

FireBeaters Phase II



Final Report
to
Scottish Natural Heritage

Project No. 23183

Colin Legg & G. Matt Davies

The University of Edinburgh
Centre for the Study of Environmental Change and
Sustainability
School of GeoSciences
Crew Building, King's Buildings
Edinburgh EH9 3JN

c.legg@ed.ac.uk
0131 650 5401

1 Introduction

1.1 Background

The significant and damaging wildfires in April 2007 again highlighted the need for a Fire Danger Rating System (FDRS) for the UK. The work to develop an appropriate system for UK conditions was started by the Countryside Agency (now part of Natural England) as part of the requirements of the Countryside and Rights of Way Act (2000). This phase of the work was conducted by the Met Office and resulted in the production of the Met Office Fire Severity Index (MOFSI) (Met Office 2005). Under the Countryside and Rights of Way (CRoW) Act 2000, Relevant Authorities are able to enforce fire prevention restrictions on open access land where necessary. Fire prevention restrictions aim to minimise accidental fires by suspending open access rights when conditions are exceptional. The FSI is a meteorological model that uses wind speed, temperature, rainfall and relative humidity to provide an objective indication of fire severity on a scale of 1 to 5, 5 being exceptional. An FSI rating is displayed daily for each 10 km x 10 km OS grid square at <http://www.openaccess.gov.uk> and <http://www.ccw.gov.uk> covering England and Wales respectively. When a FSI of level 5 occurs, a fire prevention restriction can be triggered (Thomas 2008).

While the MOFSI is ideally suited to its purpose under the CRoW Act, it provides a single index on a five-point scale which is not sufficient to capture all of the variation in weather and fuel conditions that are of interest to those who work with vegetation fires in the UK (Davies & Legg 2008). Further research was needed to develop a better understanding of the relationships between weather conditions, fuel type and fuel conditions, particularly fuel moisture content. The FireBeaters Phase I project funded jointly by the Scottish Executive and Scottish natural heritage (SNH), tested the components of the Canadian Forest Fire Weather Information System on which MOFSI is based as predictors of fire behaviour. This built on the initial research into fire behaviour and effects in heather moorland by Matt Davies at The University of Edinburgh.

1.2 FireBeaters Phase I

As part of the FireBeaters Phase I project the Scottish Executive and SNH commissioned Edinburgh University and the Met Office to extend MOFSI to cover Scotland and conduct fire tests and collect other data to assist the development of Fire Behaviour Prediction (FBP) models for heather fires.

FireBeaters Phase I (Legg *et al.* 2007) ran from January 2006 to May 2007 and achieved the following:

- the creation of the FireBeaters Web site
- the publication of the Met Office Fire Severity Index for Scotland
- experimental fires and ignition tests in conjunction with Whitburgh Estate and the Scottish Agricultural College (Pentlands) and South Drummochter Estate (Dalwhinnie)
- the collation of a more than 8000 fire records from Fire & Rescue Services, Moors for the Future, Dorset Heaths Project, Forestry Commission, various keepers and estates and our own experimental fires
- the collation of weather data from the Met Office for 2003 – March 2007
- analysis and construction of models relating behaviour of experimental fires to fuel structure, moisture content and weather data
- analysis of fire reports available from 2003-2006 to weather data
- publication of a final report following external review

The recommendations from Phase I for further research were as follows:

- Construct a model enabling moisture content of heathland fuels to be predicted from Met Office NWP forecast data.
- Conduct further ignition tests in a wider range of fuel types
- Conduct further experimental fires in a wider range of fuel types, and fire conditions. This should include fires on slopes and with a wider fire front, and should also include summer fires in 'wildfire' conditions.
- Establish a network of volunteers to record fire behaviour on normal management fires and to test preliminary fire behaviour models.
- Obtain additional records from the Fire & Rescue Services and link these to topography and vegetation maps using a GIS.

- Similar experimental fires to those conducted in heathland should now be extended to gorse and grassland. Fuel moisture models should be constructed for purple moor grass (*Molinia*) grasslands that include leaf death ('curing') in autumn and green-up in spring. Fuel moisture and fire behaviour models for gorse can be developed through collaboration with researchers in New Zealand, but need to be calibrated for UK conditions.
- Peat fire research currently underway at Edinburgh funded by the Met Office should be coordinated with the FireBeaters Phase II with ignition tests linked to fire behaviour in summer wildfires in grassland and heathland.

1.3 Phase II developments

The FireBeaters Phase II project was therefore established with three month's funding to address the following work packages:

1. Construct a model of live fuel moisture.
2. Extend the small-scale ignition tests.
3. Extend the experimental heather fires to a wider range of fuel types.
4. Establishing protocols for experimental grass fires.
5. Relate wildfire records to weather, vegetation and site characteristics.
6. Calibrate a preliminary fire danger rating for heather fires.
7. Maintain and further develop the FireBeaters Web site.

In the event, the weather conditions in March and early April 2008 were totally unsuitable for experimental burning. It was therefore not possible to make progress on packages 3 and 4. Instead, laboratory work was conducted on the ignition process for moss and litter samples and this is reported below.

In addition, there has been considerable development over the last 12 months in the proposals for the UK Vegetation Fire Standard (UKVFS) which will provide a standard incident reporting system for the Fire & Rescue Services. This is a new database that is being designed by Rob Gazzard of the Forestry Commission on behalf of the Fire and Rescue Statistics User Group and will deliver detailed and comprehensive data on future wildfires in the UK. This

therefore supersedes the fire recording database component of the FireBeaters Web site and this changes the priorities for Work Package 7.

Other notable developments in the UK fire scene include the commencement of programmes of grass fires by Ian Murgatroyd of the Forestry Commission, and of *Calluna* fires by a consortium comprising Northwoods, the Northumberland Fire & Rescue Service, the Northumberland National Park Authority and others. Although these programmes have the development of operational and management techniques as the primary focus, it is hoped that they will also provide additional data linking fire behaviour to weather and fuel conditions.

2 Work packages

2.1 Construct a model of live fuel moisture

Continue the collection of data on fuel moisture in Calluna and construct a model of live fuel moisture that would replace the Fine Fuel Moisture Code (FFMC) of the Canadian Fire Weather Index System. This model will include: estimates of drying rates of live and dead heather; estimates of drying rates for litter and mosses; the effects of soil temperature on water availability to living heather; and information on green-up of heather shoots in summer and frost damage in winter. Although there is as yet insufficient data to quantify all of these factors we believe that a simple qualitative or semi-quantitative model will greatly enhance the predictions of the Canadian FWI model.

2.1.1 Introduction

Fuel moisture content is considered the primary factor that determines ignition probability and fire behaviour. Most fire models produced elsewhere in the world consider fire behaviour to be determined largely by the moisture content of dead fuels as these fluctuate with weather conditions and may be very low under certain conditions. Fire behaviour is therefore determined largely by weather conditions and the amount of dead fuels available for combustion. Live fuels, on the other hand, are normally considered to have relatively high and

constant water content as the plant can actively regulate water uptake through the roots and loss by stomatal control.

Legg et al. (2007) proposed that in UK *Calluna*-dominated fuels, the canopy of the shrubs may, under certain circumstances, show very low moisture contents (as low as 40-45% of oven-dry weight). This is a much lower water content than is normally associated with living plant tissues and may permit the live fuel to ignite and carry a fire alone, even in the absence of dead fuels, and permit extreme fire behaviour.

Understanding fluctuation of water content in these fuels is therefore critical to understanding and predicting fire occurrence and behaviour. In the first phase of FireBeaters Legg et al. (2007) proposed an outline for a physiological model on live *Calluna* moisture content. Work completed in this phase of the project included additional collection of fuel moisture data and the development and testing of the physiological fuel moisture model.

2.1.2 Methodology

Field collection of fuel moisture data

Samples have been collected from the experimental site at Black Hill in the Pentlands (Grid Reference NT187269). The sampling protocol that was used in the FireBeaters Phase I project (Appendix 4.1) has been followed.

Samples collected include live canopy fuel, dead fuel suspended in the canopy and the top two centimetres of the moss/litter layer. Samples have also been taken of peat cores as part of the related Peat Fuel contract with the Met Office and these are also reported here.

A weather station (Table 1) at Black Hill records local weather conditions hourly (Table 2) and these are being used to model fluctuations in fuel moisture content with weather. In addition, further work has attempted to model the moisture content of fuels using the National Weather Prediction (NWP) forecast

data from the Met Office that was received as part of the FireBeaters Phase I project and with the indices of the Canadian Forest Fire Information System. This has been restricted to samples collected between 2003 and March 2007 for which weather data are available.

Table 1. Equipment installed on the weather station at Blackhill. All equipment supplied by Campbell Scientific.

MP100A Temperature and Relative Humidity Probe mounted in USR1 Unaspirated-RS Radiation Shield
107 Thermister Temperature Probe (used for soil temperature)
237 Wetness Sensing Grid
ARG100 Tipping Bucket Raingauge
Solar Panels
CR10X Data Logger and AM16/32 Channel Relay Multiplexer
05103-5 Wind Monitor
SP1110 Pyranometer Sensor
253 Soil Moisture Sensors

Table 2. Data logged by the weather station at Blackhill.

Variable	Stored statistics each hour	Units
Date/time		
Wind speed	mean, standard deviation	m s ⁻¹
Wind direction	mean, standard deviation	deg EoN
Net Radiation	mean, standard deviation	W m ⁻²
Temp	mean, max, min, standard deviation	°C
Relative humidity	mean, max, min, standard deviation	%
Rainfall	total	mm hr ⁻¹
Wetness	mean, max, min, standard deviation	%
Soil temperature (3 or 4 probes) at 2 cm below surface	Mean	°C
Soil resistance (6 or 8 probes) at 2 and 10 cm below surface	Mean	kΩ

Fuel moisture modelling

The model has been developed substantially since the end of FireBeaters Phase I (Figure 2.1.1). A background to the development of the model and justification for this approach are provided by Davies & Legg (2008). Four key processes drive the behaviour of live FMC:

- Evapotranspiration
- Changing cuticular resistance
- The development of cold and frozen ground
- The effect of water viscosity on the resistance of the root-leaf pathway.

The hypotheses underlying the model are based on observations, reported by Legg et al. 2007 and Davies et al. (in review) of low canopy FMC during periods of cold but sunny weather in early spring. Cold or frozen ground creates physiological drought conditions that, combined with low cuticle resistance due to overwinter damage, causes *Calluna* plants to dry out rapidly.

Evapotranspiration is modelled in a standard form as presented by Allen *et al.* (1998). Bannister (1964) reported that typical values of cuticular resistance range between 4 and 20 mm hr⁻¹, though the range of conditions in which these were collected is unclear. The model assumes these represent early spring minimum and summer maximum values respectively. Using the graphing function in Simile we have estimated a monthly sigmoidal decline in resistance from mid-summer to early spring and a similar pattern of recovery in early spring. The build-up and decay of frozen ground conditions is based on the calculation of a running mean temperature that defines a value for the variable “Frozen ground” between 0 and 1. The rate of development and decay of frozen conditions is currently entirely estimated. “Frozen ground” is used to control values of soil water potential Davies (2005) which was based on the range of values collected by from 2003 to 2006, and which includes values from mid-summer and deep-frozen conditions in winter (Figure 2.1.2). Viscosity of water was modelled using a standard temperature function. The Penman-Monteith equation models leaf water potential (LWP). We used data collected by G. Jackson (pers. com.) to estimate the relationship between LWP (or shoot water potential) and relative water content (RWC). Jackson’s data were collected in

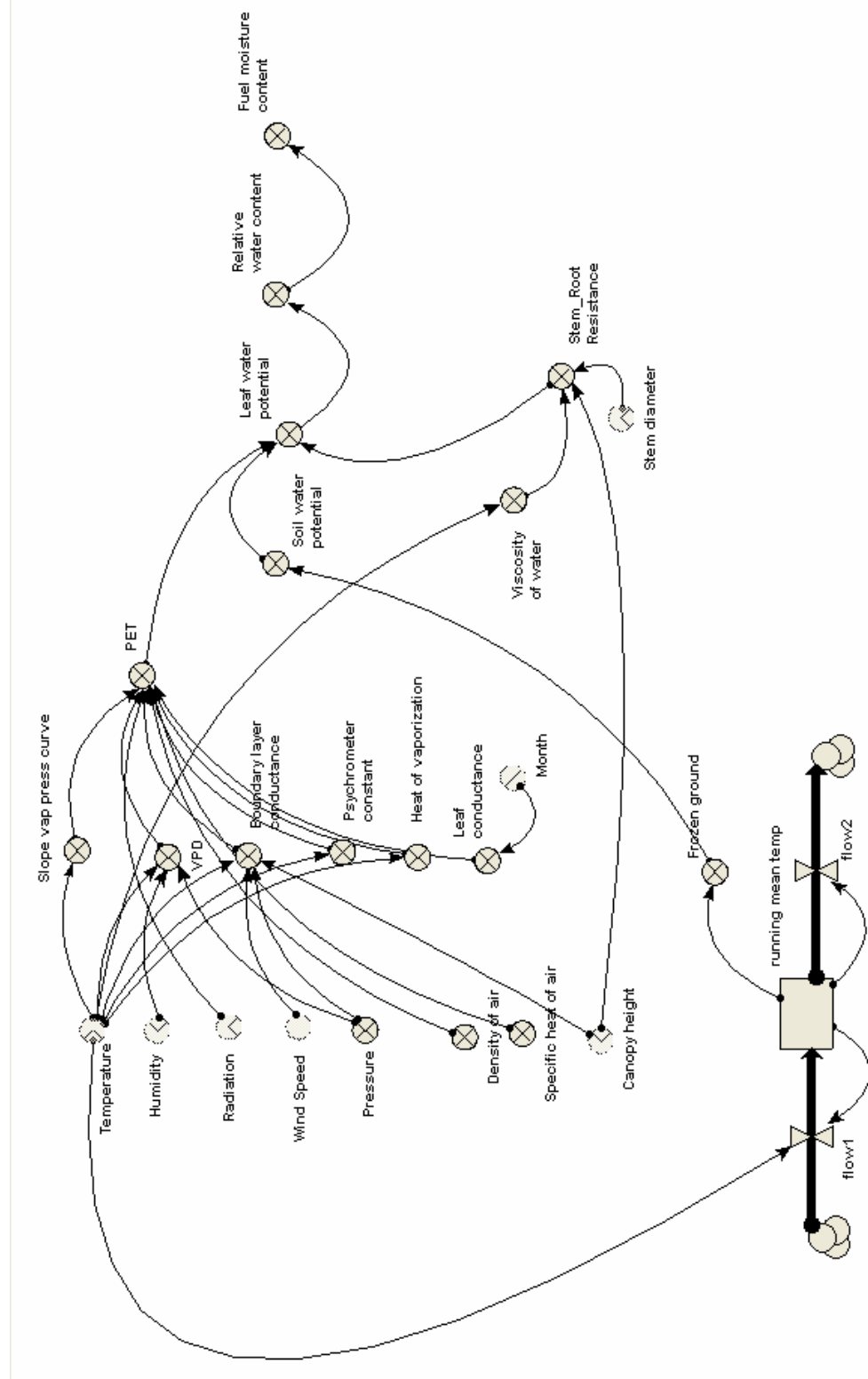


Figure 2.1.1. The main relationships in the Simile model of fuel moisture.

summer from *Calluna* in both dry heathland on mineral soils in the south of England and Scottish moorlands on peat soils. It represents only a narrow range of possible variability (Figure 2.1.3). Fuel moisture content was estimated from RWC (Figure 2.1.4) using values collected by Davies (2005). Initial analysis of these data suggests that this relationship may be day, season or site dependent (Figure 2.1.5).

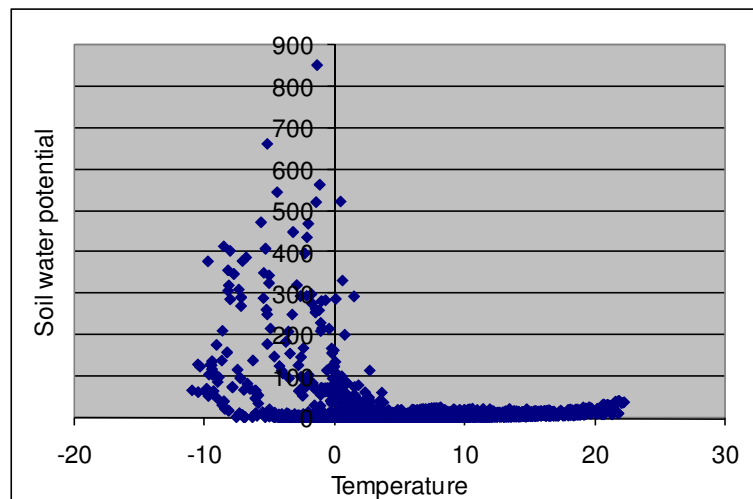


Figure 2.1.2: The relationship between soil water potential and average air temperature.

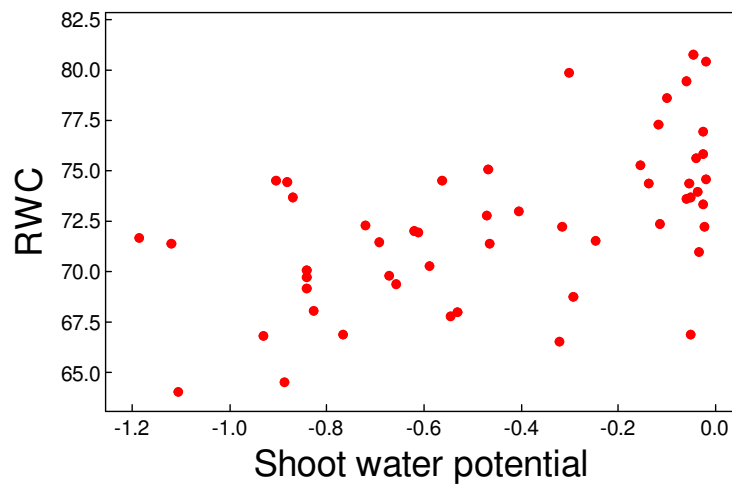


Figure 2.1.3: The relationship between shoot/leaf water potential and relative water content. Data courtesy of Gail Jackson (unpublished).

