A Fire Danger Rating System for Vegetation Fires in the UK

The FireBeaters Project Phase I Final Report

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Membership of the FireBeaters Steering Group

Michael Bruce (Chairman)	Glen Tanar Estate
Trevor Johnson	Highlands and Islands Fire Brigade
Keith McGillivray	HM Fire Services Inspectorate
Andrew Coupar	Scottish Natural Heritage
Graham Sullivan	Scottish Natural Heritage

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Executive Summary

Introduction and objectives

The objective of this research is to develop a predictive tool for the management of wildfire in the UK and for facilitating good practice by those who work with fire in semi-natural vegetation. This will include a comprehensive system for predicting the weather conditions that control fire frequency and severity. We will publish tools using weather data to predict fire behaviour across a range of vegetation types and environmental conditions.

Phase I of the project ran from January – May 2006 and from October 2006 – May 2007. The objectives for Phase I were to extend the current five-day prediction of severity of fire weather conditions in England and Wales to cover Scotland and to develop a web-based tool for predicting the behaviour of management fires in heather moorland.

The work was funded by the Scottish Executive and Scottish Natural Heritage. Work was guided by the Steering Committee comprising representatives from the Scottish Wildfire Forum (chair), the Scottish Executive, The Fire & Rescue Services and Scottish Natural Heritage.

The deliverables for Phase I, as itemised in the initial proposal, were as follows:

- A five-point Fire Weather Index published daily on the Web for Scotland providing five-day predictions at 10-km resolution.
- Fully monitored experimental fires in heather moorland at several sites throughout Scotland to extend the current knowledge base.
- Web-based system for collecting validation data for heathland management fires and for recording wildfires in all vegetation types throughout the UK.
- A fuel moisture model for heather relating fuel moisture to weather and site conditions.
- Review of end user requirements and recommendations on implementing these.
- Fire behaviour prediction for muirburn published on the Web. Implementation of a cut-down version as pocket ‘slide-rule’ or nomographs. Predictions to include estimates of rates of spread, flame length and minimum firebreak width for a range of heather-dominated fuels.
- Magazine and newsletter articles publicising the project and requesting information.
- Phase I Report for external peer review

Methods

- Fully instrumented experimental ‘management’ fires were conducted on two sites, two large burns under ‘wildfire’ conditions on two sites and twelve small ignition tests at a fifth site.
- A database has been constructed for recording experimental fires, normal management fires and wildfires.

- Heathland fuel moisture data have been collected for all fires conducted as part of this project and from a variety of other sources.
- Simple models have been developed for the prediction of rate of spread and intensity (and hence flame length and ease of control) for heather fires based on fuel characteristics, wind speed and fuel moisture.
- The Met Office has supplied weather records and forecast (National Weather Prediction – NWP) data for the UK from 2003 onwards. Various weather indices including the Canadian Fire Weather Indices* have been calculated for all fire records and fuel moisture measurements for which data are available.

Achievements

- Twelve full experimental fires, twelve ignition tests and two wildfire-type fires were fully instrumented and the data added to existing information on heathland fires.
- The database now contains detailed information for 39 fully instrumented experimental fires and basic records for 134 management fires and 6699 wildfires occurring from 2000 onwards.
- Simple models have been developed for the prediction of rate of spread and intensity (and hence flame length and ease of control) for heather fires based on fuel characteristics and wind speed.
- Fuel moisture data have been collected for 1541 samples on 84 independent days and have been related to various weather indices.
- A web site for the dissemination to the general public of information about managed burning and wildfire has been created at http://firebeaters.org.uk
- A five-point fire weather index (the Met Office Fire Severity Index - MOFSI) for Scotland has been published on the FireBeaters Web site. This provides a five-day forecast of exceptional weather conditions on a 10-km grid-square basis. Exceptional conditions are those where fires are likely to be frequent, difficult to control and to have severe environmental effects.

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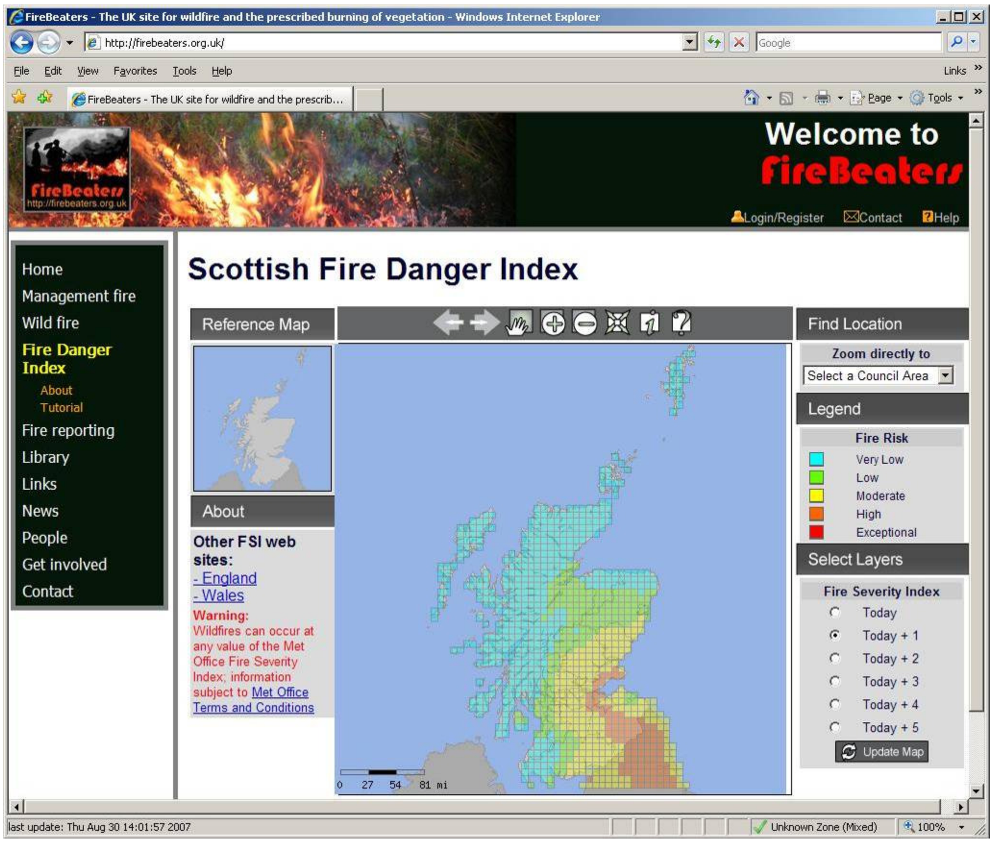
[*] For a brief explanation of the Canadian Fire Weather Indices see Appendix 4.



Warning: Wildfires can occur at any value of the Met Office Fire Severity Index; information subject to Met Office Terms and Conditions

The Met Office Fire Severity Index for Scotland for 31st August 2007 as displayed on the FireBeaters web site at http://firebeaters.org.uk

- Forms are available on the Web for recording data on managed and wild fires, although automatic web access to the database has not yet been fully implemented.

- Preliminary analysis was conducted on 4500 wildfire records and forecast weather conditions. The power of the Canadian Fire Weather Indices to discriminate days on which wildfires occur was tested.

- Qualitative feedback from stakeholders has been received through numerous workshops and seminars presented by the FireBeaters team. There was a very poor response to a web-based questionnaire conducted during the FireBeaters project.

