 5.42. These data show that the heat fluxes to the soil (i.e. beneath the moss layer) are significant lower than those measured elsewhere The heat fluxes measured ranged from 20 to 50 kW/m2. The characteristic times for these heat fluxes cannot be reliably estimated but the data suggests these may be longer than for heather and moss layer heating.

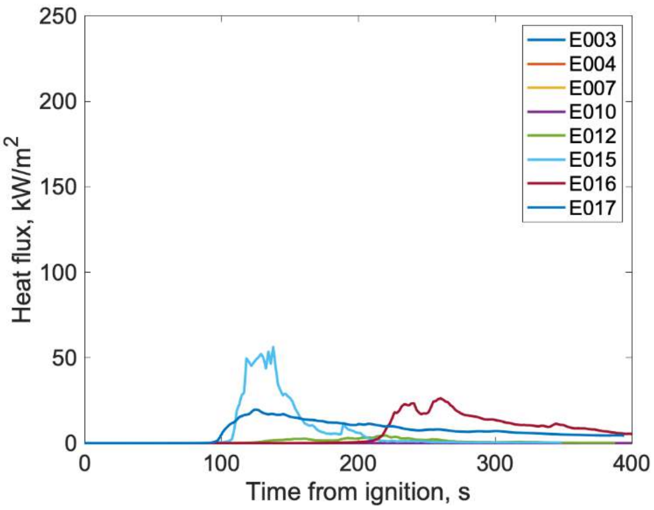

Figure 5.42 Fluxes to the soil (substrate) layer as a function of time from ignition.

5.3.7.8 CO_2 and CO emission

Measurement of carbon dioxide emissions allow the yield of carbon dioxide to be calculated for each experiment. These are presented for the experiments in which the flame spread through the whole fuel bed in

Figure 5.43. The data area characterised by a period of relatively low yield between 0.4 and 1 g/g of vegetation (including moisture) during the flaming combustion stage which increases rapidly after flame out and during the residual burning phase this may be a feature of the experiments where the mass loss rate decreases rapidly but there is a delay in detecting the decrease in CO2 production. It should be noted that these yields are calculated on a wet basis so changes in FMC will affect the results i.e. loss of moisture counts towards the biomass consumed so experiments with higher FMC will have lower apparent yields.

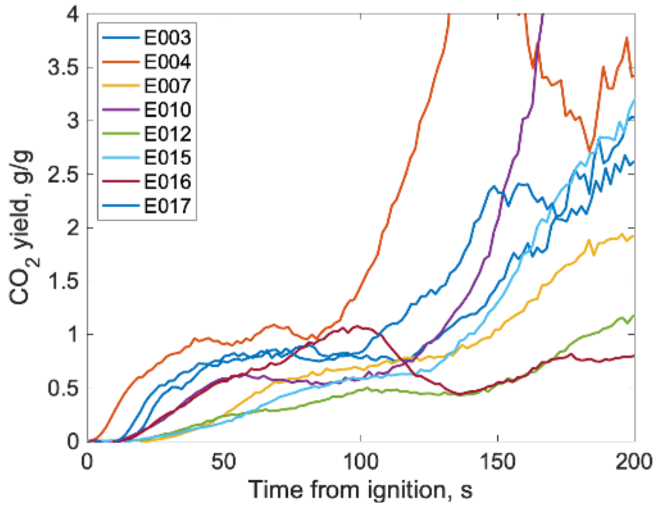

Figure 5.43 CO_2 yield as a function of time from ignition

The yields of carbon monoxide are shown in Figure 5.44. High yields of CO are indicative of low combustion efficiency. This may result in higher yields of other products of incomplete combustion. Therefore, this measurement presents an indirect assessment of the smoke that may be produced from a fire. The data are again characterised by a period during which the flame is spreading which correspond to quasi-stable values. After the flame has spread through the lab plot, the yields increase rapidly. Of particular interest in these data are the results for experiments 12 and 16 which show the highest CO yields (in excess of 0.02 g/g). These cases had relativity high values of FMC in the fine green and course fuels. A hypothesis is that this has resulted in less complete combustion which would explain the relatively low flame spread observed in these experiments. In the other experiments the quasi-steady CO yield was around 0.01 g/g.

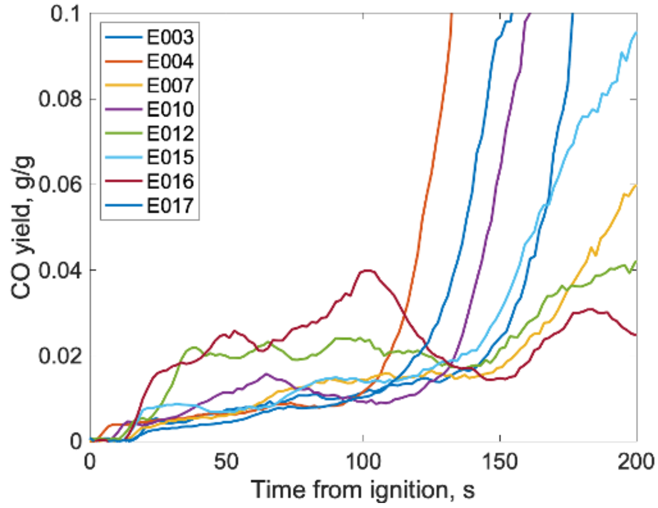

Figure 5.44 CO yield as a function of time from ignition

The cumulative CO2 released from these experiments is shown in Figure 5.45. The data show that, as expected, larger consumption of the fuel results in larger release of CO2. This allows a means to estimate the carbon release from the burning based on assessment of the fuel consumption when measurement may not be available (and assuming equal combustion efficiencies as indicated by the linear relationship in Figure 5.45).

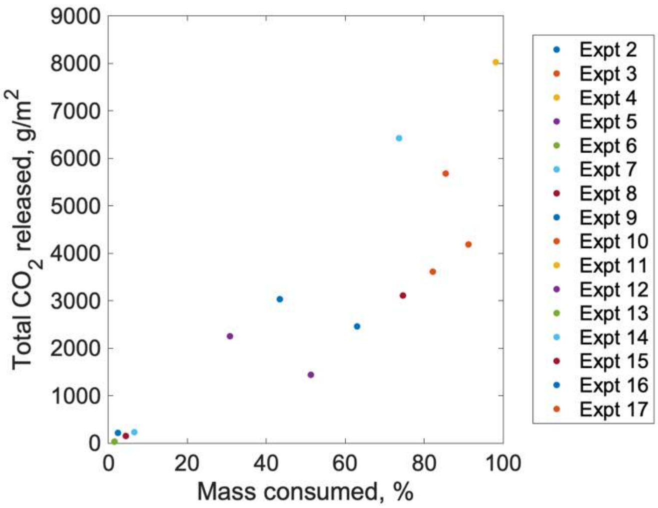

Figure 5.45 Cumulative CO2 release from ignition to the end of the experiment plotted as a function of the normalised mass consumed.

5.3.8 Conclusions

A series of laboratory flame spread experiments have been undertaken to study the process of flame spread in heather fuels. The experiments were carried out under conditions of 5-10° slope, and no wind. This allowed the study of the effects of fuel layer FMC on the flame spread and also allowed investigation into the heat fluxes and carbon emissions to be evaluated.

- Qualitative observations indicate that the FMC of the fine dead fuel is a dominant factor in determining flame spread and the size (energy release). However, low fine dead FMC is not sufficient on its own to permit the flame spread under all conditions and this must be supported by sufficiently low FMC in the other fuels, particularity the coarser heather and the fine green. It is hypothesised that these fuels burning behind the leading edge of the flame provide the energy required, over the timescale necessary to allow fire spread.
- Fuel moisture content thresholds for fire spread of the different fuel classes under controlled conditions have been provisionally identified as:
    - Fine green: 47—56%
    - Fine dead: 26—33%
    - Coarse: 54—60%
    - Moss: 84—135%
- Under these conditions, the maximum energy release of the conditions studied was measured to be between 800 and 1000 kW. This is equivalent to fireline intensity between 900 and 1100 kW/m.
- The rate of spread under the conditions studied varied between 0.66 and 1.71 cm/s and had a strong dependence on the FMC of the fine dead fuels.
- The rate of spread was shown to have a positive correlation with energy release, however there are too few data points to develop a predictive relationship.
- Heat fluxes between 50 and 100kW/m^2 were measured to the heather ahead of the flame front. Heat fluxes to the moss layer typically also varied between 50 and 100 kW/m^2 however for some cases were in excess of 200 kW/m^2. This high variability is attributed to the localised effects e.g. proximity to smouldering fuels. The characteristic times of these elevated heat fluxes was on the order of 100 s. Heating beneath the moss layer was characterised by lower heat fluxes and longer durations of heating.

5.4 Determination of field moisture contents of fuels

The FFMC code of the Canadian FWI is a function of the modelled field moisture content of the fine fuel, where the latter is the litter and other dry fine fuels in jack pine stands (see Table 4.1, Section 4, for a more detailed explanation of fine fuel). Since it is unclear at present which fuel type may be the most responsive and informative fuel for indicating fire risk in heather moorlands, we captured field moisture content data on all of the fuel categories which we identified in WP1. Determining the dynamics of the field moisture contents of these fuel components would be an integral part of FWI development. We used the following simplified version of the protocol developed in the FireBeaters II project (Legg and Davies, 2009) for measuring field moisture contents of green shoots, fine aerial dead shoots (<2mm), coarse woody stem (> 2mm diameter), and the moss and litter layer. Aerial refers to those shoots held above the moss and litter layer. This approach avoids the issue of capturing any moisture released from the sample while in the collection container that can be an issue with the FireBeaters protocol.

Protocol for measuring field moisture content of various fuel fractions.

1) Samples were collected in small metal containers. All containers and associated lids were identified by unique numbers scratched into the metal. Containers including lids were preweighed.
2) Samples were taken from each fuel type in the field and sealed in the containers by screwing the lids on securely.
3) On return to the lab, any moisture on the outside of the containers was removed and then the filled containers were weighed.
4) Containers minus the lids were then placed in an oven at 80°C for at least 48 hours, and then the lids are replaced as containers are removed from the oven.
5) The lidded containers are allowed to cool and then reweighed.
6) The weight of the container plus the dry sample, minus the container gives the dry mass of the sample, and the weight of the container plus the fresh sample minus the container and dry sample gives the water loss.

The field moisture content of samples expressed as percent of dry mass was calculated with the following equation:

$$Field\ moisture\ content\ (FMC) = \ 100\ \times\ (moisture\ loss\ /\ dry\ mass)$$

Three to five samples of each fuel type sufficient to fill the metal container were collected at dispersed point at least 5 m apart at each field site at each required time point.

5.4.1 Responsiveness of field moisture contents of different fuel fractions

The bulk of the collection of FMC data was carried out at Glensaugh farm. We focussed on measuring field moisture contents (FMC) over different time periods (minutes and hours) on multiple days to determine the range of values within fuel type and the resolution of change in FMC (see Figure 5.46, Figure 5.47, Figure 5.48, Figure 5.49, Table 5.7 and Table 5.8). In general, the data demonstrated that the fine fuel fractions can dry rapidly (Figure 5.46, Figure 5.47, Figure 5.48) and usually shows limited spatial variation which means that only a small number of samples (3) need to be taken to capture reliable data at any time point. However, there were marked differences between the fine dead and the green shoots. The fine green shoots, being live had, not surprisingly, the greatest degree of control over moisture content. The FMC of the fine green shoots could reach 160% after rain events, which then reduced rapidly over a period of a few hours (see 16th, 26th April, Figure 5.47). However, the values stabilised at ca. 95-100%. Rarely values recorded during March and April 2019 were in the low 80s (Figure 5.46, Figure 5.47). This would strongly suggest that the FMC of the green shoots reflects moisture held on the surface of the shoots after a rain event being quickly lost, until a relatively stable equilibrium is reached which is under control of the plant. The lowest FMC values recorded for green shoots was ca. 65% after prolonged very dry conditions in April 2021.

The fine, suspended dead fuel reacted similarly to the green shoots after rain events when FMC could reach 160% (200), which could subsequently decline quickly over a few hours (e.g. Figure 5.48, 26th April). However, the stabilisation of values for the fine dead occurred much lower than for the green shoots (see Figure 5.48, 8th, 22nd, 29th April). The mean values on the 8th, 22nd, 29th April were 23.7%, 15.3% and 26.1%, respectively, and were remarkably stable over the six-hour sampling period. The dead shoots have no active mechanism to influence the loss (or gain) of moisture, and the FMC of the shoots will link closely with the prevailing environmental conditions. It is clear that they can lose moisture rapidly over a matter of hours, but we do not know the dynamics of rewetting.

The differences in the FMC levels at which green and fine dead fuels stabilise under the same environmental conditions are illustrated in Figure 5.50.

The FMC of the litter and moss fraction had greater spatial variation and was less responsive than the fine fuel fractions (Figure 5.46, Figure 5.49). The range of FMC values was very broad from ca. 500% to a minimum value of 13.4% during March and April 2019. The greater spatial variation in FMC will most likely be a reflection of the variation in the natural variation in moss cover on the heather moorland and hence this will influence the proportion of moss material in the samples collected for determining the FMC. The FMC of the moss and litter layer showed a slow reduction from 5th- 22nd April 2019, then increased from ca. 40% to 200% between the 2nd and 26th April. The latter increase was the result of a rain event.

This huge range of FMC values of the moss and litter layer is a reflection of the ability of mosses to absorb many times their own mass in moisture, and their inability to control the loss of the captured moisture. Although the moss and litter represent living and dead components respectively, the mosses differ markedly from the heather green shoots, as they have evolved to survive cycles of drying and rewetting. They lack the internal transport system of heather which transports water to the green shoots from the soil, and they lack any chemical or morphological mechanisms to restrict water loss from surfaces. In this way the moss fraction will share to a certain degree the drying properties of the litter. However, their extraordinary ability to absorb water means that they will act as a reservoir of moisture which will increase the response time of the layer to drying conditions.

Table 5.7 Summary of field moisture contents (percentage of dry mass) of different fuel fractions of heather moorland at Glensaugh Farm over 3.5 hours on 27th March 2019. (Data collected from 11.20 – 14.50 GMT).

Fuel fraction	No. of samples	Mean	SE	Min	Max
Green (< 2mm)	20	97.2	1.6	83.4	109.1
Fine dead (<2mm)	20	29.7	1.0	20.8	38.9
Moss and Litter	20	345.6	18.8	210.8	503.0

Table 5.8 Summary of field moisture contents (percentage of dry mass) of different fuel fractions of heather moorland at Glensaugh Farm over 6 days in April 2019. (Data collected on 5th, 8th, 16th, 22nd, 26th, and 29th April)

Fuel fraction	No. of samples	Mean	SE	Min	Max
Green (< 2mm)	105	108.3	1.7	82.7	163
Fine dead (<2mm)	105	42.3	3.3	12.1	200.4
Moss and Litter	105	201	9.7	13.4	418.5

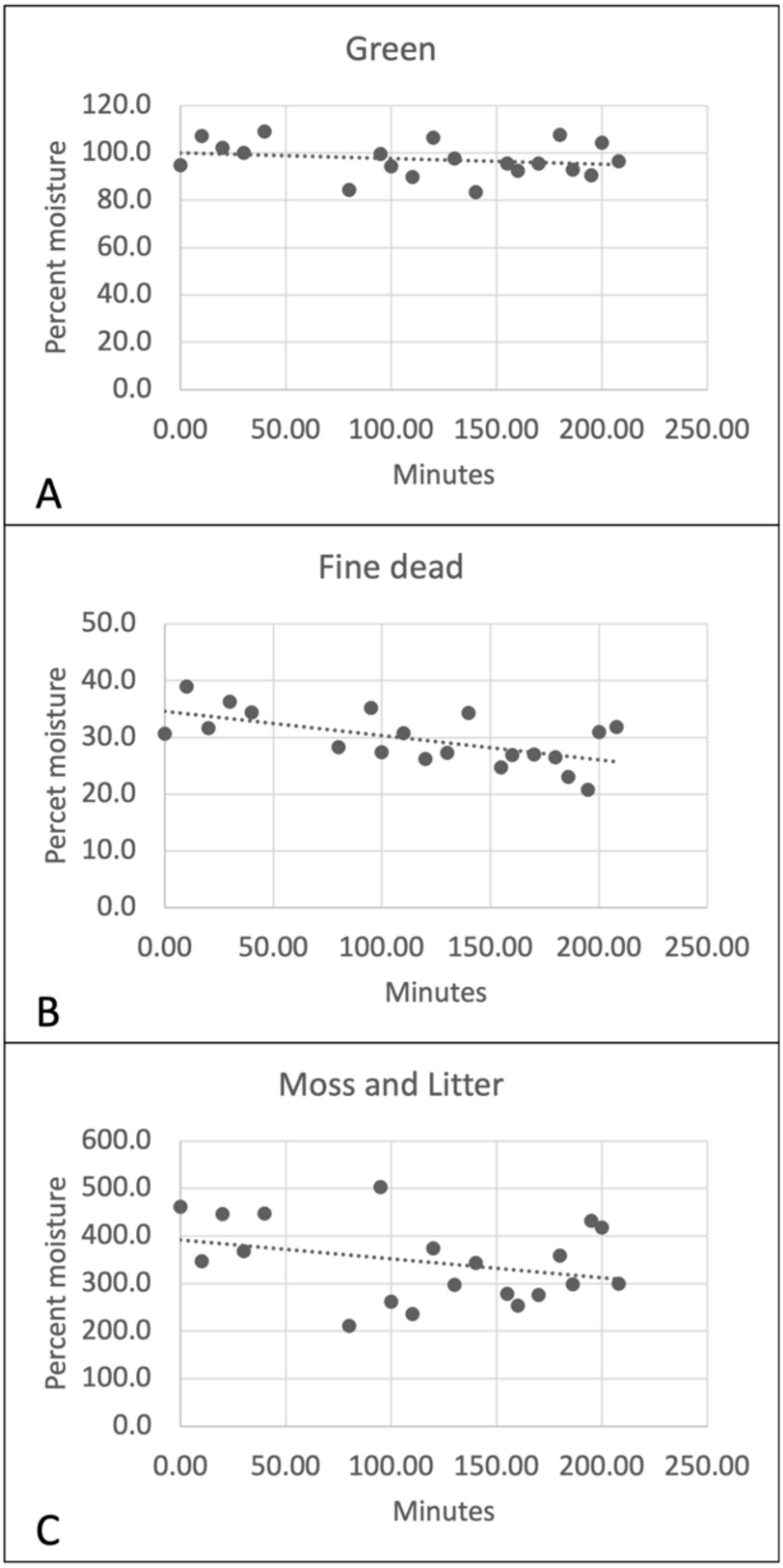

Figure 5.46 Fine scale changes in field moisture contents (percent moisture of dry mass) of green shoots, suspended fine dead (< 2mm) and the moss and litter layer of a heather moorland at Glensaugh Farm, Laurencekirk, Aberdeenshire. T-zero was 11.20 am.

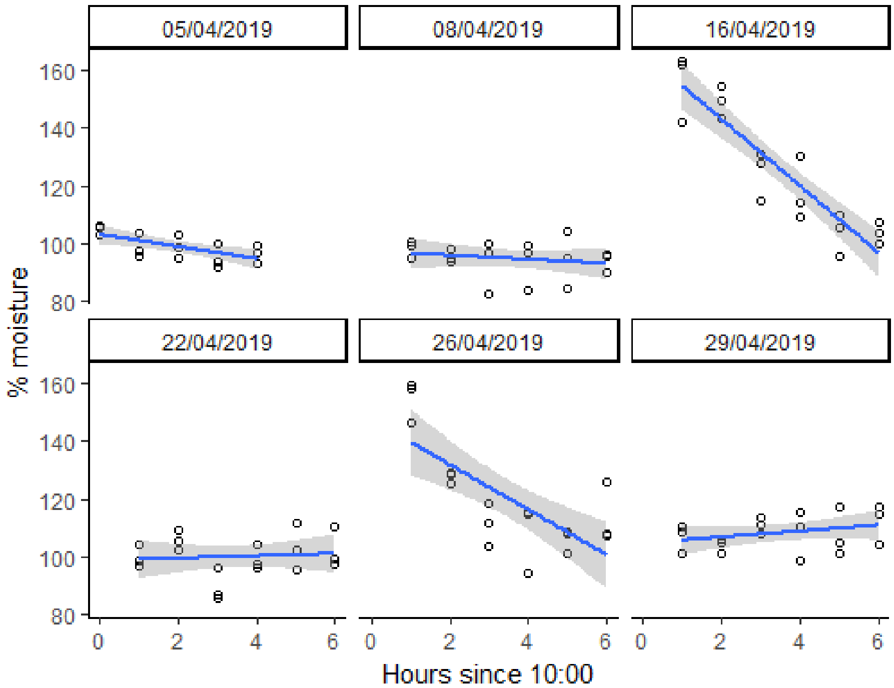

Figure 5.47 Changes in the field moisture contents over a six-hour period on six different dates of the fine, live green fuel fraction of heather in a heather dominated moorland at Glensaugh Farm, Laurencekirk, Aberdeenshire.

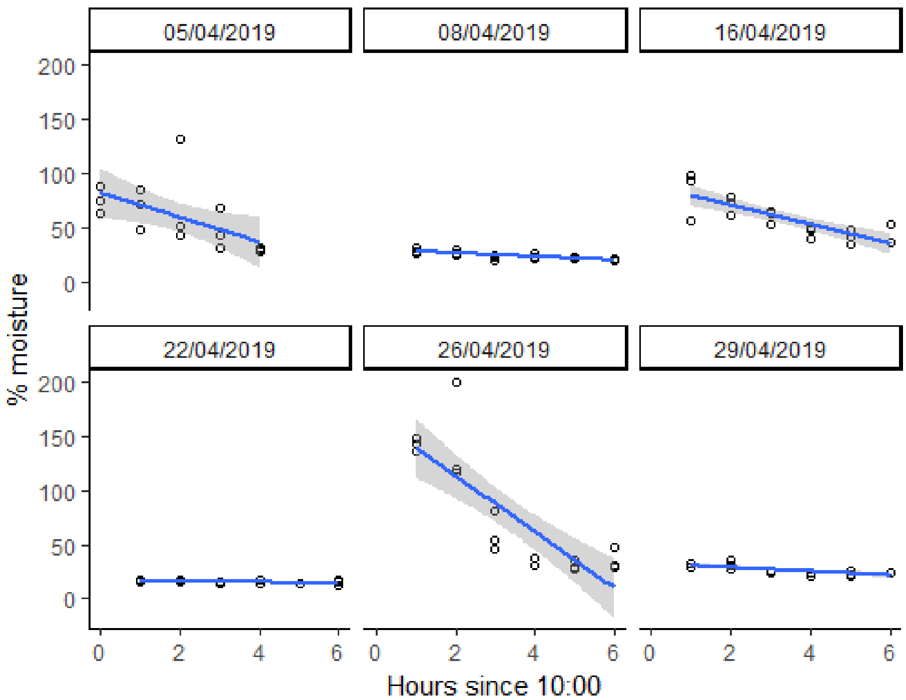

Figure 5.48 Changes in the field moisture contents over a six-hour period on six dates of the fine dead fuel fraction of heather at Glensaugh Farm, Laurencekirk, Aberdeenshire.

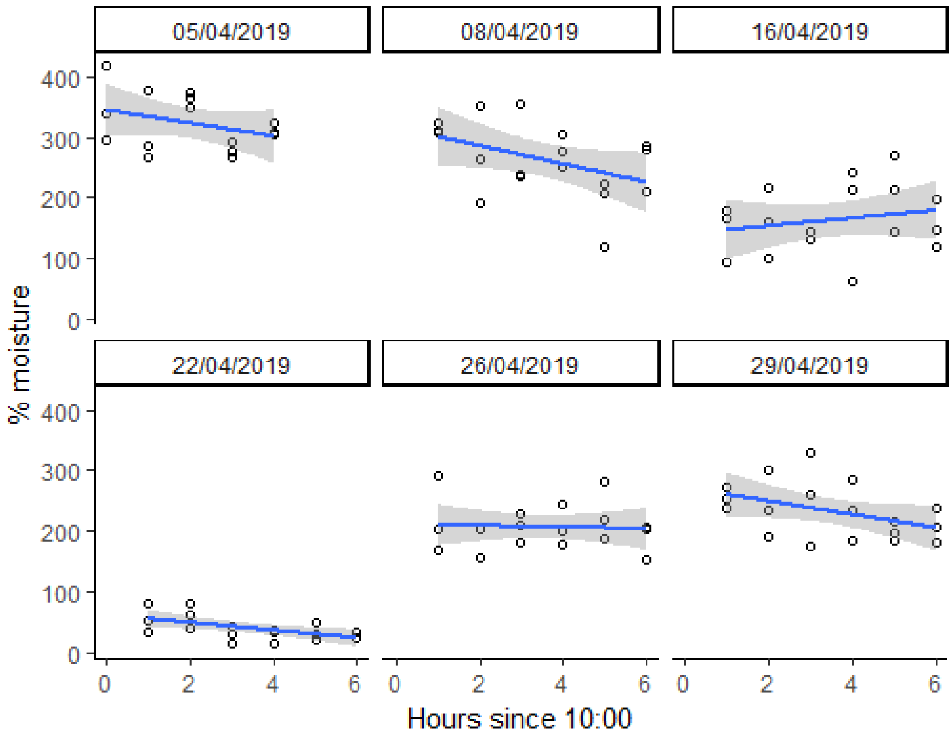

Figure 5.49 Changes in the field moisture contents over a six-hour period on six different dates of the litter and moss layer under heather dominated moorland at Glensaugh Farm, Laurencekirk, Aberdeenshire.

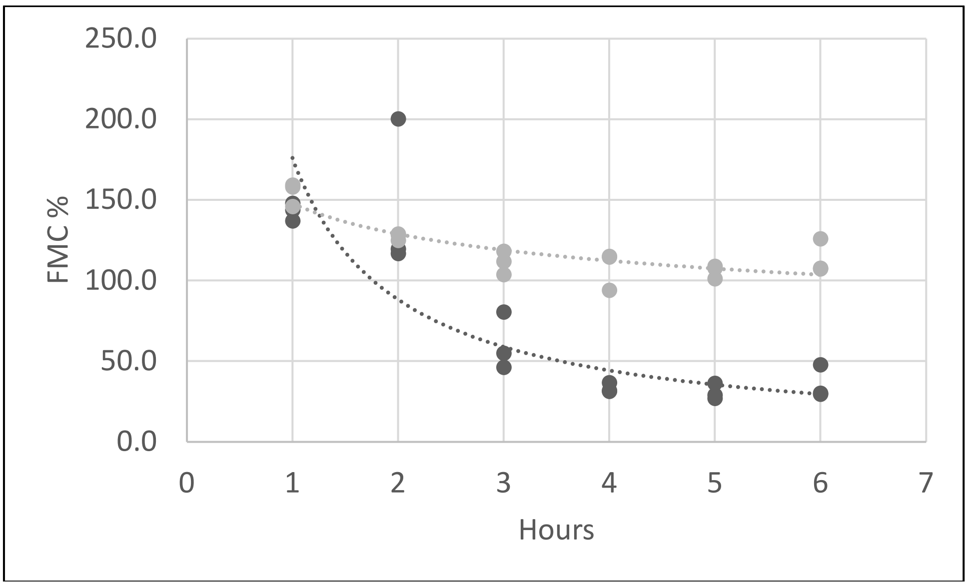

Figure 5.50 Changes in field moisture contents (FMC) of live green (grey circles) and fine dead (black circles) heather shoots over five hours (11.00-16.00) on 26th April 2019 at Glensaugh Farm, Laurencekirk, Aberdeenshire.

5.4.2 Fuel consumption during controlled field fires and field moisture contents of fuel fractions

The review of fuel loads highlighted the sparsity of data from most Scottish vegetation types, and that most available data actually refers to biomass. It is important to recognise that vegetation biomass does not necessarily equate to fuel, and data on what is actually consumed during fires are even more limited than those on biomass and appear to be largely limited to heather fires. An additional outstanding question is how does fuel FMC influence the proportion of fuels consumed during a fire? Field data on fuel consumption under different environmental conditions would be essential for calibrating lab tests on consumption and fire behaviours at different FMC. In addition, modelling release of carbon dioxide from wildfires requires data on fuel consumption from different fractions under different conditions. We addressed these knowledge gaps by developing approaches for collecting new data from both heathlands and grasslands.

In order to determine the amount of fuel consumed during fires, fuel mass was determined using the above protocol in three-five quadrats prior to the controlled burn. This was carried out in the immediate vicinity of the area rigged up for monitoring the controlled burn. The protocol was repeated in the burnt area after the controlled burn and the area had cooled sufficiently to allow safe handled of materials. Any ash which was left on shoots or on the moss/litter layer was gently shaken off to avoid over estimation of the mass left.

In addition to fuel loads, samples were taken for determining the FMC of the different fuel fractions immediately prior to the controlled burns.

Data on fuel loads and consumption, and the FMC of the different fractions were collected from six fires: 2 fires on 6th November 2020 at Glen Tanar Estate, Deeside, Aberdeenshire, and 2 fires on 14th April 2021 and 2 fires on 22nd April 2021 all four at Glensaugh Farm, Laurencekirk, Aberdeenshire.

In summary, a comparison of pre- and post-fire data showed that, in general, the consumption of fine fuels (green live and fine dead) was very high, usually complete, irrespective of FMC values (Figure 5.51, Figure 5.52, Figure 5.53). The consumption of the coarser material was much more variable, ranging from zero to 80% loss – even though the FMC values of the coarse stems were remarkably constant (74.2-79.6%; Figure 5.53). The highest consumption of the coarse fraction occurred when the moss and litter layers were at their driest. This was also observed in the laboratory flame spread studies (See Table 5.5). The greatest contrast in both the consumption of fuel fraction and FMC levels was seen for the moss and litter layer (Figure 5.51, Figure 5.52, Figure 5.53). When FMC was very high (ca. 450%), there was negligible loss of material from the litter and moss layer. However, when the layer had dried out to ca. 50% or less, the consumption by the fires was 80-90%.