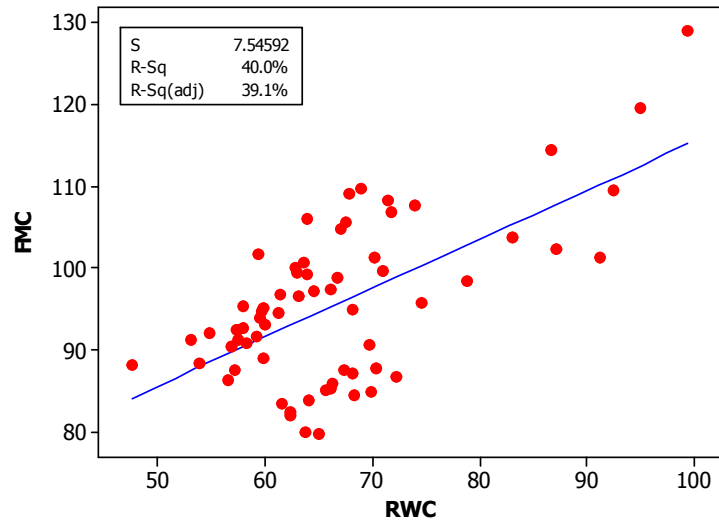


Figure 2.1.4: The relationship between fuel moisture content (fresh mass as a percentage of dry weight) versus relative water content (fresh mass as a percentage of fully saturated mass). Regression line shown is $FMC = 55.81 + 0.596 RWC$.

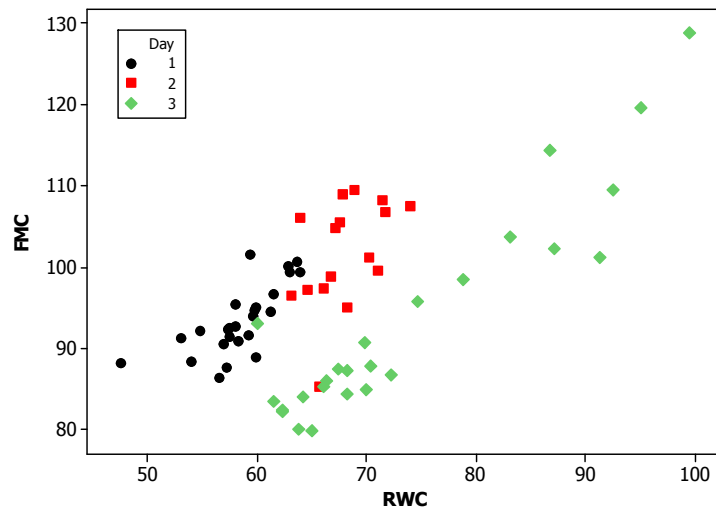


Figure 2.1.5: Scattergraph of Fuel moisture content (fresh mass as a percentage of dry weight) versus relative water content (fresh mass as a percentage of fully saturated mass). Data were collected on three separate days and significantly different relationships appear to exist.

The model was run on weather data collected by Davies (2005) during the spring of 2004. Fuel moisture contents were also collected and it included one of the periods of unusually low FMC described earlier. We compared output from the model with observed values of FMC.

2.1.3 Results

Field collection of fuel moisture data

As reported in the FireBeaters Phase I report, the moisture content of the live canopy material is not related to the Canadian FWI indices and this observation is upheld by the new data. Although high fuel moisture contents may be found at any time of year after rain, the minimum FMC relates most clearly with season and with temperatures (Figure 2.1.6). Canopy FMC is consistently high during the summer months after green-up in June when the soil is relatively warm and roots are active. The lowest FMC values are in late spring where the soil is cold and the previous-year's leaves have damaged cuticles that prevent stomatal control from limiting shoot water loss.

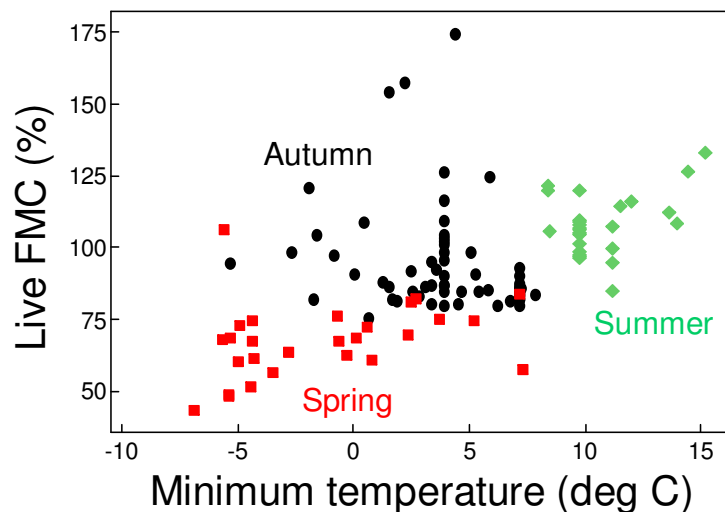


Figure 2.1.6. The relationship between live FMC and minimum temperature for data collected in spring, summer and autumn from 2004 to 2008.

Similarly, dead fuel suspended in the canopy shows considerable variation in moisture content, but does not relate to the Canadian fire weather indices of Met Office NWP data except time since last rain and wind speed.

The moisture content of moss and litter, by contrast, is relatively well modelled by the Canadian Duff Moisture Code (DMC) and relates well to the Met Office MOSES Fractional Soil Moisture (Figure 2.1.7). Thus the moisture content of moss and litter relates to the drying conditions of the weather in the previous 10 days or so. It is

possible that the MOSES Potential Evaporation may give slightly better results than either DMC or Fractional Soil Moisture (Figure 2.1.8) though there are rather few data points available to confirm this.

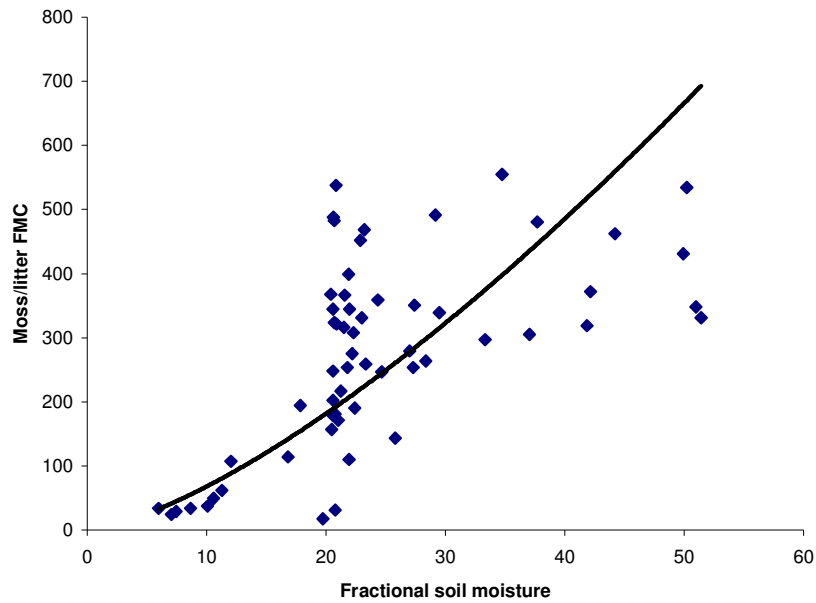


Figure 2.1.7. Relationship between the moisture content of moss and litter and the Fractional Soil Moisture calculated from the Met Office MOSES predictions. The regression line plotted ($R^2 = 0.56$) is:

$$\text{FMC} = 2.60 \cdot \text{Fractional soil moisture}^{1.42}$$

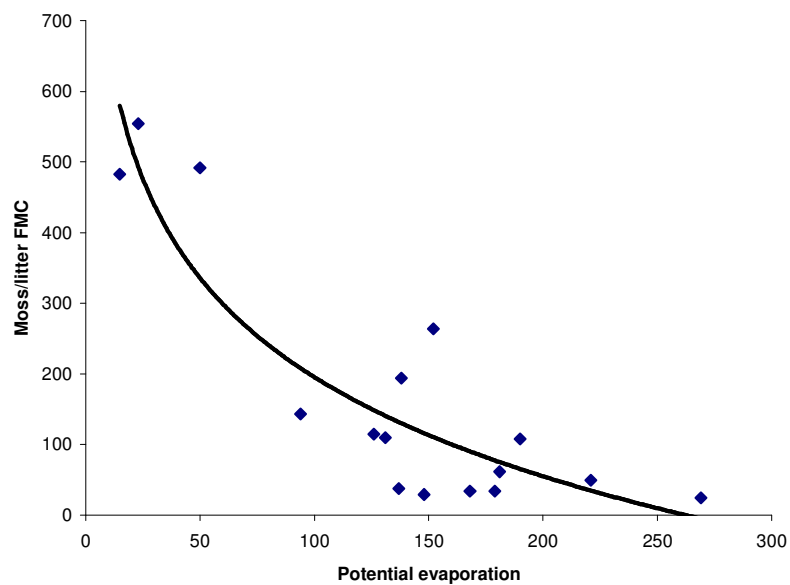


Figure 2.1.8. Relationship between the moisture content of moss and litter and potential evaporation recorded by the the Met Office MOSES predictions. The regression line ($R^2 = 0.81$) is:

$$\text{FMC} = 1128 - 202.6 \cdot \ln(\text{Potential evaporation})$$

Fuel moisture modelling

The performance of the model in terms of its ability to predict actual FMC was rather poor and negative values were predicted on several days. Observing that there were significant problems associated with relating leaf water potential with canopy fuel moisture content (Figures 2.3 and 2.4) we also compared trends in predictions of LWP with observed trends in FMC (Figure 2.1.9). Though the magnitude of the predicted changes were too great and recovery following the freezing event too rapid, the model does seem to have captured the mechanism causing the rapid decline in live *Calluna* FMC.

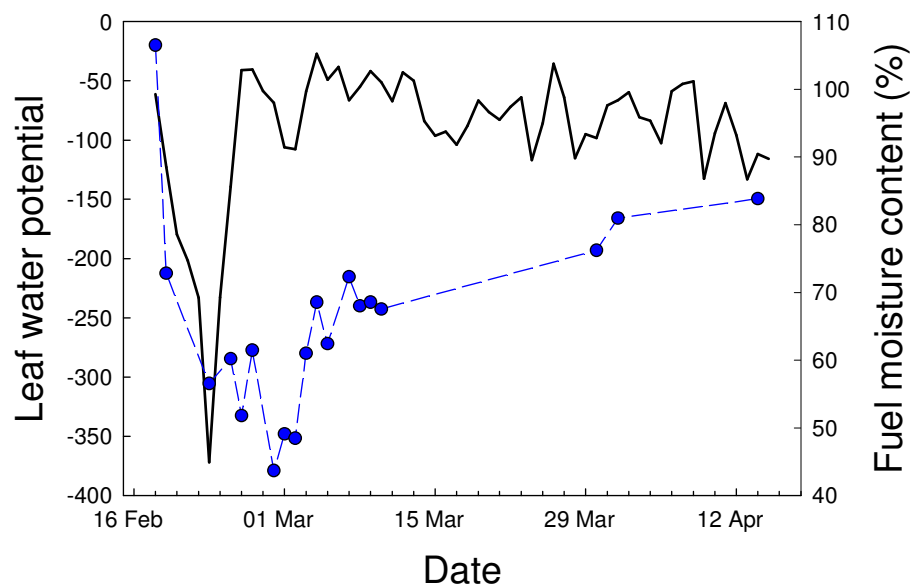


Figure 2.1.9. Modelled changes in leaf water potential (black) compared to observed changes in live fuel moisture (blue) content for data collected in spring 2004.

2.1.4 Conclusion

Attempts to provide a detailed predictive model of the different fuel components of *Calluna* moorland relating moisture content to weather have so far produced only limited success. It seems likely that the fine dead fuels suspended in the *Calluna*

canopy are so fine that they dry very rapidly after rain and reach equilibrium moisture content on a time scale too short to model with Met Office daily weather forecast data.

Though our fuel moisture model currently contains a good number of “best-guesses” and estimations for important processes it has already yielded promising results. Appropriate data are needed to allow more accurate modelling of seasonal, climatic and topographical effects on cuticle resistance. Davies and Legg (2008) demonstrate the importance of this for understanding changes in fuel moisture. Further information is also needed on the conditions and rates at which frozen ground forms and thaws as this provides a second key factor driving rapid, spring changes in FMC. It is difficult to link LWP directly to FMC as relationships may vary considerably from plant to plant depending on their structure and phenological state. More robust information on these relationships from a wider range of conditions is needed. Our results suggest that it is possible to construct a physiologically-based model of live FMC and that a working model would provide an important contribution to fire danger rating in Scotland.

A new project is currently underway by Rory Curtis of the University of Edinburgh which includes more detailed measures of fuel moisture on Black Hill. In this project fuel moisture measures will be compared directly with data from the local weather station. This should give much more precise (hourly) data for modelling fuel moisture in rapidly changing fine fuels. This project will be reporting in May 2009.

2.2 Extend the small-scale ignition tests

These will confirm initial observations (currently based on only 12 test fires) that heather fires will not be self-sustaining if live fuel moisture is > 65% and extend the observations to a wider range of fuel types. The number of fires that can be achieved is weather dependent, but the target will be an additional six tests in each of building-phase, mature-phase and degenerate-phase (rank) heather in a range of weather conditions.

2.2.1 Introduction and methods

Previous fire behaviour research in the UK (Davies *et al.* 2006, Legg *et al.* 2007) has failed to adequately identify the role of fuel moisture content (FMC) on fire behaviour, and though Legg *et al.* 2007 and Davies *et al.* (submitted 1) advanced our knowledge considerably, the relative importance of dead and live fuels and their FMC is still not well understood. The fact that *Calluna*-dominated fuels mostly comprise a live, green component that can display significant seasonal, intra-seasonal and diurnal variation (Jackson *et al.* 1999, Davies 2005, Davies *et al.* submitted 2) makes it difficult to predict changes in the flammability of *Calluna*. Large-scale experimental fires of the sort documented by Legg *et al.* (2007) and Davies *et al.* (submitted 1) are one way to try and discern the relationships between environmental variables and fire behaviour, but are labour and time intensive to set up and monitor and have focused on a restricted range of conditions when fires were likely to be self-sustaining. As part of this second phase of the FireBeaters project we had planned to expand our dataset of large experimental fires. However, limited funding introduced considerable time and labour constraints during a burning season that was already heavily curtailed by exceptionally poor weather. We therefore sought to maximise use of resources by concentrating on the increasing the number of replications of a smaller scale ignition experiment commenced as part of FireBeaters Phase I (Legg *et al.* 2007). This experiment will allow us to relate the moisture content of a number of different *Calluna* fuel particles, together with weather and fuel conditions, to the potential for the development of sustained combustion in heathlands. Coupled with a fuel moisture model (see Section 2.1) this will provide valuable information for forecasting the conditions when *Calluna* fires **can** occur.

Conditions during the legal burning period in Scotland, 1st October until the middle of April, (or mid-May in certain circumstances, see SEERAD 2001a for exact dates), are extremely variable with weather ranging from sub-zero temperatures with deep snow cover to extended warm, dry spells. Early spring constitutes one of the major periods of high fire risk on heather moorlands when over-winter damage to leaf cuticles, and both frozen ground and sunny days with low humidity can lead to low moisture contents of both live and dead fuel (Davies & Legg 2008, Davies *et al.* submitted 1). Frequent periods of rain often interrupt suitable burning periods, whilst fires may rapidly escape

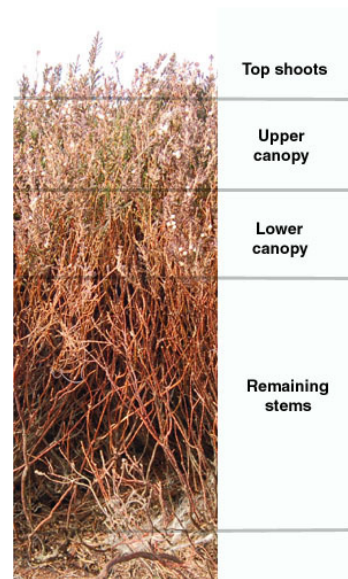
control in other conditions. Limited man power, on-top of such variable conditions, means that time spent trying to burn in conditions when fire is non-sustaining is an unnecessary cost to the land manager. The spate of wildfires in the spring of 2003 has, for instance, been linked to a period of extended dry weather combined with a cold but largely snow-free winter that froze ground and allowed *Calluna* to become exceptionally dry (Davies *et al.* 2006). Understanding the ignitability of fuels is critical from the point of view of predicting the risk of accidental and malicious wildfires. Although societal factors play an important role in governing where and when wildfire ignition occurs (McMorrow *et al.* 2006), these will only become major incidents when the vegetation is dry enough. Fuel moisture content, along with weather conditions (particularly wind speed and direction), is important in determining how easily fires can be controlled in a given fuel type. This is important both for tackling wild fires and for safe management burning.

It has been postulated that the relationship between fire behaviour and fuel moisture in shrub fuels is non-linear such that changes in moisture content function as an “on/off” switch at the lower end of the fire behaviour spectrum (Anderson 2006). Other authors (Marsden-Smedley *et al.* 2001, Fernandes *et al.* 2002, Tanskanen *et al.* 2005) have designed experiments to try and identify the conditions necessary for sustained ignition and determining these for *Calluna* would be extremely useful with regard to forecasting both the suitability of conditions for prescribed burning and fire hazard for wildfire risk prediction.

In order to determine the influence of fuel moisture and other variables on potential fire risk and behaviour a small scale field experiment was designed that combined ignition attempts with fine-scale dead and live fuel moisture monitoring, information on fuel structure, on-site weather data and fire weather indices from the CWFIS. Dense stands of heather often have obvious layers with a number of long shoots sticking out above the surrounding canopy, the top half of which is green and mostly live whilst the bottom is grey and predominantly composed of live and dead stems bearing dead foliage (Figure 1). Below this self-thinning creates a layer of dead and live stems of various sizes but with little foliage. A layer of moss and litter lies beneath this. It was hoped that by sampling these layers individually as well as taking samples of purely

dead material it would be possible to get a better idea of critical fuel moisture levels of dead and live fuels for ignition and sustained burning.

Figure 1: Cross-section through a closed *Calluna* stand illustrating the four layers harvested during FMC quadrat collection. For the ‘remaining stems’ layer dead stems (grey) and live stems 2 mm or less in diameter (thin brown) were collected separately.