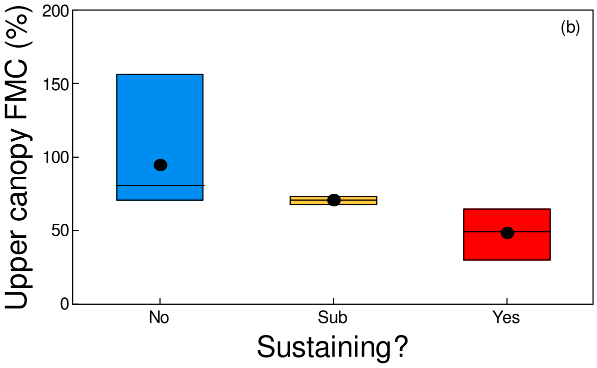
- Five papers and three posters have been presented at seven conferences; seven seminars or presentations have been given and a further five are planned to a variety of audiences; three articles have been published in magazines and newsletters, three papers published in conference proceedings; two abstracts published, one paper* accepted for publication and one under review in scientific journals (* based largely on Matt Davies' PhD but including material relevant to the FireBeaters project). The Edinburgh team were visited by fire researchers from Sweden and New Zealand.

- This final report has been externally reviewed by Dr Wendy Anderson of the School of Physical, Environmental and Mathematical Sciences, The University of New South Wales. The chapters of this report potentially provide the basis for the publication of four or five further papers in scientific journals.

Main conclusions

- The Met Office Fire Severity Index has been shown to be a useful tool for predicting exceptional fire weather conditions in Scotland.

- Ignition tests have demonstrated that a spring fire can be self sustaining in building-phase heather when the live fuel moisture is below 60%. These tests should now be extended to a wider range of fuel types and seasons.



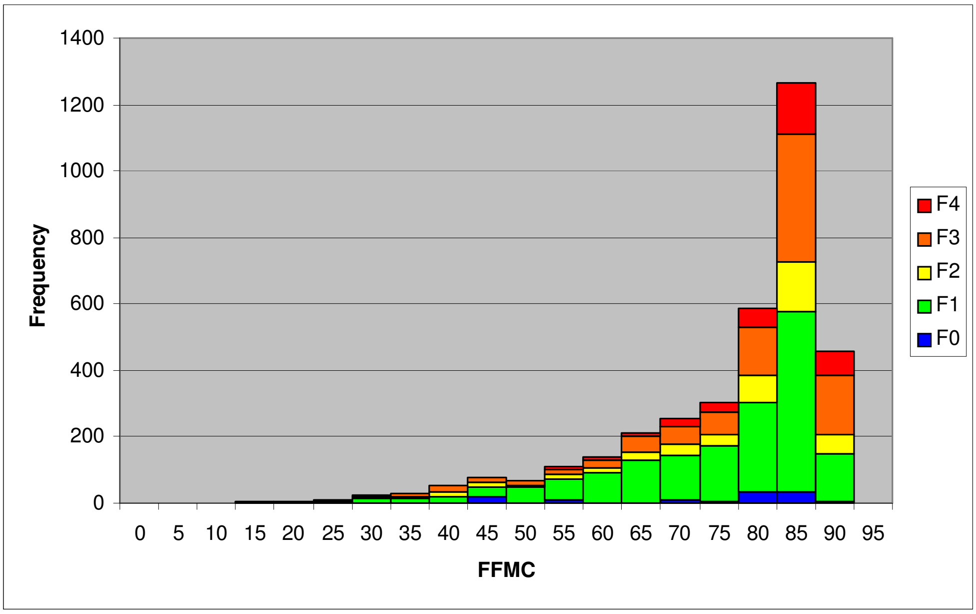
Results of ignition tests showing the range of moisture content of live fuel in the upper canopy of heather stands where fires were self sustaining ('yes', red), self extinguishing ('No', blue), or sub-sustaining ('Sub', yellow) i.e. burning incompletely and very slowly (<0.4 m min^{-1}).

- Experimental fires show that fire behaviour can be predicted successfully from information on canopy height, wind speed, live fuel moisture content and a measure of fuel heterogeneity. The models of fire behaviour in heathlands are suitable for development as nomograms or simple web-based models that can be tested by volunteer land managers, but need further validation at a wider range of conditions. Additional research is required to enable these models to be used with confidence for fires on slopes, and for accidental fires where the fire front is much wider than in the current experimental fires.

- Tests of the Canadian Fire Weather Index and the American BehavePlus model demonstrated that these models could probably be used successfully to predict fire behaviour if a detailed fuel moisture model were developed specifically for the heathland situation.

- The fuel moisture data show weak relationships with the Canadian fire weather indices FFMC, DC, but stronger relationships with other weather variables (e.g. minimum temperature for spring data, predicted fractional soil moisture for summer data). These relationships need to be explored further so that a working model of fuel moisture can be developed. Fuel moisture depends both on the weather conditions leading up to the fire event and also on the physiological state of the vegetation determined by the season. Further research is needed to improve our current understanding of fuel moisture, in particular to understand how fuel moisture relates to weather conditions in different seasons. Initial results (Fig 6.2, 6.3) suggest that it should be possible to predict fuel moisture in heathlands from the NWP (Numerical Weather Prediction) data supplied by the Met Office on a five-day forecast basis.

- Analysis of records of outdoor fires supplied by the Fire & Rescue Services demonstrated that the occurrence of wildfire can be predicted to some extent by weather indices. Most outdoor fires occur when the FFMC > 65 and most serious fires occur when FFMC > 80, although some fires can occur at almost any value of FFMC. However the data are complex and would be greatly enhanced by further analysis using GIS and detailed topographic and vegetation maps. It is anticipated that much better predictions would be possible with further analysis of season, topography and fuel type.



Frequency distributions of wildfires with respect to the Fine Fuel Moisture Code distinguishing the fires of different magnitude (F0 – F4). The majority of fires of high magnitude occur when the FFMC is above 80.

- A survey of end user requirements at the Wildfire 2005 conference showed positive interest in the development of tools for predicting fire behaviour.

Due to the structure of the contract no work on the FireBeaters project was possible during the summer months; this meant that very little direct information has been collected on summer wildfires. The occurrence and behaviour of summer fires in heathland vegetation are likely to be controlled by moisture in the moss and litter layer, while spring fires are controlled largely by moisture content of the live heather canopy. More research is required, including experimental fires in summer and autumn, before the models developed here can be safely applied to summer wildfires in heathlands.

Recommendations and priorities for FireBeaters Phase II

Phase I of this project has concentrated on heathland fires. Phase II should consolidate this research and validate the models that have been produced, but should also extend the research to other fuel types, in particular to gorse, grassland and peat fires. Some preliminary work has been done on gorse fires (Higham 2006, University of Edinburgh), peat fires (University of Edinburgh and Met Office) and grass fires (Met Office). These projects are all preliminary in nature and these different strands should be brought together into a single coherent research framework.

The following tasks are identified as priorities for Phase II of this research:

- 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.