Figure 5.51 Percentage loss of different fuel fractions (green and fine dead < 2mm, coarse > 2mm, litter and moss combined) during 6 fires on heather moorland (Burn 1 and 2 - 6/11/2020; Burn 3 and 4 – 14/4/2021; Burn 5 and 6 – 22/4/2021).

Figure 5.52 Field moisture contents (percentage + standard errors) of different fuel fractions (green and fine dead < 2mm, coarse > 2mm, litter and moss combined) during 6 fires on heather moorland (Burn 1 and 2 - 6/11/2020; Burn 3 and 4 – 14/4/2021; Burn 5 and 6 – 22/4/21).

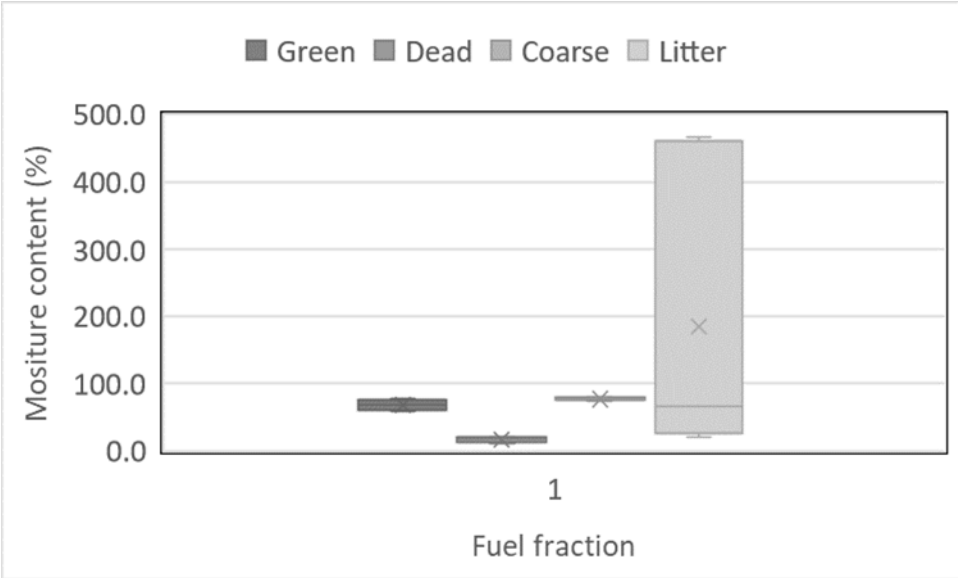

Figure 5.53 Boxplot of the variation in field moisture contents of different fuel fractions of heather showing mean, median and range of values. Data collected prior to six controlled burns carried out in 2020 and 2021.

5.5 Field flame spread

5.5.1 Introduction

Over the duration of the project there were several field deployments to obtain measurements of fire behaviour in heather fuels under different weather conditions. Deployment windows were principally constrained by meteorological conditions and guidance from the land managers. In total, ten field experiments were undertaken during prescribed burning periods. In addition, a small number of trial burns were undertaken prior to the main burns to develop the apparatus and the experimental approaches.

5.5.2 Methods

Field experiments are challenging due to the large number of variables including spatial variations in fuel, and temporal changes in meteorological conditions (especially wind). Consequently, it was decided early in the project to focus instrumentation on small areas of approximate areas 10 m x 10 m, set around 5 to 10 m downwind of the ignition line. In each case the fires were ignited as a head fire.

Fuel moisture content measurements were made in conjunction with the fire behaviour measurements reported here. Several additional field deployments were made to evaluate fuel moisture to capture field variation.

5.5.3 Measurements

The following measurements were made to characterise each fire:

- Side view and overhead video to determine spread rate.
- Temperature at various heights above ground level.
- Mass of fuel consumed.
-

An overview of the experimental arrangement is given in Figure 5.54 detailing the measurement array and individual thermocouple trees and approximate thermocouple locations.

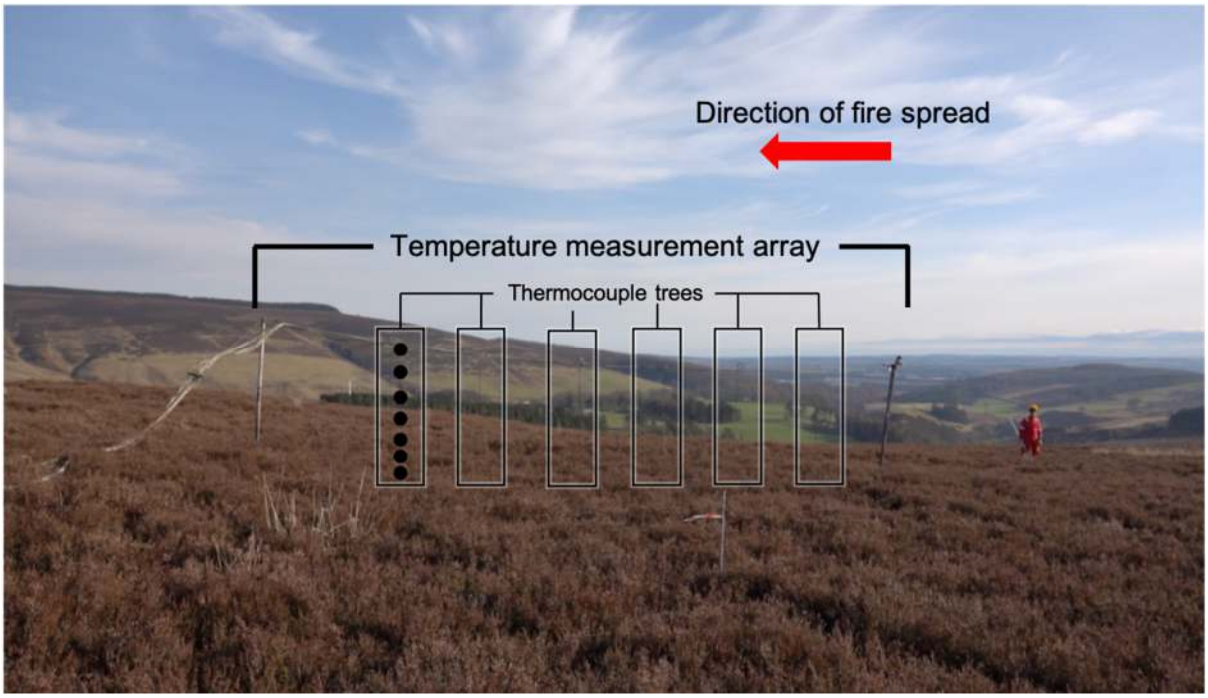

Figure 5.54. Overview of the thermocouple array and the region of interest (image from fieldwork on 22 March 2021). Approximate thermocouple locations on each tree are indicated on the left-most thermocouple tree.

The following measurements were made to characterise the fire environment:

- FMC – Fine green, fine dead, coarse and moss fuels.
- Ambient wind speed and direction.
- Relative humidity.
- Ambient temperature

Flame spread rate and qualitative fire behaviour indicators discussed below are extracted from the video data. Flame spread was calculated by measuring the time taken for the leading edge of the fire front to impact the upwind and downwind thermocouple trees. Unless otherwise specified, qualitative observations are recorded as the fire passes through the centre of the measurement array.

5.5.4 Burn locations

The majority of the field experiments were undertaken at Glensaugh Farm. Two experiments were undertaken at Glen Tanar Estate and two experiments were undertaken at Fettercairn Estate on land adjacent to Glensaugh Farm. The locations for each fire are given in Table 5.9.

Table 5.9 Locations for each experiment

Burn No.	**Plot No.**	**Date**	**Location (What3Words)**	**OS grid reference**
1	GT.8	06/11/2020	///relief.brand.enchanted	NO 4195 9397
2	GT.9	06/11/2020	///storage.kick.refills	NO 4195 9398
3	GS.8	22/03/2021	///tops.icebergs.jingles	NO 6649 7915
4	GS.9	22/03/2021	///chariots.revives.devotion	NO 6650 7917
5	GS.10	22/03/2021	///holly.fills.disposing	NO 6663 7921
6	GS.5	14/04/2021	///galloped.using.blush	NO 6646 7964
7	GS.6	14/04/2021	///ringside.showrooms.trades	NO 6655 7940
8	GS.7	14/04/2021	///hook.hill.throat	NO 6660 7940
9	FC.	22/04/2021	///subsets.sensitive.gallons	NO 6580 7905
10	FC.	22/04/2021	///carrots.flushes.unopposed	NO 6590 7895

5.5.5 FWI sub-indices for field research burn plots

The fire weather information for the locations and days of the field research burns was extracted from the EFFIS Current Situation database (Table 5.10).

Field fire tests were carried out in a range of fire danger conditions. In a very broad way the fire behaviour, especially the flame depth, seems to be reflected in the changes in FWI sub-indices, especially FFMC, ISI and DMC.

Table 5.10 European Forest Fire Information System (EFFIS) Fire Weather Index (FWI) sub-indices for locations and days of field research burns.

Burn No.	Plot No.	Date	FFMC	DMC	DC	ISI	BUI	FWI
1	GT.8	06/11/2020	73.1	1.2	4.8	0.9	1.5	0.3
2	GT.9	06/11/2020	73.1	1.2	4.8	0.9	1.5	0.3
3	GS.8	22/03/2021	83.0	5.3	10.1	2.7	5.1	1.7
4	GS.9	22/03/2021	83.0	5.3	10.1	2.7	5.1	1.7
5	GS.10	22/03/2021	83.0	5.3	10.1	2.7	5.1	1.7
6	GS.5	14/04/2021	84.6	10.9	33.5	3.0	12.0	3.5
7	GS.6	14/04/2021	84.6	10.9	33.5	3.0	12.0	3.5
8	GS.7	14/04/2021	84.6	10.9	33.5	3.0	12.0	3.5
9	FC.	22/04/2021	82.9	18.5	55.1	2.3	20.1	3.7
10	FC.	22/04/2021	82.9	18.5	55.1	2.3	20.1	3.7

5.5.6 Results

An overview of the results is presented in Table 5.11

Over the 10 experiments, the meteorological conditions varied as follows:

- Temperature: 9.6—15.7°C.
- Relative humidity: 49.1—74%.
- Windspeed: 2.7—5.5 m/s.

Fuel moisture contents were similar to those measured in the laboratory and varied as follows:

- Fine green 57.4—88.7%
- Fine dead 11.1—71.6%
- Coarse 69.8—79.6%
- Moss 27.9—465%

5.5.6.1 Qualitative observations

In all cases, fire spread was observed under the entire length of the measurement array.

The following images are taken as the fire spread under the mid-point of the array to allow for qualitative comparisons. Note that the position is estimated visually which in some cases is challenging due to obscuration by the smoke.

Burn 1 and 2 are characterised by flame height on the order of 2 m and relatively narrow flame fronts on the order of 1 metre (Figure 5.55 and Figure 5.56).

Burn 3 and 4 are characterised by similar flame lengths (~2 m) but somewhat deeper flame fronts approximately 2 m in depth (Figure 5.57 and Figure 5.58). Burn 5 has flame lengths exceeding 2 m and a flame depth of approximately 4 m (Figure 5.59).

Flame depths in burn 6, 7 and 8 approach 4 m and flame lengths are approximately low at 3 m (Figure 5.60, Figure 5.61 and Figure 5.62).

Flame length in burn 9 exceeded 4 m and flame depths were at least 5 m and probably larger (Figure 5.63). Burn 10 was the most extreme fire behaviour with flame lengths in excess of 6 m and flame depths exceeding 10 m (Figure 5.64).

Figure 5.55 Burn 1 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array.

Figure 5.56 Burn 2 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array. Note smoke obscuration of the side view.

Figure 5.57 Burn 3 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array. Note smoke obscuration of the side view.

Figure 5.58 Burn 4 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array.

Figure 5.59 Burn 5 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array.

Figure 5.60 Burn 6 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array. Note that the fire front was spreading parallel to the line of the measurement array.

Figure 5.61 Burn 7 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array.

Figure 5.62 Burn 8 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array.

Figure 5.63 Burn 9 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array.

Figure 5.64 Burn 10 (left) overhead and (right) side view of the fire as it passes at the mid-point of the measurement array.

5.5.6.2 Overview of quantitative results

A summary of the key environmental and fuel variables measured in each of the burns is presented in Table 5.11. Data on FMC are from samples immediately before ignition or during the burns in locations adjacent to the burn units. Environmental conditions are presented as the average during the burn period.

Table 5.12 shows the fire line intensity for burns 1, 2, 7, 8, 9, and 10. The fireline intensities range from 1400 kW/m to 14700 kW/m. The method proposed by Byram was used and allows comparative results to be calculated however the applicability of this method in relation to Scottish fuel types must be further developed, particularly to evaluate the meaning of available fuels.

Table 5.13 shows the fuel mass available and fuel mass consumed per class for burns 1,2, 7, 8, 9 and 10. Comparing results from Table 5.12 and Table 5.13 indicates that the consumption of coarse fuels and moss and litter is a significant in determining the fire intensity. It is not clear however whether the ‘availability’ of these fuels drives these increases in intensity, of whether the increase in intensity allows for consumption of these fuels. This highlights a key limitation of the current approaches and the need to develop a detailed understanding of the interactions between layers in determining the fire line intensity of Scottish fuels.

Table 5.11 Experimental overview for the field experiments, n.d. indicates no data recorded for these experiments.

								Fuel moisture content, %					
Burn No.	**Plot No.**	**Ignition time (GMT)**	**Temp (C)**	**RH (%)**	**Wind speed (m/s)**	**Wind dir (deg)**	**Shrub fuel load (g/m2)**	**Fine green**	**Fine dead**	**Coarse**	**Moss**	**Average mass consumed, %**	**Average spread rate, cm/s**
1	GT.8	14:21:21	11.4	64.8	5.45	~225	1275	77.9	19.8	74.2	458	69.8[1]	9.80
2	GT.9	15:25:05	9.6	74.7	3.1	~225	n.d.	74.6	20	75.7	465	49.0[1]	7.69
3	Gs.8	13:36:10	14.7	49.1	3.2	313	n.d.	88.7	60.3	69.8	119	n.d.	11.76
4	Gs.9	14:52:00	14	50.8	3.1	272	n.d.	87.7	64	78.6	124.1	n.d.	9.62
5	Gs.10	16:17:13	12.2	58.2	5.9	298	n.d.	86.1	71.6	76.7	155.5	n.d.	15.15
6	GS.5	14:00:00	15.7	46.8	3.9	136	792	70.6	13.9	79.6	57.9	88.6	n.d.[2]
7	GS.6	15:51:52	10.3	51.2	2.74	167	1230	62.3	19.9	78.8	74.5	87.7	13.56
8	GS.7	16:58:53	11	50.3	3	179	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	8.89
9	Fc.	12:34	14	46	4.4	120	3165	66.5	15.2	74.9	21.1	93.3	6.02
10	Fc.	15:33	11	53	3.3	95	2987	57.4	11.07	76.9	27.9	89.9	24.24

Note 1 Negative fuel consumption of some classes has been removed
Note 2 Fire spread was parallel to the measurement array so no measurement could be made

Table 5.12 The calculated fire line intensities for burn 1,2,7,8,9 and 10. Calculations are based on the total available shrub fuel, total available fuel and actual fuel burned.

Burn Number	Shrub mass available, g/m²	Total fuel mass available, g/m²	Rate of spread, m/s	Average fuel consumption, %	Mass of fuel burned, g/m²	Intensity (assuming total shrub consumption), kW/m	Intensity (assuming total fuel consumption)	Intensity corrected for actual fuel consumption, kW/m
1	1275	2158	0.10	69.8	1506	2200	3700	2600
2	1275	2158	0.08	49	1057	1700	2900	1400
7	792	1231	0.14	88.6	1091	1900	2900	2600
8	1230	1721	0.09	87.7	1509	1900	2700	2300
9	3165	4415	0.06	93.3	4119	3300	4600	4300
10	2987	3851	0.24	89.9	3462	12700	16300	14700

Table 5.12 shows the fire line intensity for burns 1, 2, 7, 8, 9, and 10. The fireline intensities range from 1400 kW/m to 14700 kW/m. The method proposed by Byram was used and allows comparative results to be calculated however the applicability of this method in relation to Scottish fuel types must be further developed, particularly to evaluate the meaning of available fuels.

Table 5.13 The fuel mass present in each fuel class and the consumption of each fuel class for burns 1,2,7,8,9, and 10.

Burn	Pre burn fuel mass, g/m2						Fuel consumed, %			
	Green	Fine dead	Coarse	Moss/litter	Total shrub	Total mass	Green	Fine dead	Coarse	Moss/litter
1	543.6	191.7	539.9	882.7	1275.2	2157.9	100	84.3	25.2	-6.1
2	543.6	191.7	539.9	882.7	1275.2	2157.9	100	83.5	-36.4	26.6
7	645		147	439	792	1231	100	100	63.9	90.6
8	853		377	491	1230	1721	100	100	63	87.7
9	1275		1890	1250	3165	4415	100	100	79.1	94.1
10	1614		1373	863.7	2987	3850.7	100	100	81.1	78.6

5.5.6.3 Quantitative observations

The spread rate is presented as a function of the environmental variables (RH, wind speed and shrub fuel load) in Figure 5.65. No clear trend is observed between the environmental variables and the spread rate for the conditions of these experiments.

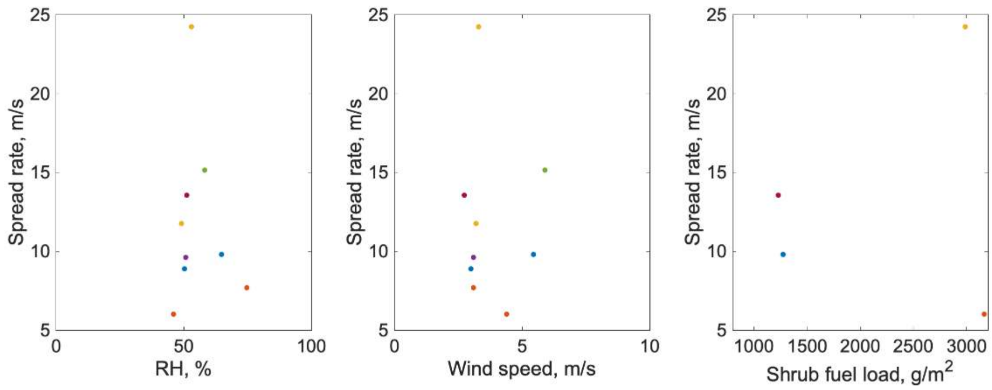

Figure 5.65 Spread rate as a function of the environmental variables RH (left), windspeed (centre) and shrub fuel load (right).

The vegetation mass lost is presented as a function of environmental variables relative humidity (RH), windspeed and shrub fuel load in Figure 5.66. No clear trend is observed between the environmental variables and the mass lost for the conditions of these experiments.

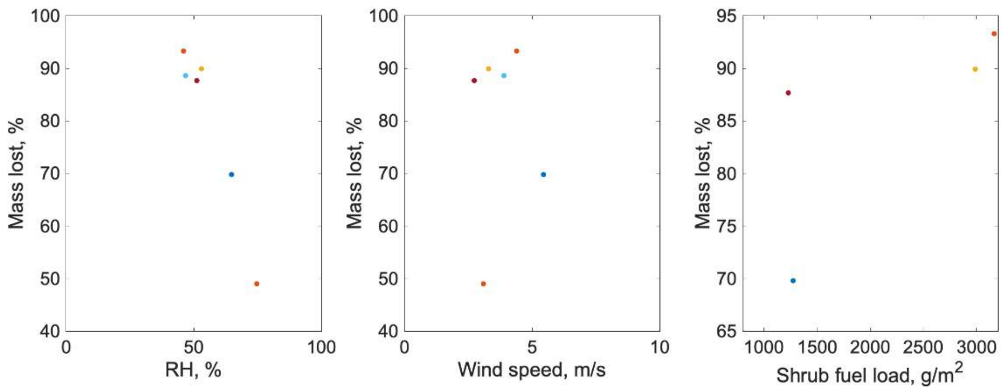

Figure 5.66 Vegetation mass lost as a function of the environmental variables RH (left), wind speed (centre) and shrub fuel load (right).

The spread rate is presented as a function of the fuel moisture content (FMC) of different fuel classes in Figure 5.67. No clear trend is observed between the FMC and the spread rate for the conditions of these experiments.

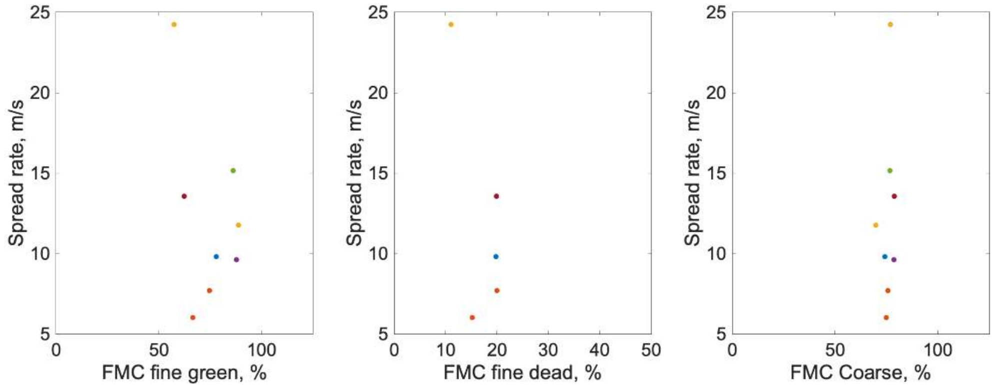

Figure 5.67 Spread rate as a function of the fine fuel moisture (FMC) for fine green (left), fine dead (right) and coarse (right).

The vegetation mass lost is presented as a function of the FMC for different fuel classes in Figure 5.68. No clear trend is observed between the FMC and the mass lost for the conditions of these experiments.

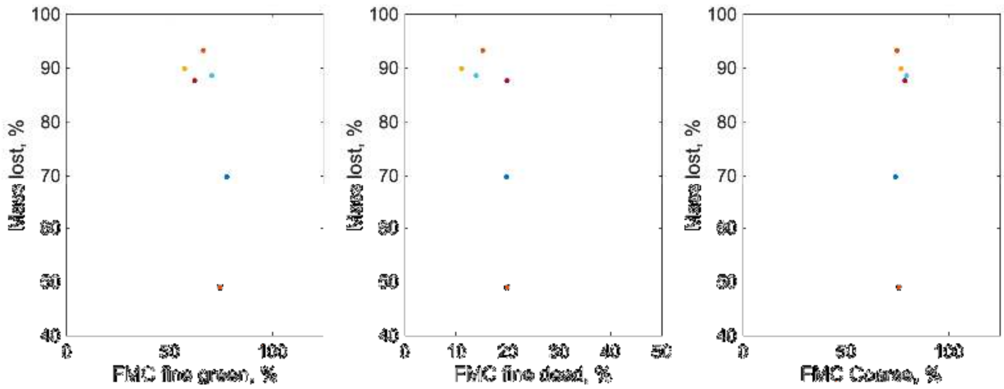

Figure 5.68 Vegetation mass lost as a function of the fine fuel moisture (FMC) for fine green (left), fine dead (right) and coarse (right).

5.5.7 Conclusions

Ten experiments have been conducted under a range of environmental and fuel conditions. The fieldwork experiments in this project have:

- Allowed the design, development, and implementation of a reliable data collection methodology for prescribed fires in heather moorland landscapes.
- Allowed qualitative assessment of the fire behaviour with flame heights ranging from 2 m to greater than 6 m, and fire depths from 1 m to more than 10 m.
- No discernible trends were observed between the environmental variables of RH, wind speed and temperature, or fuel moisture content and either the mass lost or flame spread rate in these experiments.
- The FMC values measured in the field for which fire spread was higher than the thresholds determined in the laboratory. This can be explained due to the influence of wind which will support the flame spread in the field but was absent in the laboratory experiments.

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6 WP3: Calibration Fire Weather Index (FWI) Codes to fire incidence data

6.1 Introduction

The empirical relationships used to calibrate the Canadian Fire Weather Index (CFWI) were largely determined from data collected in Canada. It is therefore important to formally assess how appropriate the relationships used in the CFWI are for predicting fire risk in Scotland. We have carried out a broad analysis of the relationships between actual fire occurrence in Scotland (and the rest of northern Europe) and the codes and indices modelled from the CFWI. These analyses were designed to identify the parameters in the relationships which exhibited the greatest sensitivity to changing geographical settings and vegetation types. However, due to their strong link with vegetation type, there was a particular focus on the empirical relationships used to calculate the fuel moisture codes.

6.2 Methodology

Datasets were obtained from the European Forest Fire Information System (EFFIS; https://effis.jrc.ec.europa.eu/), which holds the data for the predicted fire danger ratings – based on the CFWI - and the actual occurrence of fires within European countries.

The request period for the fire occurrence (as burnt areas) and the FWI layers extended from 01/07/2013 to 15/06/2019 and covered northern European countries. The datasets included:

1. Burnt areas (fire occurrence)
2. The EFFIS European Fuel map
3. Layers of daily Fire Weather Index (FWI) and the associated sub-indices

Datasets were processed and analysed both in a statistical and geospatial context to investigate relationships and patterns between FWI indices, fire incidence and area information. For incidence data, the dataset that was used was the MODIS satellite hotpsot information from EFFIS. MODIS identifies fires by the difference in temperature between the areas that are actively burning with respect to neighbouring areas, which allows the identification and mapping of active fires. The spatial resolution of the active fire detection pixel from MODIS is 1 km.

Fire area information was also provided by EFFIS MODIS data. Fire area information from MODIS is at 250m resolution. This product tends to capture fires which are larger than 30 hectares.
The fire incidence data was available for the following countries: Republic of Ireland (IE), Great Britain (England (ENG), Scotland (SCO), Wales (WLS)) and Northern Ireland (NIR), France (FR), Germany (DE), Denmark (DK), Norway (NO), Sweden (SE), Finland (FI) and Estonia (EE). Burnt areas in northern European countries were provided by EFFIS in shapefile (polygon) format. Data refers to fires captured from satellite imagery by the EFFIS system.

The shapefiles were processed within a geographical information system (QGIS 3.10.0) in order to remove duplicate entries. The data was further filtered to only include northern areas with similar bioclimatic conditions (Latitude of 46° in WGS 84). These analyses resulted in a final dataset of 571 unique fires/burnt area polygons that occurred on 226 unique calendar days (Figure 6.1). The fields reported for each burnt area included the following:

- PROVINCE: name of the province (NUTS3 administrative units)
- PLACE_NAME: name of the municipality (NUTS5 administrative units)
- COUNTRY: name of the nation in which the event took place
- AREA_HA: burnt area in hectares
- FIRE_DATE: first date recorded of active fire presence detection
- LASTUPDATE: date of the burnt area perimeter last detection and validation
- YEARSEASON: year in which the event took place

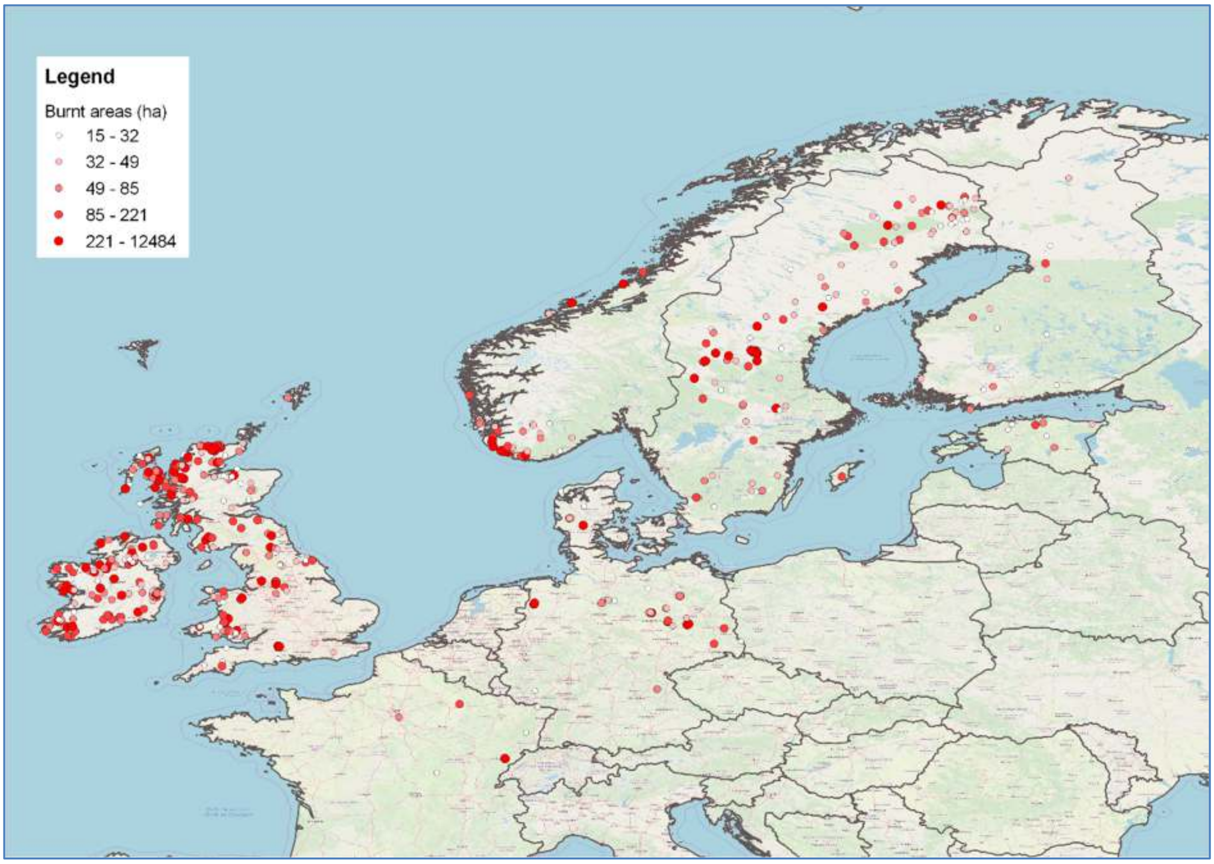


Figure 6.1. Geographic distribution of burnt areas (*n=571*) provided by European Forest Fire Information System (EFFIS) for the period 01/07/2013 - 15/06/2019.