2.2.2 Aims and objectives

The aims of these small-scale ignition experiments were:

- To determine the role of fuel moisture in governing sustained combustion of heather fires,
- To understand the relative importance of the moisture content of individual fuel components,
- To account for variability in ignition success due to other weather and fuel conditions, and
- To model the probability of ignition based on fuel moisture content, fuel characteristics and weather conditions.

2.2.3 Methods

Experimental areas

Experiments were completed at two different locations. The first site was located at the top of Castlelaw Hill in the Pentland Hills outside Edinburgh (Grid Ref: NT 225 650; Lat 55° 52' N, Long 3° 14' W) and the second site within Crubenmore Estate, near Dalwhinnie, on the edge of the Cairngorms National Park in N.E. Scotland (04°15'W, 56°57'N; OS Grid Ref. NN 6386). All fires were carried out on flat ground. The

vegetation at both sites was classified as belonging to a “Late-building” type fuel load (Davies *et al.* submitted 1, c.f. “Medium” in Legg *et al.* 2007) though it was generally taller and sparser at Crubenmore than at Castlelaw Hill. Species composition was dominated by *Calluna* underlain by a deep mat of pleurocarpous mosses, although in some denser areas these were replaced by a layer of *Calluna* litter. Areas locally dominated by *Vaccinium myrtillus* or *Empetrum nigrum* were avoided. Grasses, mainly moor matt grass, *Nardus stricta*, and wavy hair grass, *Deschampsia flexuosa*, were a regular occurrence but formed only a tiny fraction of the total fuel load. The experimental areas were both protected by swiped firebreaks.

Pre-fire monitoring

On each day, prior to the ignitions, a portable weather station was set up to record wind speed and direction, temperature, humidity and solar radiation at 5 s intervals.

Following this two 2 m x 2 m plots were marked out (Figure 2.2.1). The fuel load and structure were estimated using both the FuelRule (Davies *et al.* 2008) technique and the destructive harvesting of a single 25 cm x 25 cm, fuel quadrat. This was separated into the following fuel components: live stems with foliage, live stems < 2mm in diameter, live stems 2-5 mm in diameter, live stems > 5 mm in diameter, dead stems with foliage, and dead stems without foliage. Species other than *Calluna* were analysed separately but never constituted a significant part of the fuel load.



Figure 2.2.1. Layout of the experiment. X represents FuelRule measurement locations spaced 0.5 m from the plot edge and 0.5 m apart. Fuel load was also estimated by destructive harvesting on quarter of the ‘fuel quadrat’.

Fuel moisture monitoring was completed using a 50 cm × 50 cm quadrat gridded with 25 sub-quadrats, each 100 cm². Five sub-quadrats were randomly selected for harvesting. Within each sub-quadrat all *Calluna* was harvested in the following order: green shoots projecting above the top of the main canopy, the top half of the *Calluna* canopy and the bottom half of the canopy; each stratum comprising small stems < 2 mm in diameter bearing live and some dead foliage. Remaining live stems less than 2 mm in diameter but without foliage and dead stems were also harvested as was the top 2 cm of the moss/litter layer. Five samples of dead heather shoots were collected from the area within and around the quadrat. Samples were sealed in air-tight containers, weighed and dried (48 hours at 80 °C) to allow fuel moisture content to be calculated on a dry weight basis.

Ignition and fire behaviour

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

During the fire we estimated the maximum and average length of the flames and noted whether the fire seemed to be spreading primarily through the upper or lower canopy or equally through both (Figure 2.2.2).



Figure 2.2.2. Fire spreading through the lower layers of building phase *Calluna*. The green, live fuel-dominated upper layers often burn after the predominantly dead material below.

Data analysis

All data were analysed using Minitab 15. A preliminary investigation was made of data distributions and associations between predictor variables were tested using correlation analysis. Due to the significant correlation between predictor variables and the relatively small number of degrees of freedom Factor Analysis with varimax rotation was used to reduce the number of FMC variables to four orthogonal (uncorrelated) factors. Binary logistic regression was used to model the probability of line-ignition success (Sustaining/Non-sustaining) based on the FMC factors, raw FMC variables (some transformed to approach a normal distribution), fuel structural characteristics and weather conditions. Sub-sustaining fires were treated as non-sustaining. We used two approaches:

- 1/ We sought to explain the maximum amount of variance using all possible predictors. Each variable was tested and the variable with the highest R^2 was retained. For each subsequent step the remaining variables were tested and that which led to the greatest increase in R^2 was retained. Only variables that were statistically significant ($P < 0.05$) were retained.

2/ We developed a model that could be used for ignition probability forecasting that used only raw/transformed FMC variables and weather data. The single, best (highest R^2) FMC variable was retained first and additional, uncorrelated FMC and weather variables were added to the equation and tested to see if they significantly improved goodness-of-fit.

We modelled the probability of sustaining fires from line ignitions only. Spot ignitions are likely to be highly susceptible to small-scale variation in fuel structure, fuel moisture and weather conditions rather than larger-scale day-to-day variability. The use of such a “strong” ignition technique is well justified in existing studies of flammability in other fuel types.

Best subsets regression was also used to model the rate of spread of sustaining and sub-sustaining fires.

2.2.4 Results

Twenty ignition attempts were made (eight additional tests having been added during the course of FireBeaters Phase II) with six successes and fourteen failures (two sub-sustaining) from spot ignitions and nine successes and eleven failures (three sub-sustaining) from line ignitions.

Plot fuel characteristics are shown in Table 2.2.1.

Upper canopy FMC varied widely from a low of 29.7% during a sunny period when the ground was frozen, to as high as 163% in periods immediately following rain. The lower canopy often exhibited lower FMC values than the upper but this was dependent on how much time had passed since the last precipitation event. With the exception of live stems, which showed relatively low variability, lower-canopy strata and dead fuels showed greater variability than upper, live fuel layers (Table 2.2.2). Greatest variability was seen in the moss layer where FMC varied from less than 25% to more than 400%.

Table 2.2.1: Fuel structure of the ignition experiment plots. Fuel loads estimated using both destructive harvesting and the FuelRule. It was not possible to estimate fine fuel load with the FuelRule for a number of plots as data on % cover were missing. CDI = Canopy Density Index. S is the product of the standard deviations of height and CDI and has previously been shown to relate strongly to fire behaviour (Legg *et al.* 2007, Davies *et al.* submitted 1).

ID	Destructive		Destructive		FuelRule		FuelRule		Bulk		Calluna		S
	Total (kg m ⁻²)	Fine (kg m ⁻²)	Dead (kg m ⁻²)	Total (kg m ⁻²)	Total (kg m ⁻²)	Fine (kg m ⁻²)	Density (kg m ⁻³)	Height (cm)	Height (cm)	CDI	CDI		
13	0.61	0.39	0.11	0.77 ± 0.14	-	-	4.04 ± 1.06	19.40 ± 2.97	-0.71 ± 0.40	1.18			
14	0.43	0.29	0.10	0.91 ± 0.28	-	-	4.38 ± 0.93	20.80 ± 4.38	-0.84 ± 0.48	2.12			
15	0.56	0.34	0.19	0.89 ± 0.30	-	-	4.71 ± 1.03	18.78 ± 4.24	-1.14 ± 0.25	1.08			
16	0.64	0.34	0.14	0.92 ± 0.28	-	-	4.59 ± 0.89	20.00 ± 3.46	-1.22 ± 0.45	1.54			
17	0.94	0.31	0.23	1.00 ± 0.20	-	-	5.35 ± 0.48	18.89 ± 4.34	-0.91 ± 0.39	1.69			
18	0.52	0.29	0.11	0.86 ± 0.14	-	-	4.26 ± 0.73	20.33 ± 3.28	-0.86 ± 0.42	1.38			
19	0.58	0.23	0.26	0.98 ± 0.27	-	-	5.34 ± 1.00	18.22 ± 3.31	-1.30 ± 0.54	1.78			
20	0.74	0.41	0.27	1.17 ± 0.18	-	-	5.62 ± 0.57	21.00 ± 3.64	-1.25 ± 0.71	2.58			
22	0.38	0.26	0.06	0.99 ± 0.37	0.71 ± 0.26	-	5.29 ± 0.98	18.44 ± 5.32	-0.97 ± 0.53	2.84			
23	0.52	0.28	0.14	0.90 ± 0.17	0.75 ± 0.33	-	4.46 ± 0.92	20.44 ± 3.61	-1.00 ± 0.36	1.28			
24	0.37	0.22	0.07	1.19 ± 0.37	-	-	5.43 ± 1.58	22.00 ± 4.61	-0.72 ± 0.27	1.22			
25	0.57	0.37	0.11	1.33 ± 0.34	0.96 ± 0.23	-	5.46 ± 1.00	24.56 ± 4.48	-0.69 ± 0.18	0.82			
26	0.33	0.19	0.09	0.97 ± 0.30	0.77 ± 0.31	-	4.14 ± 1.07	23.22 ± 2.54	-0.89 ± 0.18	0.46			
27	0.54	0.28	0.19	0.81 ± 0.22	0.57 ± 0.12	-	5.00 ± 1.70	16.89 ± 4.51	-0.87 ± 0.38	1.70			
28	0.44	0.24	0.14	0.99 ± 0.26	0.69 ± 0.46	-	4.86 ± 0.81	20.33 ± 4.53	-0.76 ± 0.18	0.81			
29	0.60	0.28	0.11	0.90 ± 0.36	0.60 ± 0.30	-	4.27 ± 1.35	20.78 ± 2.86	-0.61 ± 0.23	0.66			
30	0.56	0.39	0.06	1.06 ± 0.20	0.71 ± 0.10	-	4.59 ± 1.09	23.78 ± 5.04	-0.43 ± 0.20	1.00			
31	0.34	0.26	0.06	0.84 ± 0.32	0.59 ± 0.16	-	4.18 ± 0.80	20.11 ± 7.15	-0.43 ± 0.18	1.31			
32	0.38	0.28	0.07	0.86 ± 0.25	0.51 ± 0.15	-	3.95 ± 0.80	21.67 ± 4.27	-0.44 ± 0.26	1.11			
33	0.41	0.31	0.05	1.00 ± 0.38	0.63 ± 0.28	-	5.90 ± 4.58	21.00 ± 6.75	-0.44 ± 0.17	1.16			

Preliminary analysis

Initial exploration of the data using Anderson-Darling tests for normality revealed that several of the predictor variables did not follow a normal distribution. The FMC of dead shoots, the lower canopy and live stems, and dead fuel load estimated destructively all approximated a log-normal distribution and were transformed by taking the reciprocal. This adds some complexity to the interpretation of the data as for these variables higher moisture contents will lead to lower values of the transformed variable. Time since last rain was best approximated by an exponential distribution and we therefore analysed its square root.

Correlation analysis

There was highly significant correlation ($P < 0.001$) amongst nearly all the FMC variables (Table 2.2.3). There were also significant correlations amongst the fuel structure variables and between FMC variables and weather conditions. It was interesting to note that there was little agreement in fine fuel load estimated using destructive and FuelRule techniques ($r = 0.29$). The FuelRule technique has proven reliable in this fuel type in the past (Davies *et al.* 2008) whilst destructive harvesting of a small area was not likely to be representative of the plot as a whole. We therefore use FuelRule estimates of fuel load and structure in subsequent logistic regression modelling but also include the dead:live ratio calculated from the quadrat analysis of fuel load.

Factor analysis

Factor analysis allowed the FMC data set to be reduced to four orthogonal (uncorrelated) factors (Table 2.2.4). The first factor related strongly to the moisture content of the upper, live part of the *Calluna* canopy; the second to increased moisture contents in the lower canopy and the moss layer; factor three represents the moisture content of dead stems and four the FMC of dead shoots. These four factors together explained 96% of the variation in the data set.

Table 2.2.3. Correlation coefficients showing relationship between fuel moisture content of the different components of the vegetation in the small ignition experiments.

	<i>Average FMC</i>	<i>Dead shoots</i>	<i>Dead stems</i>	<i>Live stems</i>	<i>Lower canopy</i>	<i>Moss/Litter</i>	<i>Top shoots</i>	<i>Upper canopy</i>
Average FMC of all fuels	1.00							
Dead shoots	0.85	1.00						
Dead stems	0.85	0.69	1.00					
Live stems	0.89	0.79	0.85	1.00				
Lower canopy	0.91	0.87	0.86	0.89	1.00			
Moss/Litter	0.93	0.66	0.66	0.74	0.73	1.00		
Top shoots	0.74	0.80	0.62	0.66	0.74	0.54	1.00	
Upper canopy	0.83	0.92	0.70	0.77	0.90	0.59	0.89	1.00

Table 2.2.4. Rotated (varimax) loadings for factor analysis on FMC variables. Variables marked with a star were transformed by taking their reciprocal. Values in bold indicate variables that relate strongly to a given factor.

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

Modelling ignition probability

Clear thresholds exist in the moisture content at which both spot and line ignition fires will sustain and the moisture content of the lower canopy seems to be particularly important (Figure 2.2.3). A GLM comparing successful and unsuccessful ignitions demonstrated that there were significant differences in the moisture contents of the upper canopy ($P = 0.005$, $F = 10.09$, d.f. = 1, 19), the lower canopy ($P < 0.001$, $F = 30.81$, d.f. = 1, 19), live stems ($P = 0.004$, $F = 10.57$, d.f. = 1, 19), dead shoots ($P = 0.003$, $F = 11.86$, d.f. = 1, 19) and the moss/litter layer ($P < 0.001$, $F = 24.32$, d.f. = 1, 19).

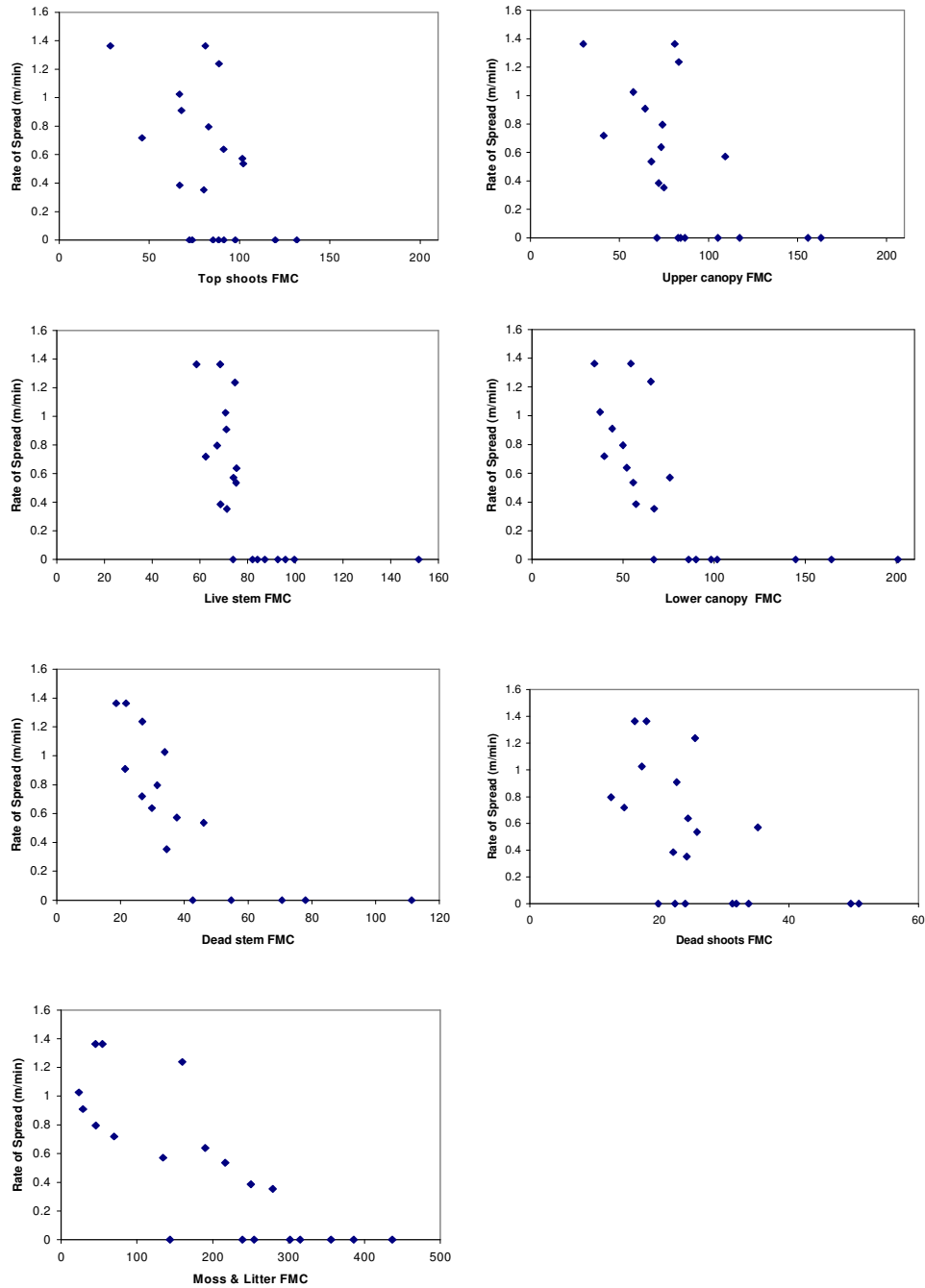


Figure 2.2.3. Effect of fuel moisture content on rate of spread of fires in the small-scale ignition experiment.

Binary logistic regression analysis showed that FMC Factor 2 alone was a powerful predictor of ignition success (Equation 2.2.1, Table 2.2.5). Addition of second predictors only slightly improved the fit of the model and were not balanced by the increased model complexity

$$\text{Ln(Odds sustaining)} = -0.824 + 1.362 \times \text{FMC Factor 2} \quad (\text{Eq 2.2.1})$$

Using raw FMC variables, Lower canopy FMC (transformed to its reciprocal to approximate a normal distribution) alone proved to be a more powerful predictor of sustained line ignition than FMC Factor 2 (Equation 2.2.2, Table 2.2.5). However, only one failed ignition occurred at a lower FMC than the highest FMC of the successful ignitions. This low degree of overlap meant it was not possible to calculate an odds ratio and the results should be treated with caution. Addition of second predictors did not significantly improve the fit of the models, considering the associated increase in model complexity. It should be noted however that the addition of bulk density as a second predictor led to perfect separation of the data (i.e. successes and failures are all modelled correctly with a predicted probability of 1 or 0).

$$\text{Ln(Odds sustaining)} = -15.94 + 968.9 \times (1/\text{Lower canopy FMC}) \quad (\text{Eq 2.2.2})$$

Table 2.2.5. Details of model performance for Equations 1 and 2. The table shows the standard errors of the constant (SE_c) and predictors (SE_p). The value G tests the hypothesis that all the coefficients are different from zero, both values are significant at $P < 0.001$. Odds R is the odds ratio and compares the odds of each level of a categorical response variable to quantify how each predictor affects the probabilities of each response level. Con and Dis are the number of concordant and discordant pairs calculated by pairing the observations with different response values and comparing predicted versus observed success. Pearson and H-L (Hosmer-Lemeshow) are P values for goodness of fit tests. The significant results for FMC Factor 4 suggests there is some evidence that the model does not fit the data accurately.