Colin Legg
31st August 2007

FireBeaters Phase I Project Report

Background

Prescribed burning is used extensively in upland Britain for habitat management for red grouse (*Lagopus lagopus scoticus*), an upland game bird that lives on heather (*Calluna vulgaris*) moorland. Fire is also used extensively to regenerate heather moorland and grassland (principally where dominated by purple moor grass, *Molinia caerulea*) for cattle, sheep and deer. In forests, fire is used both to clear branches or heather from sites as a ground preparation tool prior to forest establishment by planting and to encourage natural regeneration (Aldhous & Scott 1993).

Wildfires are common in moorland vegetation, frequently originating from accidental fires, from escaped management fires, or from arson. Wildfires are also common in lowland heathland (dominated by heather, sometimes with western gorse, *Ulex gallii*), especially where these are close to urban sites (Kirby & Tantram 1999a). Gorse (*Ulex europaeus*) fires within urban areas are also common. Fires within forests are much less common in most years, though they do occur during exceptional weather conditions or in young plantations of conifers, especially where adjacent to heather or grass-dominated vegetation, and where heather has re-invaded older stands after thinning. A very high proportion of wildland fires in the UK are anthropogenic in origin, though lightning fires do occur on very rare occasions (Bruce 2000).

Fire hazard is increasing in many areas. The main reason for this has been a reduction in staff available for heather burning operations on many estates due to economic pressures (Hudson 1992) which, combined with a reduction in sheep grazing pressure, has resulted in an increase in the average age and biomass of heather plants. There is also a move from some conservation organisations to extend the recommended fire cycle for heather moorlands from 10-15 years (Gimingham 1972) to 20 years, to retain larger areas of unburned heather (Backshall, Manley & Rebance 2001), to reduce deer numbers and to plant native pinewoods for biodiversity objectives. All of these are likely to increase fuel loads and flammability, and hence increase future fire hazard. Recent legislation has also widened public access to the countryside both in Scotland (Land Reform (Scotland) Act 2003) and in England and Wales (Countryside & Rights of Way Act 2000, the so-called CROW Act). It is widely expected that this will increase the frequency of accidental ignition in some areas. Current predictions of climate change suggest summers will become warmer and drier and that the frequency of extreme weather conditions, particularly summer droughts, will increase and this will bring greatly increased fire hazard over the next few decades.

Exceptional weather conditions during the spring of 2003 demonstrated the effect of drought conditions on fire events with many wildfires occurring throughout the UK, including several large fires that burned for several days. One such fire on the Ardnamurchan peninsular on the normally wet west coast of Scotland was 70 km^2 in extent. The April 2007 fire in the Galloway Forest Park burned 55 km^2 of heather and grass moorland including 500 ha of forest; the fire took three days to extinguish and at times was burning 3 km from the nearest vehicle access. These fires made considerable demands on both local land managers and the Fire and Rescue Services with resources being deployed from surrounding areas and compromising fire cover in urban areas. The unforeseen nature of these fires resulted in unprecedented insurance claims and many insurance companies withdrawing wildfire cover.

Between 2000 and 2006 the Highland & Islands Fire & Rescue Services attended 3351 outdoor fires involving 4734 journeys by appliances and 25,937 journeys by personnel. Over the same time the Grampian Fire & Rescue Service attended 1151 outdoor fires, deploying 2245 appliances;

the10,654 personnel-journeys totalled 24,113 man-hours away from station. While these statistics may include some vehicle fires and some other fuels, the majority are wildland fires and this demonstrates the scale of the problem in Scotland.

The environmental and economic cost of these fires cannot be easily estimated but is considerable. The economic costs include both the destruction of property (forestry, fencing, etc.) and lost income. Forest Enterprise estimate that the re-planting costs alone for the 700 ha of plantation damaged in Wales in the exceptional season of 2003 would be £500,000 (Farmer 2003). The environmental costs are also considerable, particularly where peat is ignited resulting in destruction of the seedbank, a higher risk of erosion and a complete change in ecosystem function. The fire at Fylingdales in the North York Moors effectively removed the surface peat and seedbank from 258 ha, affecting over 30 Scheduled Ancient Monuments, and requiring extensive restoration work (estimated cost excluding staff time £290,000). The scars from similar fires on the North York Moors in 1976 (Maltby, Legg & Proctor 1990) are still clearly visible 30 years later and the area has not yet returned to its former productivity for either grouse or sheep.

A robust Fire Danger Rating System is needed for the UK that serves the needs of the fire brigades for predicting times of maximum fire risk and land-managers for forecasting safe periods for the application of prescribed fire. The Met Office Fire Severity Index (MOFSI) (Met Office 2005) has been recently developed in response to the CROW (Countryside and Rights of Way) Act 2000 for England and Wales (Stationery Office 2000). This fire danger index is based on the Canadian Fire Weather Index (FWI) and has provides a five-point scale that is calibrated for England and Wales to give a five-day prediction of 'exceptional weather conditions'. Predicted exceptional weather conditions provide an object criterion that enables the relevant local authority to close public access to open access land.

A questionnaire survey of some of the participants at the Wildfire 2005 conference showed the value of the recently developed Met Office Fire Severity Index for England and Wales, but it also showed the perceived need to develop other tools for predicting fire behaviour (Appendix 2). It is clear that, while the MOFSI may adequately predict exceptional conditions, the lower points on the scale do not provide information useful to the the fire & rescue services wishing to predict the fire risk, nor for the land manager wishing know when it suitable to used prescribed burning. Other tools that might be useful include both simple nomographs for predicting rate of spread and flame length for typical UK fuels as well as more complex computer-based models of fire spread. A certain amount of existing research exists in the UK with regards to fire danger rating and fire danger prediction (Kayll 1966, Thomas 1971, Hobbs & Gimingham 1984, Rouse 1959, Hamilton 2000, Davies 2005, Davies et al. 2006) but previous efforts have met either with limited success or have been discontinuous. A concerted effort is needed over a number of years if we are to develop a robust and more generally useful Fire Danger Rating System for the UK.

Deliverables

The original proposal for the first phase of FireBeaters set out eight deliverables. Table 0.1 summarises what was proposed in each and describes their current status. Most deliverables have been met in full or in large part. Deviations from the original proposals were approved by the steering group. The delay in agreeing the contract prevented the summer field work and the development of fuel moisture model beyond a conceptual model that now needs to be calibrated and validated. Section 5 of this report is additional to the original deliverables.

Table 0.1 Current status of the deliverables of the original proposal.