6.3 The European Forest Fire Information System (EFFIS) European Fuel Map

The EFFIS European fuel map covers the European Economic Area countries area plus Turkey and is based on mapping of vegetation complexes that are then assigned to fuel type groups from fire behaviour models. The map has a 250mx250m grid resolution.

EFFIS European Fuel Map: https://effis.jrc.ec.europa.eu/applications/data-and-services
Reference for EFFIS European Fuel Map: European Forest Fire Information System (EFFIS) - European Fuel Map, 2017, based on JRC Contract Number 384347 on the "Development of a European Fuel Map", European Commission.

6.3.1 The European Forest Fire Information System (EFFIS) Fire Weather Index layers

A total of 2,176 layers in raster (multi-band Geotiff files) were downloaded from the EFFIS database that covered the investigated time period. Figure 6.2 shows the area of interest covered by the provided EFFIS raster layers. The following information from the Canadian Forest Fire Weather Index is stored as a separate band in each EFFIS layer:

- Band 1: Fire Weather Index (FWI)
- Band 2: Fine Fuel Moisture Code (FFMC)
- Band 3: Duff Moisture Code (DMC)
- Band 4: Drought Code (DC)
- Band 5: Initial Spread Index (ISI)
- Band 6: Built-up Index (BUI)

The FWI and other sub-indices are calculated using climatic forecasts from the European Centre for Medium-Range Weather Forecasts ECMWF) at 16km grid resolution (resolution improved to 8km resolution from 2019 onwards).

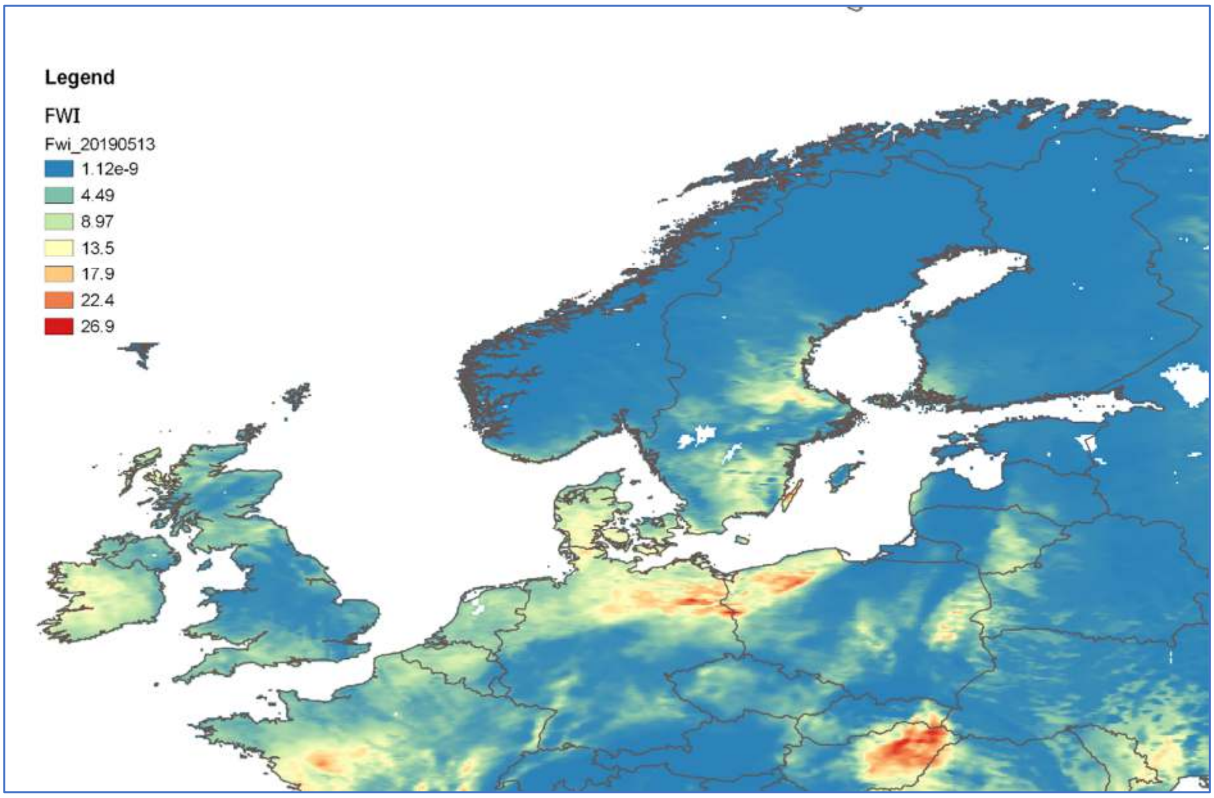


Figure 6.2. Map showing the area covered by the raster layers obtained from European Forest Fire Information System (EFFIS). The map shows the range of the predicted Fire weather index for May 13th 2019.

6.4 Dataset processing and analysis

The areas and proportions of fuel type groups were calculated for each individual fire polygon by spatially intersecting the burnt area and fuel map layers (Table 6.1). In addition, the FWI and sub-indices information were extracted from the EFFIS layers for each fire incident by selecting the EFFIS layer that corresponded to each particular fire date and then using random sampling within the burnt areas. The number of samples drawn was determined by the respective burnt area (1/3 of each area in ha). This approach was selected primarily because it was computationally efficient. In addition, for bigger fires that covered parts of more than one grid cell, it enabled the calculation of descriptive statistics (e.g. mean and median values) of FWI and sub-indices that helped to depict the spatial variability of the predicted EFFIS information.

Table 6.1. The dominant fuel type group involved in the largest proportion of fires in each country.

Countries	**No. fires**	**Area (ha)**		**Dominant fuel type (% of fires)**
		Min	**Max**	
IE	94	22	3,865	Peat bogs (93%)
NIR	20	22	666	Peat bogs (85%)
SCO	127	21	5,430	Shrublands (46%)
ENG	47	15	1,478	Shrublands (51%)
WLS	48	21	1,322	Pastures (71%)
FR	7	24	239	Pastures (57%)
DE	40	22	1,057	Transition (38%)
DK	8	28	331	Shrublands (88%)
NO	54	21	1,065	Pastures (43%)
SE	102	22	12,844	Forest (78%)
FI	15	23	90	Forest (60%)
EE	9	28	106	Peat bogs (56%)

Within Ireland (IE and NIR), most fires occurred in peat bogs, while in Scotland and England most fires occurred in shrublands. However, an additional 41% of all fires in Scotland occurred on peat bogs. This distinction between shrublands and peat bogs may be rather misleading as it is effectively based on the depth of the organic layer of the soil. A major fuel type above ground on peat bogs is also shrubs (mainly heather). In Scandinavia, forest fires dominated in Sweden and Finland, while most fires in Norway occurred in pastures. Although mean burnt area was similar for most countries in the dataset, there was a huge range of the size of the individual fires (Figure 6.3).

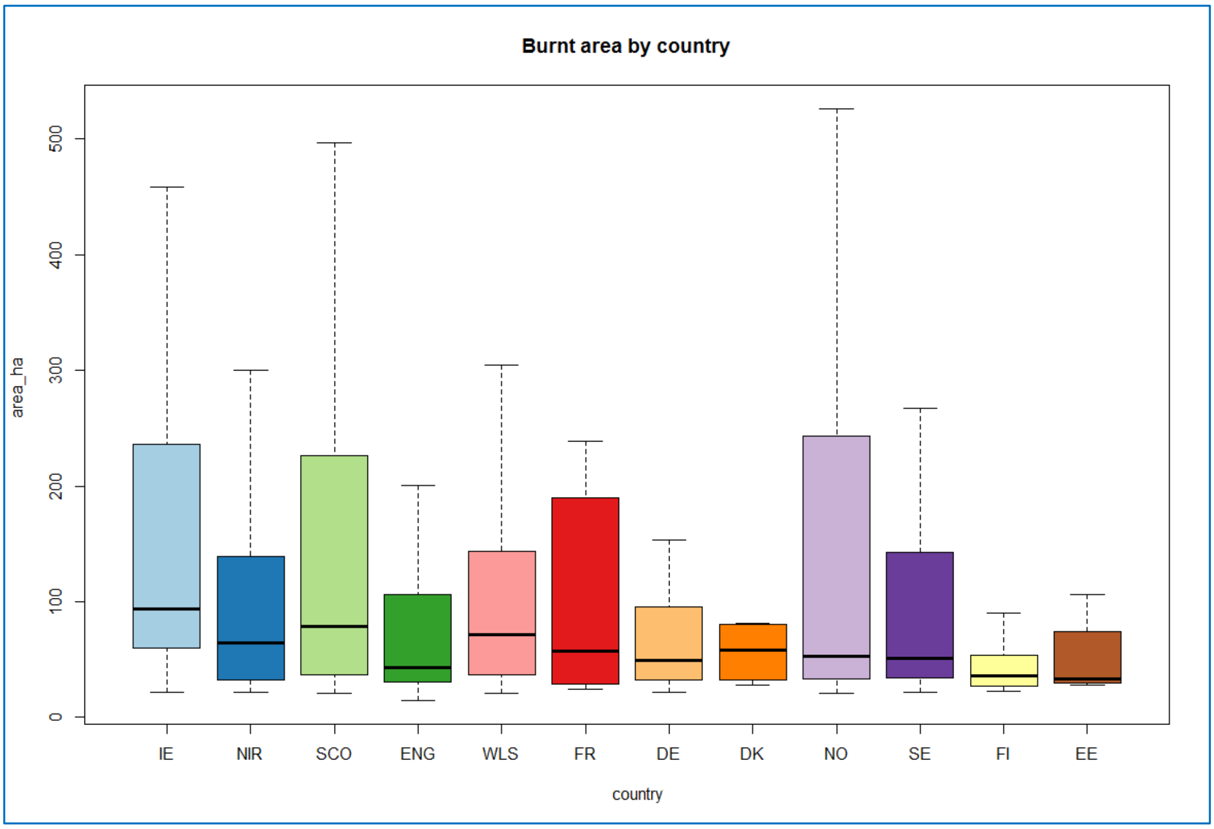


Figure 6.3. The median burnt area (ha) of fires in northern European countries during the period 01/07/2013 - 15/06/2019.

With regards to the seasonality of fire incidents, most fires in the British Isles and Norway occurred in late winter to early spring (February to April). There was a strong seasonal pattern of fire occurrence in Scotland and Ireland, with the great majority of fires occurring in April (Figure 6.4). By contrast, the recorded fire season for Sweden was from May to August, with most fires occurring in July.

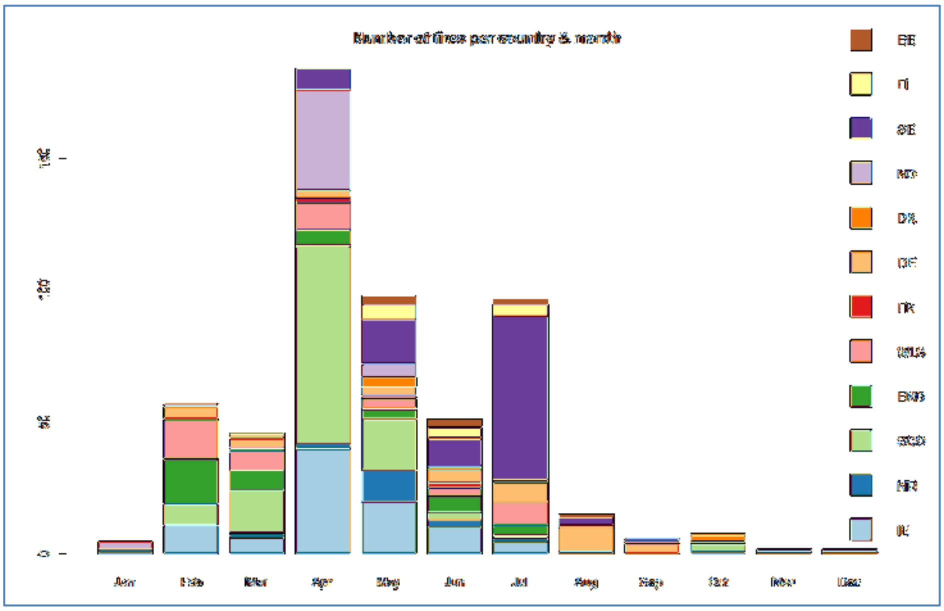


Figure 6.4. Distribution and timing of fires in northern European countries during the period 01/07/2013 - 15/06/2019.

Taking the group of countries with similar fuel characteristics together the dominance of shrub and peat fires becomes clearer (Figure 6.5). There was a strong contrast between the distribution of fires in England with both Ireland and Scotland with the peak of fire occurrence in February and March in England, whereas it was in April in Scotland and Ireland. Figure 6.5 also shows the dominant fuel types for the fires per month for the three countries, with peat bogs predominating in Ireland irrespective of the month.

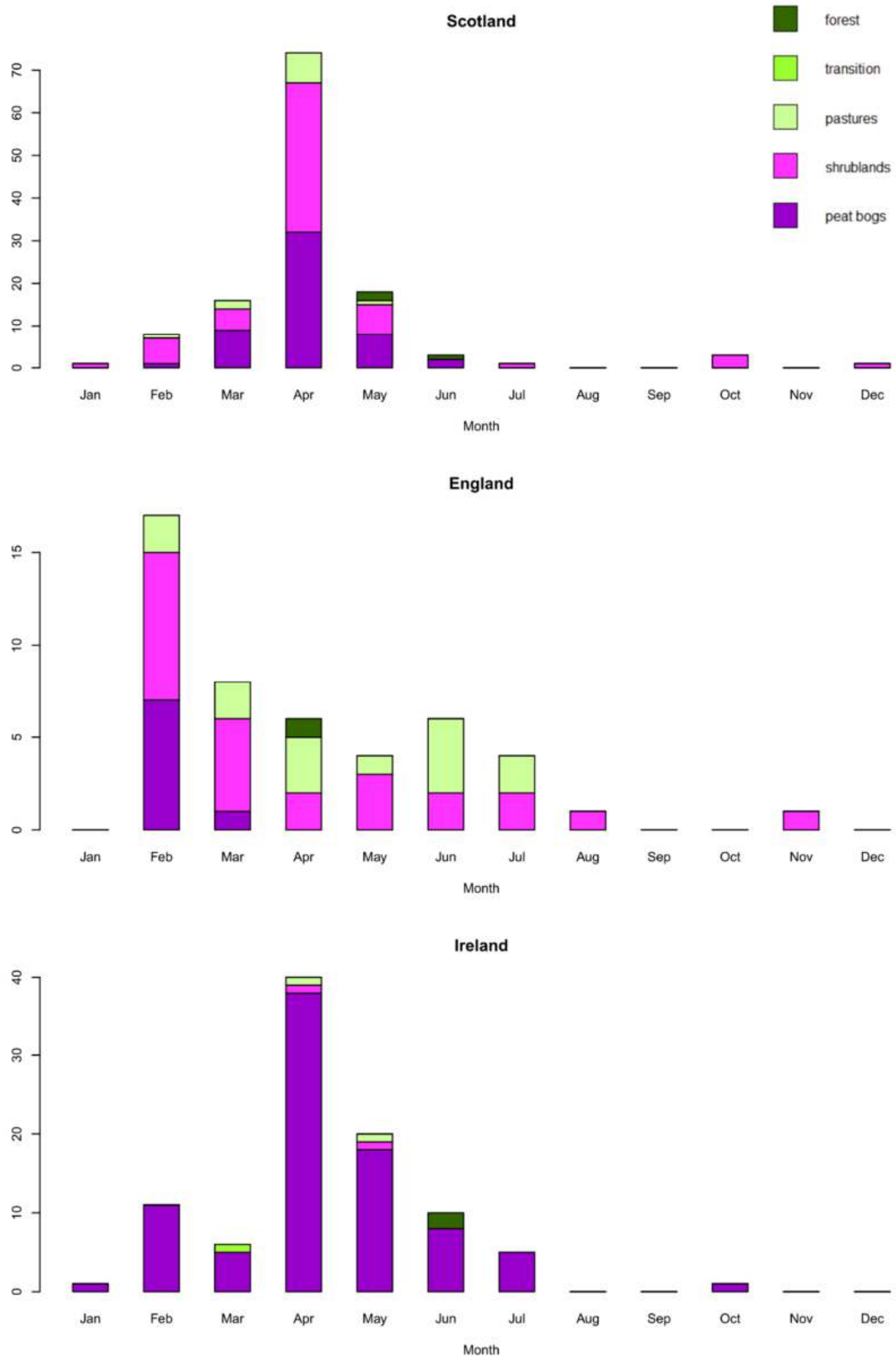


Figure 6.5. Number of fires per month and fuel type group for Ireland, Scotland and England.

6.5 Comparison of Fire Weather Index (FWI) and sub-indices

An analysis of the median FWI and sub-indices values for the recorded fire incidents, showed that all countries had similar median FFMC values ranging from around 82 in Scotland to 91 in Sweden (Figure 6.6). However, median values of the other moisture codes, ISI, BUI and FWI were notably lower in the GB countries (Scotland, England and Wales).

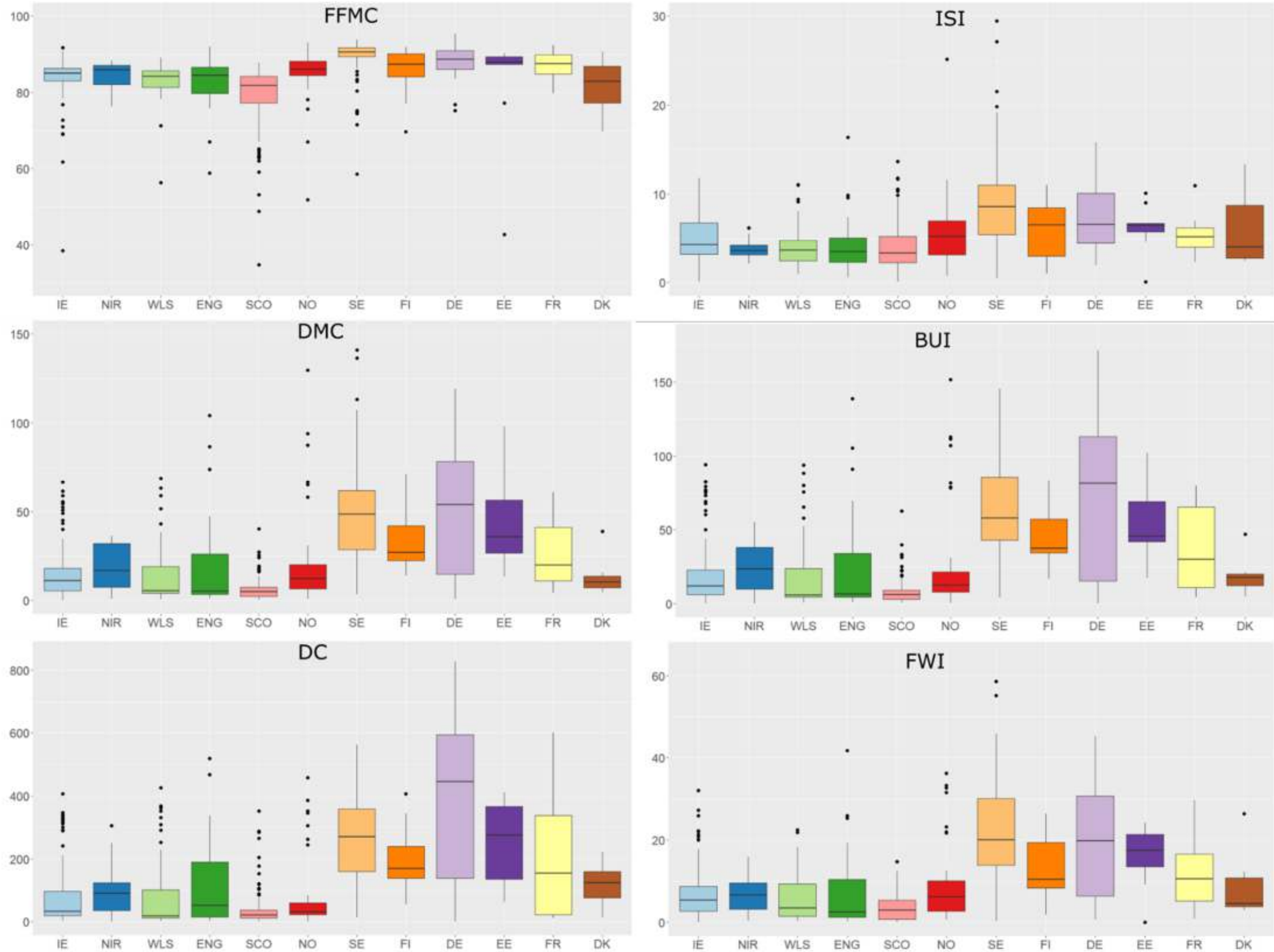


Figure 6.6. Boxplots of median Fire Weather Index (FWI) and sub-indices values for fires in northern European countries during the period 01/07/2013 - 15/06/2019.

6.6 Investigation of relationships between fires using cluster analysis

Ward's method of hierarchical cluster analysis of the 571 recorded fire incidents was used to investigate patterns within the fires and EFFIS combined dataset that could help explain the observed differences in fuel type, fire occurrence and area burnt. The variables used as input were - burnt area (in ha), proportions (% cover) of main fuel type groups (forest, peat bogs, shrublands, pastures, transition) within each fire polygon and median values of FWI and sub-indices. The analysis grouped the fires into three main clusters (Figure 6.7): cluster 1 (n=241 fires), cluster 2 (n=204 fires) and cluster 3 (n=126 fires). The former was strongly separated from 2 and 3.

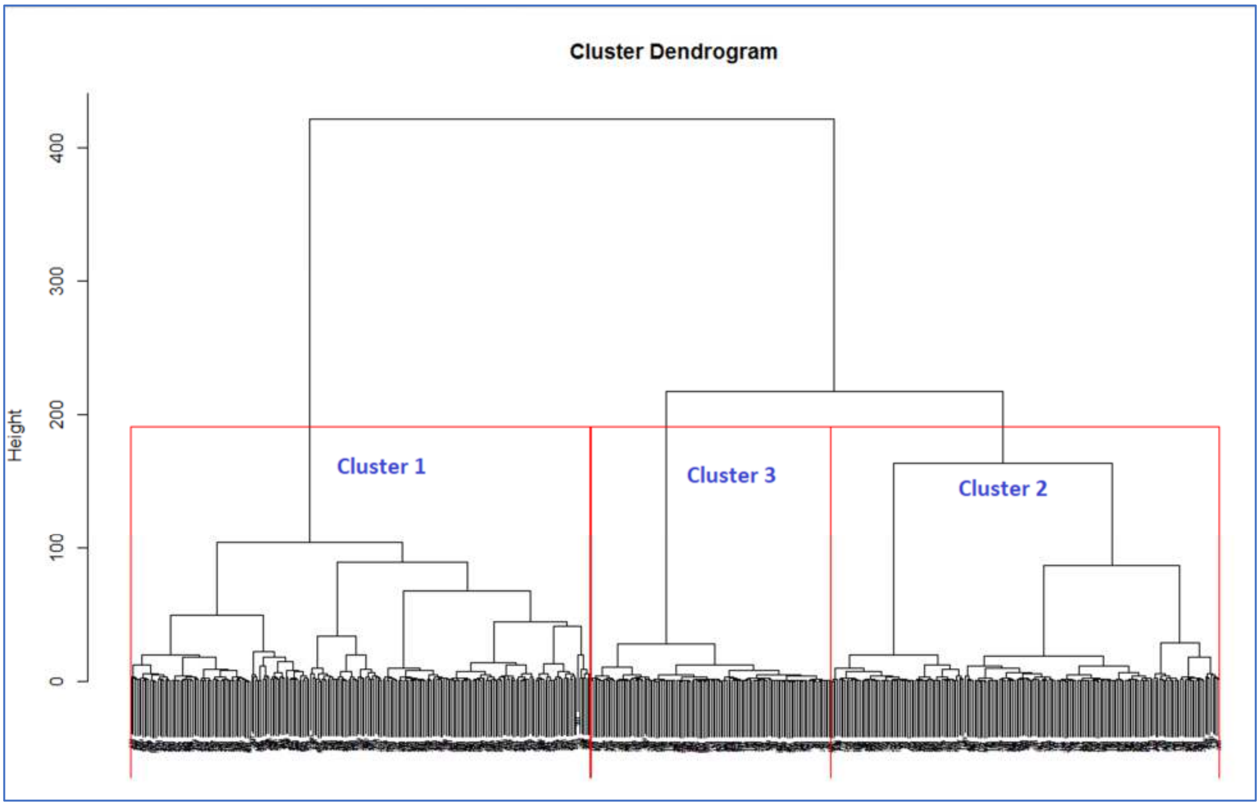
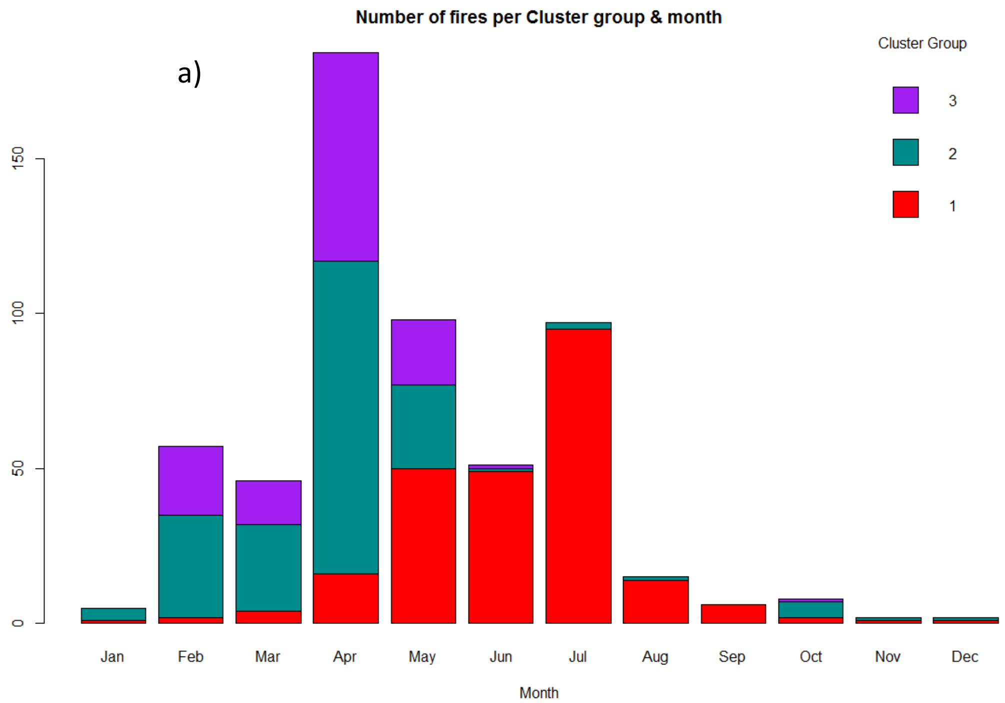


Figure 6.7. Dendrogram of 571 fires in northern European countries showing relatedness based on fire parameters and on the modelled Fire Weather Index (FWI) and sub-indices

The main results of the cluster analysis are that:

- The majority (around 55%) of fires within cluster 1 occurred in Sweden and Germany. Most of the fires within cluster 2 occurred in Scotland (39%), Norway (19%) and Wales (16%), while most fires within cluster 3 occurred in the Republic of Ireland (51%) and Scotland (32%).
- Almost all fires within clusters 2 and 3 occurred between February and May while almost all fires in cluster 1 occurred between May and September and showed country specific patterns (Figure 6.8a & b).

- Most fires in cluster 1, 2 and 3 occurred in areas covered by forests, shrublands and peat bogs, respectively (Figure 6.9).
- Fires in cluster 1 had higher median FFMC, DMC, DC, ISI, BUI and FWI values than clusters 2 and 3. The median values for clusters 2 and 3 were quite similar, for all FWI sub-indices (Figure 6.10).