Predictor	SE_c	SE_p	G	Odds R	Co n	Di s	Pearso n	H-L
FMC Factor 4	0.84	1.36	13.67	0.05	91	8	0.48	0.49
Lower canopy	508.6	8.44	20.24	N/A	98	1	0.99	1.00

2.2.5 Results

The observations of fire behaviour (Table 2.2.6) indicate the patchy nature of fire in these small-scale experiments. Where the fuels are uneven, moisture may be retained in dense areas of fuel when more sparse fuels have dried to a much greater extent. It is likely that a larger fire will, once established, generate a greater heat output to pre-heat fuel ahead of the fire front and sustain a fire in situations where these small-scale experiments self-extinguish. However, these experiments give a good indication of the conditions when a fire will be easy to ignite and show the relationships between fuel moisture and fire behaviour.

The fuel failed to ignite with a self-sustaining fire in eight of the twenty experimental ignitions (Table 2.2.2). There were several occasions where the spot ignition failed to establish self-sustaining fire, but this was possible with a line ignition. This again demonstrates the importance of the size of the fire for achieving sufficient heat output to maintain the fire.

The moss and litter layer was not consumed where the moisture content was 140% or greater, but where the moss/litter moisture content was less than 70% significant amounts of the moss were consumed and continued smouldering after the flaming combustion was extinguished (Table 2.2.6).

Moss and litter FMC does not provide a threshold that determines whether or not the vegetation will burn. Once burning, however, the rate of spread of the fire correlates more strongly with FMC of the dead stems and the moss and litter layer than it does with any of the other fuel components. A dry moss/litter layer will add significantly to the quantity of available fine fuel and our results suggest that fires in conditions where the moss is dry enough to burn may be extremely difficult to control.

Table 2.2.6. Descriptions of fire spread in small-scale ignition experiment

Ignition ID	Comments
13	No burn.
14	No burn.
15	FMC seemed very variable as fire established in some places but did not spread far.
16	FMC seemed very patchy and fire would establish in places but not spread.
17	Marginal burn, spread through sparse, dry canopy but avoided denser, moister areas.
18	Spread through sparser, drier patches and eventually made it across whole plot. Burn very patchy.
19	Not clean burn, very patchy. Two small spots ignited and spread better outside plot boundary through taller, sparser <i>Calluna</i> .
20	Patchy fire, burnt through tall, sparse heather avoiding denser areas
22	Moss dry with significant consumption. Worked hard to extinguish. Prolonged smouldering after flaming combustion extinguished.
23	Much moss consumed. Prolonged smouldering once flaming combustion extinguished.
24	Moss dry and burnt well. Back fire burnt well. Wide front rapidly established.
25	Moss dry and burnt well.
26	Burnt in sparser, drier areas but self extinguished in wetter, denser patches.
27	Purely dead fuel dry enough to burn and fire found way through dry, sparser patches but extinguished on reaching denser areas.
28	No spread at all. Once ignition fuel burnt off rapidly self-extinguished.
29	Getting there. Fuel heterogeneity had big effect in breaking up line ignition through usual impact of sparse and dense areas. Line ignition burnt for a bit before breaking up and extinguishing. Left behind dense lower canopy where thick and still wet.
30	Intense fire established rapidly. Back fire burnt strongly. Most fuel consumed. Moss consumed in places and smouldered after flaming combustion extinguished.
31	Intense burn with prolonged moss and litter layer smouldering. Flames licked to ca 1 m. Narrow pointed front, spread faster forward than outwards at flanks
32	Line self-extinguished as it reached end. Did not burn whole plot. Line repeatedly needed to be filled in. Intensity dropped dramatically when flank was controlled to plot edges. Average flame length is from spot ignition, maximum is from line.
33	Spots rapidly self-extinguished. Heavy ignition required to get line going but thereafter spread well.

2.2.6 Conclusion

These results imply that there is a moisture threshold for the canopy fuels that determines whether or not a fire will be self-sustaining. This threshold is where the live stem FMC exceeded 80% of oven-dry weight, where the dead stem FMC exceeded 50% and where lower canopy exceeded about 75%.

The low degree of overlap in lower canopy FMC between successful and failed line ignitions meant it was a powerful predictor of sustaining fires.

Though FMC Factor 4 also performed well, its relationship with the FMC of other fuel components essentially only added noise to the model. We suggest that were data available for a wider variety of conditions, for example at low moss FMCs, then lower-canopy FMC alone might not perform so well. The perfect separation of successes and failures when using lower canopy FMC and bulk density as predictors is an artefact of the small size of the dataset. Bulk densities of fuels at Crubenmore Estate were consistently lower than those on Castlelaw Hill. This effect combined with the low degree of overlap in FMC between successful and failed ignitions allows the ignitions to be correctly classified (Figure 2.2.3). Though combustion theory suggests that bulk density may well be an important control on ignition success further tests are required in a wider variety of fuel types to confirm this. Previous, similar research (Marsden-Smedley *et al.*) has shown that wind speed is an important control on the development of sustaining fires. Though the addition of wind speed to our models did improve their predictive ability and its effects were not statistically significant. The majority of our tests were, however, completed at rather high wind speeds (Table 2.2.2) and we anticipate that tests in a wider range of conditions would lead to it having a significant effect.

Once the fire is established then initial rate of spread may be influenced primarily by the moisture content of the dead stems and of the moss and litter layer. There are two different mechanisms that may be operating here. Firstly the fire may spreading primarily through the dead stems within the lower part of

the *Calluna* canopy and the moisture content of these stems is determining the rate at which the dead fuel is pre-heating to reach ignition temperature. Alternatively, the moisture in the moss and litter layer where this is damp may be generating steam as the fire passes which significantly suppresses the combustion process by starving the fire of oxygen. Where the moss is very dry and is being consumed by flaming combustion this may contribute to the fire spread. Davies *et al.* (2006, in review) show however that, for larger, established fires, live fuel moisture content is a significant control of rate of spread. We suggest that for initial fire establishment the moisture content of the fine dead fuels is critical. If this fuel is available for combustion and a fire establishes then the fuel moisture content of the live fuel may exert a significant control of established spread. Where live fuels are dry, as seen in early spring, fire may be fast and intense. It is likely that the balance between the relative amounts and moisture contents of live and dead fuels is critical for fire behaviour. Future fire experiments should examine the effect of a weighted mean moisture content based on the FMC of different fuel components and their relative loadings. Our results and previous research suggest that the development of a fuel moisture model that incorporates both live, dead and moss FMC is needed to adequately capture moorland fire behaviour. From the point of view of forecasting conditions when a fire can occur (as opposed to subsequent levels of fire behaviour) it may be sufficient to focus on the behaviour of dead canopy fuels.

A further important consideration when attempting to identify the mechanisms that determine fire behaviour is the error associated with the fuel moisture measurements. There is a relatively small range of variation in moisture content of live stems which increases the relative importance of error of measurement. The upper and lower canopy, however, are heterogeneous both in ratio of live to dead material, and in canopy density. Where the canopy is locally dense the shoots are sheltered from drying winds and will retain moisture much longer than relatively sparse and aerated parts of the canopy. This means that the sampling protocol used may be insufficiently sensitive to identify clear relationships between moisture content and fire behaviour. However, for

practical purposes it appears that the moisture content of dead stems is the most useful measurement for predicting both ignition probability and rate of spread of the fire.

2.3 Extend the experimental heather fires to a wider range of fuel types

Additional experimental heather fires will be conducted in a wider range of heather fuel types than has been used heretofore. This will include sites in the Pentland Hills near Edinburgh (e.g. heavily grazed sites on Castlelaw or Black Hill) and Glen Tanar (where fuel loads are much higher than the sites used in Phase I). These will be used to validate the fire behaviour models of Phase I. The number of fires that can be achieved is weather dependent, but the target will be an additional four fully-instrumented fires in each site. It is not anticipated at this stage that time or resources will permit inclusion of fires on slopes and with a wider fire front, or inclusion of summer fires in 'wildfire' conditions.

Due to the poor weather conditions in the spring of 2008 it was not possible to conduct full-scale burning experiments. Time instead was spent on characterising the ignition properties of a fuel bed of moss (See Section 2.8).

A new project has recently been established to provide demonstration fires in *Calluna* moorland. This is being done by the Northumberland Fire Group comprising a consortium of Northwoods, the Northumberland Fire & Rescue Service, the Northumberland National Park Authority, The Rural Development Initiatives and others. This project has several objectives including:

- 1) to determine the effect of different managed burning techniques and wildfires on peat and heather moorland (e.g. biodiversity, vegetation ecology, specific land features, carbon storage, etc.)

- 2) to establish baseline data on wildfire behaviour in peat and heather moorland,
- 3) to provide wildfire fighting training to Northumberland organisations,
- 4) on the back of this research and training, the project's long term goal is to create a "fire management" course that will promote the use of best practice managed burning and wildfire suppression techniques.

It is hoped that this programme of burning, which is due to start in late March/early April 2009, will provide further opportunities to develop the research on fire behaviour in different fuels, different ground conditions (e.g. slope angle) and burning techniques (e.g. back-burning and flank fires as well as head fires).

2.4 Establishing protocols for experimental grass fires

Three days will be dedicated to establishing standard techniques for experimental grass fires in Molina grasslands in the West of Scotland. This work will collaborate with Ian Murgatroyd and Richard Deboys of Forest Research in the Forestry Commission and Gary Servant of Upland Ecology all of whom have fire research experience. The aim will be to establish common protocols for conducting and monitoring grass fires as a precursor to extending the FireBeaters fire prediction capability to grass fires in the future. The target, weather permitting, will be to burn three fully-instrumented experimental grass fires.

Due to the poor weather conditions in the spring of 2008 it was not possible to conduct burning experiments on grass moor. Time instead was spent on characterising the ignition properties of a fuel bed of moss (See Section 2.8).

The Forestry Commission (co-ordinated by Ian Murgatroyd and Richard Deboys) has planned for experimental grass fires in spring 2009 but, at the time of writing, it has not been possible to co-ordinate a joint experiment. Some

discussion has taken place to plan priorities for experimental burning in grassland and these are summarised in Appendix 4.4.

2.5 Relate wildfire records to weather, vegetation and site characteristics

Additional wildfire records will be obtained from the Scottish Fire & Rescue Services. The dataset will be extended to cover the whole of Scotland and include standard information on the magnitude of the fires. These data will be stored in a GIS with overlays from a DTM and the LCM 2000 vegetation map available from CEH. The GIS will be used to provide an accurate classification of fuels and site characteristics for each fire. Work in Phase I demonstrated on an ad hoc basis the potential of these records for calibrating the Fire Danger Rating; accurate classification of site characteristics should greatly increase the precision of the fire risk models developed so far.

Preliminary work on relating fire records to vegetation will be done by an undergraduate student as part of an Honours dissertation. Further work to develop and calibrate the Fire Danger Rating will be offered as an MSc project to be completed in September 2008.

2.5.1 Introduction

As part of the FireBeaters Phase I report a preliminary analysis was made of the Fire & Rescue Service (F&RS) records of wildfires for four regions of Scotland (Highlands & Islands, Grampian, Lothian & Borders and Dumfries & Galloway). Weather data from the Met Office NWP (Numerical Weather Prediction) forecasts were used to calculate the Canadian Forest Fire Weather Information System fire weather indices. Fire frequency was plotted against each of these indices to test their predictive power.

From this analysis it was shown that the frequency of wildfires reported to the F&RS was much greater when the Fine Fuel Moisture Code (FFMC) exceeded

65 and the probability of a severe fire was much greater than normal when FFMC exceeded 80.

The F&RS data included a category for vegetation type. From these it was shown that fires in different vegetation types occur with different distributions with respect to season and weather conditions. However, it was clear that the classification of vegetation types was being used inconsistently between the different regions and was not sufficiently precise to enable full analysis of the data. As part of the Phase II report the data were therefore re-analysed using vegetation maps obtained from remote sensing to obtain more consistent classification of the vegetation at the site of each fire.

This work was done by Frances MacKinnon as part of her dissertation for the degree of MSc in Geographical Information Science at The University of Edinburgh. The methods and results of the analyses are summarised here, but full details are available in the thesis (MacKinnon 2008, Appendix 4.5).

2.5.2 Methods

Detailed descriptions of the data received from the Met Office and from the Fire & Rescue Services are given in the FireBeaters Phase I report. After scanning the data and matching fire information against the available weather data, 4303 wildfire records were identified as suitable for analysis. The Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Build-up Index (BUI), Fire Weather Index (FWI) and Daily Severity Rate (DSR) were calculated for the day and location (10 km x 10 km grid square) of each fire. In addition, the weather indices for fires in 2003 – 2007 were calculated for the same location and same day of the year, but for the previous year; for fires in 2003 the calculations were for the same location and same day in 2006. These data are referred to as 'Control days' and represent the weather conditions on a representative set of days with the same spatial and seasonal distribution as the fire records. The distribution of fire weather indices with respect to the control days provides a null model against which the fire records can be judged.

The F&RS wildfire records included 8-figure grid references. These locations were superimposed on the LCS2000 maps of vegetation classification level 3. The LCS2000 data set, derived mainly from a classification LandSat remote sensing data with ground truthing based on the Countryside Survey data, provides 72 vegetation classes. These were pooled into a reduced number of classes considered to represent different fuel types.

Inspection of the grid references suggests that they are not always precise records of the exact location of the fire, but rather reflected the general area where the fire was reported or where the F&RS gathered. Any one fire may also burn over several different vegetation types. A buffer was therefore located around the grid reference location and the dominant vegetation type within the buffer zone was identified. Buffers used were 25 m, 50 m, 100 m and 200 m radius about the reference point. Clearly this is still not a precise record of the vegetation type that is being burned, but it provides a standard and repeatable method to attribute fires to a vegetation type and the error involved will be small by comparison with the analyses presented in the Phase I report. Differences in the distribution of fires in different vegetation types shows that this method is identifying meaningful variation in fuel types.

The fire locations were also related to a digital terrain model to provide information on the altitude, slope and aspect of the site. Ordnance Survey maps were used to identify the distance to the nearest road and distance from the nearest town.

2.5.3 Results

The majority of fires in the F&RS database were found to be either in the urban land cover type, or associated with arable farmland (Figure 2.5.1). Presumably many of the 'arable' fires will be fires associated with hedgerows and road-side verges where the LCS2000 data identifies arable as the nearest land use. Unfortunately, the LCS2000 data do not distinguish between different habitat types within the urban setting and many of the urban fires are likely to be in gorse (*Ulex europaea*). Very few fires are present in vegetation identified as gorse in the LCS2000 data. Gorse fires are of particular importance to the

F&RS as much time is diverted to urban gorse fires, but it will require new data to distinguish this fire type.

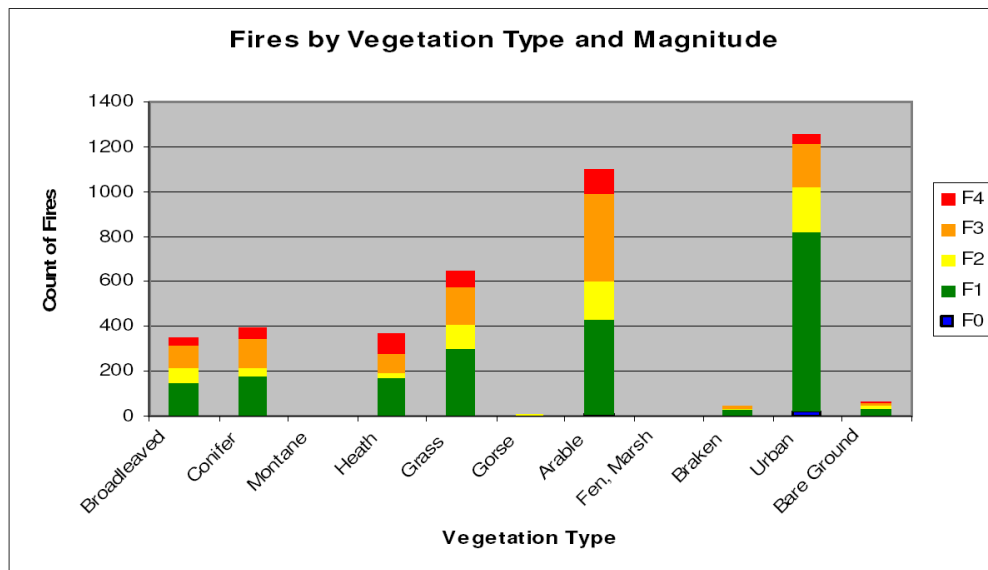


Figure 2.5.1. Number of wildfires reported to the Fire & Rescue Services according to broad vegetation or fuel type. Figure from MacKinnon 2008.

When the number of fires is divided by the area of each land cover type to give a density of fires (Figure 2.5.2) then the dominance of urban fires is more apparent. This shows that the number of heath and grass fires is actually rather low compared to the large area that these vegetation types cover in Scotland, while fires in broadleaved woodland and gorse are more frequent when expressed on a per-unit-area basis.

Analysis of the Canadian fire weather indices shows that the Fine Fuel Moisture Index (FFMC) is a good predictor of when fires are reported to the F&RS (Figure 2.5.3). Fires are more frequent than expected according to the null model when the FFMC is above 70, 2.3 times more than expected when FFMC is 80-84 and 4.4 times expected when above 85.