Deliverable	Description	Status
1	The five-point Met Office Fire Severity Index (MOFSI) published daily on the Web for Scotland providing five-day predictions at 10-km resolution.	Implemented at http://firebeaters.org.uk
2	Fully monitored experimental fires in heather moorland at several sites throughout Scotland to extend the current knowledge base.	Twelve full experimental fires, twelve ignition tests and two wildfire-type fires fully instrumented and recorded. (See Appendix 1)
3	Web-based system for collecting validation data for heathland management fires and for recording wildfires in all vegetation types throughout the UK.	Database complete. Web-based fire reporting forms complete but require linking to database.
4	A fuel moisture model for heather relating fuel moisture to weather and site conditions.	The underlying codes of the Canadian Fire Weather Index (Van Wagner 1987) and hence of the Met Office Fire Severity Index have been tested. A new model for live heather moisture is proposed but requires calibration and validation. Further work on dead fuel moisture is also required.
5	Review of end user requirements and recommendations on implementing these.	A user-requirements survey has been initiated though the response rate was very low.
6	Fire behaviour prediction for muirburn published on the Web. Implementation of a cut-down version as pocket 'slide-rule' or nomographs. Predictions to include estimates of rates of spread, flame length and minimum firebreak width for a range of heather-dominated fuels.	Models are proposed that could be implemented on the web or turned into nomographs though further work is required to examine the effects of using Met Office forecast data. Models require further development in a wider range of heather fuel types before becoming publicly available. Models require peer review before being developed into tools. An experiment linking fuel moisture to ignition potential has yielded promising results but needs to be expanded and twinned with an operational fuel model.
7	Magazine and newsletter articles publicising project and requesting information.	Five papers and three posters presented at seven conferences; seven seminars or presentations given and further five planned to a variety of audiences; three articles published in magazines and newsletters, three papers published in conference proceedings; two abstracts published, one paper accepted* for publication and one under review in scientific journals (*based largely on Matt Davies' PhD but including material relevant to the FireBeaters project). Refer to Appendix 3
8	Phase I Report for external peer review.	Reviewed by Wendy Anderson, Senior Lecturer, School of Physical, Environmental and Mathematical Sciences, UNSW, Canberra, Australia.
Additional	Examination of wildfire occurrence in relation to weather, existing fire danger rating systems and coarse fuel types	Assessment has been made of the usefulness of MOFSI and the Canadian FWI for forecasting periods of wildfire risk. This is additional to the original proposal.

Section 1

Weather data and the Met Office Fire Severity Index

Provision of weather data

A full overview of the weather data used within the study is provided in Section 5 and summarised in Table 5.5, and will not be repeated in detail here. However, it is worth making some general points on the sources of these data and their inherent idiosyncrasies.

Observational data provides the most accurate picture of weather conditions at any particular single location and time. Instrument errors for most variables (probably all variables used within fire related studies) are typically less than the errors involved in modelling the data or inferring the values from other techniques, such as radar intensities and so. As such, observed data, whether from manual or automatic weather stations, generally represents a ground truth.

However, point based observations are only valid for the time and location that the observations are made. When studying events away from the observation site, it is likely that the weather conditions will be different. The extents to which the conditions vary are related to a number of factors. Obviously, further away from an observational site the weather conditions will become increasingly un-representative. Whilst in some situations, such as may be found over large tracts of homogeneously flat terrain during anticylonic conditions, variables such as temperature and wind speed may be expected to represent larger swathes of land.

However, under either more unsettled conditions, such as the passage of a frontal system, and in areas where topography or land use change significantly, it may be difficult to interpolate weather conditions too far from the observational site. Particularly, wind will vary according to local terrain changes, temperature will vary according to the height differences between the station and study area.

Under many situations, rainfall is perhaps the most difficult to transpose due to its inherent sporadic spatial pattern, particularly during convective conditions under which highly localised convective rain clouds may develop. For all of these reasons, whilst observations provide the best ground truth for any single time and location, they may not be the most appropriate data source for spatial modelling across large spatial domains.

Other data, such as that derived from Numerical Weather Predictions (NWP) models may be more appropriate in certain circumstances. NWP models are initiated by a process called the assimilation cycle. This process combines the most up to date measurements of meteorological variables available at the time to produce an analysis of weather conditions across the NWP domain, which typically varies from high resolution (4km) domains covering the UK through to coarser (40km) models covering the globe. This analysis forms the basis of any forecast.

The data ingested into the assimilation cycle includes satellite data, radar rainfall data, observations from land based and over-sea instruments. Upper air data collected from planes and weather balloons are also included. Whilst the assimilation scheme used by the Met Office is one of the most advanced in use anywhere in the world, there are inherent errors in any analyses which are produced. These will arise from uncertainties in observed data (with some data sources conflicting with others) together with errors in the assimilation scheme itself.

With regard to fire related studies, it is likely that errors within the rainfall fields are the most significant. Analyses of surface temperatures, relative humidities and wind speed are perhaps sufficiently accurate across the domain. There may also be seasonal cycles in biases and errors produced within the analyses, relating to the seasonal variations in the frequencies of particular weather conditions.

More significantly, the values derived from NWP models represent average conditions across a grid square, rather than the specific values for any particular location. Hence, it is likely that where a significant storm cell is predicted to deposit large amounts of rainfall at a specific location in a very short space of time, this high intensity event will be reduced in value when the rainfall is averaged over a grid square and over the modelling period of the NWP. The impact of such averaging is reduced of course, as both the spatial and temporal resolution of the NWP modes are decreased.

Furthermore, the purpose of many fire danger systems is to predict the likely the fire danger conditions for the forthcoming day. Given that the NWP data assimilation and forecast cycle starts at around midnight and completes at about 4am in the morning, forecasts of fire danger for the day ahead are typically made at around 4:30am and disseminated to customers. Hence, fire danger predictions for 3pm are based on analyses and forecasts using observational data which is some fifteen hours old. Whilst errors in a fifteen hour ahead forecast continue to improve, they will not be without error.

Another source of information arises from Nowcasting systems, such as NIMROD. These systems continue to produce new analyses of weather conditions throughout the day, though provide much more limited forecasts. These systems use very specific techniques for producing analyses and very short range forecasts which could not be employed in a larger NWP model. They use the latest radar imagery available together with other similar sources of data available to the NWP.

The use of radar rainfall is extremely useful in producing the spatial analyses in near real time. However, as a result, there will be some artefacts in rainfall patterns associated with errors and biases in assessing rainfall amounts from radar signatures. These include shadow effects (where the radar can not see precipitation hitting the ground due to obscuring hills etc.), together with other errors relating to correction techniques employed to improve rainfall estimates across upland catchments. Any errors in analyses from these systems will propagate through when estimating variables such as soil moisture, for example. There is much to learn about how best to employ these data sources in fire models.

Whilst all of the data sources described here and used within this study have limitations, they also have tremendous benefits. The ability to assess fire conditions at relatively high spatial resolutions across large domains is extremely powerful. The use of observed data to help provide reassurance that such techniques are adequate and to help correct any final model output is extremely useful. All of these data sources have a role to play in studying fire behaviour but we need to constantly be aware of any issues and errors which may arise from their use.

Description of the Met Office Fire Severity Index

In support of recent legislation and in response to managing the potential for an increase in accidental fires the Met Office, supported by other government departments, has developed a fire weather index that provides a five day prediction of fire weather conditions. The existing MOFSI, (Marno 2005) is an implementation of the Canadian Forest Fire Danger Rating System (See Appendix 4). It was selected after reviewing a number of other potential candidate systems. From that review, three systems were considered for further study based upon the availability of required driving data (such as meteorological information) and the logistics involved in developing the system into an operational forecast model covering England and Wales.

The three short listed methods were the Forestry Commission Fire Danger Rating System (Peace 1948); the Canadian Forest Fire Danger Rating System (Van Wagner 1987) and the Australian Fire Danger Rating Systems (Cheney 1992).

The Canadian Fire Weather Index system uses a combination of three indicators of soil moisture content to produce an index. The fine fuel moisture code (FFMC) gives a rating for surface litter. The duff moisture code (DMC) provides a rating for loosely compacted organic layers of moderate depth and the drought code (DC) indicates moisture levels of deep compact layers and larger fuel elements. These indices are combined to provide the Fire Weather Index. The weather data used comprises daily rainfall totals and midday values for temperature, windspeed and relative humidity. The system is based on empirical work for mature and immature jack pine (Stocks 1987, 1989) with a forest floor base of cured feather mosses and pine needles.