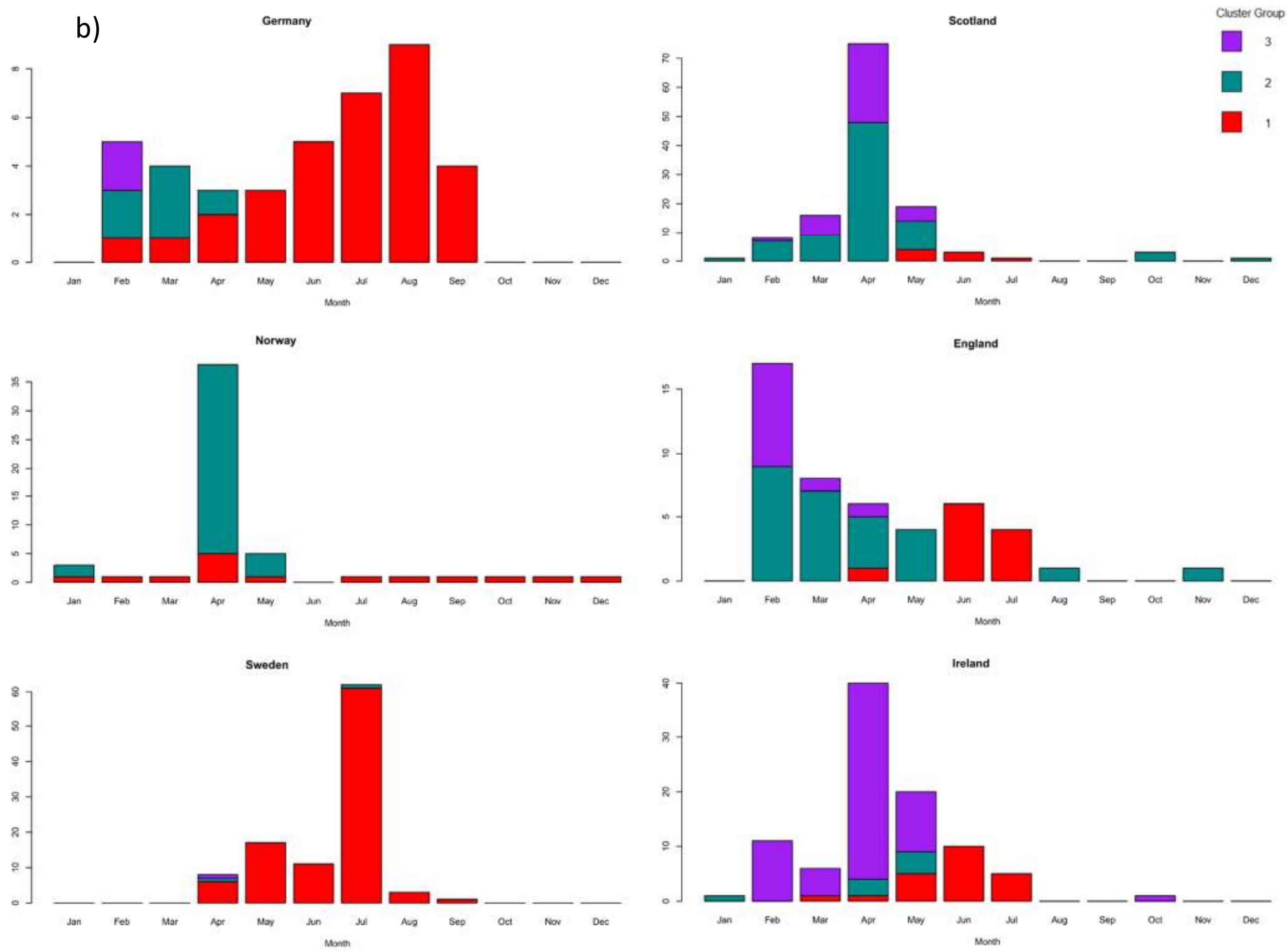


Figure 6.8. Distribution of 571 fires following cluster analysis into three main clusters, plotted by month for a) all countries and for b) Germany, Norway, Sweden, Scotland, England and Ireland.

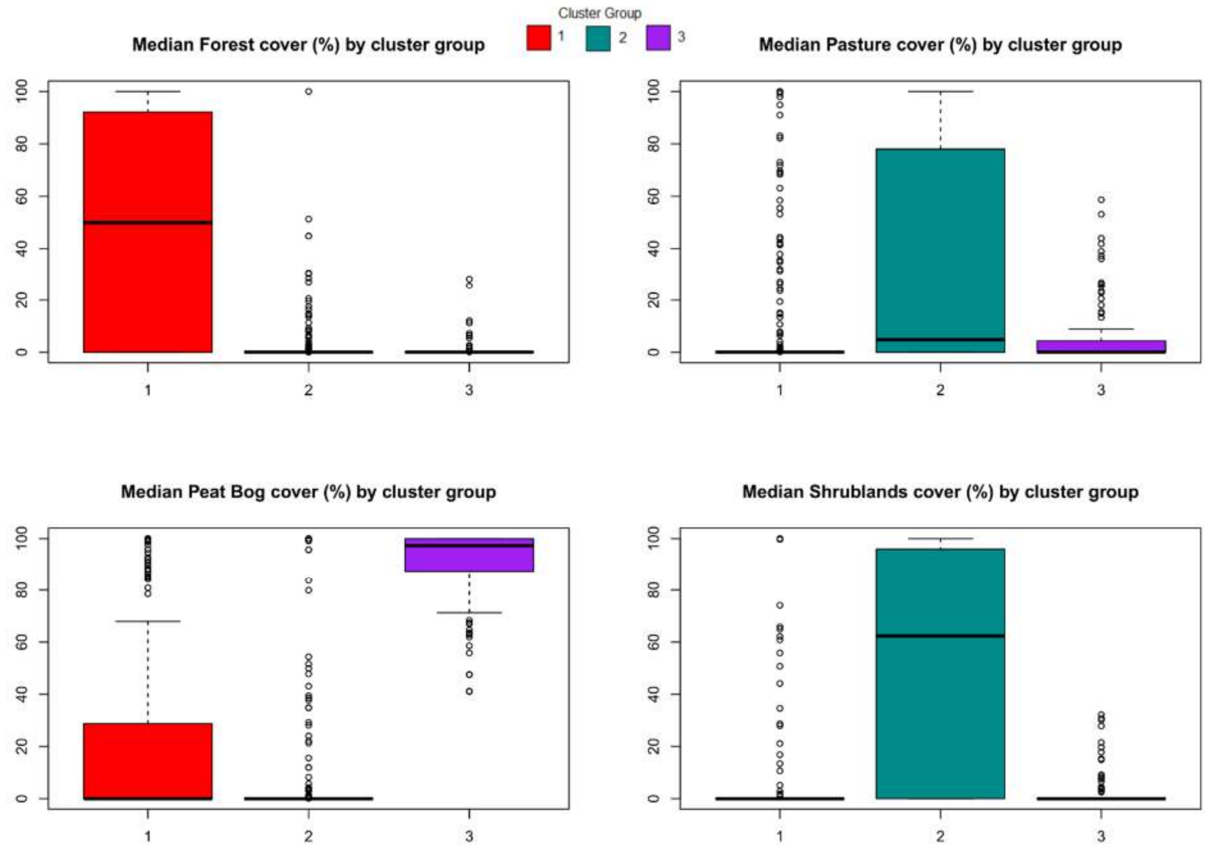


Figure 6.9. The relative proportions (%) of main fuel type burnt within each cluster group.

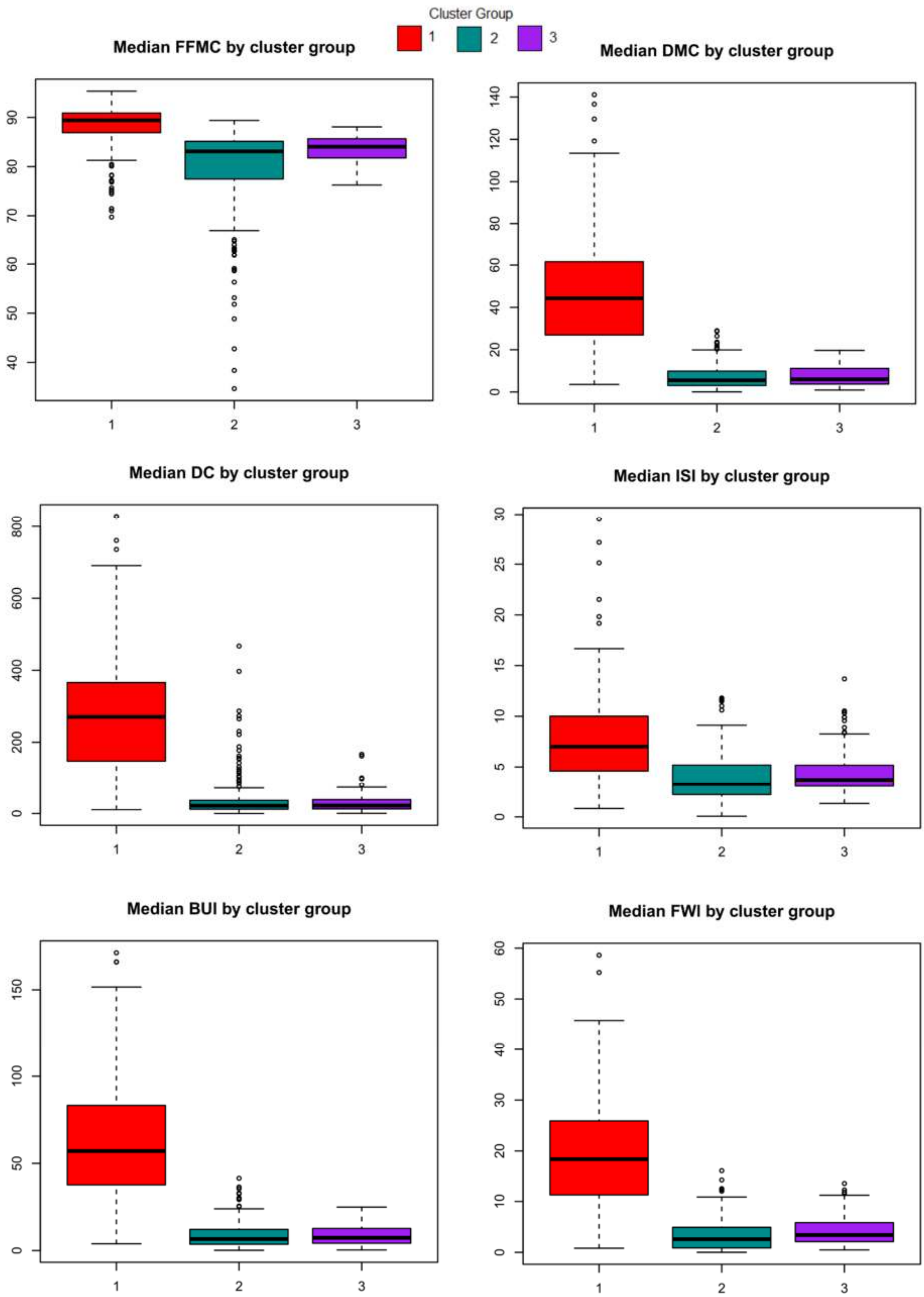


Figure 6.10. The median Fire Weather Index (FWI) and sub-indices values within each of the cluster groups.

The main conclusions from the cluster analysis of the 571 fires are the following:

- Fires in cluster 1 represent mainly fires in the forest fuel type that occur in late spring and summer months, which were mostly found in Sweden and Germany. Values of FWI sub-indices indicate that the Canadian FWI works well for these fires, which is probably due to the dominant fuel type (forest/trees) and the continental climatic conditions resembling the conditions used for initial model development.
- Fires in clusters 2 and 3 represent fires in shrublands (moorlands and heathlands) (cluster 2) and peat bogs (cluster 3) that occur in late winter and spring. These fires were mostly found in locations within the British Isles and Norway that have oceanic temperate climatic conditions. Median FFMC values for fires within clusters 2 and 3 (83 and 84, respectively) were similar to the median FFMC value for cluster 1 fires (89). However, all other values of the FWI sub-indices were much lower than for the cluster 1 fires, including the final FWI assessment. Therefore, it seems that the Canadian FWI fails to accurately predict the occurrence of fires in clusters 2 and 3 based on the final FWI assessment, despite satisfactory FFMC predictions.

6.7 Model component importance

For the purpose of modifying the FWI system for Scottish conditions, a variety of methods were used to train and test the system. One statistical approach was to use regression decision trees to build predictive models (non-linear regression by a form of data-partition and a measure of variable importance).

The training dataset included the same variables as the ones used in the cluster analysis, plus information on month, year, country and dominant fuel type group (decision trees can handle categorical variables). BUI and ISI values were omitted, since they are not independent variables. The algorithm built a model that predicted FWI values from the training dataset. For this kind of analysis, it would be better to use the primary climatic information to calculate the sub-indices (FFMC, DMC, DC) and not the indices themselves, but that data was not within the scope of this project. Also for this exercise we were not interested in predicting FWI for the fire incidents (because we already have a model that does that) but to use the capabilities of the algorithm for data partition and variable importance calculation.

FFMC and DMC were by far the most important variables for FWI prediction (Figure 6.11). This supports the suggestion that FFMC is a good indicator at least for fire initiation.

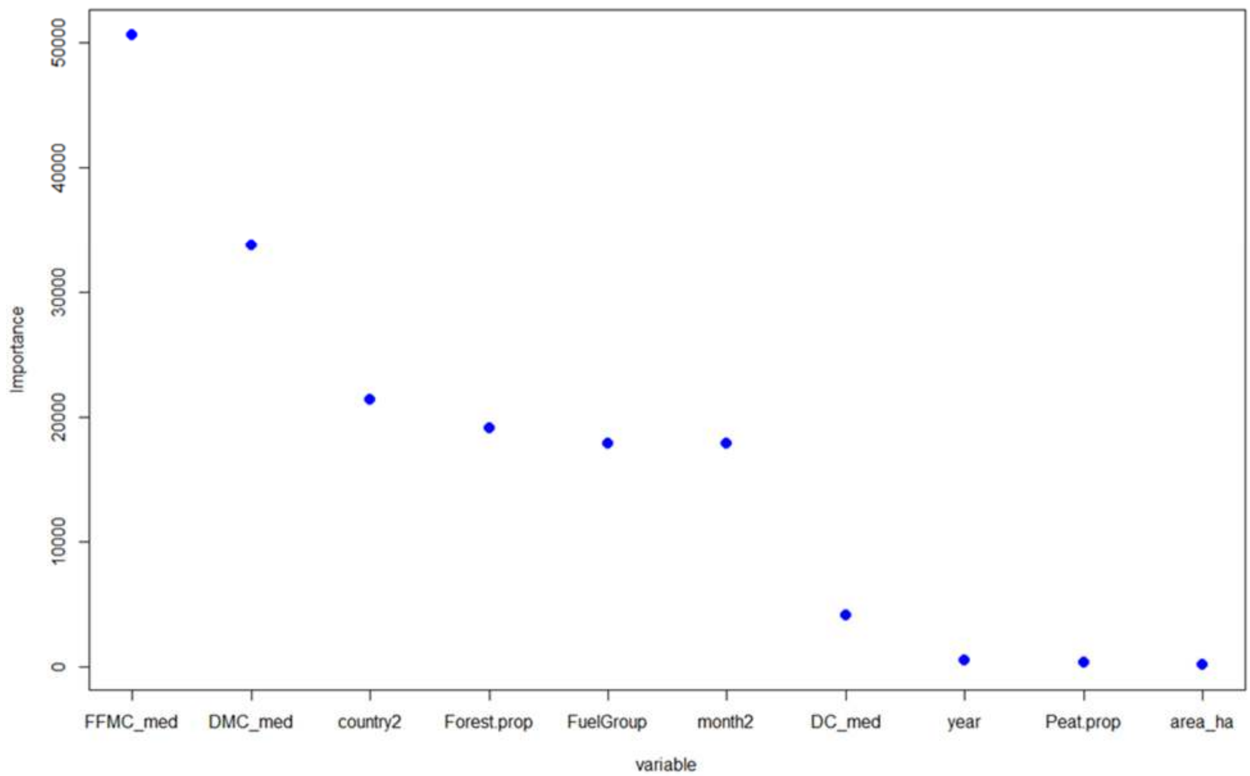


Figure 6.11. Relative importance of the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC) and a range of variables in predicting fire occurrence.

6.8 Fires in Scotland during the period 01/07/2013 - 15/06/2019

Focusing on Scotland, the majority of the cluster 3 fires (n=40) occurred in the north-west, cluster 2 fires (n=79) occurred mainly in the north, north-east and south-west while almost all cluster 1 fires (n=8) occurred in the north-east (Figure 6.12). All fires within cluster 1 occurred between May to July, and in three of them the dominant fuel type cover was conifer forest. The median values of FWI sub-indices (with the exception of ISI) were greater for the fires within cluster 1 than in clusters 2 and 3 (Table 6.2). In addition, 81 out of 127 fires recorded in Scotland had FFMC and ISI values greater than 80 and 2, respectively. These were thresholds identified in the original FireBeaters project (Legg et al., 2007).

Table 6.2. Distribution of median values of Fire Weather Index (FWI) and respective sub-indices in cluster groups within 127 fire incidents in Scotland during the period 01/07/2013 - 15/06/2019.

Cluster	FFMC	DMC	DC	ISI	BUI	FWI
1	85.0	21.8	120.2	3.9	32.1	9.8
2	80.5	4.5	21.6	2.8	6.2	2.1
3	83.0	4.2	17.4	4.1	5.1	3.8

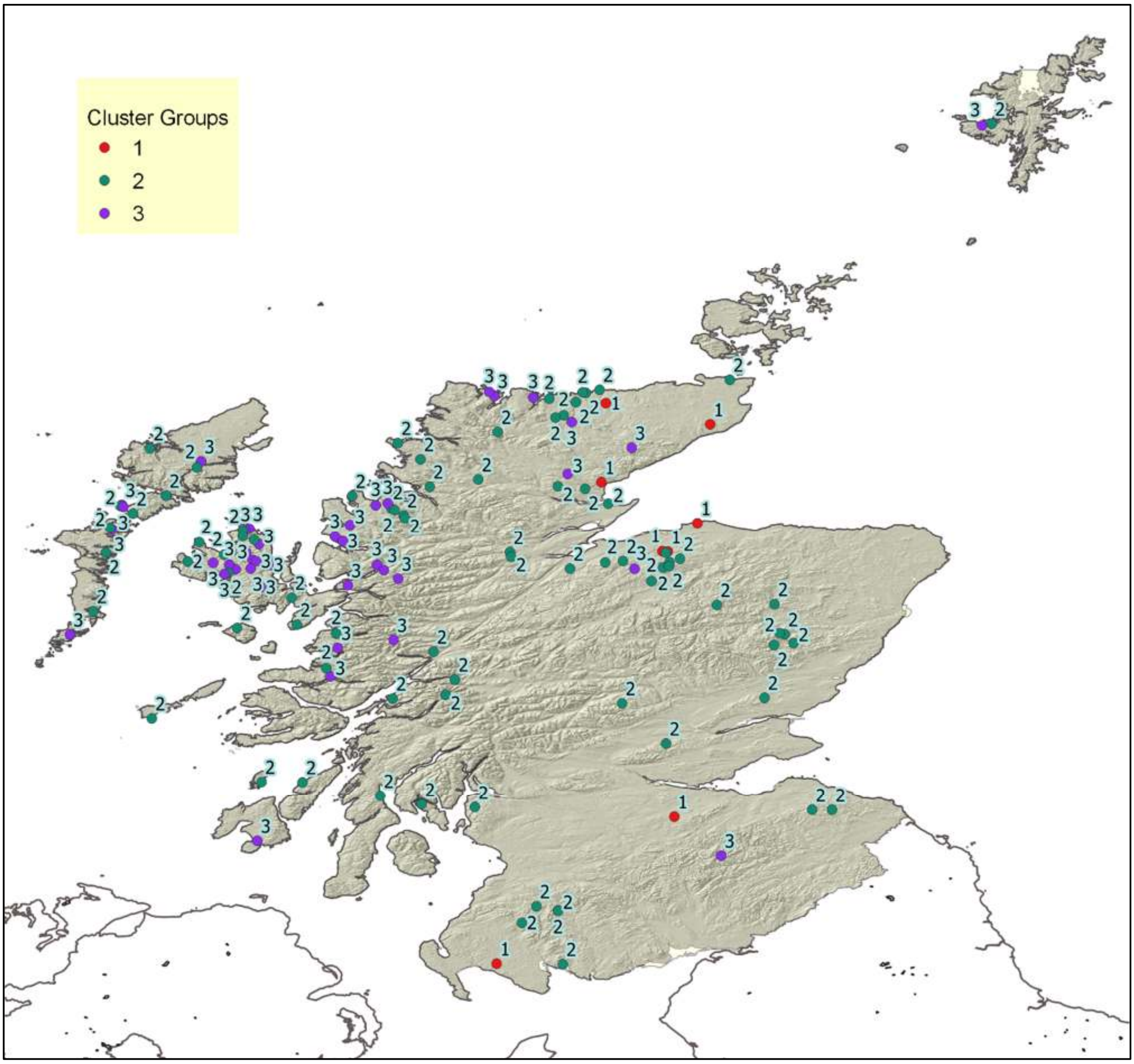


Figure 6.12. Locations of 127 recorded fire incidents Scotland grouped into three clusters based on fire parameters.

6.9 Further analyses of European Forest Fire Information System (EFFIS) data

Fire weather index and sub-indices threshold values. The map in Figure 6.13 shows the number of days in 2019 where predicted FFMC by EFFIS was greater than 80 in Scotland along with the locations of the fires recorded for the same year. Similar maps can be produced for other indices and thresholds and other years, also a mean value of days can be calculated for the 2013-2018 period (grid resolution changed in 2019). This indicates that there were relatively few days where FFMC > 80 but it also showed that fires are still occurring.

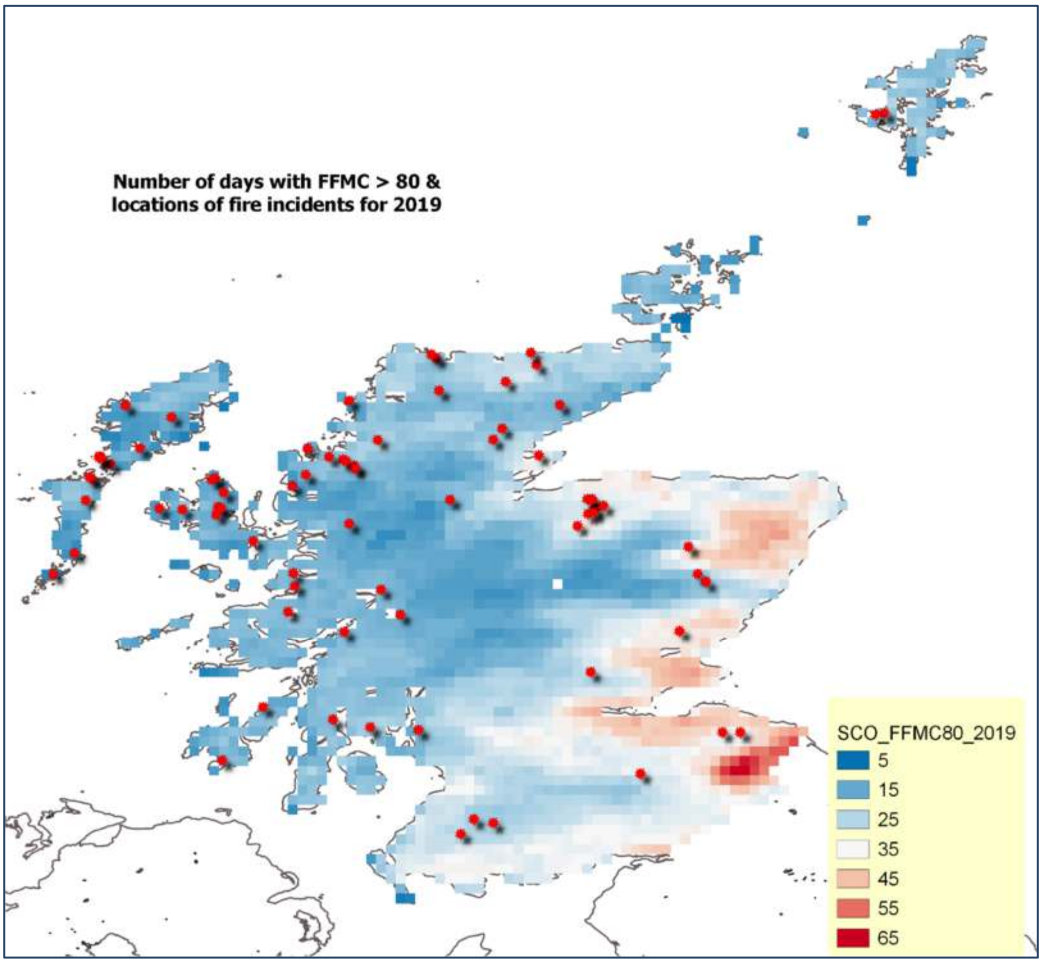


Figure 6.13. The occurrence of fires in Scotland in 2019 in relation to the days where Fine Fuel Moisture Code (FFMC) was above a value of 80.

6.10 Analysis of Fire Weather Index sub-indices

The CFWIS structure starts with the three soil moisture indices, FFMC, DMC and DC, which then feed into three fire behaviour indices, starting with ISI and BUI, which then ultimately feed into the FWI. This following discussion follows the structure using data provided by EFFIS. The EFFIS fire danger class boundaries sourced from EFFIS on 29th June 2021 are used for comparative purposes (Shown in Table 6.3; https://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast).

Table 6.3. The Fire Weather Index (FWI) sub-indices fire danger classes used by the European Forest Fire Information System

	1	2	3	4	5	6
	VERY LOW	**LOW**	**MOD**	**HIGH**	**VERY HIGH**	**EXTREME**
	Green	Yellow	Orange	Red	Brown	Black
FWI	< 5.2	5.2 - 11.2	11.2 - 21.3	21.3 - 38.0	38.0 - 50.0	>50
FFMC	< 82.7	82.7 - 86.1	86.1 - 89.2	89.2 - 93	>= 93	
DMC	< 15.7	15.7 - 27.9	27.9 - 53.1	53.1 - 140.7	>= 140.7	
DC	< 256.1	256.1 - 334.1	334.1 - 450.6	450.6 - 749.4	>= 749.4	
ISI	< 3.2	3.2 - 5	5 - 7.5	7.5 - 13.4	>= 13.4	
BUI	< 24.2	24.2 - 40.7	40.7 - 73.3	73.3 - 178.1	>= 178.1	

6.10.1 The Fine Fuel Moisture Code (FFMC) (top 1-2cm of litter layer)

Previous work (Legg et al, 2007, 2008; Davies & Legg, 2016) has indicated that greater accuracy on ignition potential and fire behaviour for heather moorland fuels, can be gained from FFMC and ISI rather than the final FWI.

The majority of wildfires in this dataset of Scotland, UK and Northern Europe occur at FFMC values below 86 in the late winter / spring period and at 86 and above in the late spring/summer period. In the UK, May is a transition month (Figure 6.14). This means that the majority of large wildfires in Northern Europe are occurring in the EFFIS FFMC based fire danger classes (Table 6.3) of “very low” or “low”. For the wildfires that occur in the summer, the majority of wildfires are occurring in the “moderate” FFMC fire danger class. Fires in Northern Europe are igniting at lower FFMC values than the average for Europe.

There is a seasonal influence on the relationship between fire occurrence and FFMC. The FFMC that fires occur at progressively rises through the late winter – spring – summer seasons, especially from March to July. A relationship was established between colder temperatures and lower fuel moisture in heather shrub fuels (Legg et al 2007, Davies and Legg, 2011). It is likely that the FFMC model is not reflecting the drying conditions found in late winter – early spring. The FFMC model is designed so that the code value always rises as the underlying inputs rise. The fact that the opposite is occurring in the late winter – spring is creating a structural “false negative pattern”.

A reversal of this situation could occur in early summer during the significant seasonal period of vegetation growth. Often this period is called the “green-up” and in the UK this usually occurs in the month of June. The “green-up” period is likely to change with latitude and climate, so is likely to be later in northern Scotland compared to southern England. This seasonal pattern related to latitude and climate is reflected in other countries in northern Europe (Figure 6.8). In later summer, a key change is when grasses start to cure (die-back). Fire spread in grass, often a component in heather moorland, is known to only start when >50% of the grass is cured.