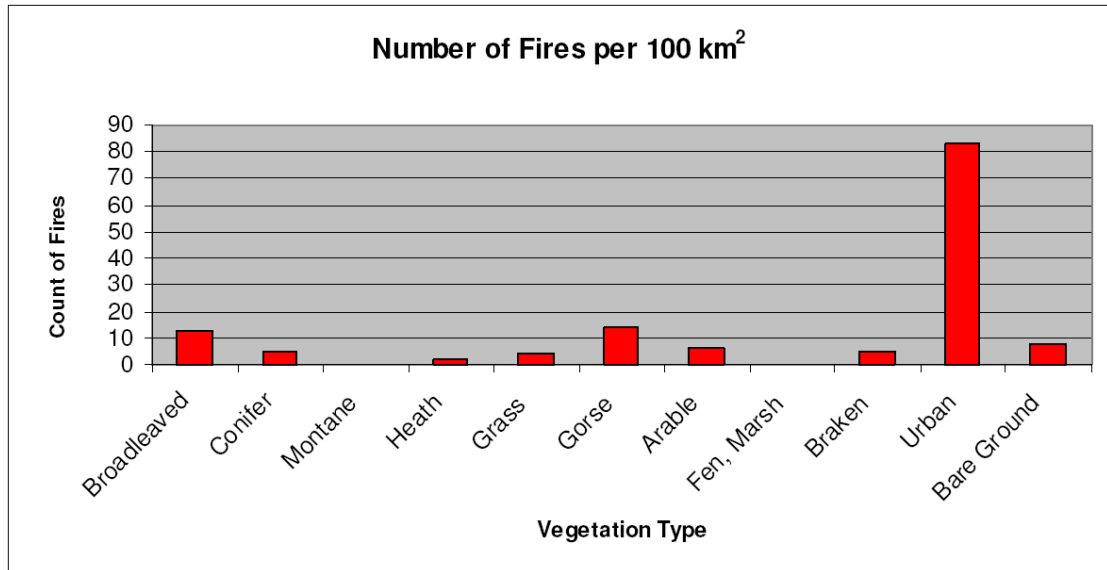


Figure 2.5.2. Number of wildfires reported to the Fire & Rescue Services per 100 km² of each broad vegetation or fuel type. Figure from MacKinnon 2008.

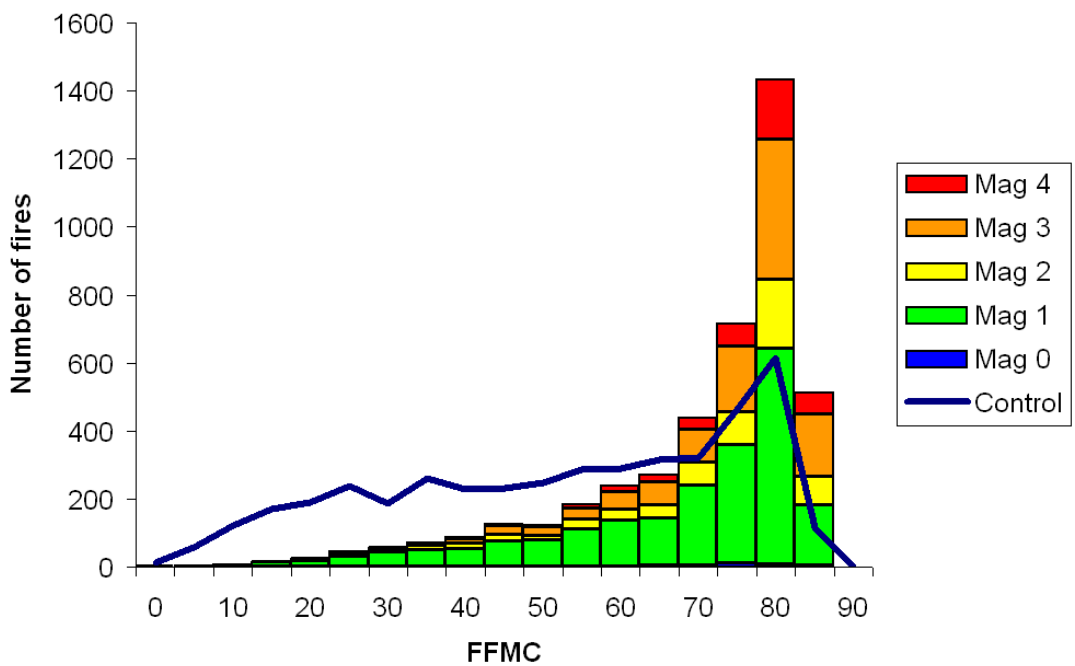


Figure 2.5.3. Frequency of all fires reported to the Fire & Rescue Services and control points plotted against the Fine Fuel Moisture Code (FFMC).

Breaking the data down into vegetation type and seasons shows a much clearer picture. For fires in dwarf-shrub heath (LCS2000 vegetation types 10.1.1 ‘Dense Heath’ and 10.2.1 ‘Open Heath’) FFMC is a much stronger

discriminator of fire days in spring (March – May) (Figure 2.5.4). Fires reported to the F&RS are 2.4 times expected when FFMC is 75-79, 4.6 times expected at FFMC 80-84 and 7.7 times expected at FFMC above 85. Similarly, fires reported to the F&RS are more frequent than expected according to the null model when the Initial Spread Index (ISI) is greater than 0.8. The Canadian Initial Spread Index is based partly on the indices of fuel moisture, and also on wind speed though ISI and FFMC are very closely related and it is not possible from this to show that wildfires are more frequent on days with high wind.

Interestingly, records of regular burning for grouse-moor management occurs on days with a wide range of FFMC (Figure 2.5.5). In this case records were received from keepers conducting normal fires for which ‘ease of control’ was recorded using the criteria in Table 2.5.1. Although the majority of fires were conducted on days when the FFMC was in the range 30-45, twenty of the fires were where FFMC was less than 15, this despite the fact that there were only two days in the control set with FFMC below 16. Wildfires reported to the Fire and Rescue Services are therefore occurring in much more extreme weather conditions than the majority of management fires, but heather-dominated vegetation can be burned even when FFMC is very low. There is, however, in contrast with the wildfires illustrated in Figure 2.5.4, a trend for managers to burn when the Initial Spread Index (ISI) is less than 0.4. This implies that managers are avoiding burning on days with high wind.

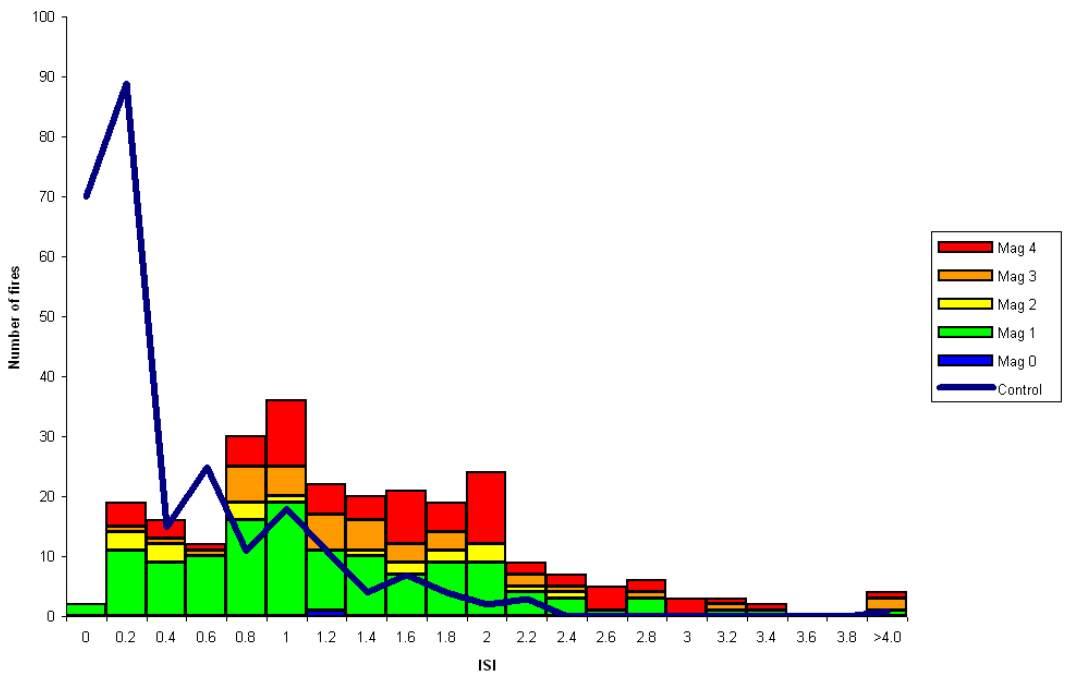
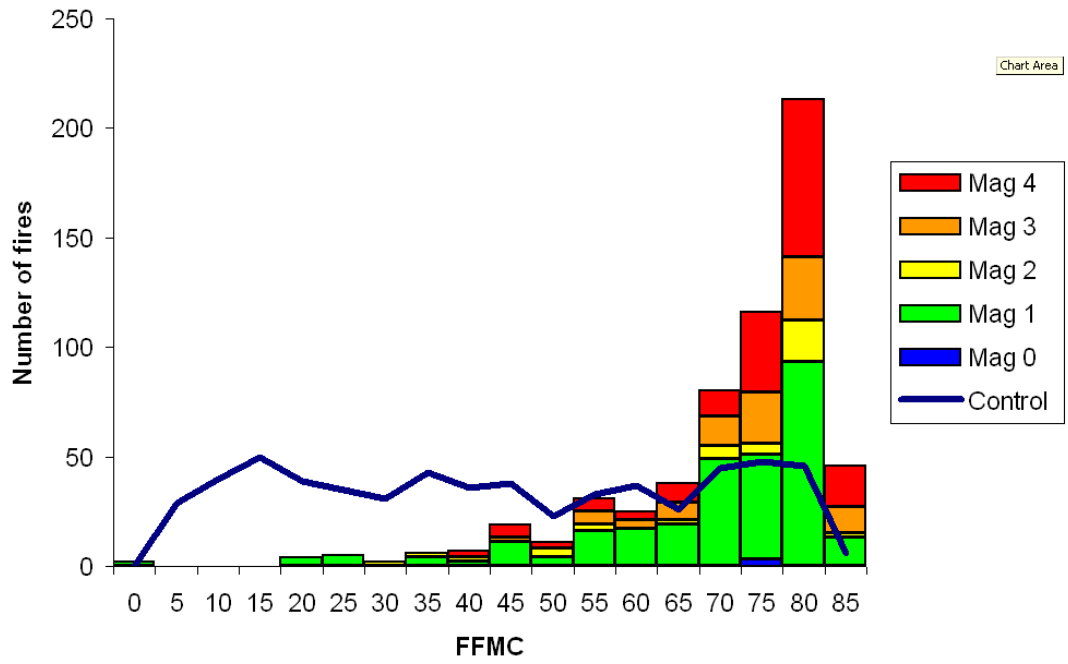


Figure 2.5.4. Number of heath fires reported to the Fire & Rescue Service in spring (March-May) plotted against the Canadian FFMC and ISI.

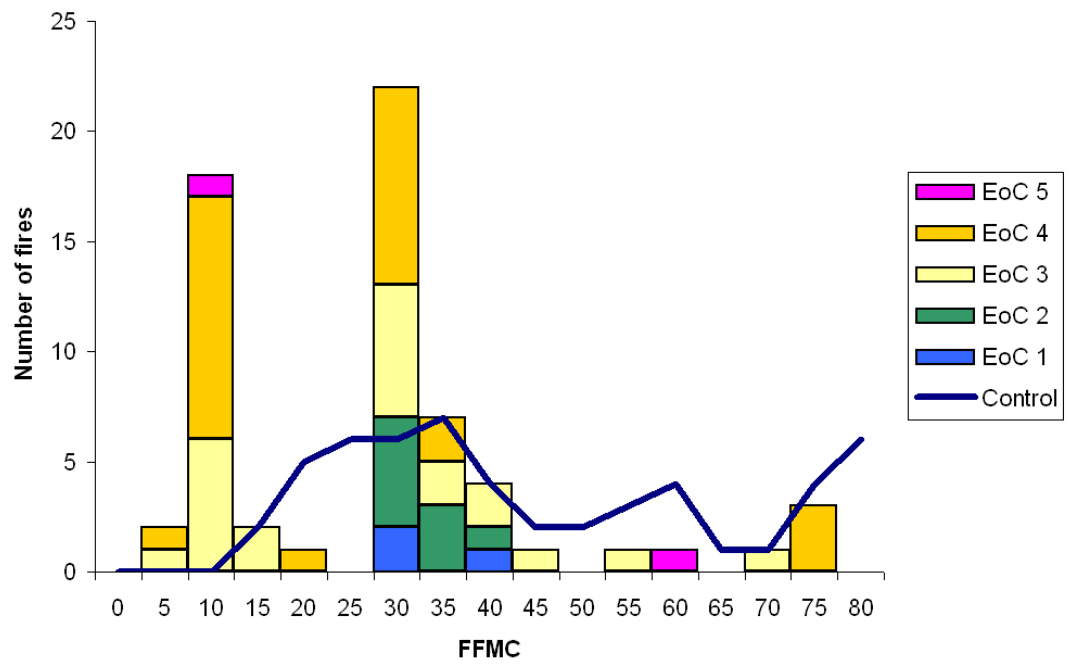
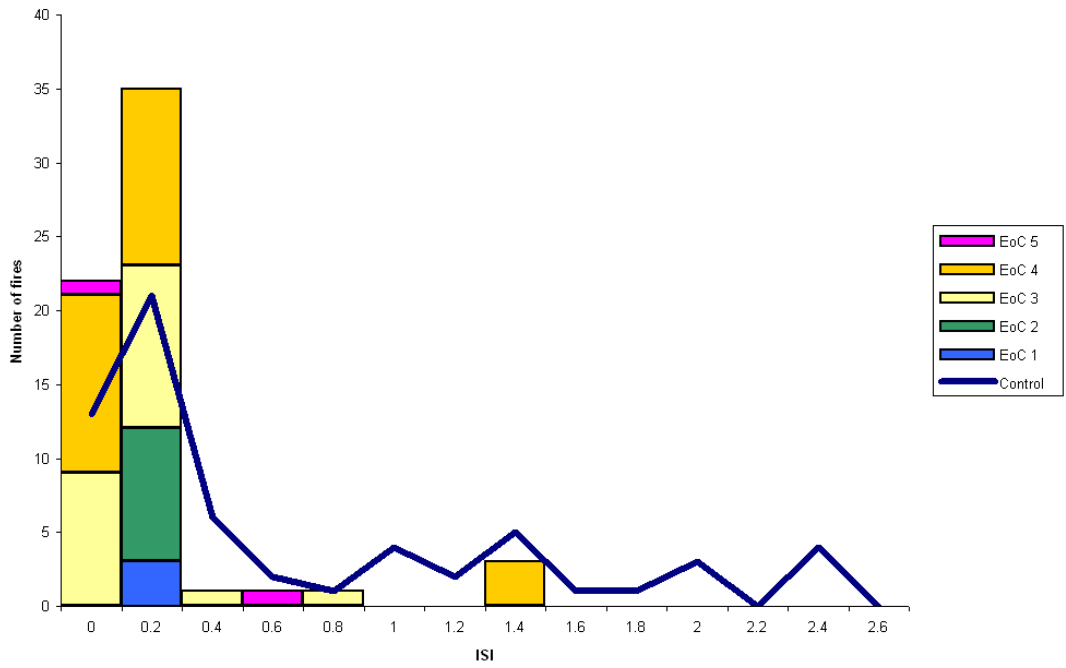


Figure 2.5.5. Distribution of regular management fires with respect to FFMC and ISI showing ease of control. (See Table 2.5.1 for the scale of ease of control.)

Table 2.5.1. Classification Scale of Ease of Control used to assess burning conditions for management fires.

Value	Meaning
1	Fire not sustainable and goes out rapidly after diesel, etc. burns off
2	Control easy with beaters alone, fire extinguishes using beaters
3	Control simple with beaters, sprayer held in back-up, fire stops at previous burns
4	Control difficult, but just maintained, firebreaks/sprayers play major role
5	Fire rapidly escapes all control or would have done were it not for firebreaks

In summer (June – August) the situation is less clear. The number of fires reported to the F&RS is rather small (85 fires in heathland, compared with 260 spring fires) and the relationship with FFMC is much weaker (Figure 2.5.6). The frequency of fires for FFM in the range 80-84 was only 2.9 times greater than expected from the null model. This is partly due to the much higher frequency of days with the higher FFMC values in summer than in spring, so that there is a higher proportion of days when fires are possible. A similar pattern is found with ISI as would be expected for two indices that are so closely related.

In the summer fires tend to occur when the Duff Moisture Code (DMC) and Build-up Index (BUI) are high (Figure 2.5.7). This relationship is retained in spring fires even though DMC and BUI are nearly always low (mostly below 15, Figure 2.5.8). Again, DMC and BUI are very closely related and there is a lot of redundancy in these two pieces of information.