The Australian Fire Danger Index (FDI) differs from the Canadian FWI in that it incorporates the annual average rainfall as well as the 24 hour total to calculate a drought factor using accumulations of temperature and rain and the number of days since the last rainfall. Within the UK Forestry Commission Hazard Rating Index (HRI) method, rainfall and temperature are considered to determine the basic hazard. This is modified by a diurnal risk to produce the HRI incorporating similar variables to the Canadian model.

One key criterion used to select the most appropriate index was an assessment of whether the index can clearly discriminate between high and low risk periods with noticeable, significant corresponding variations in the model output value. The index needed to show both heightened risk during periods of prolonged drought and those severe conditions arising from combinations of high winds, low humidity and warm temperatures when drought is absent or not severe.

For each of the three short-listed methods, two sets of results were created and used to analyse the performance of the different indices. Firstly, a set of daily index values was calculated using daily weather data from eight geographically dispersed weather stations for the period from 1971 to 2001. This was useful for establishing the long term behaviour of the indices and assessing their performance against notable high fire-severity events from historical events. Secondly, a set of daily indices was calculated for April to September for 2003. These indices were compared against observational data collected during that period.

The hot and dry summers of 1976 and 1995 are the most memorable high fire risk summers of recent decades (Entec 2000). The warm, dry spells in the springs of 1980 and 2003 similarly represent extreme fire risk conditions. Any index selected would clearly need to identify these periods of significant risk.

Results

Data from Heathrow near London are discussed by way of example as the station has an excellent observing record. Figure 1 shows model results for the summer of 1976. The Australian FDI is shown on the right hand axis whilst the Canadian DSR and Forestry Commission HRI are shown on the left hand axis on both graphs.

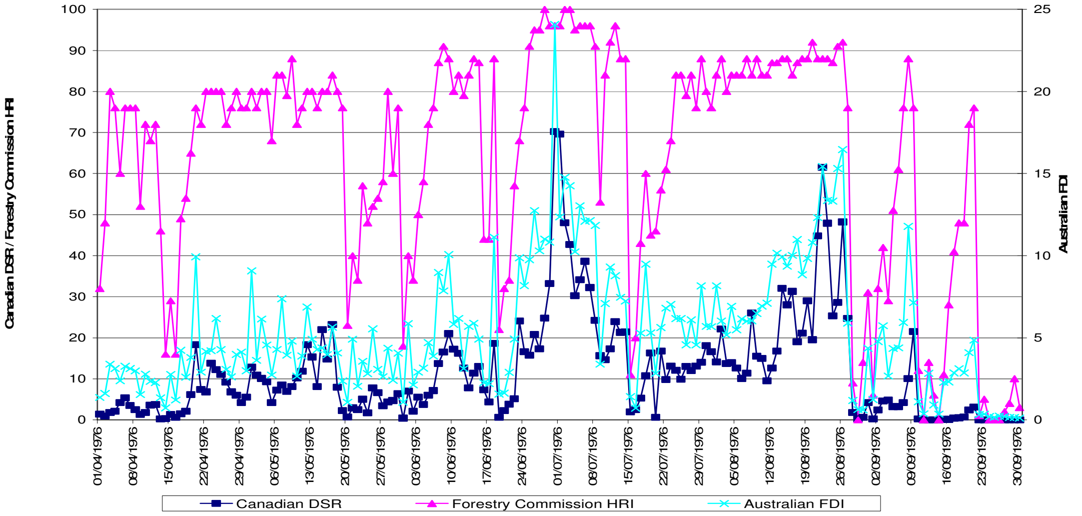


Figure 1: Comparison between DSR, FDI and HRI: daily values for Heathrow in the summer of 1976

Figure 1 shows that for Heathrow there are two major peaks of calculated fire severity, one in late June/early July and a second later in August. The Canadian DSR and the Australian FDI easily pick out the two peaks and in general follow similar patterns. The HRI is quite different. This index is at a high risk level (greater than 95) for several days, but shows little discrimination for picking out peaks as reflected by the other two indices. In 1995, a similar pattern occurred at Heathrow with a calculated fire risk peak at the end of June through to early July, and a second, greater peak which occurred in August. The Canadian DSR and Australian FDI identified this but the Forestry Commission HRI was less good at distinguishing peaks as it remained at a high level for several days at a time.

In April and May of 1980 large parts of England and Wales experienced spells of dry weather accompanied by high temperatures and prolonged sunshine. In April warm and sunny conditions were recorded during the middle of the month with London and Manchester recording unusual maxima of 21°C on 13th April. This was followed by windy conditions and lower temperatures with some thundery showers at the end of the month. May was mainly dry with a prolonged hot and sunny spell from 9th to 19th. The range of conditions experienced during these two months provides a good test for investigating whether the indices can identify risk due to a combination of weather conditions following a warm period rather than a severe drought as may be expected later in the summer. Figure 2 shows the index values for this period for Heathrow as a typical example.

Figure 2 shows two calculated high risk periods in early and mid May identified by the Canadian DSR and Australian FDI, but the Forestry Commission HRI suggests moderate to high risk most of the time.

Data were also available from a trial which took place during April to September 2003 involving a number of observers around the country taking manual observations of ground state and weather at 32 sites across England and Wales. This allowed the predictions from the indices to be compared to actual impressions of the likelihood of fire occurring on the ground for a range of vegetation types. In general there was an increase in DSR as the perceived fire risk increased. The perceived risk was higher for vegetation with a high proportion of grasses than for other vegetation types, including those with trees.

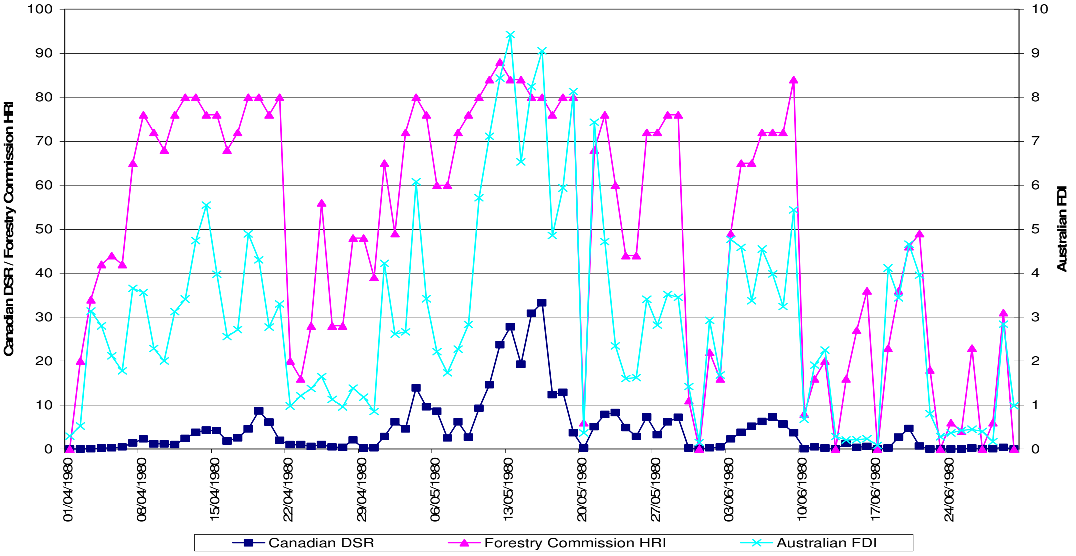
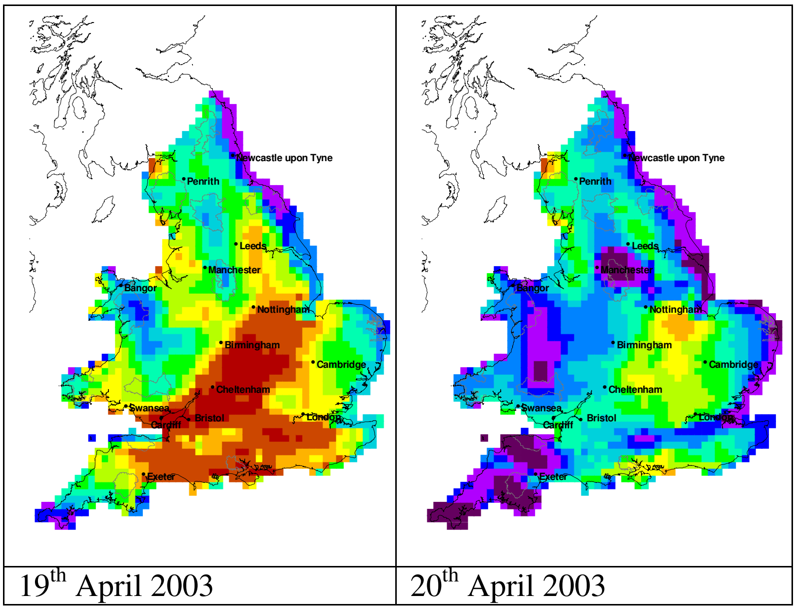