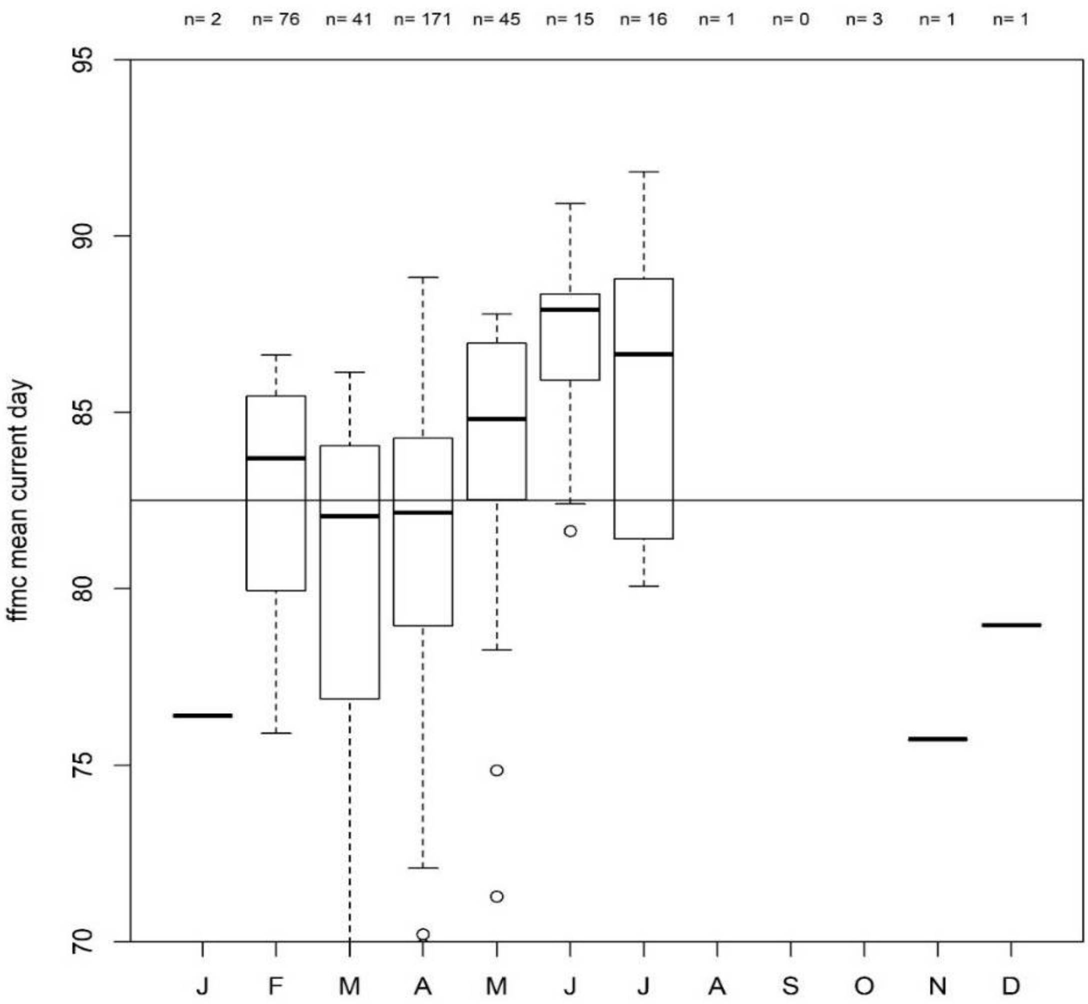


Figure 6.14 Boxplot of Fine Fuel Moisture Code (FFMC) values of wildfire incidences by month in the UK

It is possible to run the FFMC algorithm in reverse to generate the FMC values for the fine fuels in the recorded UK fires. This allows a comparison with FMC data generated during the present project. The results from the reversal of the FFMC model showed a dead fine fuel moisture of around 20% for fires in the UK, with slightly higher fuel moisture values in the spring compared to the summer (Figure 6.15). However as noted in the Firebeaters Report (Legg et al, 2007) there is a fuel moisture / FFMC reversal effect in the winter/spring months.

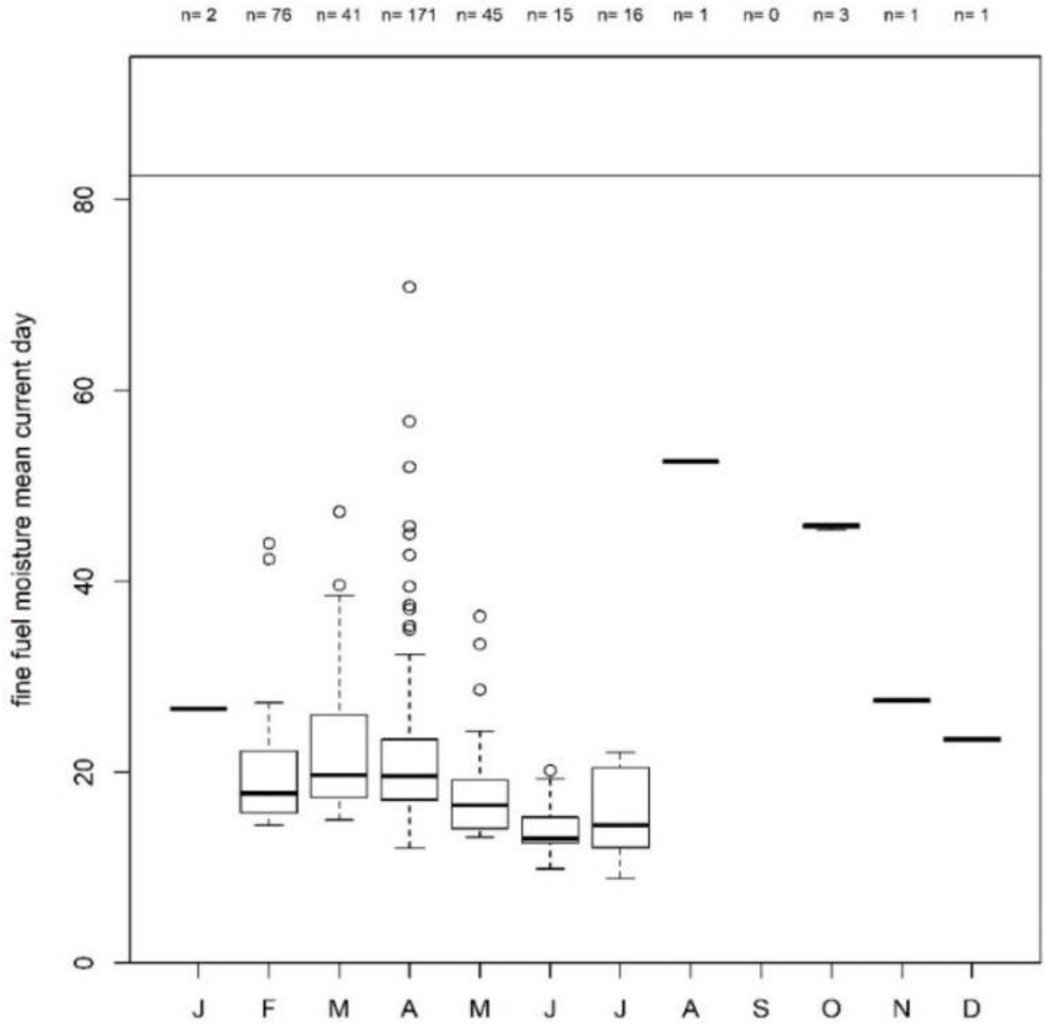


Figure 6.15 UK Fine fuel moisture content of fires per month derived from Fine Fuel Moisture Code (FFMC) data.

The value of 20% FMC for the fine fuel corresponds to a similar value measured for the fine dead suspended fraction in the field experiments and lab test in the present project.

6.10.2 The Duff Moisture Code (DMC) - (top 10cm of organic layer)

The duff moisture code drives the FWI via the Build-up index (BUI). The DMC reflects soil fuel moisture at 5 – 10cm in depth and has a time-lag of 15 days. The threshold for this fuel layer to support fire intensity is around DMC 20. In terms of EFFIS the relevant DMC fire danger class would be "low" with a DMC range of 15.7 - 27.9 (Table 6.3).

In Northern Europe, the majority of fires and area burnt occur at DMC values of less than 28 (Figure 6.16), when the risk would be considered "very low" and "low" in EFFIS DMC fire danger classes (Table 6.3). The DMC is a moderately deep soil moisture index and it is unlikely to rise during autumn/winter/spring due to greater seasonal precipitation and will usually only start to rise with drier summer conditions.

The CFWIS was, as previously noted, created with the Canadian summer fire regime and autumn - spring snow-cover in mind. Many of the fires included in the European (UK) datasets will share fuel types and conditions at similar latitudes to those in Canada. However, the climate is more oceanic with significant warming influence from the Gulf Stream and there is therefore much less snow cover in autumn and spring. It is therefore hardly surprising that there appears to be little relationship between DMC and the area burned in Northern Europe, where spring fires predominate. It should also be noted that EFFIS MODIS generally does not identify fires of less than 30 hectares, the lower end of the scale of the areas burned.

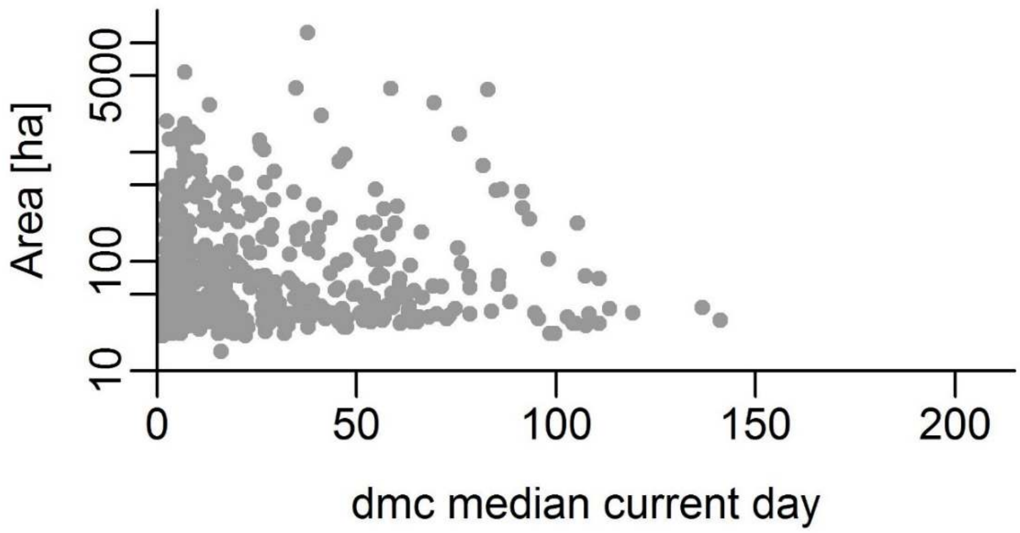


Figure 6.16. The relationship between area burnt and duff moisture code values for fires in North Europe during the period 01/07/2013 - 15/06/2019.

In Northern Europe, the fires grouped into clusters 2 and 3 (i.e. moorland, pasture and bog fires) occur primarily in the winter / spring period (Figure 6.8 and Figure 6.9). The seasonal effect also is clear in Figure 6.17 below, where median DMC values on fire days is plotted by number of fires and per month. The highest number of fires occur in the late winter – spring period, when DMC values are low and fewer fires occur in the summer when DMC values are higher. Increasing values of the duff drought code may relate to fires in Northern Europe but only during the summer months (i.e. cluster 1 fires).

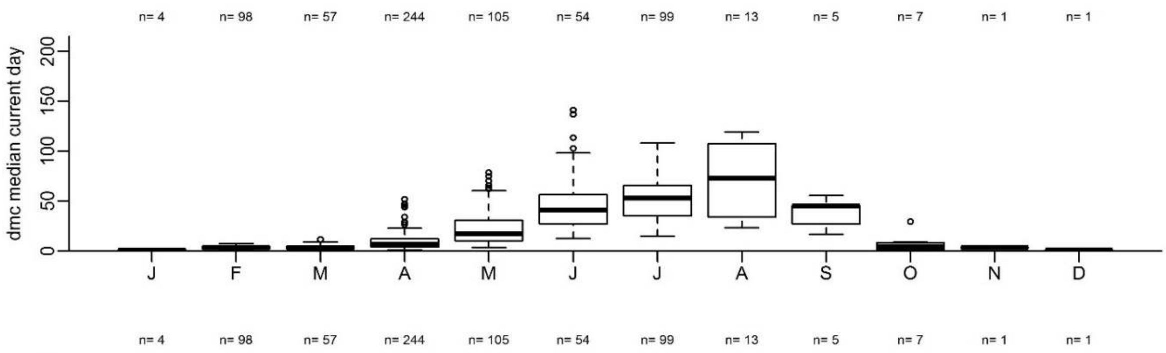


Figure 6.17. Numbers of fires per month in Northern Europe and duff moisture code (DMC) fire day values.

6.10.3 The Drought Code (DC)

The pattern observed for fires occurring when DMC was below threshold values was even more evident when DC is considered. Most fires in northern Europe occurred when DC values are lower than the threshold of 500 set for smouldering in Canada. The majority of fires and area burned occurred at DC values of less than 450 (Figure 6.18), with a significant number occurring when DC was less than 100.

In terms of the EFFIS fire danger classes for DC, with DC values below 450 representing the “very low”, “low” and “moderate” fire danger classes.

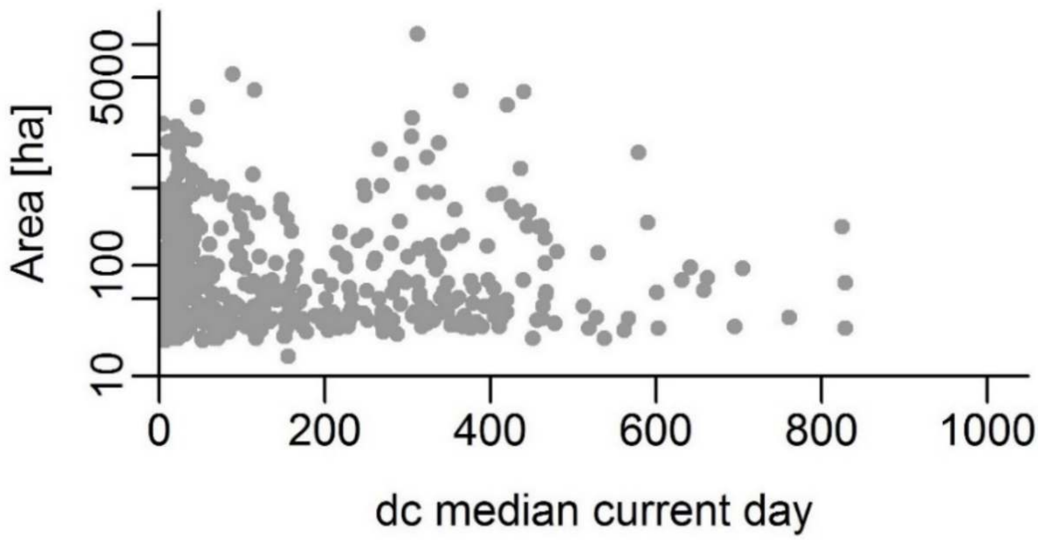


Figure 6.18. The relationship between area burnt and drought code (DC) values for fires in North Europe during the period 01/07/2013 - 15/06/2019.

With a time-lag of 53 days the drought code normally contributes to fire behaviour towards the end of a summer drought period. This is reflected in the data, with higher DC values associated with fires rising above 400 through June to September (Figure 6.19).

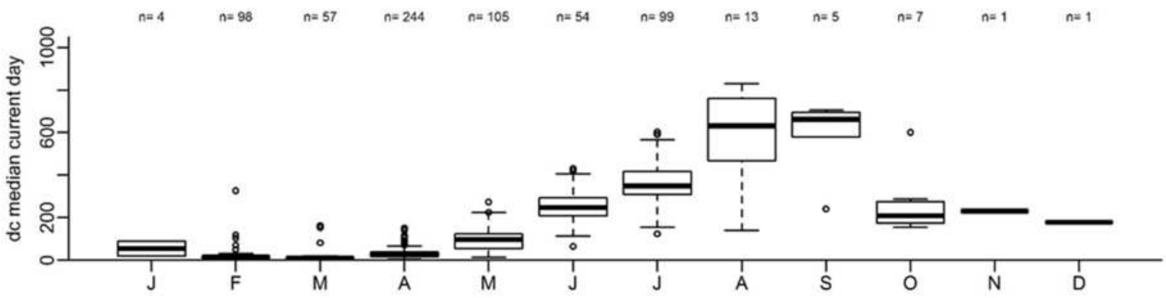


Figure 6.19 Numbers of fires per month in Northern Europe and drought code fire day values.

6.10.4 Initial Spread Index and the Build-up Index

The three moisture codes FFMC, DMC and DC to feed into three fire behaviour indices: the Initial spread index (ISI), the Build-up index (BUI) and ultimately the Fire Weather Index (FWI) (see Figure 2.1).

The ISI is derived from the FFMC plus an additional wind factor and is considered to give an indication of fire spread potential i.e. area burned in a fire. For the UK fire data, no relationships were found for increasing ISI values with the area burned in fires (Figure 6.20). The majority of fires burned at ISI values lower than 5. Note - The fire areas input to this graph are from EFFIS MODIS and only include fires greater than 30 hectares.

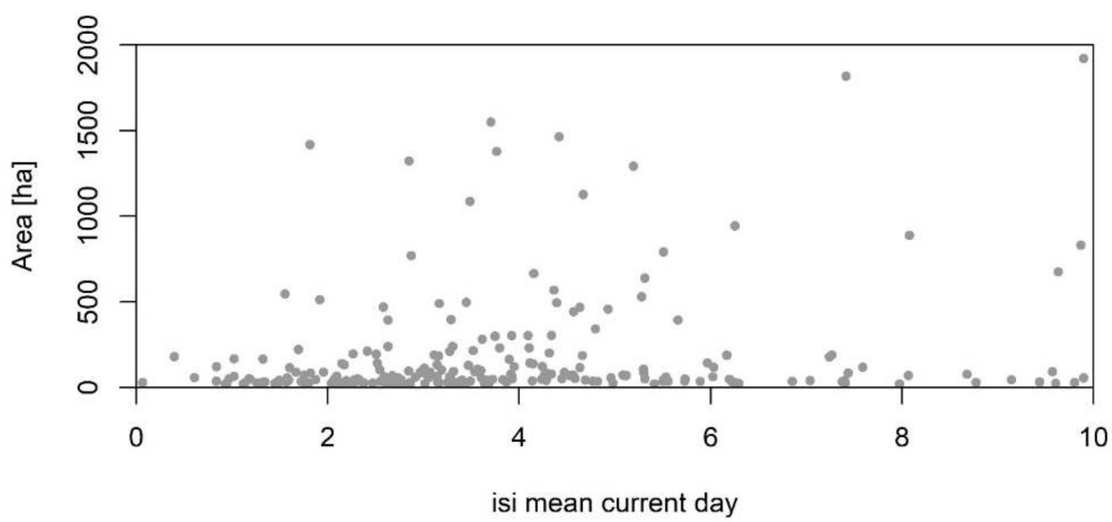


Figure 6.20 The relationship between area burnt and initial spread Index (ISI) values for fires in the UK during the period 01/07/2013 - 15/06/2019.

When FFMC and ISI are considered together a clearer pattern develops of fires occurring when FFMC is above 75 and ISI is above 2. There is a clear increase in the number of wildfires occurring when FFMC values are greater than 80. Also a high proportion of fires occur at ISI values less than 5 (Figure 6.21). These are similar results as found in the earlier Scottish Government funded FireBeaters Project (Legg & Davies, 2009) and the subsequent further analysis of FWI sub-indices in relation to wildfires in Scotland (Davies & Legg, 2016)

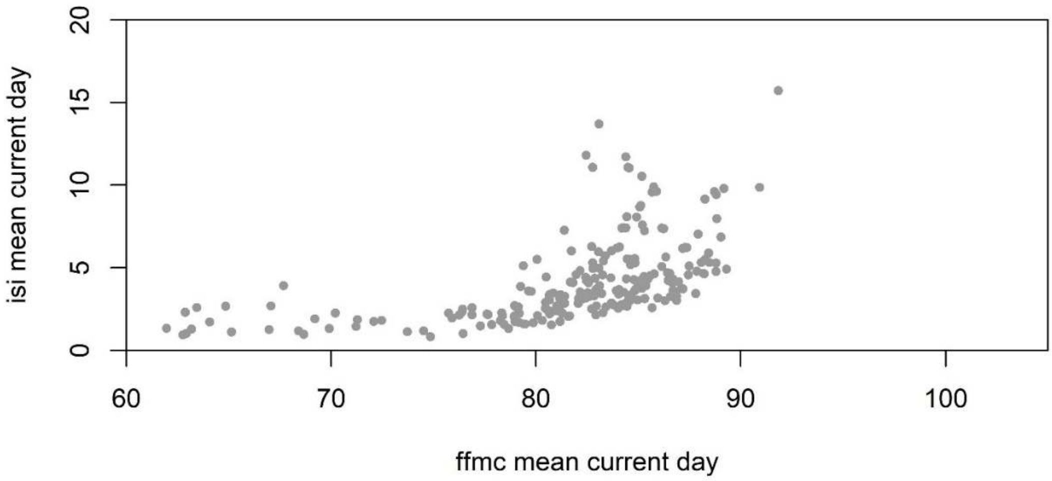


Figure 6.21 Relationship between Fine Fuel Moisture code (FFMC) and Initial spread Index (ISI) for fires in the UK during the period 01/07/2013 - 15/06/2019.

When FFMC is plotted against fire area and with fires with ISI values higher than 2 highlighted, relationships between the three variables become clearer (Figure 6.22). The vast majority of fires are occurring at FFMC values between 80 and 90 and at ISI values greater than 2. Combined with Figure 6.21 above support the view that the vast majority of large wildfires are occurring at ISI values of between 2 and 5. These ISI values are “very low” and “low” ISI fire danger classes in EFFIS (Table 6.3).

In the original development of the CFWIS in Canada, ISI was calculated empirically for forested environments, which on average have lower windspeeds in comparison to open ground (Van Wagner, 1987). The effect of this would be to lower the average ISI for fires on open ground for equivalent rates of spread and, conversely, lower open wind speeds would generate higher rates of spread on open ground. A better fit between rate of spread and direct wind speed observations for heather fires, than those predicted by the CFWIS ISI model, can be found in the FireBeaters project (Legg & Davies, 2009).

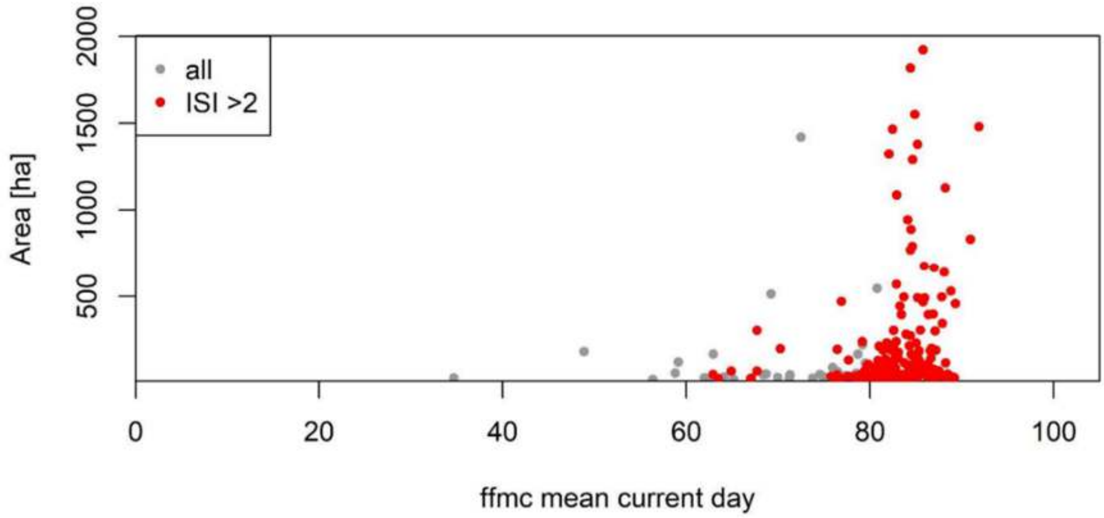


Figure 6.22. Relationship between fire area and Fine Fuel Moisture code (FFMC) for fires with an Initial Spread Index (ISI) greater than 2 for fires in the UK during the period 01/07/2013 - 15/06/2019.

The next input to the FWI is the Build-up index (BUI), which represents fuel consumption. Both the duff moisture code and the drought code feed into the BUI. Fuel consumption is a significant part of the fire intensity calculation. BUI values greater than 40 are normally associated with more significant fire behaviour. The majority of fires in northern Europe are occurring at BUI values lower than 40 (Figure 6.22 and Figure 6.23) which, in terms of the EFFIS BUI fire danger classes, means that these fires would be in the "very low" and "low" classes (Table 6.3).

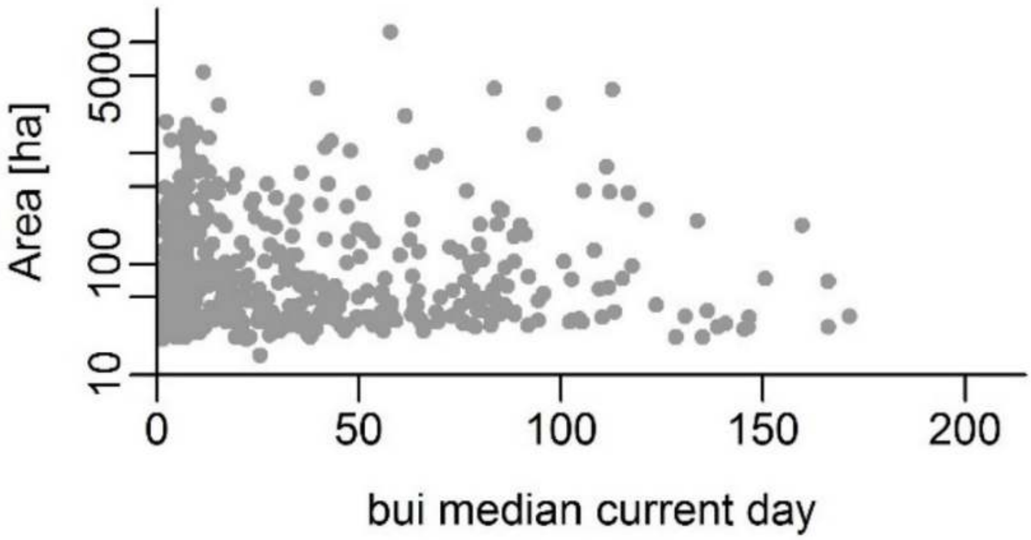


Figure 6.23 The relationship between area burnt and the Build-up Index (BUI) values for fires in North Europe during the period 01/07/2013 - 15/06/2019.

The seasonal fire pattern plotted against BUI is very similar to DMC (Figure 6.24). The BUI does not capture late winter / spring fires but does identify summer fires when conditions are more similar to the conditions that the CFWIS was developed for.

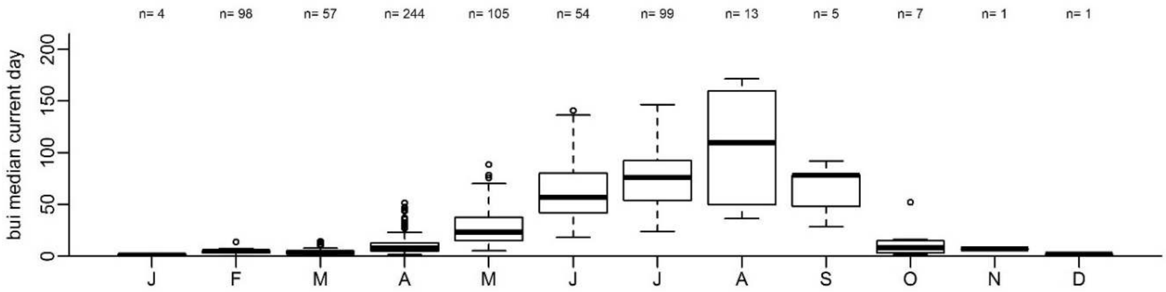


Figure 6.24. Numbers of fires per month in Northern Europe and Build-up Index (BUI) fire day values during the period 01/07/2013 - 15/06/2019.

The seasonal relationship is also reflected in differences between countries, and the fuel types common in those countries, with BUI having little influence on the fires in countries such as Great Britain and the island of Ireland that predominantly have cluster 2 and 3 fuel types (Figure 6.25).

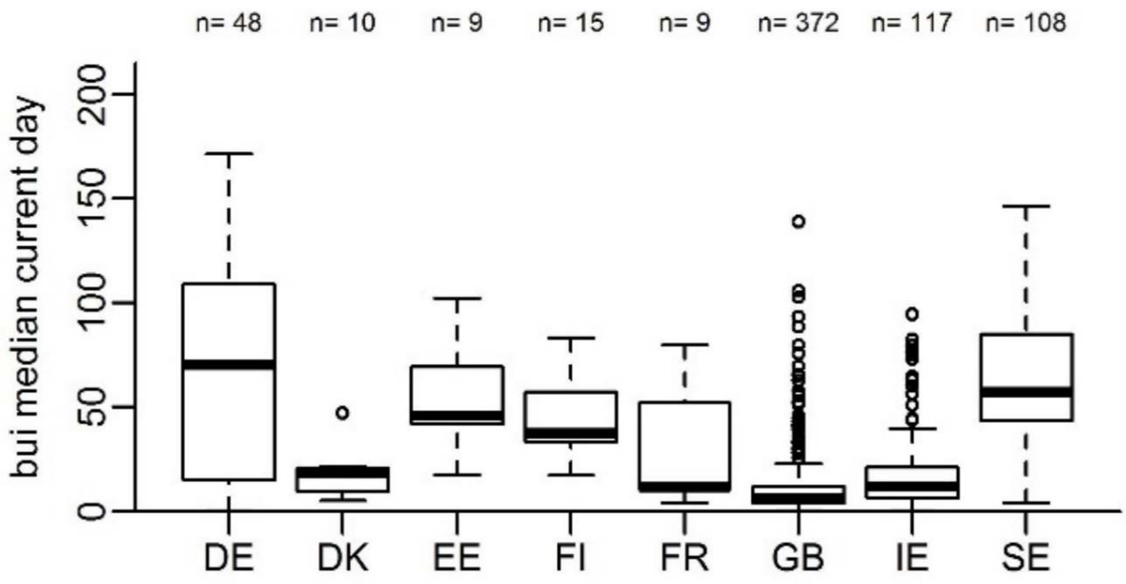


Figure 6.25. Values of the build-up Index (BUI) for fires in northern European countries during the period 01/07/2013 - 15/06/2019.

6.10.5 The Fire Weather Index (FWI)

The ISI and BUI are finally combined to create the FWI, which is used as an indirect indicator of fireline intensity. Given the limitations shown above for the predictive capacity of ISI and BUI on fire parameters, it is little surprise that there are no strong relationships between FWI and the area burned in Northern Europe (Figure 6.26).

In terms of EFFIS fire danger classes, although there is a slightly wider spread, the majority of fires are occurring, including a high number of large fires, when the fire danger classes are "very low" to "low" fire danger. There is an obvious mis-match and a significant number of "false negatives" are being generated by the system.