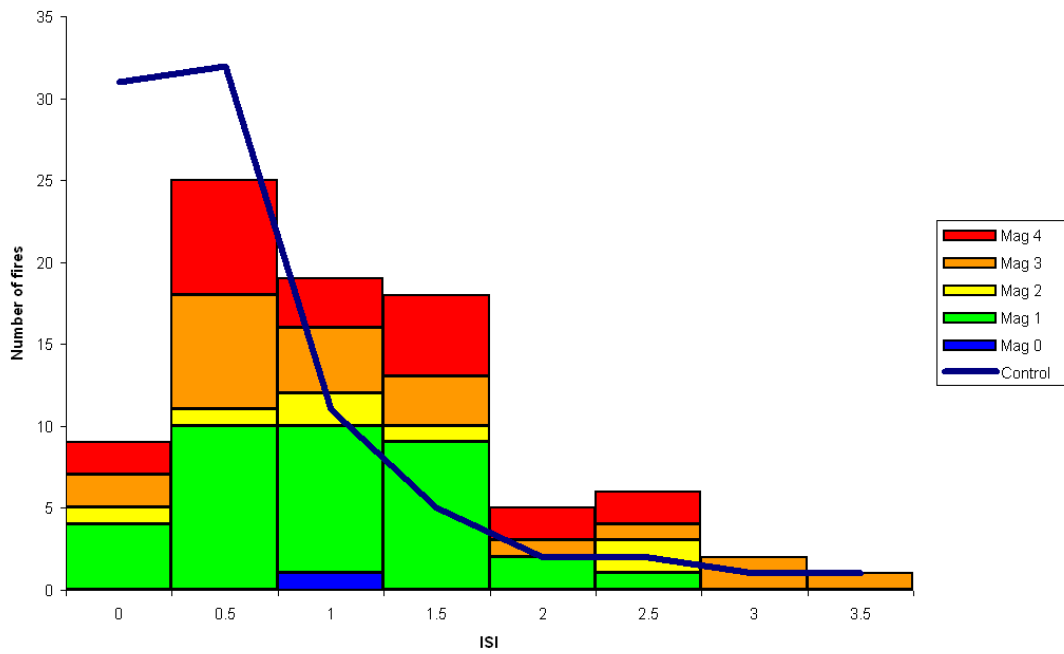
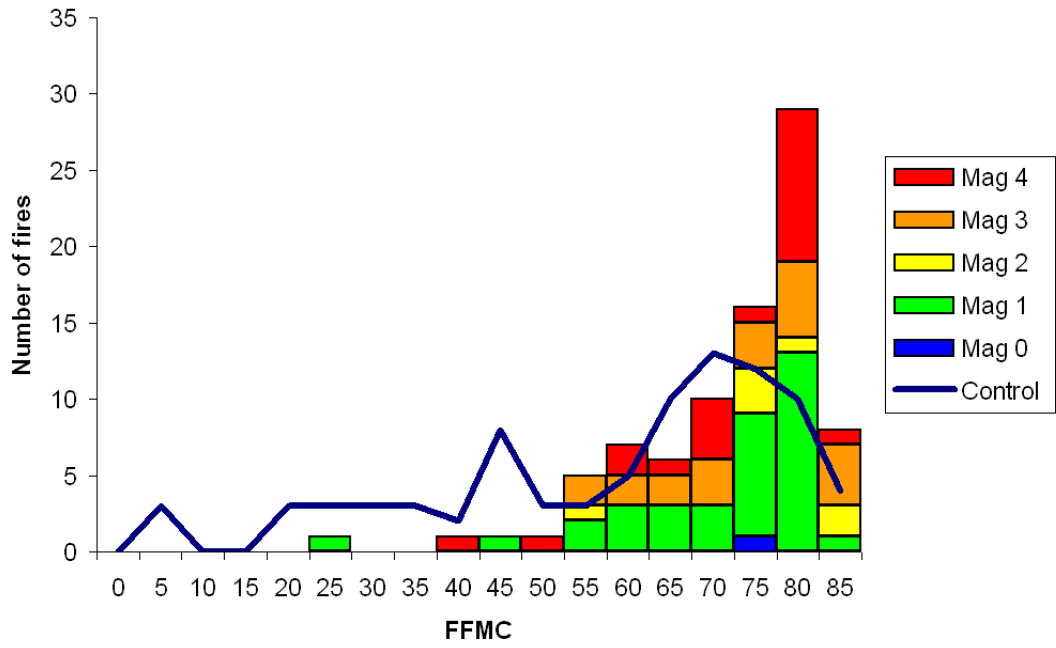


Figure 2.5.6. Number of fires reported to the Fire & Rescue Service in summer (June - August) plotted against the Canadian FFMC and ISI.

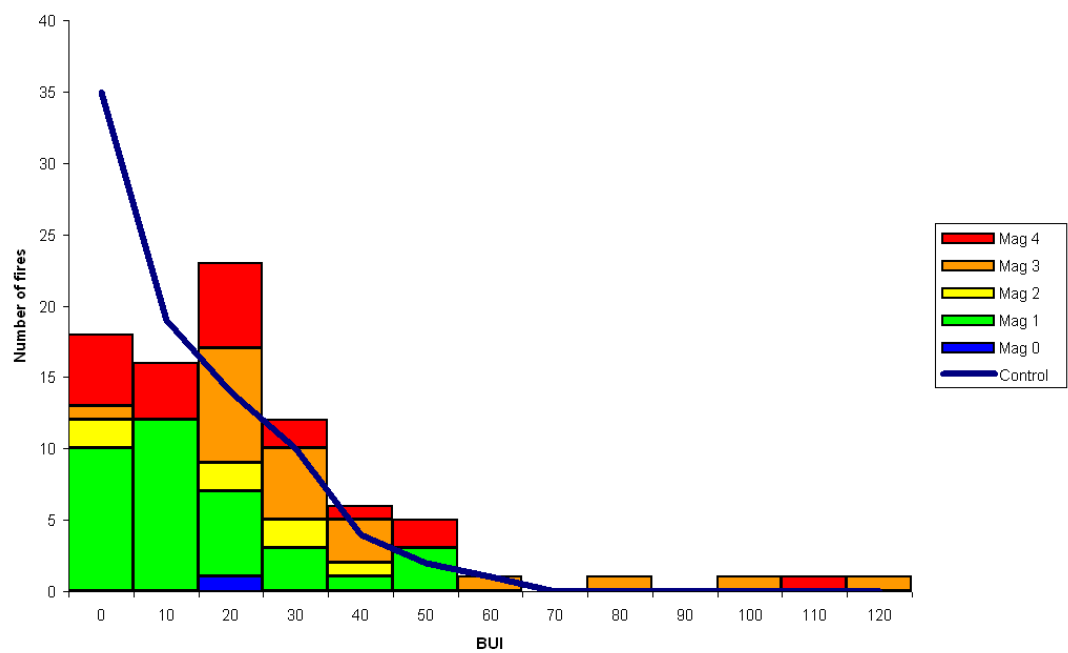
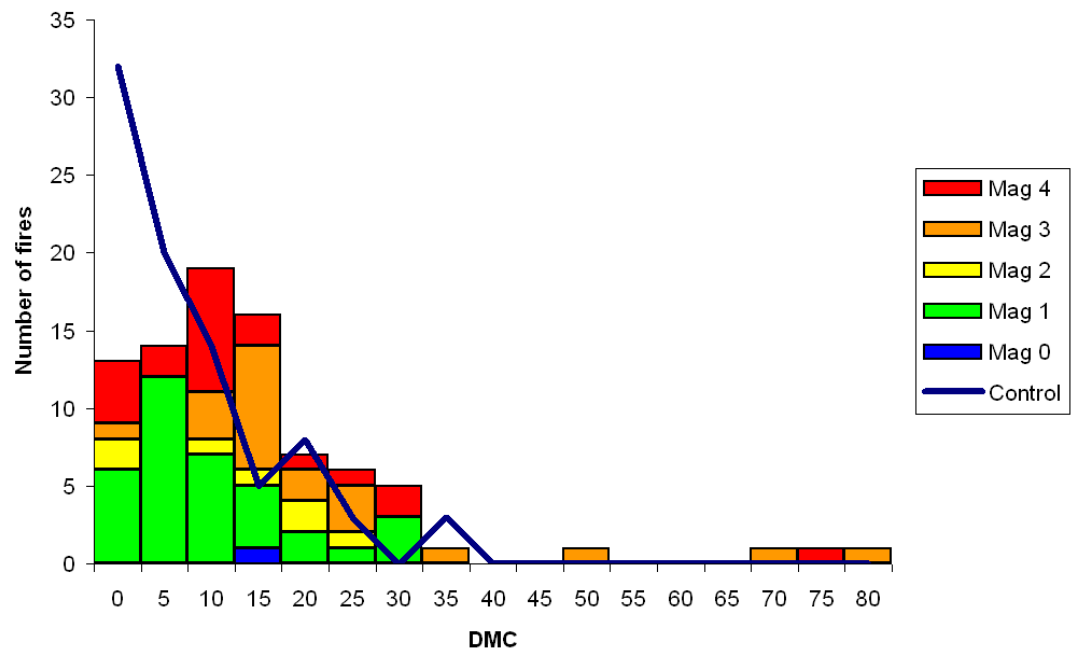


Figure 2.5.7. Number of fires reported to the Fire & Rescue Service in summer (June - August) plotted against the Canadian DMC and BUI.

An analysis of grass fires shows a similar pattern to heath fires in that most fires occur in spring and the frequency of grass fires is much greater than expected according to the null model when the FFMC is above 80 (Figure 2.5.9a). In summer (Figure 2.5.9b) the threshold of FFMC appears to rise to 85 as even

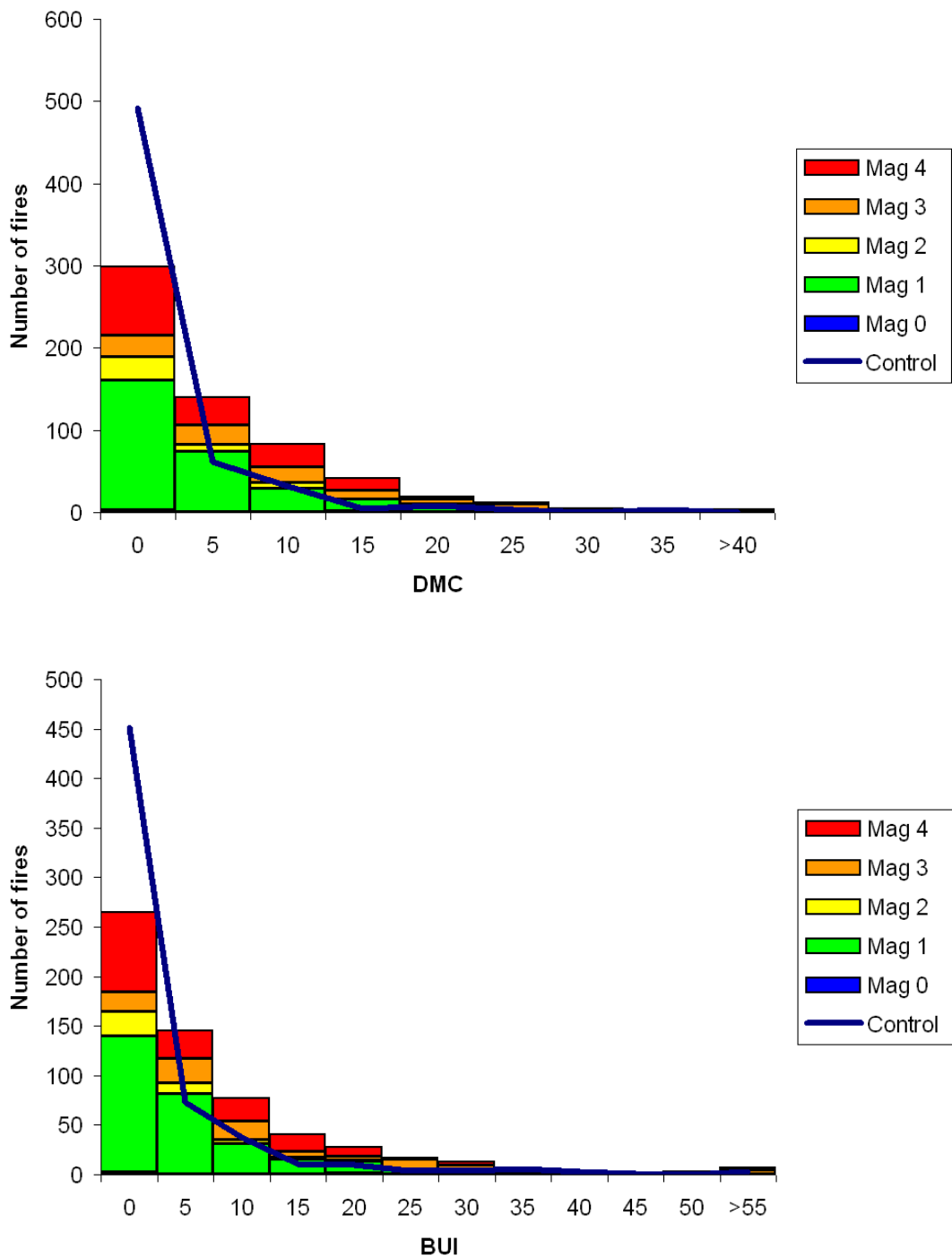


Figure 2.5.8. Number of fires reported to the Fire & Rescue Service in spring (March - May) plotted against the Canadian DMC and BUI.

though the frequency of days with an FFMC of 80 – 84 is quite high there are relatively few fires. The vegetation category extracted from the LCS2000 database is referred to as ‘Acid grassland’ and does not distinguish different types of grassland. It is assumed here that the majority of spring fires will be

fires in *Molinia* grassland in the south-west and north-west Scotland, though summer fires may include other grasslands types where low grazing results in a build-up of dead foliage and flower stems later in the season. The spatial distribution of these fires needs to be checked to assess this more carefully.

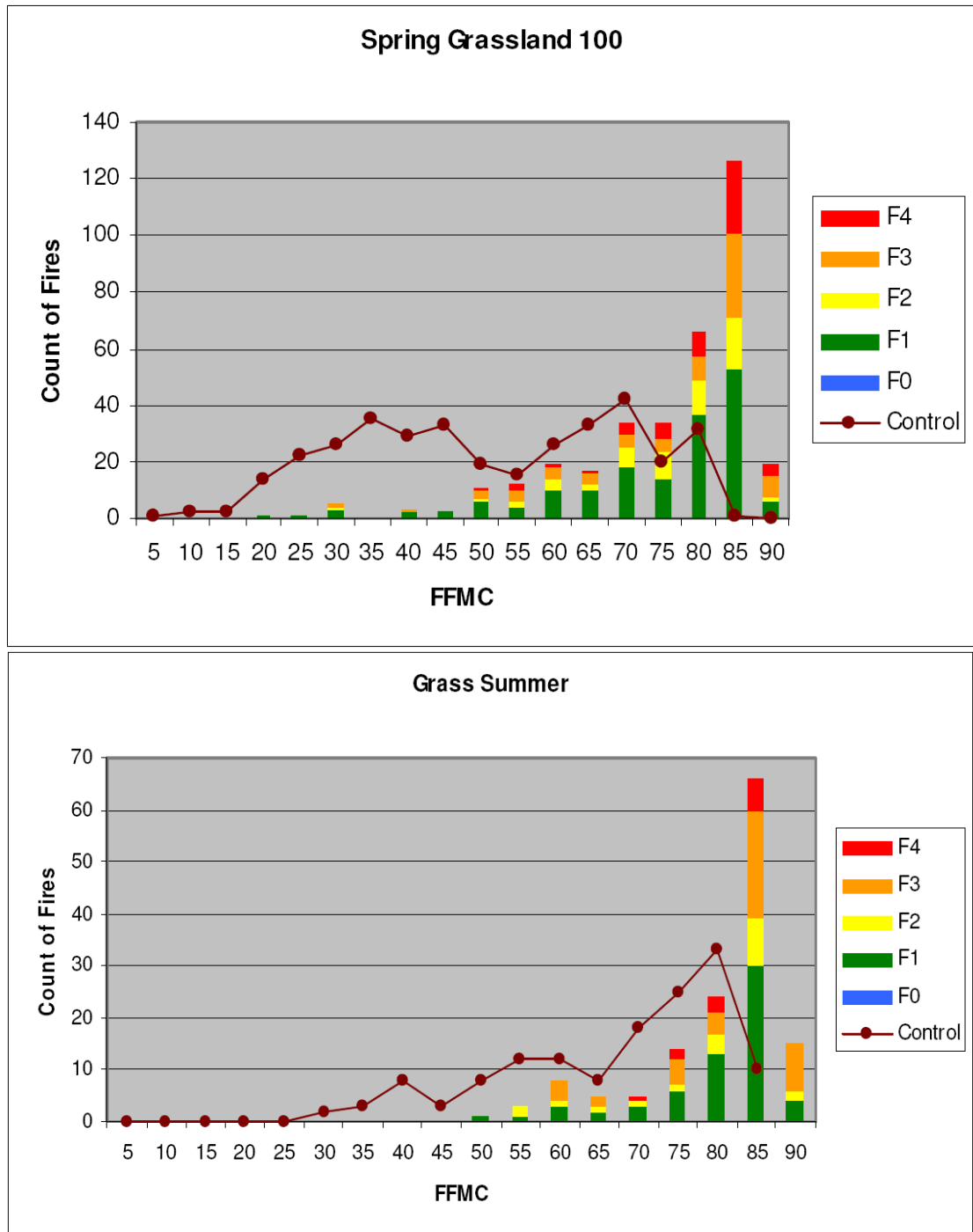


Figure 2.5.9. The frequency of fires in acid grassland reported to the Fire & Rescue Services in a/ spring (March – May) and b/ summer (June – August) plotted against the Fine Fuel Moisture Code.

2.5.4 Conclusions

This study of fire occurrence as recorded by Fire & Rescue Service records demonstrates that the Fine Fuel Moisture Code (FFMC) of the Canadian Forest Fire Weather Information System (CFFWIS) can successfully predict the occurrence of heathland wild fires and many of the grass fires in spring. It performs less well in summer when a much higher proportion of days have weather conditions when fires in appropriate fuels might be possible, but where most heather and grass fuels are dominated by fresh green growth with a high moisture content. In summer the Duff Moisture Code (DMC) and Build-up Index (BUI) also provide information. Although the CFFWIS contains seven codes, there is a lot of redundancy and the information is mostly (97%) can be contained in just two numbers. The simplest way to represent this would be a plot of FFMC against DMC; The FFMC contains most of the information contained in the Initial Spread Index (ISI), Fire Weather Index (FWI) and Drought Severity Index (DSR), while DMC and BUI share most of their information. The Drought Code (DC) does not appear to contribute any useful information in this data set, although it is likely that the risk of peat fire will be strongly related to DC.

Management fires lit by grouse-moor managers show a very different distribution with respect to the Canadian weather indices and weather conditions selected by managers are not usefully predicted, though there appears to be a tendency to avoid days with high FFMC and ISI (possibly avoiding days with high wind speed).

2.6 Calibrate a preliminary fire danger rating for heather fires

Data from Phase I and from the above will be used to calculate and calibrate a fire danger rating for heather fires. This will use weather forecast data to predict rate of spread and flame length in standard heather fires. The model will be published for testing by volunteers. Implementation of an operational version of this model as a web-based forecast will be dependent on a

separate contract including the Met Office for continued data feed and will require a further funding.

The simplest way to represent the two dimensions of variation in the Canadian Fire Weather Indices for this data set is to plot FFMC against DMC (Figure 2.6.1). This graph shows that the majority of fires occur when the FFMC is above 50 and DMC is above 10 (i.e. $\log(\text{DMC}) > 1.0$) and should be the basis for defining a fire danger classification. However there is rather little pattern in the distribution of fires of different magnitudes. Although most of the fires at very low FFMC are minor fires, there are some 'Magnitude 4' fires that occur when the DMC is very low. This suggests that the Canadian system is not able to discriminate between fires of different magnitudes as measured in this data set.