Figure 2: Daily values of Canadian DSR, Forestry Commission HRI and Australian FDI at Heathrow in spring 1980

In 2003 a spell of high fire risk occurred in mid April and fires were observed in many areas throughout England and Wales. A detailed assessment of the period March-April 2003 is provided in the report by Asken Ltd (Asken 2004) which records 449 fires in open country and 17,071 grassland fires, although even this is likely to underestimate the number of fires as the dataset was not complete. Figure 3 shows the MOFSI model results predicting the peak fire danger on 19th April before it subsides the following day. Later in August and September further spells of hot and dry weather increased the fire risk.



19th April 2003	20th April 2003

Figure 3: MOFSI results across England and Wales for two days during Spring, 2003. The high fire risk predicted on April the 19th is reduced the following day following heavy rain across large parts of the country

In April 2003 the high risk period was mainly between 16th and 19th. The Canadian DSR and Australian FDI both show peaks in this period with the Canadian DSR showing the greatest range and the Australian FDI showing a flatter peak. The Forestry Commission HRI picks out several high risk periods in April, which have similar index values, and shows less discrimination than the other indices. For example, at Warcop, Cumbria, NW England, on 17th April the Australian FDI and Canadian DSR have the maximum value for the month, but the Forestry Commission HRI missed this high risk day and instead gave a zero rating. In the Asken (2004) report, the number of Cumbrian grassland fires recorded peaks slightly earlier on the 12th, 14th and 15th April. Although these are the dates when the fires started, they are not necessarily when the greatest risk occurred.

Discussion

The analysis in previous sections has identified that for hot dry summers, the Forestry Commission HRI shows less discrimination than the Canadian DSR and Australian FDI which both successfully capture peaks of greatest risk. The Australian FDI performs well under most circumstances, but it tends to emphasise drought situations as would be appropriate for Australian climatic conditions. It is less good at emphasising the fire risk in spring before drought has built up, or in summers without severe drought. The Canadian DSR includes a drought factor, but places greater emphasis on short term risk due to high winds and low humidity than the Australian FDI. These short term conditions are an important consideration in England and Wales. The modelling of fuel moisture content of duff and deeper organic content of soils, which forms part of the Canadian DSR, gives it a distinct advantage over other indices and it is more sensitive, particularly in terms of identifying risk from a range of different weather scenarios. For these reasons, the Canadian DSR index was proposed as the most appropriate for identifying exceptional conditions in England and Wales.

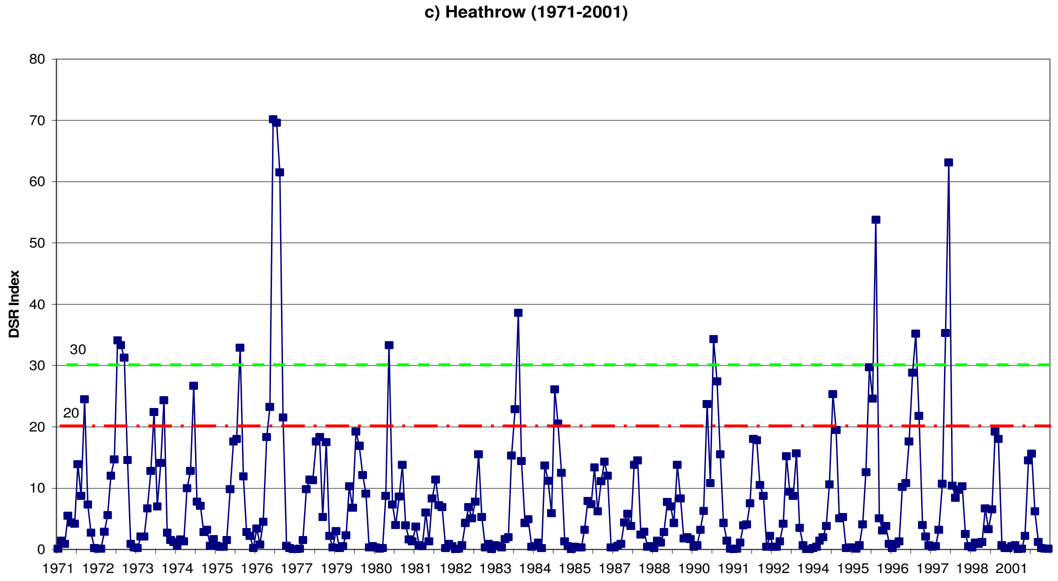


Figure 4: Monthly Maximum values of DSR for all available years for Heathrow

After analysing many years of results from a number of sites around the UK with long observational records, it was established that a daily DSR value of 30 would capture exceptional fire risk periods as defined by the hot summers of 1976 and 1995. For example, looking at Heathrow, one can see the general trend in DSR values over a thirty year period in Figure 4. The DSR value of 30 captures all of the known historical fire events of interest. This is reflected at the other sites across the UK.

A significant point should be stressed - the threshold level for these *exceptional* cases is not in any way similar to the threshold used to define *extreme* conditions, more commonly used in other countries. The main purpose of the existing MOFSI system is currently to identify those rare (exceptional) events which happen once every few years or more – not the more usual annual extreme events which will undoubtedly occur more frequently. This difference in interpretation of the upper threshold is related to existing regulations arising from the CROW act.

Implementation of the Met Office Fire Severity Index

Understanding the Effects of Using Forecast Data

MOFSI is used operationally as a forecast model providing information on predicted fire severity for the next five days. It uses forecast meteorological data from the Met Office Numerical Weather Prediction (NWP) model. Analysing MOFSI values based on both observational and forecast data gave different results, prompting work to understand the variation in greater detail. American research (Hoadley et al. 2004) which explored differences between observations and forecast data also found variations between predicted and actual temperature, wind speed and relative humidity values. They concluded that these discrepancies could have a substantial impact on predictions of fire danger if the bias was not accounted for in some way.