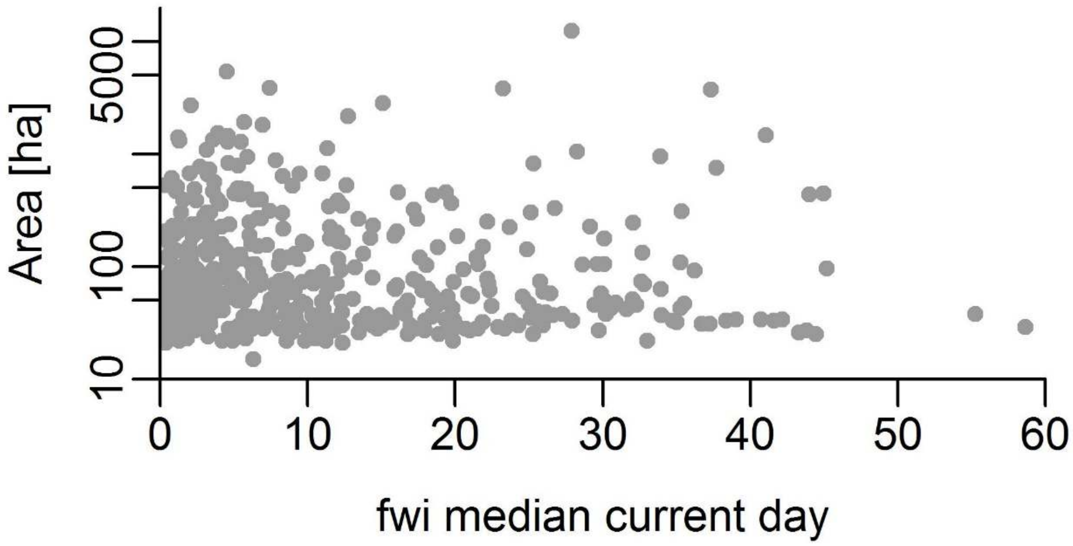


Figure 6.26. The relationship between area burnt and the Fire Weather Index (FWI) for fires in North Europe during the period 01/07/2013 - 15/06/2019.

Most late winter / spring fires are occurring at low FWI values (Figure 6.27). However, as there is a relationship between FFMC to FWI as part of the ISI function, FWI is starting to capture fires in April and May. The conventional relationships hold up much better in summer when there are fewer fires in the UK.

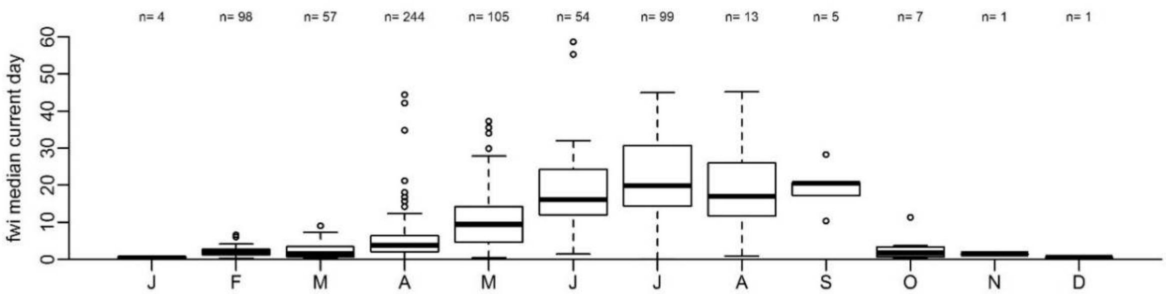


Figure 6.27 Numbers of fires per month in Northern Europe and Fire Weather Index (FWI) fire day values during the period 01/07/2013 - 15/06/2019.

The seasonal pattern associated with the predominant fuel types present in the respective countries in Northern Europe is also reflected in the relationship between the number of fires at low or high FWI values. Countries with cluster 1 fuel types have fires with higher FWI values and countries having cluster 2 and 3 have fires with lower FWI values (Figure 6.28).

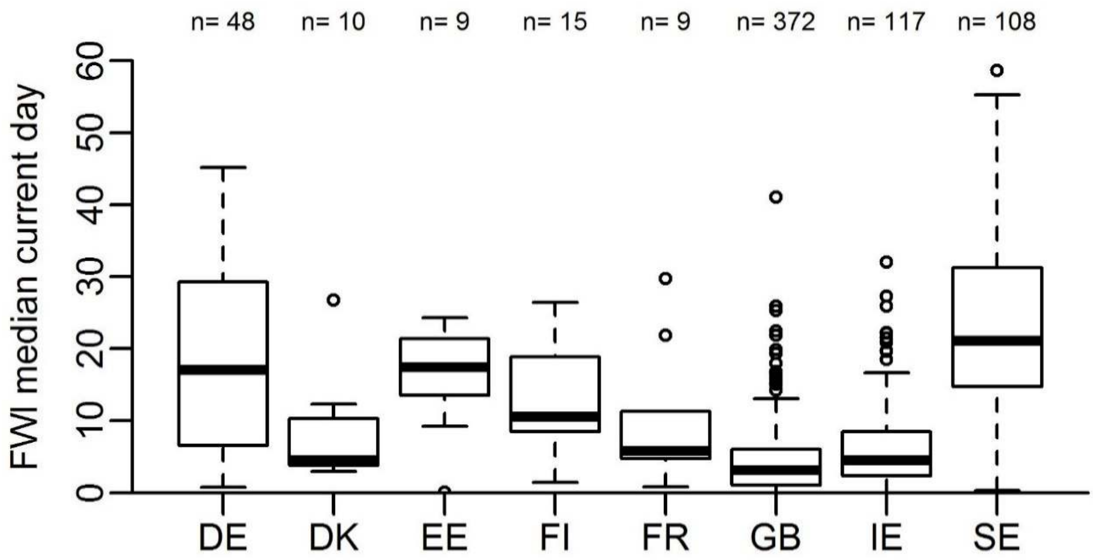


Figure 6.28. Values of the Fire Weather Index (FWI) for fires in northern European countries during the period 01/07/2013 - 15/06/2019.

6.11 Further analysis of Fine Fuel Moisture Code (FFMC) and Initial Spread Index (ISI)

The results from the FireBeaters project (Legg & Davies, 2007, 2008), plus the further analysis of Scottish fire data by Davies & Legg (2016) supported the view that FFMC and ISI were important indicators of high fire danger periods in Scotland. This has also been supported by the present analyses of EFFIS data. However, current analyses have raised a question regarding the accuracy of the ISI model, with the issue being that the EFFIS data showed that wildfires in Scotland are occurring at low FFMC and low ISI values.

The original version of CFWIS was a system which was used manually with fire danger information held in tables. One table was a comparison of FFMC values, plus wind speed to create ISI values (See example in Table 6.4).

The original tables for predicting ISI start at high FFMC values (Van Wagner, 1984). However, a more recent version of this from (Pearce et al., 2012) starts the Table at FFMC of 40. We have used the original algorithm for calculating ISI to generate a table with lower starting FFMC values (Table 6.4). The boundary value of ISI 2 was then used to generate a key boundary for fire danger class purposes i.e. higher and lower than 2. It is informative to see the influence of wind speed when an ISI of 2 intersects with the FFMC values. There is a …significant change in the relationship at wind speeds of 20-25 kph. A wind speed of 20kph is noted as a key constraint in the Muirburn Code (SNH, 2017), which originates from traditional knowledge.

Table 6.4. Fine Fuel Moisture Code (FFMC), windspeed and Initial Spread Index (ISI) look-up table recalculated for low FFMC values

	WINDSPEED K.P.H.										
	0	5	10	15	20	25	30	35	40	45	50
FFMC	INITIAL SPREAD INDEX (ISI) VALUES										
30	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0.1
32	0	0	0	0	0	0	0	0	0	0.1	0.1
33	0	0	0	0	0	0	0	0	0.1	0.1	0.1
34	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1
35	0	0	0	0	0	0	0.1	0.1	0.1	0.1	0.2
36	0	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.2
37	0	0	0	0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
38	0	0	0	0	0.1	0.1	0.1	0.1	0.2	0.2	0.3
39	0	0	0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4
40	0	0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4
41	0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5
42	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.6
43	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.6	0.7
44	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.7	0.9
45	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.8	1
46	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.6	0.7	0.9	1.2
47	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.8	1.1	1.4
48	0.1	0.2	0.2	0.3	0.3	0.4	0.6	0.7	1	1.2	1.6
49	0.1	0.2	0.2	0.3	0.4	0.5	0.7	0.8	1.1	1.4	1.8
50	0.2	0.2	0.3	0.3	0.4	0.6	0.7	1	1.2	1.6	2
51	0.2	0.2	0.3	0.4	0.5	0.7	0.8	1.1	1.4	1.8	2.3
52	0.2	0.3	0.3	0.4	0.6	0.7	0.9	1.2	1.6	2	2.6
53	0.2	0.3	0.4	0.5	0.6	0.8	1	1.3	1.7	2.2	2.9
54	0.3	0.3	0.4	0.5	0.7	0.9	1.2	1.5	1.9	2.5	3.2
55	0.3	0.4	0.5	0.6	0.8	1	1.3	1.6	2.1	2.7	3.5
56	0.3	0.4	0.5	0.6	0.8	1.1	1.4	1.8	2.3	2.9	3.8
57	0.3	0.4	0.5	0.7	0.9	1.2	1.5	1.9	2.5	3.2	4.1
58	0.4	0.5	0.6	0.8	1	1.3	1.6	2.1	2.7	3.4	4.4
59	0.4	0.5	0.6	0.8	1.1	1.4	1.7	2.2	2.9	3.7	4.8
60	0.4	0.5	0.7	0.9	1.1	1.4	1.9	2.4	3.1	4	5.1
61	0.4	0.6	0.7	0.9	1.2	1.5	2	2.5	3.3	4.2	5.4
62	0.5	0.6	0.8	1	1.3	1.6	2.1	2.7	3.4	4.4	5.7
63	0.5	0.6	0.8	1	1.3	1.7	2.2	2.8	3.6	4.7	6
64	0.5	0.7	0.8	1.1	1.4	1.8	2.3	3	3.8	4.9	6.3
65	0.5	0.7	0.9	1.1	1.4	1.9	2.4	3.1	4	5.1	6.6
66	0.5	0.7	0.9	1.2	1.5	1.9	2.5	3.2	4.1	5.3	6.8
67	0.6	0.7	0.9	1.2	1.6	2	2.6	3.3	4.3	5.5	7.1
68	0.6	0.8	1	1.2	1.6	2.1	2.7	3.4	4.4	5.7	7.3
69	0.6	0.8	1	1.3	1.7	2.1	2.7	3.5	4.5	5.9	7.5
70	0.6	0.8	1	1.3	1.7	2.2	2.8	3.6	4.7	6	7.8
71	0.6	0.8	1.1	1.4	1.8	2.3	2.9	3.8	4.9	6.2	8
72	0.7	0.9	1.1	1.4	1.8	2.4	3	3.9	5	6.5	8.3
73	0.7	0.9	1.2	1.5	1.9	2.5	3.2	4.1	5.2	6.7	8.6
74	0.7	0.9	1.2	1.5	2	2.6	3.3	4.2	5.5	7	9
75	0.8	1	1.3	1.6	2.1	2.7	3.5	4.5	5.7	7.4	9.5
76	0.8	1	1.3	1.7	2.2	2.9	3.7	4.7	6.1	7.8	10.1
77	0.9	1.1	1.4	1.9	2.4	3.1	3.9	5.1	6.5	8.4	10.8
78	0.9	1.2	1.6	2	2.6	3.3	4.3	5.5	7.1	9.1	11.7
79	1	1.3	1.7	2.2	2.8	3.6	4.7	6	7.7	9.9	12.8
80	1.1	1.5	1.9	2.4	3.1	4	5.2	6.6	8.5	11	14.1
81	1.3	1.6	2.1	2.7	3.5	4.5	5.7	7.4	9.5	12.2	15.7
82	1.4	1.8	2.4	3	3.9	5	6.5	8.3	10.7	13.8	17.7
83	1.6	2.1	2.7	3.4	4.4	5.7	7.3	9.4	12.1	15.6	20.1
84	1.8	2.4	3	3.9	5	6.5	8.3	10.7	13.8	17.8	22.9
85	2.1	2.7	3.5	4.5	5.8	7.4	9.6	12.3	15.8	20.3	26.2
86	2.4	3.1	4	5.2	6.6	8.5	11	14.1	18.2	23.4	30.1
87	2.8	3.6	4.6	5.9	7.6	9.8	12.6	16.3	20.9	26.9	34.7
88	3.2	4.1	5.3	6.9	8.8	11.3	14.6	18.8	24.2	31.1	40
89	3.7	4.8	6.1	7.9	10.2	13.1	16.8	21.7	27.9	35.9	46.1
90	4.3	5.5	7.1	9.1	11.7	15.1	19.4	25	32.2	41.4	53.3
91	4.9	6.4	8.2	10.5	13.5	17.4	22.4	28.9	37.1	47.8	61.4
92	5.7	7.3	9.4	12.1	15.6	20.1	25.8	33.3	42.8	55	70.8
93	6.6	8.4	10.9	14	18	23.1	29.8	38.3	49.2	63.4	81.5
94	7.5	9.7	12.5	16.1	20.7	26.6	34.2	44	56.6	72.8	93.7
95	8.7	11.1	14.3	18.4	23.7	30.5	39.3	50.5	65	83.6	107.5
96	9.9	12.8	16.4	21.1	27.2	35	45	57.9	74.5	95.8	123.2
97	11.3	14.6	18.8	24.2	31.1	40	51.5	66.2	85.2	109.6	141
98	13	16.7	21.5	27.6	35.5	45.7	58.8	75.6	97.3	125.1	161
99	14.8	19	24.5	31.5	40.5	52.1	67	86.2	110.9	142.7	183.6
100	16.8	21.6	27.8	35.8	46.1	59.3	76.3	98.1	126.2	162.4	208.9

6.12 Development of Beta Fire Danger Classes

Firebreak Services Ltd has been delivering wildfire danger assessments on behalf of the Scottish Wildfire Forum (SWF) since 2014 (M. Bruce, personal comment). The criteria used to generate the warnings are a combination of:

- Knowledge of seasonal and weather-related fuel conditions
- Knowledge of fire behaviour of key fuel types from previous experience
- Application of limited parts of the Canadian Fire Weather Index System (CFWIS), using key threshold values:
    - Fine Fuel Moisture Code (FFMC) >80
    - Initial Spread Index (ISI) >2
    - Duff Moisture Code (DMC) >20
    - Drought Code (DC) > 300

These thresholds were based on the work published in Phase 1 and Phase 2 Firebeaters reports (Legg & Davies, 2007, 2008) and (Davies and Legg 2016). Development of the process was also carried out in association with the series of UK Wildfire Conferences, especially the 2011 and 2013 conferences. For the 2011 conference, a series of case studies of well-known fires was developed by M. Bruce and K. Kitchen (Met Office) with FWI sub-indices and the underpinning weather information along with descriptions of fire behaviour.

For the 2013 conference, a comparison of fires in the Highlands and Islands region of Scotland was made using EFFIS fire danger classes and FFMC >80 criteria. There was a clear improvement of accuracy. Firebreak Services started producing “Wildfire Danger Assessments” based on this analysis and the FFMC, ISI, DMC and DC thresholds for the Scottish Wildfire Forum in 2014.

The system of wildfire danger assessments produced by Firebreak Services Ltd has been reasonably successful in capturing extreme periods of fire danger, as evidenced by large intense wildfires that have occurred during the “fire warning” periods. The key relationships that were considered, especially in the spring period, have been between FFMC and ISI. In the early summer DMC seems to become more important and in the late summer DC may also be informative. Elevated values of FFMC and ISI are still relevant, but the plants are at a different stage of phenological development, and it may be that different deeper “dead” fuel layers may have more influence on fire behaviour.

A first attempt to create a series of fire danger classes was made in 2018, a year when a record 21 “Wildfire Danger Assessments” were produced (Table 6.5).

Table 6.5. Draft 1 spring fire danger classes for Scotland using Fine Fuel Moisture Code (FFMC) and Initial Spread Index (ISI) 14.10.18

Fire Danger Class	Probability of ignition	FFMC		EFFIS FFMC	ISI		EFFIS ISI
		Spring	Summer		Spring	Summer	
Low	<0.5	<65	<75	<82.7	<1	<1	<3.2
Mod	<0.6	65-75	75-80	82.7-86.1	1-1.5	1-2.25	3.2-5
High	<0.7	75-80	75-85	86.1-89.2	1.5-2	2.25-3	5-7.5
Very high	<0.8	80-85	85-90	89.2-93	2-3	3-5	7.5-13.4
Extreme	>0.8	>85	90>	>93	3>	5>	>13.4

After further discussion with consultant Matt Davies (Ohio University) during this project, a second attempt to develop possible draft fire danger class options was made (Table 6.6 & Table 6.7).

Table 6.6. Option A, draft fire danger classes for Scotland based on Fine Fuel Moisture Code & Initial Spread Index

Option A					
Fire Danger Class	Probability of wildfire	FFMC	ISI	EFFIS ISI	EFFIS FFMC
Low	<0.5	<50	<0.3	<3.2	<82.7
Mod	<0.6*	50 - 75	0.3 - <1	3.2-5	82.7-86.1
High	<0.7	75 - 80	1> - <2	5-7.5	86.1-89.2
Very high	<0.8	80-85	2> - <2.5	7.5-13.4	89.2-93
Extreme	>0.8	>85	2.5>	>13.4	>93
	* Not exact probability				

Table 6.7. Option B, draft fire danger classes for Scotland based on Fine Fuel Moisture Code & Initial Spread Index

Option B					
Fire Danger Class	Probability of wildfire	FFMC	ISI	EFFIS ISI	EFFIS FFMC
Low	<0.5	<50	<0.3	<3.2	<82.7
Mod	<0.6*	50 - 70	0.3 - <1	3.2-5	82.7-86.1
High	<0.7*	70 - 80	1> - <2	5-7.5	86.1-89.2
Very high	<0.8	80 - 85	2> - <2.5	7.5-13.4	89.2-93
Extreme	>0.8	>85	2.5>	>13.4	>93
	* Not exact probability				

The proposed options were tested using the EFFIS data. These are illustrated in Figure 6.29, Figure 6.30, and Figure 6.31.

It should be noted that although the fire danger class shown by the coloured boxes has been used to fit with the data, further analysis may be needed such that the higher ISI values, within FFMC bands, should be placed in the next higher fire danger class band.

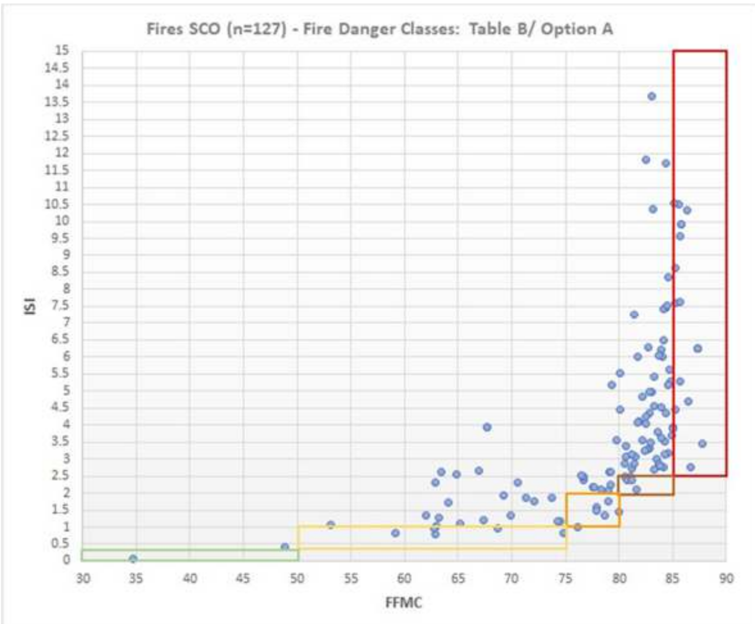


Figure 6.29. Categories of fires in Scotland arranged by draft fire danger class set in Table 6.6 Option A

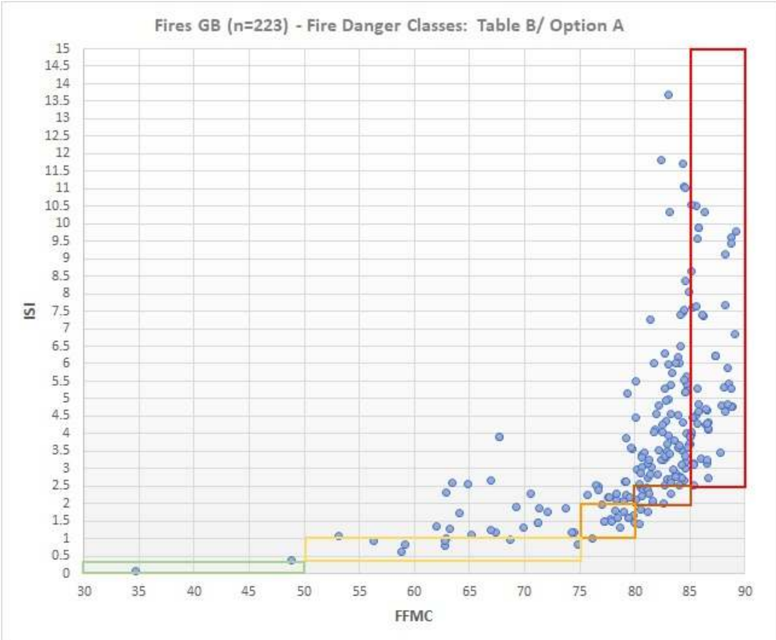


Figure 6.30. Categories of fires in Great Britain arranged by draft fire danger class set in Table 6.6 Option A

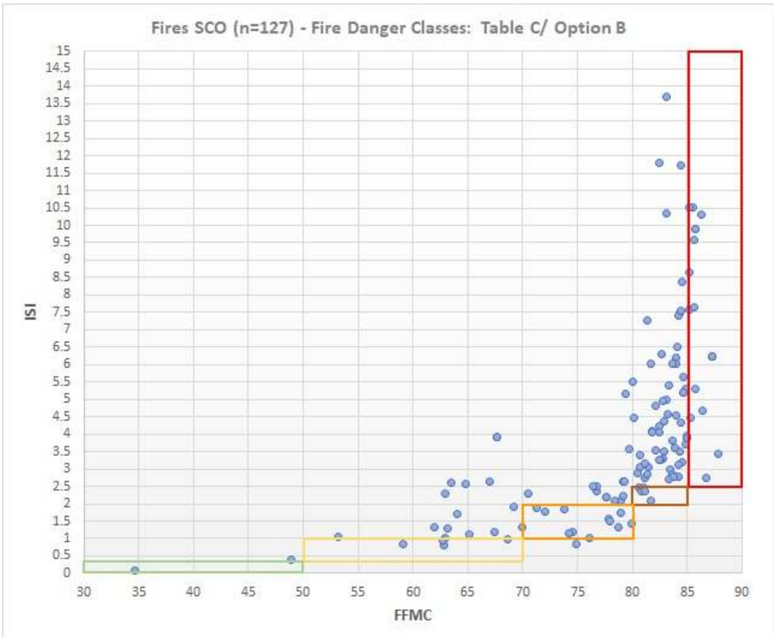


Figure 6.31. Categories of fires in Scotland arranged by draft fire danger class set in Table 6.7 Option B

A further assessment to improve the fit the data on fires to draft fire danger classes was made. This analysis was then used to create the fire danger classes for spring fires in Scotland in Table 6.8.

Table 6.8. Modified draft fire danger classes for spring fires in Scotland

Draft Fire Danger Class	**FFMC**	**ISI**
Low	<50	<0.5
Mod	50 - 70	0.5 - <1.5
High	70 - 80	1.5 > - <2.5
Very high	80 - 85	2.5 > - <4.5
Extreme	>85	4.5>

These modified draft fire danger classes were then plotted using the EFFIS fire data for Scotland and Great Britain (Figure 6.32, Figure 6.33).

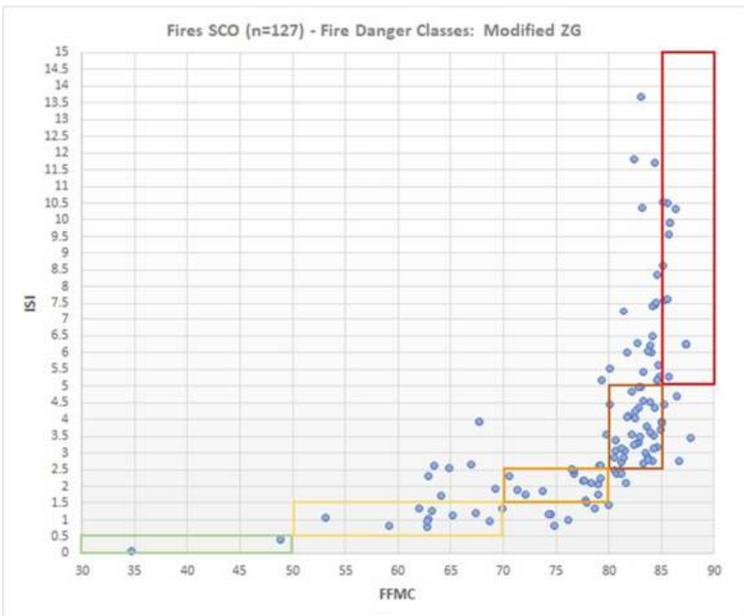


Figure 6.32. Modified draft fire danger classes related to European Forest Fire Information System (EFFIS) fire data from Scotland

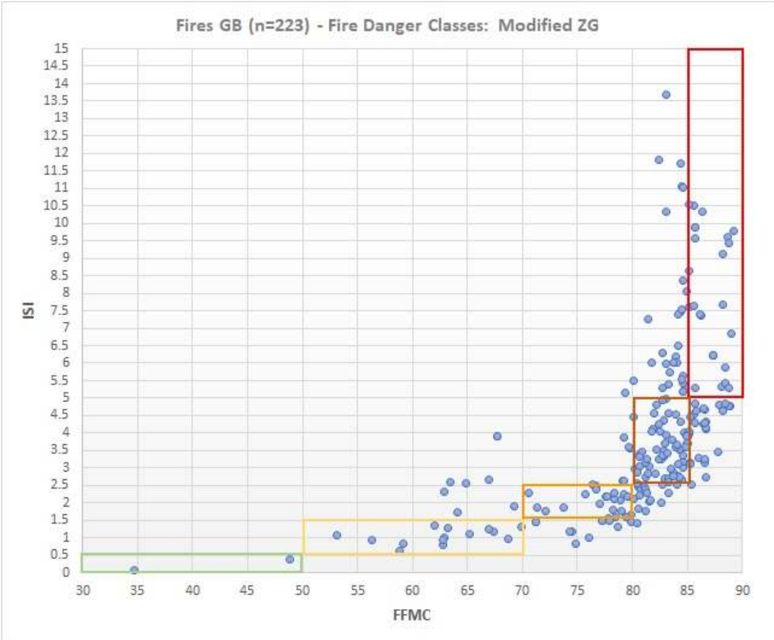


Figure 6.33. Modified draft fire danger classes related to European Forest Fire Information System (EFFIS) fire data from Great Britain

Although the modified versions of the fire danger classes capture more of the EFFIS data, further detailed modelling, including different approaches to defining ranges, is required to optimise class categories.

6.13 Conclusions:

- Fires in Northern Europe are igniting at lower FFMC values that the European average. With the predominance of late winter / spring fires occurring at an even lower range (83-85) of FFMC values.
- Similarities in dead fine fuel moisture content of around 20%, are found from the FFMC model for the litter layer and elevated dead fuel moisture in laboratory and field surveys.
- No relationship was found between DMC and area burned in late winter / spring fires.
- DMC has a positive seasonal relationship with summer fires.
- No relationship was found between DC and area burned but with a trend for DC to rise through the summer (June – September) and become associated with fires.
- No relationship was found between ISI and area burned.
- Most wildfires occurring in the UK have ISI values of between 2 – 5.
- A positive, clear relationship was found between the occurrence of large wildfires in the spring, with the combination of FFMC>80 and ISI>2. In the ISI model an ISI range of 2 – 5 represents a wind speed range of 0 – 50 kph. The wind speed range reduces as FFMC rises. At FFMC 75 this represents wind speeds of 20 – 35 kph and at FFMC 80 this represents wind speeds of 10 – 30 kph. At FFMC 85 the range of wind speeds is only 0 – 15kph.

- The BUI, driven by DMC, shows no relationship with area burned in late winter / spring fires.
- May is clearly a transition month for many CFWI sub-indices, including BUI, where there is a positive relationship between rising BUI and fire days.
- The lack of a relationship between BUI and fire days in countries reflects the dominant fuel type in those countries.
- No relationship was found between FWI and the area burned in most Northern European countries with significant areas of pasture, shrub and bog fuel types involved.
- There is a positive relationship between area burned and countries with a predominance of forest fuel types, such as Sweden and Germany.
- FFMC and ISI can, on their own, be used to discriminate fire danger classes in Scotland and the UK and other places with similar fuel types.

6.14 References

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7 General summary, overall conclusion and future work

7.1 General summary of project

The risk of wildfires in Scotland and the UK as a whole is likely to increase due to changes in precipitation patterns as a result of land-use and climate change. While significant wildfire seasons may still only occur intermittently in Scotland, there is a concern that we are unprepared to deal with this potential increasing risk of difficult wildfire seasons. Fire danger rating systems designed to predict potential fire risk can be a powerful tool in planning for managing increasing periods of significant wildfire activity and for supporting safe use of burning as a land management practice. Currently, fire danger forecasts in Scotland rely heavily on modelled scenarios from the Canadian Fire Weather Index System (CFWIS) sub-indices, which was originally designed for predicting fires in mature jack pine stands in Canada. Although this system has been widely adopted, it has not so far been adapted to the fire environment and fire regime in Scotland.
The primary aim of this project was to explore how the CFWIS could be adapted to the vegetation most commonly involved in wildfires in Scotland: moorland vegetation types, primarily those dominated by heather and/or grass. The project was split into three work packages, each investigating different aspects of the applicability of the CFWIS to moorland vegetation.