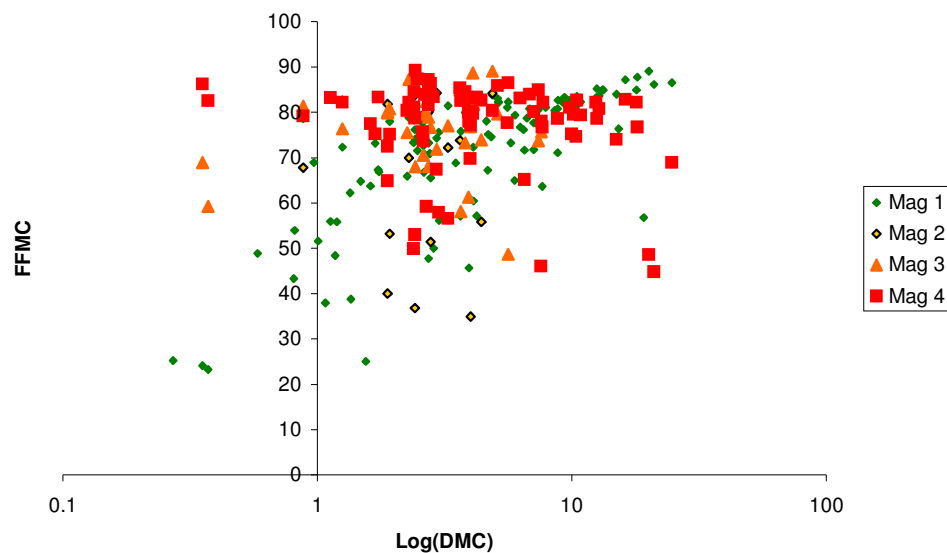


Figure 2.6.1. FFMC of spring heath fires plotted against $\log(\text{DMC})$ showing different fire magnitudes.

Undoubtedly the classification of fires into different 'magnitude' classes (as described in detail in the FireBeaters Phase I report, Legg *et al.* 2007) is very weak data with several different criteria of area burnt, man-power and equipment used by the Fire & Rescue Services and time take to extinguish the fire being combined from different regions. There may be several reasons why a fire increases in size of difficult of control that are unrelated to weather

conditions and fire hazard, including remoteness of the fire and the difficulty of terrain. Fires that take a long time to reach are much more likely to burn large areas and take a long time to put out regardless of weather conditions.

Nonetheless, the magnitude 3 and 4 fires are well spread across the diagram. This suggests that the Canadian system may be adequate to predict the occurrence of fires to some extent using FFMC or a closely related index, but that fire severity cannot yet be predicted.

Further analysis of these data is required before a reliable fire danger rating system can be produced, but a high priority must be to obtain better quality of data from the Fire & Rescue Services on fire behaviour and severity.

2.7 Maintain and further develop the FireBeaters Web site.

There will be maintenance and some further development of the FireBeaters Web site. This will include on-line access to forms for fire reporting, and implementation of some of the results from Phase I (such as the predictions of fire rates of spread and flame length) in a form for testing by volunteer recorders.

Since the end of FireBeaters Phase I project and the proposal for Phase II there have been several changes of significance to the FireBeaters Web site. Firstly, the data stream from the Met Office that was used to display the MOFSI for Scotland was turned off at the end of the Phase I contract and has been removed from the Web. Secondly, there are detailed plans for the implementation of the United Kingdom Vegetation Fire Standard (UKVFS). These plans have been proposed by Rob Gazzard of the Forestry Commission and, once implemented, will provide a standard and detailed monitoring scheme whereby the Fire & Rescue Services will record much greater details of wildfires that they attend.

The objectives of the UKVFS are (Gazzard 2009):

- a) To ensure that the United Kingdom has a standardised approach to the reporting of vegetation fires,
- b) To define the needs and requirements for reporting vegetation fires,
- c) To research existing fire reporting systems to define best practice,
- d) To develop and define a framework for the reporting of vegetation fires.

This data collection system will effectively supersede one of the primary objectives of the FireBeaters Web site which was to provide forms for collecting fire data from around the country, and will achieve far more than would have been possible on a voluntary basis through FireBeaters. The decision was therefore taken to withdraw the database aspect of FireBeaters and to collaborate with UKVFS as far as possible.

The FireBeaters web site remains a source of general information on vegetation fires in the UK and will be updated at regular intervals as new information becomes available.

2.8 Ignition properties of a fuel bed of mosses

Although this was not one of the originally proposed work packages, the poor weather conditions in the spring of 2008 prevented burning experiments in the field and was therefore replaced with the following laboratory experiments on the ignition properties of mosses.

Understanding smouldering fire behaviour is critical for predicting when fires can develop from two key ignition sources: embers and cigarettes. Embers transported by the fire plume can dramatically increase fire spread rates, whilst discarded cigarette ends are often blamed as important causes of accidental wildfires. The significant relationship between FFMC and the occurrence of wildfires (Section 2.5), combined with the fact that the FFMC is known not to accurately relate to dead or live *Calluna* FMC, but to correlate well with moss/litter FMC and DMC (Legg *et al.* 2007, Section 2.1) suggests that the moisture content of this layer may be important for determining when accidental wildfires occur.

There has been comparatively little research into fire initiation from burning embers and in those few experiments that have been completed (Manzello *et al.* 2008) it has been noted that it is somewhat difficult to define the conditions under which smouldering ignition sources cause fires that develop into flaming combustion. Capturing this process is crucial to understanding the conditions when wildfires can occur. We are aware of just one, largely theoretical, study examining the potential for cigarette ends to ignite wildland fuels (Grishin *et al.* 1998). The principal problem in studying the ignition process is the need to define and control the power and heat output of the ignition source such that one can be certain that relationships observed are controlled by the fuel structure/moisture variables of interest. In this regard previous studies using actual flaming and smouldering embers (Manzello *et al.* 2008) may be relatively inaccurate. We used a heated coil to simulate smouldering ignition of a constructed fuel bed. The methodology is replicable and allows the investigator control over the power, shape and size of the ignition source. We investigated the flammability of pleurocarpous mosses collected from *Calluna vulgaris*-dominated heathlands in Scotland.

2.8.1 Methodology

Fire tests were conducted in a steel tray with internal dimensions 30 cm x 30 cm x 4 cm (Figure 1). Analysis of data collected by Davies *et al.* (2008) in 66 separate quadrats showed that the average depth of moss/litter layers in the field (based on nine measurements in a 0.5 m x 0.5 m quadrat) varies from less than 0.5 cm to 25 cm and bulk densities from 0.007 g cm⁻³ to 0.319 g cm⁻³. Bulk density values were highly skewed with very shallow fuel beds having high densities possibly due to an under-estimation of fuel-bed depth (see Davies *et al.* 2008). We built fuel beds using the median bulk density value of 0.02 g cm⁻³. Moss was collected from intact mats on Castlelaw Hill in the Pentlands. The fuel was made up of a mixture of pleurocarpous mosses, *Pleurozium schreberi* and *Hylocomium splendens* formed the largest proportion of the fuel with *Hypnum jutlandicum* and *Rhytidiadelphus loreus* occurring frequently but at low covers.

The fresh moss had a moisture content in excess of 300%, and so was dried to constant mass (c. 12-16% FMC) under ambient lab conditions and sealed in airtight bags. The samples were left to equilibrate for 3 to 7 days and samples were then taken from each bag to determine their FMC. The moisture content of each bag was then manipulated by spraying the bag contents with water or drying for variable periods in an oven at 80°C. Following these manipulations the bags were re-sealed and left to equilibrate for a further 7 to 10 days. Further samples were taken to determine the final FMC of each bag. Each bag contained a sufficient volume of fuel to run three to four ignition tests.

Knowing the actual moisture content of the fuel allows the calculation of the fresh weight of fuel required for testing at a given moisture content:

$$\text{Test load} = \text{dry load} + \text{dry load} / 100 \times \text{FMC}$$

The appropriate mass of fuel was taken from a bag and distributed evenly within the test tray, compressing it or “fluffing” it sufficiently to 4-cm depth. Seven twisted-pair thermocouples (K-type), linked to a Campbell Scientific 21X datalogger, were inserted through small holes in the base of the fuel tray (Figure 2.8.1). The datalogger was programmed to collect temperature data every half second.

Smouldering ignitions were attempted using an electrically heated nichrome coil. A series of pilot tests on oven-dried moss (48 hours at 80°C) were used to define the final ignition protocol. This used an igniter coil 3 cm long, 3 mm wide of 15 turns. The coil was heated with a power of 20 W and lowered into the moss, in the centre of the fuelbed, until it was buried with its top surface 2 cm below the surface of the fuel bed. Such a configuration may over-estimate moisture of extinction as it will lead to reduced heat losses and an increased surface area of igniter in contact with the fuel compared to a discarded cigarette. The total power of the ignition was also greater than a typical cigarette but was chosen on the basis of pilot studies used to determine the minimum power required to guarantee ignition of oven dry material. The method provides a

conservative estimate of moisture of extinction that reduces the risk of flammable conditions not being forecast. Our final protocol can be summarised as follows:

- Fuel structure 0.02 g cm⁻³ (oven-dry weight)
- Fuel moisture Varied
- Ignition strength Fixed
 - Power 20 W
 - Duration 10 minutes
 - Size 3 cm, 15 turns
- Wind speed Trace

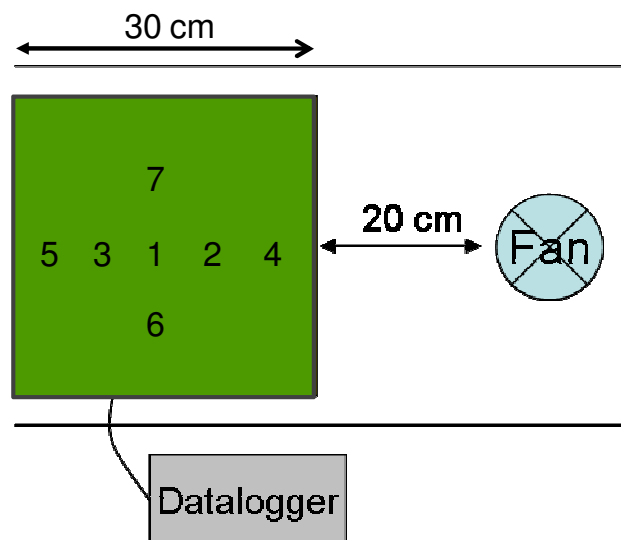


Figure 2.8.1. Layout of small-scale ignition experiments showing positions of the thermocouples (1 – 7). The igniter was placed at position 1. Thermocouples 5, 3, 1, 2 and 4 are each 5 cm apart, while 7, 1 and 6 are 10 cm apart.

Prior to the start of each test a sample of moss was taken by pinching out a small mass of moss from the vicinities of thermocouples 1, 4, 5, 6 and 7 (Figure 2.8.1). Samples were weighed and then dried in an oven for 48 hours at 80°C to determine their final, pre-test moisture content. This also allowed us to calculate the actual mass and bulk density of moss used in each test. Tests were

considered complete once all thermocouples had cooled to a temperature of less than 50°C. Any remaining fuel in the tray was placed in a paper bag, and dried in an oven (48 hours, 80°C) to allow determination of the proportion of fuel consumed.

2.8.2 Results

Pilot studies

Our initial pilot tests with different ignition protocols demonstrated the importance of the nature of the ignition source and small scale variation in fuel bulk density. The first series of tests used a small coil, no more than 1 cm long. The igniter was placed in the centre of the fuel tray and the moss fuel-bed built up around it. A successful ignition with transition to flaming was only achieved for half the tests (Table 2.8.1). Failed ignitions did not smoulder beyond the immediate vicinity of the igniter. Casual observations suggested that low bulk density around the igniter, due to the difficulty in building-up the fuel bed around it, meant that the fuel that was in contact with the coil was rapidly “vaporised”, leaving a small hollow, with no time for the development of a strong smoulder front. To counter this problem of poor igniter-fuel contact we changed the ignition strategy and first built the fuel bed and then lowered the heated coil down into the moss to a depth of 2 cm. This also better simulated the fact that an ember or cigarette butt will fall into any small hollow that initial smouldering may create, thus maintaining igniter-fuel contact. Ignition success was improved but still appeared to be susceptible to small-scale variation in bulk density and the presence of small gaps or hollows in the bed. On this basis we enlarged the size of the igniter to its final dimensions (see methods) and retained the technique of lowering the heated coil into the moss. This technique achieved a near 100% success rate with one test smouldering out the whole tray without developing flaming combustion. These initial results suggest that the development and spread of initial smoulder fronts may be highly dependent on micro-scale variation in fuel conditions.

Table 2.8.1. Performance of three different ignition techniques in pilot experiments.

	Small	Small dropped	Large dropped
Success	3	2	3
Failure	3	1	1*

Full-scale tests

Seventeen full-scale tests were completed at moisture contents ranging from less than 3% to roughly 30% FMC. In all tests smouldering was observed around the igniter, with nine tests resulting in strong smoulder fronts that burnt out more than 30% of the fuel. Flaming combustion was observed in six of the tests (Table 2.8.2). A clear threshold moisture content of roughly 16% seems to exist (Figure 2.8.2). At moisture contents below this transition to flaming was common whilst for higher values not only did the fuel not ignite but smoulder fronts often self-extinguished before the majority of the fuel was. Fuel consumption was generally less than 60% complete even for those tests which developed flaming combustion.

Binary logistic regression was used to model the probability of a transition to flaming (Figure 2.8.3, Equation 2.8.1) on the basis of FMC ($P = 0.05$). The model had an odds ratio of 0.80 and a G -statistic of 6.21 ($P = 0.01$, test that coefficients associated with predictors do not equal zero). Analysis of concordant and discordant pairs showed 59 concordant, 6 discordant and 1 tie.

$$\text{Ln}(\text{Odds flaming}) = 2.69 + -0.22 \times \text{Fuel moisture content} \quad (\text{Eq 2.8.1})$$

Table 2.8.2. Results of the full ignition tests. The table shows the measured FMC and fuel load, whether the test achieved flaming combustion, the seconds passed before flaming initiated, the estimated area of fuel burnt and the measured mass of fuel consumed.

Experiment ID	FMC (%)	Fuel load (g)	Flaming?	Time to flame (s)	Area burnt (%)	Fuel consumed (%)
Ldry1	4.13	69.02	N	-	30	44.98
Ldry2	2.96	75.69	Y	435	100	44.05
Ldry3	6.34	73.99	Y	325	100	59.33
L40_1	28.82	71.89	N	-	5	-
L18_1	16.74	70.77	Y	225	100	69.38
L18_2	15.24	72.05	Y	683	100	63.45
L18_3	14.79	72.43	Y	360	100	43.35
Ldry4	4.40	68.83	Y	129	100	44.05
L24_1	19.37	71.76	N	-	4	12.35
L24_2	21.33	70.02	N	-	5	6.22
L24_3	21.79	69.61	N	-	2	4.14
L20_1	17.92	71.16	N	-	10	23.60
L20_2	19.18	69.83	N	-	3	9.58
L20_3	18.47	69.47	N	-	1	7.61
L19_1	16.68	71.40	N	-	45	36.70
L19_2	16.70	71.38	N	-	1	7.67
L19_3	16.82	70.29	N	-	2	11.28

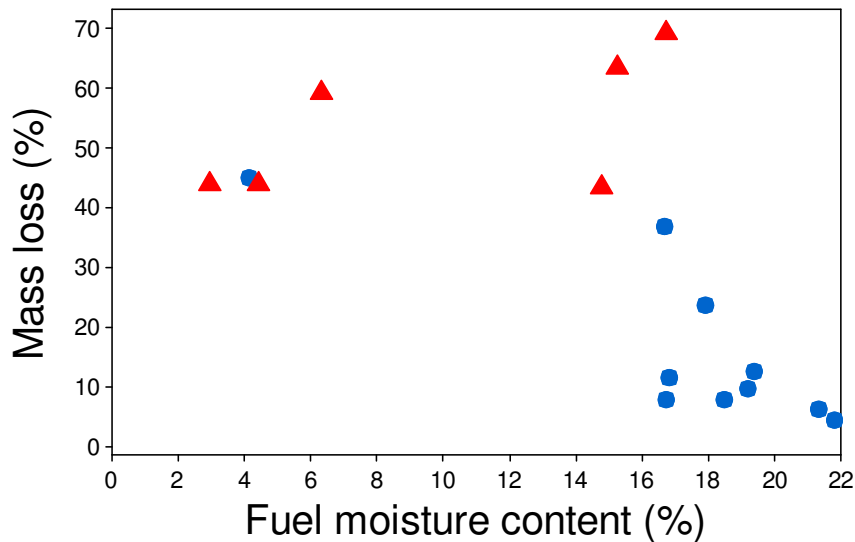


Figure 2.8.2. The proportion of fuel consumed in 16 of the smouldering ignitions. Tests are shown as those with (red triangles) and without (blue circles) transitions to flaming combustion.

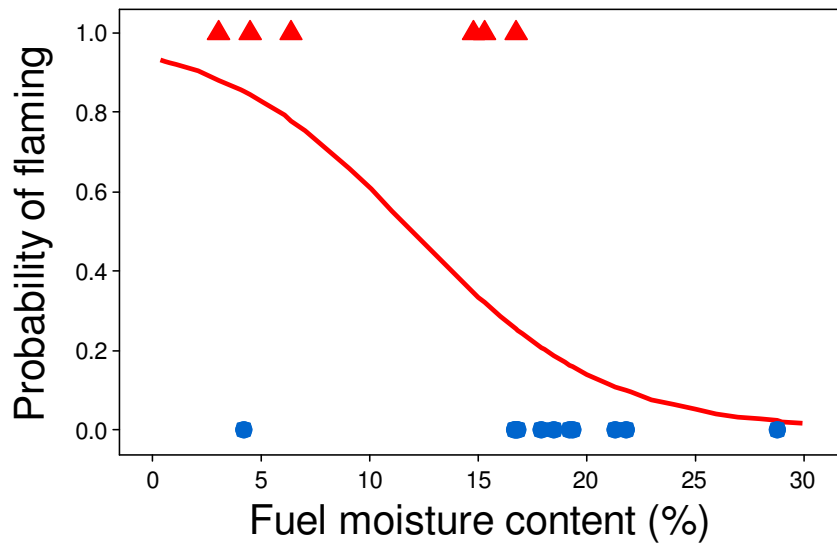


Figure 2.8.3. Modelled probability (Equation 2.8.1) of transition to flaming on the basis of fuel moisture content. The graph also shows tests that did (red triangles) and did not (blue circles) show transition to flaming.