There are a number of known differences between forecast and observational data arising from errors in both techniques. Observations are subject to instrumentation error and errors generated from the geography surrounding the observing site (such as localised wind–flow effects). They are point based and therefore comparisons to the forecast generated fire index values, which are averaged across 10 kilometre grid squares, will have some spatial error. This is likely to be particularly significant for rain as an isolated shower within a 10 kilometre square area may be completely missed by a single observing site. Forecast errors are inherent in the way the forecast is derived. For particular variables there may be biases depending on land condition or difficulties in capturing the physics within the model equations.

For the Fire Severity Index, the most significant meteorological variable is rainfall. Figure 5 shows two measures of the accuracy of the rain forecast by the mesoscale or short range (up to 48 hours) model. The first gives the proportion of times the model was correct in predicting whether rain occurred or not, averaged across the country. The second measure provides an assessment of the precipitation bias as a ratio of the number of occasions on which rain was forecast compared to the number of occasions on which rain was observed.

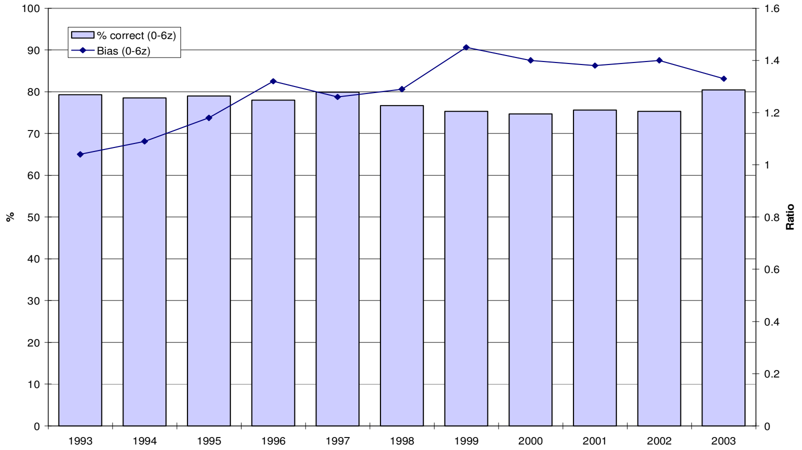


Figure 5: Verification of the Mesoscale Model (Rain). Percentage of times when the NWP model was correct in predicting the presence of rain and bias as the ratio of number of occasions when rain was forecast : observed.

Both of these measures focus on the first six hours of the forecast. Errors will increase as the forecast period increases

DSR results derived both from observational and from NWP data were considered for the period between January and September 2003. Significant differences between the two sets of results were identified at numerous sites

The pattern of values was very similar (correlation of c. 0.7) with the FSI continuing to demonstrate considerable sensitivity in responding to different weather conditions. However there was a difference in the amplitude of the model output depending on the weather source of the DSR values. Those based on observed data had a greater magnitude in peak values. For example, Figure 6 illustrates the difference in values for Sheffield. This shows that when the model is predicting high fire risk (e.g. mid April, late August, mid September), the difference in magnitude is in the order of fourfold, although this factor varies somewhat between sites.

A comparison of temperature, relative humidity, wind and rainfall for observational and NWP data for a number of sites identified that whilst observed temperature was consistent with that predicted by the model, observed relative humidity tends to differ from the model by 5-10% particularly during the warmest months. There was some evidence that wind measurements were underestimated by the model in the summer and overestimated in the winter. For rainfall, although overall there is only perhaps 1 mm difference on average between model and observational data, there are more significant day-to-day variations in the values which give rise to frequent discrepancies.

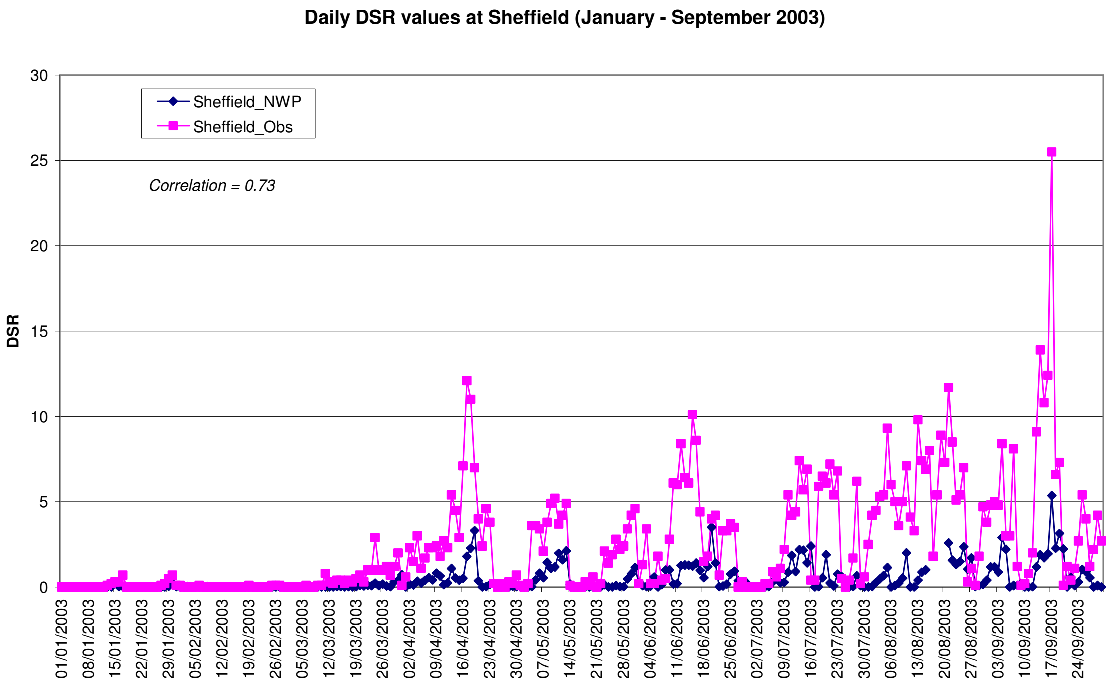


Figure 6: Comparison of NWP and Observational derived DSR values for Sheffield

The variations in DSR values appear to be predominantly caused by the accumulation of differences in a number of the meteorological variables produced by the NWP model. The direction of the bias for the main three elements has an accumulative effect in damping the index because low rain and relative humidity and high winds are the significant components.

The Initial Spread Index (ISI) is doubly influenced by wind, as wind speed is both an input to the FFMC and a separate component combining with the FFMC. The wind speed function is expressed exponentially and every 14 km h^{-1} increase in wind speed results in the doubling of the ISI. Consistently lower wind speeds predicted by the NWP model will therefore have a damping effect on the ISI. Relative humidity also contributes towards both the FFMC and DMC. Therefore the combination of higher relative humidity and rain and lower wind values predicted by the forecast model maximises any variation between DSR-NWP and DSR-Obs values.

These findings suggest that a threshold of 30 for defining exceptional conditions based on observational data is too high when calculating the DSR using NWP data. An analysis of a wide range of sites suggests that the model results differ by a factor of around five. The fire danger class boundaries in the operational forecast model were therefore appropriately scaled to account for this significant difference.