The following is a summary of the findings of the project grouped under each work package.

7.1.1 WP 1: Mapping and characterising fuel types in Scottish moorland habitats

Main topic: Investigations into current state of knowledge of fuel loads in Scottish vegetation, potential fuel types and loads in heather and *Molinia* dominated vegetation and comparison with fuel types in the CFWIS.

- More studies measuring fuel loads across a range of habitats in a comparable way are required to improve our ability to map fuel loads and fuel characteristics for multiple habitats.
- Measurements of fuel load characteristics along latitudinal, altitude and climatic gradients in Scotland for a range of soil types and plant communities are required to enable fuel loads to be better predicted over a wide geographic range.
- Before producing any map one key question arises - at what spatial resolution do we need to map fuel loads to usefully inform on fire danger in Scotland?
- The jack pine litter and fine debris of the fine fuel fraction of the CFWIS used in particular by the FFMC model, can be related to the moss and litter beneath heather shrubs, but there are important distinctions.
- There is no variable in the CFWIS to account for any component of the shrub or grass layer in moorlands.
- There is no equivalent soil ‘Duff’ layer used in the CFWIS in moorland soils.

- The dead leaves of *Molinia* are retained late in the spring/early summer, potentially prolonging the potentially fire danger season.
- The large quantities of fuels in the moss and litter and deep undecomposed organic layer in all moorland soils could become available to burn in drought scenarios.

7.1.2 WP 2: Ignition for Scottish fuel types

Main topic: Investigations of fuel flammability, ignitability and fire spread in the laboratory were undertaken.

- Fire spread in heather is largely driven by the Fuel Moisture Content (FMC) of the fine parts of the vegetation. The FMC of the coarse fuels and the moss and litter are more significant in determining total fuel consumption.
- FMC values between different fuel fractions varied significantly, especially between live and dead fine fractions.
- FMC values of fine fuels were highly responsive to drying conditions, but live fine fuels FMC stabilised at far higher values than dead fine fuel.
- FMC values of live coarse fuels in the field were very stable.
- FMC values of the moss and litter fraction show the greatest spatial and temporal variation of all fuel fractions.
- The FMC thresholds for the ignition of fine fuels subjected to small ignition sources were determined.
- The fuel flammability (ease of ignition and energy release) indicates that fine fuels ignite most readily but that the burning of coarse vegetation is likely to release the majority of the energy.
- Laboratory fire spread experiments indicate relationships between spread rate and fuel consumption, and fine fuel moisture content.
- Field experiments highlighted the importance of wind in driving the fire spread. The rate of fire spread in the field was much higher than observed in the laboratory. Fire spread was also observed to occur at higher FMCs than could sustain spread in the laboratory.
- No significant relationships were found between the rate of spread and the fuel consumption for the environmental or fuel variables explored here. It is likely this is due to the relatively small number of experiments and the relatively narrow range of conditions explored.
- These investigations highlight that a coupled laboratory and field experimental campaign may present an efficient way forward in calibrating a fire danger system in addition to allowing a holistic assessment of the different aspects of fire danger.

7.1.3 WP 3: Calibration of Fire Weather Index (FWI) codes to fire incidence data

Main topics: investigations into how actual fire data for large fires in northern Europe can inform on the output and sub-indices of the Canadian FWIS and reciprocally how the indices can predict the fire data.

- Fires in Northern Europe group into three clusters of characteristics, largely defined by fuel type. Fires in cluster 1 represent mainly fires in the forest fuel type that occur in late spring and summer months, which were mostly found in Sweden and Germany. Values of FWI sub-indices indicate that the Canadian FWI works well for these fires, which is probably due to the dominant fuel type (forest/trees) and the continental climatic conditions resembling the conditions used for initial model development.
- Fires in clusters 2 and 3. The majority of fires are in shrublands (moorlands and heathlands) (cluster 2) and peat bogs (cluster 3) that occur in late winter and spring. These fires were mostly found in locations within the British Isles, the island of Ireland, Denmark and Norway that have oceanic temperate climatic conditions.
- Median FFMC values for fires within clusters 2 and 3 (83 and 84, respectively) were similar but lower than the median FFMC value for cluster 1 fires (89). However, all other values of the FWI sub-indices were much lower for cluster 2 and 3 fires than for the cluster 1 fires, including the final FWI assessment. Therefore, it seems that the Canadian FWI fails to accurately predict the occurrence or areas of fires in clusters 2 and 3 based on the final FWI assessment, despite satisfactory FFMC predictions.
- A positive relationship has been found between FFMC, and also FFMC combined with ISI fire occurrence and burned areas in Scotland, UK and Northern Europe for winter-spring fires. This relationship can be roughly linked to some existing EFFIS fire danger classes and related maps (Table 7.1 Proposed fire danger classes for winter - spring wildfires in Scotland).

Table 7.1 Proposed fire danger classes for winter - spring wildfires in Scotland

Draft Fire Danger Class Bands	Scotland FFMC	Scotland ISI	EFFIS FFMC	EFFIS ISI	EFFIS colours	Scotland colours
Low	<50	<0.5	<82.7	<3.2	Green	
Mod	50 - 70	0.5 - <1.5	82.7-86.1	3.2-5	Yellow	Very High
High	70 - 80	1.5 > - <2.5	86.1-89.2	5-7.5	Brown	Extreme
Very high	80 - 85	2.5 > - <4.5	89.2-93	7.5-13.4	Red	
Extreme	>85	4.5>	>93	>13.4	Black	

- No relationship has been found between DMC, DC, ISI, BUI or FWI with burned areas in winter and spring fires in pastures, shrubs and bog fuels in Scotland, UK and Northern Europe.

- Fuel type and the seasonal phenological condition of fuels are key influences on potential “false positive” or “false negative” fire danger assessments, based on CFWI or CFWI sub-indices alone, with May being a key transitional month between late winter and spring conditions and summer conditions.
- The CFWIS works best for summer conditions in countries with predominance of forest fuel types. Further work is needed to analyse appropriate fire danger classes for summer fires in pasture, shrub and bog fuel types.
- The lack of relationships between pasture, shrub and bog winter and spring fires, the majority of fires in Northern Europe, and the CFWIS fire behaviour indices, namely ISI, BUI and FWI means that the use of CFWIS should be limited to fire intelligence purposes and the term “FDRS” should not be used.

7.2 Overall conclusion

The project was essentially an evaluation of the power of the Canadian Fire Weather Index System (CFWIS) to predict potential ignition, fire spread and fire intensity of fires in moorland vegetation in Scotland.

The CFWIS has provided an excellent structure with which to investigate the many elements involved in developing a fire danger rating system in Scotland. However, the fuel types and the fire behaviour of fires in Scottish moorlands appear to be very different from the original CFWIS forest fire scenarios.

In support of the above statement, we present the congruences, disparities and anomalies between the CFWIS and Scottish fires and fuels.

The CFWIS poorly represents the fuel types and characteristics of vegetation and soils in moorland systems.

A detailed investigation of the EFFIS fuel map and fire data of 571 fires in northern Europe during the period 01/07/2013 - 15/06/2019 showed that only some elements of the CFWIS performed adequately for the prediction of fire occurrence. In addition, fuel type and season have a significant effect on fire occurrence independent of fire weather i.e. the seasonal condition or phenology of the fuels has a significant influence on ignition potential and fire behaviour.

A robust and reliable Fire Danger Rating System must be informed and underpinned by a thorough understanding of how fires spread in different fuel types; there are no appropriate fuel models within CFWIS that match the fuel structure of heather moorland and adequately capture the fire spread drivers in these systems.

We therefore suggest that new approaches are supported to develop a Fire Danger Rating System that captures the variables inherent with the particular combination of fuel types, fire regime and weather in Scotland.

7.3 Future work towards developing a Fire Danger Rating System (FDRS) for Scotland

International experience in the development of a functional FDRS indicates that a distinct and sustained programme of multi-disciplinary, fundamental, applied and operational research and development is required. To make significant progress with this complex and difficult environmental research topic, there needs to be a long term focussed collaborative commitment from government(s) and agencies for an appropriate funding, structured programme supporting research into underlying models, concepts, and applications. This also requires support for the development of appropriate governance policies, institutional frameworks, staff roles and structures, training of operators, end-users and the public.

This project has identified that there is scope to adopt the philosophy and framework of the Canadian system but that it needs significant further adaptation making it bespoke to the drivers of fire behaviour in Scottish vegetation and soils. This section sets out the framework for future work.

This project has shown that an approach using laboratory studies and fieldwork together are an effective way to reduce the typically large number of experiments required to calibrate an empirically based system. Laboratory studies are well suited to measurements of the physical processes that drive fire behaviour because the fuels and environmental conditions can be studied independently.

An understanding of the purpose of a FDRS also helps frame discussions on future work. A Fire Danger Rating System is a description of the fixed and variable factors of the fire environment that affect the ease of ignition, rate of spread, difficulty of control, fire severity and cumulative impacts of multiple fires. Once research has established the fire behaviour relationships a FDRS will also provide information of the potential impact of wildfires on fire-fighting resources, economic and societal assets and the environment.

Developing any fire danger system will require experimentation to calibrate thresholds, develop relationships between inputs and fire behaviour, and to evaluate system performance as future landscapes and climate and weather patterns change.

This research process requires a multi-disciplinary approach with an understanding of vegetation and fuel (including organic soils), combustion and fire processes, and fire weather.

Overarching aim for future work: *To create a modular FDRS decision support system for Scotland that can incorporate improvements in accuracy, gained from research and development work, along with improved visibility, interpretation and presentation of fire danger information for end-users.*

Timelines and recommendations

Immediate/Short-term (12 months):

- A workshop to share research results, stimulate conceptual thinking about FDRS issues and develop a focused research and development programme.
- Optimise the current situation by creating a reliable wildfire intelligence decision support system for Scotland using existing evidence, infrastructure, and other capabilities.
- Further develop collaboration with related research and development work on similar fuel types in other countries and jurisdictions.
- Maintain fire-related field work to retain a core research skills base in Scotland

Medium term (1-5 years):

- Establish dedicated Scottish wildfire research group within existing HE or SG infrastructure
- Application of existing landscape mapping tools for assessing fuel type and loads
- Development of relevant government policies for fire awareness and prevention
- Detailed investigations of the interactions between the different fuel layers and fire behaviours
- Determine moisture dynamics of different fuel layers.
- Model real-time effects of weather on fire behaviour.
- Develop fire behaviour models that allow fuel, weather and terrain conditions to be related to time-dependent assessments of fire intensity and fire severity
- Refinement of fire danger classes, that are related to the thresholds of control for fire suppression, and can be used as triggers for fire prevention activities and thresholds for prescribed fires
- Stimulate co-operation between fire management agencies, research institutions and programmes through the Scottish Wildfire Forum, to set common standards for the use of fire danger information and disseminate this through awareness raising, and training initiatives.
- Work with end-users in government agencies, third sector and private organisations on the standards, presentation, descriptors, and communication of fire danger information

Long term (5-10 years):

- Continue the development of cost-sharing agreements between interested agencies and interests that will support a long-term multi-purpose, multi-stakeholder fire danger information platform.
- Continue the development of a suite of fire danger guidance material for fire and land managers to support training and decision making on the ground for fire management and suppression purposes.
- Continue FDRS development in view of changing land-uses, climate, policy development, economic and social change.

8 Appendices

8.1 Fire Training Syllabus – Firebreak services

BASIC FOREST & MOORLAND FIRE FIGHTING

ONE DAY COURSE

COURSE AIM:

To enable the individual to contribute to the control of vegetation fires, including: grass, heath, scrub, brash or woodland; safely and according to organisational procedures.

PARTICIPANTS (CANDIDATE PROFILE)

A basic course for all employees who may use fire in controlled (prescribed) burning operations or who may become involved in fire suppression operations at a wildfire incident. The course is relevant to employees of the Forestry Commission, private sector workers, fire brigade and other public authority personnel. The course is relevant to all vegetation fire situations including: forest, heather, grass, scrub, peat and lop and top fires whether deliberately lit or otherwise.

The course gives both the underpinning knowledge to operate safely and effectively under supervision in a vegetation fire environment and covers the appropriate use of tools and techniques by individuals and small teams.

The basic training event will involve instruction in: personal safety issues, fire behaviour, fire action procedures, and the appropriate use of hand tools, pumps and foam in different situations.

Successful completion of this event would provide evidence towards V.Q. element B3.1.1.

The event is based both in the classroom and in the open. It is physical in nature and requires the operation, carrying and movement of hand tools, high pressure water systems and pumping accessories. The exercises are carried out in the open, next to water and in the proximity of small fires.

LEARNING OUTCOMES

At the end of this training participants will be able to:

1. Identify personal hazards present at vegetation fires, including risks from equipment.

2. List the personal protective equipment required for vegetation fire suppression.

3. Recognise how to work with equipment safely, including: vehicles, fire beaters, spades, axes, mattocks, knapsack sprayers, high pressure pumps and foam.

4. Describe the elements required for a fire to exist (heat, oxygen, fuel) and how removing elements puts out a fire.

5. Describe vegetation fires and how different fuels, weather and terrain affect the spread, intensity and nature of a fire.

6. Describe and contrast common fire types: ground (peat), surface (grass, heather, & scrub) and crown fires (forest).

7. Select appropriate tools to use to suppress different types of fires.

8. Recognise operations likely to occur in the three stages of fire suppression: knockdown, containment and mop up and patrol.

9. List three fire suppression strategies: direct attack, flanking attack and indirect attack. Be able to assess which is appropriate when compared to fire behaviour.

10. Recognise how their role fits into organisational fire action plans and procedures in a fire emergency.

11. Recognise for safe and effective fire fighting the importance of: acting calmly, complying quickly with instructions, team working, and good communications.

12. List the main environmental risks that may be encountered (smoke, peat fires, foam/water.)

13. List the elements of the "WATCHOUT" guide for vegetation fire fighting.

SYLLABUS

1. Update and revise on:- Protective clothing, safety regulations, fire action plan - procedures and map, risks and hazards inherent from fire environment and equipment.

2. Update and revise on:- typical vegetation fire suppression equipment and accessories.

3. Identification of elements of fire, description of fire, and stages of burning.

4. Identification of factors which affect fire behaviour (wind, slope and fuel) including the dynamics of the relationships leading to increases in fire rate of spread and fire intensity.

5. Identify how fire to put out by breaking fire triangle: removing oxygen (beaters), cooling (water) and removing fuel (spade or tractor and swipe).

6. Assessment of fire type and fire intensity. Description of ground, surface and crown fires.

7. Identification of safe use of each tool and machine. Pro's and cons of different tools: beaters, scrubbers, flappers, spade, axe, mattock, knapsack, pump, high pressure fire fogging pump*, tractor and swipe*, wet water and foam*.

8. Assessment of appropriate tools, tactics and techniques to use with each fire type and fire intensity. Relate fire type and fire intensity to safe operating practice on the fire ground. Identify pro's and cons of use of each tool. Emphasise safe working practice.

9. Assessment of fire suppression tactics: direct attack, flanking attack, indirect attack, parallel attack and back burning. Identify which tactic is appropriate for different ranges of fire behaviour. Identify 3 phases of fire suppression and which tools, tactics and techniques likely to be appropriate for each. Emphasise safe working practice.

10. Identify environmental risks from different fire types e.g. peat fire, environmental hazards to public e.g. smoke, and environmental hazards created by working method e.g. foam.

12. Identify basic features of fire action maps and plans, (include organisational plans where appropriate*). Identify rural fire group procedures, roles and responsibilities.

13. Assess work organisation, teamworking, and communication in 3 fire suppression exercises, with: pumped water, fire beaters and "pump and roll" tanker or fire fogging unit. Emphasise dynamic nature of fire to help identify appropriate tools and techniques for different situations.

*** Optional depending on customer needs.**

8.2 Mapping fuel loads in Scottish upland heaths and grasslands: a review of current knowledge. Andrea Britton, James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH

1. Scope of this review

Fire Danger Risk Rating Systems (FDRS), first developed in Canada, are used world-wide to provide advance warning and danger notices during periods of wildfire risk (typically late winter to late autumn in Scotland). This information is widely used by landowners, land managers, fire services and others to help with managing the land to prevent and reduce fire risk and as a call to readiness in preparation of fire outbreaks.

A key element of the FDRS is information on fuel type characteristics and fuel moisture being critical to accurate predictions of fire risk and fire behaviour. Currently, Scotland uses information on fuel type and fire behaviour obtained from elsewhere, but it has been recognised that current international data on fuel type and characteristics are not entirely appropriate to the fire environment and fire regime in Scotland. The need to characterise Scottish fuel types has therefore been identified as an essential aspect in the development of a Scottish-relevant FDRS.

In this review we examine, firstly, the current availability of vegetation mapping data for Scotland and the suitability of this data to inform on the spatial distribution of fuel loads. Secondly, we review current knowledge of fuel loads in Scottish heathland and upland grassland habitats and the modifying effects of season, phenology, management and environmental factors (climate, nitrogen deposition). The scope of this review is limited to heathland and upland grassland types (especially *Molinia* dominated grassland) present in Scotland, but information from comparable systems in the UK, Europe and elsewhere is included where relevant.

2. Vegetation mapping data in Scotland

Knowledge of the spatial distribution of habitat types or vegetation communities is the first step towards determining the spatial distribution of fuel types and fuel loads across Scotland. Vegetation mapping data may be derived from detailed mapping exercises by surveyors on the ground, or from remotely sensed data, but must be sufficiently detailed to differentiate communities according to stand structure (e.g. forest, dwarf-shrub heath, grassland), climatic effects on fuel load (e.g. prostrate alpine heath vs tall dwarf-shrub heath) and phenological differences (e.g. evergreen vs deciduous grassland).

2.1 Availability of vegetation mapping data

Vegetation mapping data for Scotland is currently available at a range of scales. Comprehensive areal coverage is provided by two products; the Centre for Ecology and Hydrology (CEH) Land Cover Map 2015 (LCM 2015) covering the entire UK and the Scottish Natural Heritage (SNH) Habitat Map of Scotland (HabMOS). The LCM 2015 identifies 21 broad land cover categories (Figure 1) based on UK biodiversity action plan Broad Habitat definitions and is a parcel-based map, with a minimum mapping unit size of 0.5 ha. Land cover categories relevant to Scottish heathland and upland grasslands are: 'acid grassland', 'heather', 'heather grassland', 'inland rock' and 'bog'. The 'acid grassland' category includes bracken stands, while 'heather' and 'heather grassland' categories are separated based on heather density (heather: grass cover ratio). The 'bog' category includes ericaceous, herbaceous and mossy vegetation in areas with a peat depth of > 0.5m. Alpine heaths and grasslands are included within the 'inland rock' category (which also includes cliffs, caves, screes and limestone pavements) if rock is the dominant spectral signature. Otherwise they are not distinguished from other grassland and heath vegetation.

Figure 1. Centre for Ecology and Hydrology Land Cover Map 2015 (available from https://www.ceh.ac.uk/services/land-cover-map-2015).

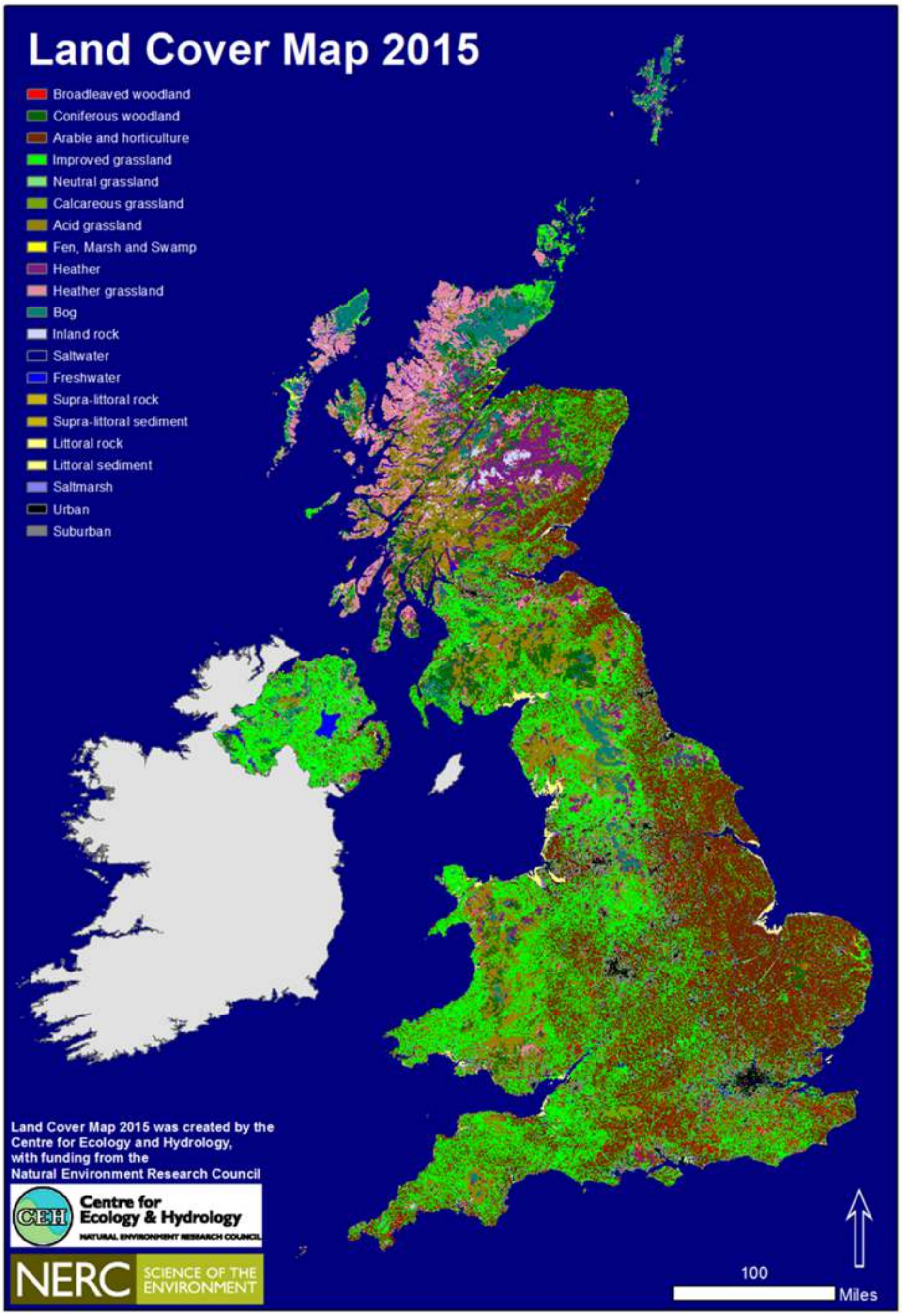
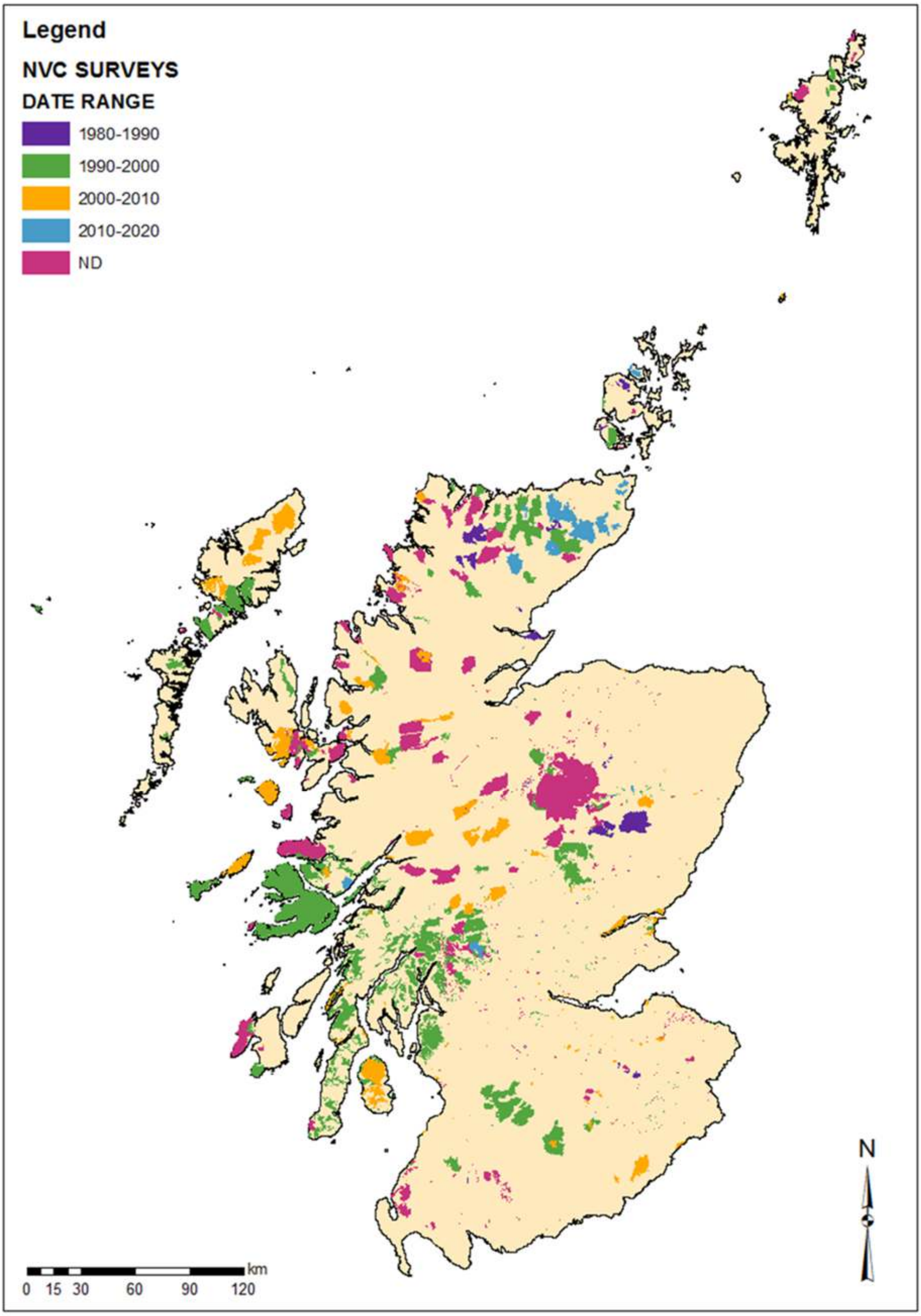


Figure 2. Availability of National Vegetation Classification survey data across Scotland, based on dataset available from the Scottish Natural Heritage Natural Spaces data portal dated March 2017. Spatial coverage of NVC survey data is shown, coded according to date of survey (ND: no date given).



The Habitat Map of Scotland (HabMOS) developed by SNH, compiles data from various sources to produce a comprehensive coverage of Scotland using the EUNIS (European Nature Information System) classification. This is a hierarchical habitat classification system with the top level (level1) categories being similar to the broad habitats used in the LCM 2015. Heathland and upland grasslands in Scotland fall into three level 1 categories; D. Mires, bogs and fens, E. Grasslands and lands dominated by forbs, mosses or lichens, and F. Heathland, scrub and tundra. At its lower levels (levels 4 - 5) the EUNIS scheme approaches the level of detail captured by the UK National Vegetation Classification (NVC) (Rodwell, 1991, 1992), and correspondences between these two classification systems have been defined (Strachan, 2017). In HabMOS, where available, existing NVC survey data have been converted to equivalent EUNIS categories, providing an improved level of detail over the LCM 2015. However, the availability of NVC survey data across Scotland is very limited, with large areas of the Scottish uplands having no coverage (Figure 2). The remaining upland area, for which detailed habitat mapping is not available, covers approximately 2.7 million hectares (one third of Scotland) and is referred to as the 'upland survey gap' (Scobie, 2018). Only very coarse vegetation classification data (level 1 or 2 of EUNIS) is currently available for this area. Methods for producing a more detailed survey of this area by combining remote sensing and on the ground survey have been developed by Scottish Natural Heritage (Scobie, 2018), but are yet to be rolled out. A similar project covering the Yorkshire Dales National Park (Bradter *et al.*, 2011) used a combination of aerial photography and remotely sensed environmental data layers (elevation, aspect, slope and soil type) to successfully predict the distribution of NVC communities with a good degree of accuracy.

2.2 Suitability of vegetation survey data for prediction of fuel load

Vegetation classification schemes were developed to describe plant communities, but at finer levels of detail they also encapsulate information which is of use when predicting fuel type and loads. Vegetation types can provide a clue to the vegetation morphology, amount of dead woody debris and surface litter properties, but may present a range of very different fire propagation rates if fuel load and other vegetation characteristics change over time, for example with accumulation of biomass across the stages of the heather cycle (Keane *et al.*, 2001; Chuvieco & Kasischke, 2007). Also the increases in fire risk and fire behaviour due to the increasing proportion of dead fuel as heather ages (Log *et al*., 2017, Davies & Legg, 2011). Schemes such as the one used in the LCM 2015 product, while providing consistent, comprehensive coverage, are at too low a resolution to convey information on vegetation stand structure or biomass in heathlands and grasslands beyond the most basic distinction of dwarf-shrub dominated vs mixed dwarf-shrub / grassland communities and, to some extent, wet vs dry communities. Hence, they would be unlikely to provide much data of use in predicting fuel load distribution at anything other than a very coarse scale. Similarly, the higher levels of the EUNIS habitat classification would not provide much detailed information on fuel load distribution, but, at finer levels, this scheme may provide better information. For example, describing the distribution of altitudinal sequences of communities differing in biomass or species composition (e.g. lowland – upland – alpine heaths). Mapping data based on the UK NVC is likely to be the most informative in relation to fuel load, as this classification scheme provides the most detail and is backed up by comprehensive floristic descriptions and information on the physiognomy of the vegetation (Rodwell, 1991, 1992; Averis *et al.*, 2004).