Data from the thermocouples demonstrates the differential behaviour of tests with (Figure 2.8.4a) and without (Figure 2.8.4b) transitions to flaming. For tests without flaming combustion thermocouples detect rises in temperature sequentially but in a somewhat random order, as smoulder fronts pass each location. For those with flaming combustion an initial increase in temperature is seen at thermocouple one followed by cooling as the smoulder front moves away, finally there is a near simultaneous rise in temperature of all thermocouples associated with the initiation of flaming and the rapid spread of the fire front across the fuel-bed. Further analysis is needed to estimate rates of spread from these data but the results are not considered robust due to the solid wall of the fuel tray.

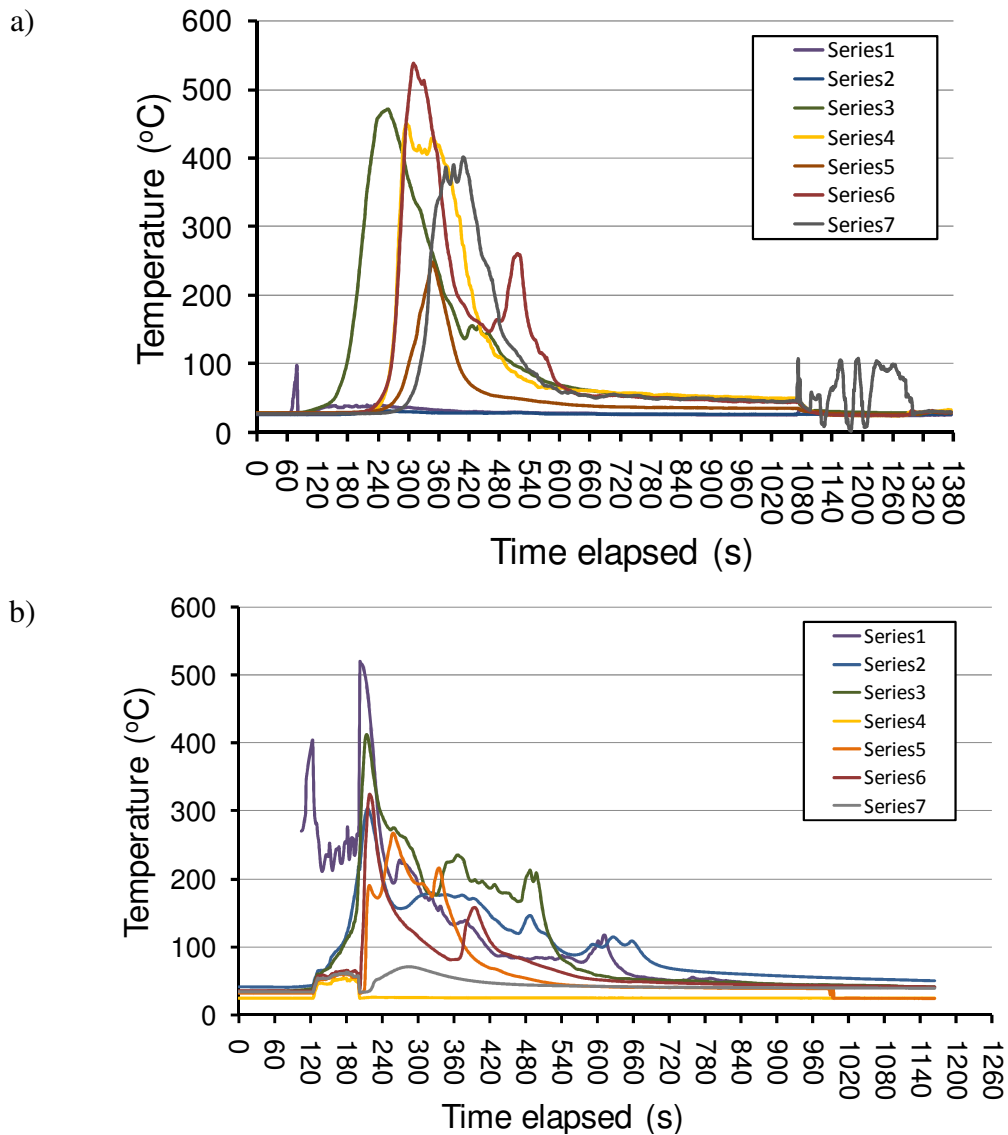


Figure 2.8.4: Thermocouple traces from tests a) without and b) with transitions to flaming combustion.

2.8.3 Conclusion

A critical fuel moisture threshold of c. 16% was defined; below this point moss smouldered rapidly and frequently switched to flaming combustion. Transitions to flaming frequently occurred at the edge of the fuel bed, possibly due to increased air flow. Ignitions also seemed to be highly dependent on the size of the igniter, its position within the fuel-bed and the bulk density of the fuel surrounding it.

Further tests are required with a simulated wind field but those to date suggest that rather particular conditions need to be met in order for cigarettes to ignite forest fuels. The fuel in the immediate vicinity of a smouldering ignition source needs to be dry enough to allow the onset of smouldering, and needs to have and even FMC to allow subsequent spread and build-up of a strong smouldering front. The fuel must also be of an appropriate bulk density that allows both good contact with the ignition source and the necessary balance between air flow (oxygen supply) and heat retention (Ohlemiller 2002). The size, heat release rate and burn time of the ember or cigarette end will also be critical. One test smouldered over nearly the entire area of the box but did not result in a transition to flaming. This suggests that future attempts to model the proportion of fuel consumed may prove to be a better method of estimating ignition propensity at a given moisture content than whether flaming was actually achieved in the small area of the fuel bed.

Modelling and predicting transitions to flaming has been seen as a notoriously difficult task. Our results show that for moss fuels where sustained smouldering can be achieved flaming combustion will often result. The moisture contents at which we observed sustained smouldering and flaming were extremely low, generally lower than values we have observed in the field to date. The presence of increased airflow will raise the moisture content at which ignition can take place. Further tests in a wider variety of fuel types are recommended as a method that can potentially provide rapid and robust estimates of the conditions when accidental wildfires can occur. Future tests should also focus on fire initiation from flaming ignition sources. Considering the generally good ability of the FFMC, DMC and other meteorological variables (Section 2.5) to forecast the moisture content of moss fuels we anticipate that an accidental fire danger forecasting system could be developed with only a moderate amount of additional research effort.

3 References

- Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. (1998). *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56*. FAO – Food and Agriculture Organisation of the United Nations, Rome. Available from: <http://www.fao.org/docrep/X0490E/x0490e00.HTM> [Last accessed March 2009]
- ANDERSON, S.A.J. 2006. Future options for fire behaviour modelling and fire danger rating in New Zealand. In: *Proceeding of the Bushfire Conference 2006: Life in a fire-prone environment: Translating science into practice*. Brisbane, 6-9 June 2006. [Abstract online], URL: <http://www.griffith.edu.au/conference/bushfire2006/> [Accessed February 2009].
- Bannister, P. (1964). Stomatal responses of heath plants to water deficits. *Journal of Ecology*, **52**, pp. 151-158.
- Davies, G.M. & Legg, C.J. (2008). Developing a live fuel moisture model for moorland fire danger rating. In “*Modelling, Monitoring and Management of Forest Fires I*” WIT Transactions on Ecology and the Environment, Vol 119. Pp 225–236.
- Davies G.M., Legg C.J., Hamilton A. & Smith A (2008). Using visual obstruction to estimate fuel load and structure. *International Journal of Wildland Fire* **17**, 380-389.
- Gazzard, R. (2009). United Kingdom Vegetation Fire Standard (UKVFS). Executive Summary. Unpublished paper presented to the Scottish Wildfire Forum, February 2009.
- Grishin A.M., Dolgov A.A., Zima V.P., Kryuchkov D.A., Reino V.V., Subbotin A.N. & Tsvyk R. Sh. (1998). Ignition of a layer of combustible forest materials. *Combustion, Explosion and Shock Waves* **24**, 613-620.
- Legg, C, Davies, M, Kitchen, K, & Marno, P. (2007). *A fire Danger Rating System for Vegetation Fires in the UK*. The FireBeaters Project Phase I Final Report. CECS, The University of Edinburgh. Unpublished report to the Scottish Executive. Executive Summary available from <http://firebeaters.org.uk/> [Accessed March 2009].
- MacKinnon, F. (2008). *How GIS and Fire Indices can be Used in Developing a Fire Prediction Model for Scotland*. Unpublished Dissertation, MSc in Geographical Information Science, The University of Edinburgh.
- Manzello S.L., Cleary T.G., Shields J.R., Maranghides A., Mell W. & Yang J.C. (2006). Experimental investigation of firebrands: Generation and ignition of fuel beds. *Fire Safety Journal* **43**, 226-233.

Met Office (2005). *The Met Office Fire Severity Index for England and Wales*. Met Office ref: M/B O/P87. Unpublished report prepared for: Countryside Agency, Countryside Council for Wales and the Forestry Commission. Available from: <http://www.openaccess.gov.uk/> [Accessed March 2009].

Thomas, M. (2008). *A Review of the Performance of the Fire Severity Index During 2007 and an Analysis of Exceptional Thresholds*. Unpublished report for Natural England and the Countryside Council for Wales. Exeter: The Met Office. Available from: http://www.openaccess.gov.uk/lwwcm/resources/file/ebed9040b19322d/2007_FSI_analysis.pdf [Accessed March 2009].

4 Appendices

4.1 Protocol for small-scale ignition tests

The small-scale ignition tests were described in the FireBeaters Phase I report from which the following is an extract:

4.1.1 Experimental area

The experimental area was located on an homogenous area of *Calluna* on flat ground near the summit of Castelaw Hill in the Pentland Hills outside Edinburgh (Grid Ref: NT 225 650; Lat 55° 52' N, Long 3° 14' W). The vegetation was classified as belonging to a “Medium” type fuel load (Section 2) or building phase (Gimingham 1988) *Calluna vulgaris*. Species composition was dominated by *Calluna* underlain by a deep mat of pleurocarpous mosses although in some denser areas these were replaced by a layer of *Calluna* litter. Crow berry, *Empetrum nigrum* and blaeberry, *Vaccinium myrtillus*, were locally co-dominant but such areas were avoided. Grasses, mainly moor matt grass, *Nardus stricta*, and wavy hair grass, *Deschampsia flexuosa*, were a regular occurrence but formed only a tiny fraction of the total fuel load. The experimental area was protected to the north and south by swiped firebreaks that had been heavily overgrazed with vegetation consisting of scattered *N. stricta* and *D. flexuosa* plants and a compacted layer of mosses. To the east the site was bounded by a wide gravel track.

4.1.2 Pre-fire monitoring

On each day, prior to the ignitions, a portable weather station was set up at the site which recorded wind speed and direction, temperature, humidity and solar radiation at 5 second intervals. Following this two 2 m x 2 m plots were marked out (Figure 4.2). Their fuel load and structure were estimated using both the FuelRule (Davies *et al.* in press) technique and the destructive harvesting of a

single 25 cm x 25 cm, fuel quadrat. This was returned to the lab and separated into the following fuel components: live stems with foliage, live stems < 2mm in diameter, live stems 2-5 mm in diameter, live stems > 5 mm in diameter, dead stems with foliage, dead stems without foliage. Species other than *Calluna* were analysed separately but never constituted a significant part of the fuel load.

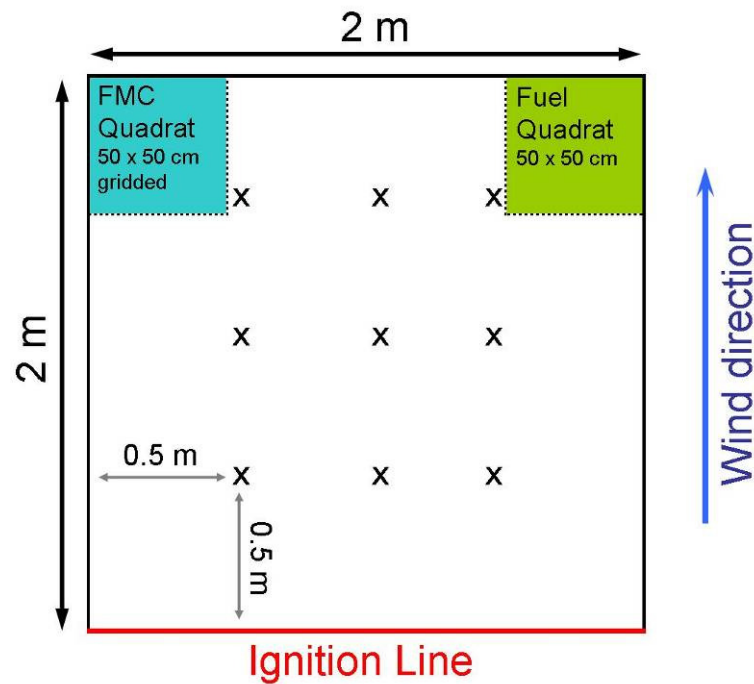


Figure 4.2: Layout of the experiment. X represents FuelRule measurement locations spaced 0.5 m from the plot edge and 0.5 m apart.

The experiment followed a split plot design with a number of covariates (Table 4.1). On each day two ignitions were attempted one in the morning, normally around 11 am, and another in the afternoon around 3 pm.

Table 4.1: Detailed description of the experimental design. CDI, BM and 50%h are fuel description indices produced using the FuelRule technique (Davies *et al.*, submitted). CDI relates to canopy density; BM is a measure of biomass and 50%h is a robust measure of canopy height. SD Mean height and SD CDI refer to the standard deviations of mean *Calluna* height and CDI respectively.

Plot	Treatment	Co-variates variables	Independent variables	Dependant
Day	am	Dead FMC	Fuel load	<i>Sustaining</i>
	pm	Live FMC (mean)	Fine fuel load	<i>Sub-sustaining</i>
		Top shoot FMC	Dead:live ratio	<i>Non-sustaining</i>
		Top canopy FMC	Bulk density	Rate of spread
		Basal canopy FMC	Mean <i>Calluna</i> height	Flame length
		Live stem FMC	CDI	
		Dead stem FMC	SD Mean height	
			Wind speed	SD CDI
		Solar radiation		
		Time since last rain		

Fuel moisture monitoring was completed using a 50 cm × 50 cm quadrat gridded with 25 sub-quadrats, each 100 cm². Five sub-quadrats were randomly selected for harvesting. Within each sub-quadrat all *Calluna* was harvested in the following order: green shoots projecting above the top of the main canopy, the top half of the *Calluna* canopy and the bottom half of the canopy; each stratum comprising small stems < 2 mm in diameter bearing live and some dead foliage. Remaining live stems less than 2 mm in diameter and dead stems were also harvested as was the top 2 cm of the moss/litter layer. Five samples of dead heather shoots were collected from the area within and around the quadrat. Samples were sealed in air tight containers, returned to the lab and weighed and dried (48 hours 80 °C) to allow fuel moisture content to be calculated on a dry weight basis.

4.2 Ignition and fire behaviour

Fires were ignited using a mini drip-torch (500 ml) filled with no more than 125 ml of a 3:1 diesel, petrol mix. Initially a single spot ignition was made by holding the lit torch in the heather canopy for 30 seconds. If this ignition failed to establish then a 2 m line ignition was attempted along the down-wind edge of the plot. A stop watch was started when each ignition attempt was made. Fires that failed to spread were recorded as un-sustaining. For established fires the time taken for them to spread across the 2 m plot was recorded. Fires that took more than five minutes to spread across the plot were recorded as sub-sustaining.

During the fire we estimated the maximum and average length of the flames and noted as to whether the fire seemed to be spreading primarily through the upper or lower canopy or equally through both (Figure 4.3).



Figure 4.3: Fire spreading through the lower layers of a stand of building phase *Calluna*. The green, live fuel-dominated upper layers burnt after the predominantly dead material below.

4.3 Priorities for grass burning experiments

The following represents priorities for burning experiments in *Molinia* grassland agreed through discussion between Ian Murgatroyd (Forestry Commission), Alistair Hamilton (Scottish Agricultural College) and Gary Servant (Highland Ecology):

- 1/ To develop a protocol for sampling *Molinia* litter for estimating fuel moisture that takes into account the strong vertical gradient in moisture.

- 2/ To develop a sampling procedure to estimate total fuel load and, taking 1/ into account, to estimate the 'available' fuel that will be expected to burn given the current moisture gradient and fire conditions. The base of the 'available fuel' will be largely dependent on the position of the moisture gradient.

The procedure used previously has been to measure fuel consumed after the fire by observing the amount of fuel consumed and then collecting (from an unburnt site) what is judged to be an equivalent load of fuel.

- 3/ To devise a simple measure of fuel heterogeneity/continuity/ tussockyness or fuel structure (e.g. mixtures with *Calluna*) that might influence fire behaviour.

- 4/ To devise protocols that would be appropriate for collecting useful information from both wildfires and experimental fires. To include measures of:
 - a/ rate of spread of fire (including observations and estimation of the importance of spotting)
 - b/ flame length
 - c/ a simple measure of 'ease of control' (i.e. effectiveness of a beater) use work study approach, e.g. time taken to beat out 100 m of fire front
 - d/ amount of fuel consumed (as under 2/ above for 'available fuel')

- e/ characteristics of the remaining surface/seedbed - ecological impact
- f/ description of environment (slope, aspect) and simple measures of weather conditions.

5/ To draw up plans for experimental burns including:

- a/ ways of isolating experimental burn patches with firebreaks, etc;
- b/ appropriate plot size;
- c/ weather records;
- d/ numbers of samples for fuel moisture/biomass;
- e/ strategy for measuring all of 4/ above.

6/ Think about how we might collect and analyse data on a/ wildfires as and when they occur, and b/ fluctuations in fuel moisture through the season and with weather conditions with a view to developing a predictive system that would run off Met Office data.

7/ Develop a research proposal with for further funding.

4.4 How GIS and Fire Indices can be Used in Developing a Fire Prediction Model for Scotland

The thesis by Frances MacKinnon (2008) is available as a separate pdf file

MacKinnon, F. (2008). *How GIS and Fire Indices can be Used in Developing a Fire Prediction Model for Scotland*. Unpublished Dissertation, MSc in Geographical Information Science, The University of Edinburgh.