3. Other approaches to mapping fuel loads

The most accurate way to assess fuel loads is through field survey, but this approach is time consuming and therefore expensive and is often not feasible at large scales (Fischer *et al.*, 2015). Thus, in many areas, indirect estimates of fuel loads have been produced, based either on climate driven models of net primary production (NPP) (Clarke *et al.*, 2016) or using data derived from satellite imagery (Chuvieco & Kasischke, 2007; Fischer *et al.*, 2015). Satellite imagery has the potential for regular updating and can be useful for mapping fuel types (Arroyo *et al.*, 2006), but it has limitations in that optical data is 2D and so cannot be used to identify fuel types beneath forest canopies, and cannot be used to directly estimate fuel loads in vegetation types where height estimates are required (Chuvieco & Kasischke, 2007). Satellite based radar sensors may help with height estimation, but an uncertainty of +/- 5 m makes these data unsuitable for use in low-stature vegetation. Lidar data are an improvement over radar, but this type of data is expensive to collect as it is currently only suited to use on fixed wing aircraft rather than satellite (Chuvieco & Kasischke, 2007). In Scotland, Lidar data currently have very limited coverage (A. Gimona, Pers. Com.) with most data having been generated for specific localised projects. Regardless of which indirect method of fuel load mapping is used, its effectiveness is reliant on the existence of good baseline data on fuel load for ground truthing models (Miller *et al.*, 2003).

Satellite data can be very useful however, in the estimation of fuel moisture content (FMC), especially of live fuels, with indices such as NDVI (Normalised Difference Vegetation Index, a measure of greenness) showing strong correlations with field measurements of FMC. Short wave infrared (SWIR) reflectance has also been used to estimate FMC and is greatly affected by moisture content (Chuvieco & Kasischke, 2007). While dead fuel FMC is strongly affected by weather and environmental conditions, live fuel FMC (which has a strong modifying effect on ignition probability and fire behaviour, especially rate of spread) is closely linked to soil moisture and the eco-physiological characteristics of the species concerned (Jurdao *et al.*, 2012) and so is more difficult to predict from weather indices alone.

4. European Forest Fire Information System fuel type map

A fuel type map for Europe was developed by the EU-funded FUELMAP project (Lanorte *et al.*, 2011) as part of the development of the European Forest Fire Information System (EFFIS). This map covers the whole of Europe with a 250 m grid cell resolution and includes 48 land cover classes, the majority of which are forest types (26 out of 48 categories are forest or shrub-forest transition vegetation types). The map was developed using existing cartographic datasets and information on vegetation from across Europe, with the aim of producing a product that could be used both in fire danger assessment and as a means to model biomass consumption and estimate emissions resulting from fires.

The FUELMAP map was derived in several steps; firstly, using data on ecoregions of Europe and the CORINE land cover dataset, natural vegetation landcover types with burnable components (wildland fuels), agricultural land susceptible to burning (non-wildland fuels) and areas not susceptible to burning e.g. urban areas and artificial land uses (non-fuels) were identified. In a second step, maps of potential natural vegetation were used to classify the area within the wildland fuels category into vegetation types, with associated information on the main species present in the vegetation and on the vegetation physiognomy. Vegetation types with similar physiognomy (and therefore similar burning responses were grouped together into fuel types.

For each fuel type, the proportion of the total fuel load in different size classes (fine fuels, medium fuels and heavy fuels) was categorised as low, medium or high and the live: dead fuel ratio was classified as low or high, to allow modelling of fire behaviour (Scott & Burgan, 2005). Since field data on the size distribution of fuels within different vegetation types in Europe was extremely scarce (except for some Mediterranean countries), this was achieved by matching the FUELMAP fuel types to a set of 40 standardised models of fuel load fractionation (Scott & Burgan, 2005) in order to derive these parameters. If locally derived data were available however, they were used in preference to the models.
The amount of biomass associated with each fuel type was estimated using MODIS satellite data to derive foliage biomass (Zhang *et al.*, 2008). Biomass was calculated as:

Foliage biomass = Leaf Area Index / Specific Leaf Area

Leaf Area Index (LAI, leaf area m^2 / m^2) was calculated from MODIS data compiled to give maximum monthly values and then averaged for the period 2002-2009. One value was derived for each fuel type. Specific Leaf Area (SLA, leaf area m^2 / kg leaf carbon) was calculated using data on SLA of the individual component species of each fuel type available in the literature and in the LEDA plant trait database (Kleyer *et al.*, 2008). An average value for each fuel type was calculated, assuming equal abundance of all component species. The foliage biomass estimate was then used to derive estimates of the biomass of other fuel components, including branch biomass and understorey biomass, using the AFOLU database of biomass compartments in different vegetation types from across the world (Lanorte *et al.*, 2011). As for SLA, estimates for each fuel type were based on the average of species level data for the component species, assuming equal abundance. Shrub biomass and herbaceous biomass were calculated from the cover of shrub and herbaceous species using simple regression equations. These values were then combined to produce a single value for biomass in each component per fuel type.
Within the FUELMAP dataset, upland vegetation in Scotland is categorised as three fuel types: peat bogs; temperate, alpine and northern grasslands; and temperate, alpine and northern moors and heathlands. The low resolution of fuel types limits the usefulness of the map in terms of describing the variability in fuel loads across Scotland, but it is possible that the methodology used to create the European FUELMAP could be used to construct a more detailed map of fuel load distribution across upland areas in Scotland.

5. Review of what is known about how NVC communities relate to fuel load (biomass)

5.1 Fuel load measurements in UK upland vegetation

Characterisation of the fuel load associated with a vegetation type requires information on the total amount of biomass present, the distribution of that biomass between different fuel components e.g. live vs dead fuels or different size components, and the bulk density of the fuel (mass of fuel per unit volume of the fuel-bed). These fuel properties will determine important fire characteristics such as the likelihood of ignition, rate of spread and sustainability (Davies *et al.*, 2008; Davies *et al.*, 2009; Santana & Marrs, 2014). Very few studies have directly addressed the characterisation of fuel loads for different vegetation types in the UK. Those studies which have measured fuel loads, have principally been concerned with development of methods for rapid assessments of fuel load in the field (Davies *et al.*, 2008) or with field methods to calibrate remote sensing approaches to measuring fuel load (Egan *et al.*, 2000) and have measured fuel loads in a very limited number of locations and vegetation types.

Fuel loads in upland *Calluna* dominated heathland have been assessed for a small number of sites in eastern Scotland (Egan *et al.*, 2000; Davies *et al.*, 2008; Davies *et al.*, 2009). Davies *et al.* (2009) characterised total fuel load, fine fuel load, height and bulk density for building, late building and mature phases of an NVC H12 *Calluna* dominated species poor community. They showed that vegetation height and total fuel load increased from building to mature phase *Calluna*, but that the fine fuel load was maximal in the late building phase and did not increase further in the mature phase, when the ratio of woody stems to fine fuels in the canopy increased (Davies *et al.*, 2008; Davies *et al.*, 2009). Bulk density of the fuel declined in the mature phase as the canopy became more open. Around 80-85% of fuel in the heathlands they assessed was live fuel, which is a particular characteristic of UK heathland vegetation and contrasts with vegetation dominated by dead or seasonally desiccated fuels where most research has been carried out (Davies *et al.*, 2009). The two studies which focussed on calibrating methods for the assessment of fuel load (Egan *et al.*, 2000; Davies *et al.*, 2008) sampled over a range of heathland vegetation types (mainly *Calluna* dominated) and so give indicative values for fuel loads over a broad 'heathland' category only. One further study (Santana & Marrs, 2016) has investigated fuel loads associated with graminoids in upland moorlands in the Peak District. Graminoids ignite easily and once alight can exhibit high rates of fire spread and intensity, making them an important fuel component to characterise. Graminoids also typically contain high proportions of dead fuels which can respond quickly to dry conditions. Santana and Marrs focussed their study at the species level rather than on any particular vegetation type, but vegetation height, total fuel load, fuel bulk density and dead fuel proportion were assessed in both spring and summer for three common species (*Eriophorum angustifolium*, *Eriophorum vaginatum*, and *Molinia caerulea*). The study showed that there were seasonal differences in fuel structure for all three species. Two species (*Eriophorum angustifolium* and *Molinia caerulea*) showed differences in height between spring and summer and increased dead fuel load in spring, while all species showed an increase in dead fuel proportion in spring. *Molinia caerulea* is likely to be of particular importance when mapping fuel load characteristics because it is deciduous, and all of its leaf tissue dies back over winter, creating a large pool of dead fuel.

5.2 Biomass measurements in UK upland vegetation

Measurements of biomass have been made much more commonly than fuel load measurements in UK upland vegetation types. Standing biomass and biomass production (Net Primary Productivity - NPP) data have been collected to characterize vegetation as part of a wide range of studies with different purposes. However, while total biomass data provides part of the information required to characterise the fuel loads associated with upland vegetation types (i.e. the total fuel load), it is important to note that many important characteristics, including the live: dead ratio and the proportion of fine fuels are not captured by this measurement. Total biomass production data are available from many studies, but often comprise a small piece of background information for any one study site and biomass is rarely assessed in terms of spatial and temporal variability across a range of vegetation types. Annual biomass production of upland vegetation types has particularly been studied in the context of grazing management and the prediction of the amount of forage available for grazing animals. Such studies generally focus on the amount of green forage produced, and production of woody biomass in stem increments and accumulation of dead material may be ignored, as they are unsuitable for grazers. Most studies of standing biomass and biomass production in UK upland vegetation types took place prior to the 1980s and measurement of biomass in its own right, is rarely an objective of recent studies.

5.2.1 Models of biomass production in UK upland vegetation

Armstrong *et al.* (1997) collated all available data (both published and unpublished) describing standing biomass and biomass production for the most common upland vegetation types in the UK with the aim of producing a model of forage available for sheep (the Hill Grazing Management Model produced by the Macaulay Institute). This model included dwarf-shrub dominated vegetation types and both indigenous and reseeded grasslands. The model structure comprised two sub-models, one predicting monthly *Calluna* dry matter production and another for grassland predicting monthly dry matter production, senescence, litterfall, standing live and dead biomass per unit area and sward height. Biomass production of different vegetation types was then based on the outputs of these two models.

In the model of *Calluna* dry matter production, the annual production of lowland *Calluna* was taken to be 2935 kg ha^{-1} (Chapman *et al.*, 1975). While for upland *Calluna* annual dry matter production was predicted from a linear regression of production vs altitude based on 28 measurements of *Calluna* productivity at sites in north east Scotland. At the time of the study, there was no data to suggest that *Calluna* productivity was any different between dry heath and blanket bog, so these habitats were treated the same. Only very limited data were available describing *Calluna* productivity for prostrate growth forms at higher altitudes, so a single productivity figure was used to represent this habitat.

For the grassland productivity model, Armstrong *et al.* (1997) commented that a large amount of data was available, giving dry matter production estimates for *Agrostis-Festuca* grasslands at a wide range of sites across the UK. However, the methods used to measure biomass varied, and this made it very difficult to compare results across studies. They also found that there was often little or no replication within any given study, even though variability was high. When collating the data, they found no effect of altitude, or degree days on grassland dry matter production, but they suggested that this was probably an artefact caused by the high variability in the methods employed. Very little information was available on the productivity of *Molinia* grasslands.

Milne *et al.* (2002) attempted to address some of the data gaps identified by Armstrong *et al.* (1997) with a study of biomass production of upland vegetation types across England and Wales. Their study focussed on productivity of six key plant species of the UK uplands; *Calluna vulgaris*, *Vaccinium myrtillus*, *Nardus stricta*, *Molinia caerulea*, *Eriophorum vaginatum* and *Agrostis-Festuca* grassland over a three-year period and across 6 regions of England and Wales. Measurements of live biomass were made at four points during the growing season, and for *Calluna*, measurements were made for each phase of the *Calluna* cycle. Annual biomass production of *Calluna* was found to be greatest in the older phases due to the greater size of the plants. They also found significant effects of region and year on production of *Calluna*, but when production was regressed against a range of climatic

variables, only limited relationships were found. For *Vaccinium myrtillus* and the grass species, limited or no effects of region and year were found.
Subsequently, the data gathered by Milne *et al.* (2002) were tested as additional calibration data for the model relationships within the Hill Grazing Management Model, and the improved models were tested against further unpublished data (R. Pakeman, Pers. Com.). However, despite the increase in the amount of data underlying the models, the Hill Grazing Management Model outputs did not give strong predictive relationships with measured data, and it seems that further field measurement data and better representation of the factors influencing biomass production would be required to produce accurate predictions.

5.2.1 Biomass variation between plant communities

Few studies have simultaneously measured total above ground biomass across a range of vegetation types in the UK uplands, with most studies focussed on a single habitat or species and often on annual biomass production rather than total standing biomass. Britton *et al.* (2011) investigated above ground biomass in the context of estimating carbon pools associated with different vegetation types. They measured total above ground biomass carbon for five widespread upland/alpine vegetation types along a topographic sequence at a single site in the Cairngorms and demonstrated that total biomass varied significantly between blanket mire (NVC class M19) and drier heathland and grassland habitats, but that differences between boreal heath (NVC H12/21) and alpine heath (NVC H13) were smaller and not significant (although this was a small study with only five replicates). This study also demonstrated that the contribution of different species groups (e.g. shrubs, graminoids, mosses) to the total biomass carbon pool varied substantially between vegetation types. Milne *et al.* (2002) showed that annual biomass production varied between common upland species, but species also differ in their litter production, total biomass accumulation and seasonality of the production of live / dead fuels (Santana & Marrs, 2016) and this variability means that vegetation types with differing species composition would be expected to have very different fuel load characteristics.

Total vegetation biomass data and annual productivity data are also available for a range of different vegetation types in single habitat studies. When trying to use these data to compare total standing biomass across different vegetation types, however, issues around the comparability of methods arise, as previously noted by Armstrong *et al.* (1997). The issue of comparability is a particular issue in studies of grasslands, where in many older studies the height above the ground at which vegetation was harvested could vary significantly, potentially having a large effect on measured biomass. Another issue with existing studies is that they are generally focussed on a fairly small geographic area. Most studies of upland heathland biomass have been carried out in the Deeside area of north east Scotland or the north Pennines (Moor House) while grassland studies are focussed on mid Wales and north east Scotland (Milne *et al.*, 2002). This geographic bias means that the range of altitude and climatic conditions covered by the studies is fairly limited which can cause issues when trying to determine the drivers of variability in standing biomass. It also means that many vegetation types more characteristic of western area of Scotland have never been studied.

5.2.2 Seasonal change

Seasonal variability in standing biomass is of greatest importance when considering the graminoid component of upland vegetation, since graminoid species, and especially deciduous species such as *Molinia caerulea*, show pronounced seasonal cycles in standing biomass and live: dead ratio (Albertson *et al.*, 2009; Santana & Marrs, 2016). Santana and Marrs (2016) measured a range of fuel characteristics for *Eriophorum vaginatum*, *Eriophorum angustifolium* and *Molinia caerulea* in the Peak District. They showed that all three species had a greater proportion of dead fuel in spring versus summer but the increase was particularly marked for the deciduous species *Molinia caerulea*. Changes in the amount of fuel present were less marked; total fuel load only differed significantly between spring and summer for *Eriophorum vaginatum* where it was higher in spring than in summer, while dead fuel load was significantly greater in spring for *Eriophorum vaginatum* and *Molinia caerulea*. Studies of biomass production in *Molinia caerulea* meadows in the Czech Republic showed similar seasonal dynamics (Bartos *et al.*, 2011; Dolezal *et al.*, 2019); in unmown plots, green biomass peaked in August, while litter biomass was least in August and greater in spring and autumn. Similarly in *Agrostis-Festuca* grassland in Snowdonia live biomass peaked in August, while attached dead biomass peaked in October and the declined slowly during the winter and spring (Perkins *et al.*, 1978). Milne *et al.* (2002) measured biomass accumulation during the growing season (April – October) for *Molinia caerulea*, *Nardus stricta* and *Eriophorum vaginatum* across England and Wales. As in the other studies mentioned above, they found that *Molinia* biomass peaked in August, followed by a sharp decline during senescence in October. *Nardus stricta* showed a similar increase from April to August followed by a decline, while *Eriophorum vaginatum* biomass followed a pattern that was more variable between regions, generally increasing slowly from April to October, but in some regions showing faster growth with a peak in August and decline in October.

Seasonal variation in production or standing biomass of dwarf shrubs has been measured less often, with most studies focussed on annual production of biomass. Milne *et al.* (2002) measured biomass production of *Calluna vulgaris* shoots in pioneer, building and mature phases over the April to October growing season and found that biomass production was greatest during the spring and summer (April – August), levelling off in Autumn. This concurs with an earlier study (Miller, 1979) which also showed that the rate of production of current year shoots in *Calluna* increased sharply from April to June and was highest during June – August before declining almost to zero by October. Aerial biomass of current year's shoots thus peaked in October and was steady for the rest of the year. Miller (1979) also showed that biomass of woody stems increased slowly from June to November, presumably due to lignification of stems, followed by a decline over the early part of the winter period, likely as a result of litter fall. Biomass of flowers peaked in August, while biomass of previous year's shoots slowly declined during the year. Overall the total biomass of the stand showed a small positive increment over the year of around 90 g m^{-2}.

Information on seasonal biomass change for other dwarf shrubs is extremely scarce. Milne *et al.* (2002) measured seasonal biomass production for the deciduous dwarf shrub *Vaccinium myrtillus* and found that biomass production was greatest in April – June but reduced over the later part of the summer.

5.2.3 Effects of climate

Since biomass measurements in upland heathlands and grasslands have a relatively restricted geographical distribution in the UK, as noted previously (Armstrong *et al.*, 1997; Milne *et al.*, 2002) our knowledge of spatial variability in biomass production in relation to climate is also rather limited. Miller and Watson (1978) compared annual production of *Calluna* shoots and flowers between several studies from across the north east of Scotland and showed that annual production was inversely related to elevation, declining from 3000 kg ha^{-1} at 100 m, to 1500 kg ha^{-1} at 550 m. A similar reduction in heathland biomass with altitude between 550 m and 850 m was found by (Marrs *et al.*, 2018). This relationship suggests a strong influence of climate on productivity and when productivity was compared across several years it was found that variability in production was negatively related to rainfall and positively related to air temperature during May-August (Miller, 1979). Summers (1978) measured standing biomass and annual biomass production in alpine heaths at a range of sites in the Cairngorms. *Calluna* production was shown to be strongly inversely related to an index of exposure based on the growth of *Festuca rubra* at each site. However, when productivity of alpine heaths was calculated per day of growing season (using a 5.6 °C threshold for growth) the productivity of alpine heaths was found to be very similar to that of upland and lowland heaths elsewhere. Inter-annual variation in productivity was also found to be related to variation in growing season length and growing season was thus proposed to be the main control on biomass production in alpine *Calluna* heaths. A more recent study (Britton & Fisher, 2008) also investigated climatic correlates of inter-annual variability in shoot production in alpine heaths. This study found that in *Calluna*, shoot extension was positively related to mean spring temperature, while in *Vaccinium myrtillus*, growth was negatively correlated with winter rainfall and positively related to winter temperatures.

Similarly to heathlands, inter-annual variability in biomass production of upland grasslands was primarily related to temperature (Perkins *et al.*, 1978). Temperature tended to be the main constraint on growth in spring, while moisture could become limiting later in the growing season. When they were extreme, low winter temperatures could also impact on biomass production in the following growing season. When considering spatial variability in aboveground biomass carbon over a range of plant communities, Britton *et al.* (2011) showed that above ground biomass was positively related to mean winter soil temperature.

5.2.4 Effects of management

The effects of management are the most frequently studied influence on *Calluna* biomass production. In the eastern half of Scotland, many areas of low to mid-altitude heathland are managed for grouse shooting by rotational burning, and biomass accumulation during the growth phases of *Calluna* following burning has been well studied (Gimingham, 1972; Gimingham *et al.*, 1979; Hobbs & Gimingham, 1987). Following fire, *Calluna* dominated vegetation goes through several phases of development termed pioneer, building, mature and degenerate, where the plants first establish, then grow to form a dense canopy which eventually becomes more open as plants age and their branches spread and become prostrate. This sequence of developmental phases is known as the '*Calluna*-cycle' and is a key feature of *Calluna* dominated heathlands (Barclayestrup & Gimingham, 1969; Hobbs & Gimingham, 1987). It is most important in managed heathlands, where rotational burning ensures that the cycle is synchronised for all plants within a burned patch. In unburned heathlands, uneven-aged stands of *Calluna* develop, with a mixture of *Calluna* phases present. Total vegetation biomass increases during the pioneer (ca. 0-6 years post fire) and building (ca. 6-13 years) phases and reaches a maximum in mature (13-20 years) stands before declining during the degenerate phase (Barclayestrup, 1970; Hobbs & Gimingham, 1987). This pattern is dominated by the biomass of *Calluna*, whereas biomass of grasses, sedges and other dwarf shrubs within the community shows the opposite pattern, being maximal in the pioneer phase (Barclayestrup, 1970). Annual biomass production of *Calluna* is greatest in the late building/early mature phase when the plants are biggest (Hobbs & Gimingham, 1987; Milne *et al.*, 2002). Standing biomass in stands of different phases can vary from zero immediately post fire, to around 20 000 kg ha^{-1} in mature stands, with obvious and significant implications for fuel load. The overall impact of burning management on fuel loads at the landscape scale will depend on the frequency (fire return period) and extent (proportion of area burned) of burning management; lower fire frequency is generally associated with increased fuel loads (Milligan *et al.*, 2018) and can result in the build-up of dry litter materials.

It should be noted that there has been a focus on the above ground components of heathlands. The quantity of potential available fuel in the moss and litter layer is almost the same as the above ground biomass (Gimingham, 1972). In the 2018 summer fires around Manchester, such as at Winter Hill, exhibited fire behaviour that was driven from the moss and litter layer when the above ground biomass e.g. grasses were still green. This highlights the importance of the non-biomass fuels.

In higher altitude alpine heaths, *Calluna* is generally not burnt and so biomass in these heaths is considered to remain in a steady state (Summers, 1978). In western Scotland, heathlands are not generally managed for grouse, and are instead more likely to be used for extensive grazing. These western heathlands may be intermittently burned to remove build up of graminoid litter and encourage nutritious growth for grazing animals, but the impact of this type of burning regime on standing biomass and production has not been studied. Aside from burning, the other major management influence on upland heathland and grassland biomass is grazing. Since grazers remove biomass, their effect will generally be to reduce the standing crop of biomass and thus also fuel load, to a degree dependent on the intensity of grazing (Silva *et al.*, 2019; Starns *et al.*, 2019). However, some UK studies have found no effect of grazing removal on above ground biomass in upland heath and bog communities (Marrs *et al.*, 2018) and the effects of extensive grazing may often be small. Unless levels of grazing are excessive it will generally have only limited effects on productivity in subsequent years. In heathlands, Grant *et al.* (1982) found that at rates up to 40% utilisation, dry matter production of *Calluna* was unaffected by grazing. Similarly Armstrong *et al.* (1997) found that sward height had little effect on growth rate per unit area in sown grass unless it was reduced below 3cm. They found little information for native grasslands, so assumed that productivity in these systems was also unaffected by grazing intensity. Feeding preferences of grazing animals will also alter the effects of grazing (Silva *et al.*, 2019), preferential grazing of certain species groups e.g. grasses in UK upland communities, may alter fuel load characteristics of the plant community such as the amount of graminoid versus dwarf shrub biomass and the amount of dead litter. Ultimately, grazers may also influence the species composition of vegetation, favouring graminoids and grazing-tolerant herb species in preference to dwarf shrubs. Dwarf shrubs can become a more important part of the diet of upland graziers, such as red deer, in winter.

5.2.5 Nitrogen deposition

Deposition of nitrogen (both oxidised and reduced forms) is typically greater over upland areas of the UK than in the surrounding lowlands, due to high wet deposition in rainfall (NEGTAP, 2001). In Scotland there is a gradient of nitrogen deposition from low levels in the north and west, to higher levels in the south. Nitrogen is a key plant nutrient which is often in short supply in the typically nutrient poor, acid soils of the Scottish uplands. Addition of extra nutrient nitrogen in rainfall would therefore be expected to have a positive impact on plant biomass production, assuming that growth is not also co-limited by other nutrients such as phosphorus (Butterbach-Bahl & Gundersen, 2011; Tipping *et al.*, 2017). Increased nutrient availability may also cause changes in the competitive balance between species in plant communities, as some species are more able to exploit additional nutrient supply than others (Dise *et al.*, 2011).

Several experimental and field survey studies have investigated the impacts of nitrogen deposition on upland heaths in the UK. Evidence from experimental nitrogen additions to a range of upland and alpine heathland types shows that nitrogen deposition generally increases annual biomass production of *Calluna* (Phoenix *et al.*, 2012). Measurement and modelling of carbon stocks in biomass also suggests that the increased productivity leads to greater total standing biomass of *Calluna* and to greater biomass in the litter layer (Field *et al.*, 2017). Effects of nitrogen deposition on productivity are seen even at relatively low levels (10 kg N ha^{-1} y^{-1}) but stimulation of productivity tends to saturate at higher levels of nitrogen addition as plants are unable to retain all of the added nitrogen (Phoenix *et al.*, 2012). These findings suggest that nitrogen deposition likely has a positive effect on productivity of heathlands in the UK which may act to increase fuel loads in areas receiving moderate to high nitrogen deposition. In survey studies of heathlands across Scotland and the UK, increased nitrogen deposition is also associated with increased abundance of graminoids (Maskell *et al.*, 2010; Southon *et al.*, 2013; Field *et al.*, 2014; Britton *et al.*, 2017). Since graminoids grow faster than dwarf shrubs they are generally better able to exploit the increased nutrient availability and nitrogen deposition may shift the competitive balance in their favour. This could have an important influence on fuel characteristics.
In contrast to heathlands, experimental studies in UK upland grasslands have found only limited effects of nitrogen deposition on productivity (Phoenix *et al.*, 2012) and it has been suggested that this is due to growth being limited by nutrients other than nitrogen. Changes in grassland species composition have, however, been observed along gradients of nitrogen deposition in the UK, with richness of forb species declining as nitrogen deposition increases (Stevens *et al.*, 2006; Maskell *et al.*, 2010). These observations suggest that, unlike in heathlands, nitrogen deposition is not likely to have a major impact on the fuel characteristics of upland grasslands.

6. Key unknowns

This review has highlighted several key gaps in our knowledge in relation to mapping fuel loads and understanding the relationships between vegetation types and fuel load characteristics in the UK. **Measurements of fuel load, which include characteristics such as the amount of biomass in different fuel size categories, or live: dead fuel ratios are scarce in the literature**. While methodologies for rapid assessment of fuel loads have been developed (Davies *et al.*, 2008) they have not yet been implemented to any degree for broad scale assessment of fuel load. Data describing standing biomass or annual biomass production are much more common, mostly deriving from studies of biomass production for grazing animals. These studies providing data on biomass are primarily focussed on a narrow range of community types (dry heathlands and grazed grasslands) and a limited number of geographical locations (east of Scotland, north Pennines and mid-Wales). **Biomass or fuel load data from wet heathlands, blanket bog, grassy heaths, semi-natural grasslands and habitats in the west of Scotland are lacking**.

Most studies to date focus on single plant species or communities; comparing across studies to assess relative fuel loads associated with different vegetation types is often difficult, due to differences in methodologies used, making comparisons uncertain. **More studies measuring fuel loads across a range of habitats in a comparable way are required** to improve our ability to map fuel load for multiple habitats.

Studies of heathland and grassland biomass to date indicate that climatic parameters such as growing season length, air/soil temperature and rainfall probably influence biomass production and standing biomass. Previous modelling exercises suggest, however, that the currently available pool of data is insufficient to allow robust relationships between climate and vegetation biomass/ fuel load to be derived. **Measurements of fuel load characteristics along latitudinal, altitude and climatic gradients in Scotland for a range of soil types and plant communities are required** to enable fuel loads to be better predicted over a wide geographic range.

Producing maps of fuel load or fuel characteristics for Scotland raises a number of issues. Before producing any map one key question arises which is **'at what spatial resolution do we need to map fuel loads to usefully inform on fire danger in Scotland'**. It is vitally important to determine the required mapping resolution before embarking on an attempt to map fuel loads in order to ensure both that the end product is useful and that unnecessary resources are not consumed in its production. Currently available vegetation mapping data would enable only very coarse mapping of fuel loads. If, as seems likely, NVC level data on community composition is required, **the current 'upland survey gap' and lack of detailed vegetation mapping for most upland areas in Scotland will be a major barrier to production of a fuel load map**.

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8.3 Glossary

The international wildfire community use a broad range of specialist nomenclature. The websites below contain glossaries of the accepted terminology.

- 1999 Revision of the FAO Wildland Fire Management Terminology by the Global Fire Monitoring Centre (GFMC)

  GFMC- UN FAO 2018 - https://gfmc.online/wp-content/uploads/GFMC-FAO-Fire-Management-Glossary-1999-edited-2018.pdf

- National Wildfire Coordinating Group (NWCG)

  NWCG (USA) - https://www.nwcg.gov/glossary/a-z

- International Association of Fire and Rescue Services (CTIF)

  CTOF - https://www.ctif.org/library/european-glossary-wildfires-and-forest-fires