As the accuracy and resolution of the NWP model increases, this factor will need to be revisited. Also, as data feeds to the MOFSI system change, for example, the inclusion of radar rainfall estimates to replace model predictions, further tuning will also be necessary. Such tuning will be an ongoing effort for some years until the NWP model and other data sources used within MOFSI are sufficiently close to observed values so as to warrant such an exercise redundant.

Section 2

Understanding fire behaviour on heather moorlands

Introduction

A good understanding of fire behaviour is crucial for the safe application of prescribed fire, whilst robust fire behaviour models are a central plank of any fire danger rating system. Even an apparently simple five point scale of fire danger such as is used in Canada (Canadian Forest Service, undated) and New Zealand (National Rural Fire Authority, undated) is based on a thorough understanding of factors affecting fuel flammability and fire spread and intensity. Recent work in New Zealand (e.g. Anderson 2006) demonstrates that, especially with regard to shrubland fuels, we still have a lot to learn about predicting fire behaviour. Though there has been some previous research in Scotland much of it has focused on measuring fire temperatures and ecological effect rather than fire behaviour *per se*. The work of Kayll (1966), Hobbs & Gimingham (1984), Hamilton (2000) and Bruce & Servant (2002) provides a starting point and was significantly expanded by Davies (2005, Davies et al. 2006) but further research was required to develop a better understanding of the factors affecting fire behaviour and to make informed decisions about the direction in which the creation of a fire danger rating system for Scotland, and eventually the UK, should proceed.

We know from studies conducted elsewhere that important controls on fire behaviour may include fuel loading and structure (Brown & Bevins 1986, Fernandes 2001), fuel height (Catchpole *et al.* 1998, Fernandes *et al.* 2000), fuel moisture (Pompe & Vines 1966, Sylvester & Wein 1981), the quantity of dead fuel present (Baeza *et al.* 2002), windspeed (Molina & Llinares 1998, Morvan *et al.* 2002, Bilgili & Saglam 2003), relative humidity (Molina & Llinares 1998), topography of the fire site (Fernandes *et al.* 2002) and ignition line length (Hobbs & Gimingham 1984, Cheney *et al.* 1993).

The Scottish heather-dominated moorlands are of international importance (Thompson et al.) and fire is a key factor determining environmental quality. The characteristics of fire in heather-dominated moorlands are also unique due to the combination of the particular characteristics of heather as a fuel and oceanic climate. Moorland fuels in the east of Scotland, and many parts of the UK, are dominated by a single dwarf-shrub species, heather or *Calluna vulgaris* (hereafter *Calluna*), which forms a dense canopy; under which, in older stands, frequently lies a deep layer of pleurocarpous mosses, lichens and litter. Also, unlike many other situations the fuel is dominated by a green, live component with a relatively high fuel moisture content which may have important dampening effects on fire behaviour (Catchpole & Catchpole 1991, Dimitrakopoulos & Papaioannou 2001) though work conducted to date has failed to detect a significant effect of fuel moisture on fire rate of spread (Davies et al 2006). Previous work failed however to measure dead fuel moisture content and it may be that this fuel component plays an important role in driving fire behaviour. Small variations in its moisture content may be important as may variations in the overall proportion of dead material retained within the *Calluna* canopy (De Luis *et al.* 2004, Schwilk 2003). As stands age gaps will become more frequent (Gimingham 1988), and the ratio of woody stem to fine fuels within the canopy will increase (Davies 2005). Greater heterogeneity in the fuel-bed with age means that relationships between increasing fuel load and fire behaviour may not be simple.

Whereas in other areas fire behaviour investigations have been focused on a meteorologically controlled “fire season” and fire behaviour risk in relatively hot, dry summer conditions, the UK climate together with the legislation surrounding heather and grass burning in the UK (summarised in SEERAD 2001 and Ministry of Agriculture Fisheries and Food 1994) and the widespread use of muirburn as a management tool mean that our interest in fire behaviour is as focused on the core legal burning period of October 1st to April 15th as it is on summer wildfire activity in July and August. The nature of weather in the UK uplands means that conditions can vary rapidly from cold and wet, to warm and dry with low atmospheric humidity and periods of physiological drought when the ground is frozen. Variations in fuel moisture can be large, particularly in spring due to frequent precipitation, frozen ground and cuticular damage caused by over-winter ice abrasion (Davies et al. 2006). Days suitable for burning are thus often few and far between which makes understanding fire behaviour all the more important if we are to enable land-managers to make efficient use of time and resources available without feeling under pressure to burn in unsafe conditions.

For any controlled burning or wildfire fighting operation some prior knowledge of likely rate of spread is highly desirable as this will be extremely important in determining a fire's controllability; knowledge of the factors controlling fire behaviour allows fire fighters and land-managers to take into account the effects of rapidly fluctuating weather conditions, to ready fire control resources and to effectively plan the use of tools and tactics. Over the course of our research programme we therefore sought to define relationships between weather conditions and aspects of fire behaviour related to fire controllability. To this end, experimental fires of constant area, ignition-line length and slope were conducted in three different fuel loading categories on different days. This allowed us to investigate linkages between a variety of aspects of fire behaviour, fuel characteristics and variation in weather conditions while removing, as far as possible, the influences of other factors such as slope and ignition-line length; though this still leaves an enormous number of other factors which could potentially affect fire behaviour. With a need to ensure safety and controllability with limited resources our experimental fires were necessarily small. Although possibly insufficient to allow the fire to reach a true "quasi-steady state" of advance of a wildfire (Pyne *et al.* 1996), safety considerations remained paramount while our plot size was still well within the range of recommended fire widths for moorland management.

Aims and objectives

The objectives of this section of the project were as follows:

- Identify and understand key factors controlling variation in fire behaviour
- Develop robust empirical models of rate of spread, fireline intensity and flame length that could be used in fire forecasting
- Clarify the role of fuel moisture in fire behaviour

Methods

In order to reduce the number of factors affecting potential fire behaviour and to focus attention on establishing relationships between weather conditions, fuels, fire behaviour indices and actual fire behaviour experimental burns were set up at two sites using a randomised block design. This saw three fires burnt on any one day, one in each of fuels classified as belonging to High, Medium and Low fuel loading classes. A total of nine burn days were completed giving twenty seven fires in total. Plots were assigned to the High, Medium and Low fuel loading categories subjectively before measurements were taken. This was done in order to achieve a balanced randomised block design in which one plot from each fuel category was burnt on each burn day. The categories are easily recognised in the field and represent the early building pahse, late building phase and mature phases of the *Calluna* developmental cycle (Watt 1955).

The effect of ignition line length is complex and interacts with wind speed (Cheney et al. 1993). This will be investigated in a separate experiment in a subsequent phase and will provide relationships to enable fire data to be scaled up to wildfire size. Two different plot designs were used and these are illustrated in Figure 2.1 below. Overall, twenty one plots were burnt according to design one whilst six were burnt according to design two. For design one fifteen of the fires utilised in the analysis were burnt as part of Davies' (2005) PhD and to these were added a further six fires during the period of the FireBeaters project. The design of the experiment was modified slightly to give a longer fire front and permit burning in a wider range of wind directions. Changes also included the collection of dead fuel moisture samples. Information collected during each fire is summarized in Tables 2.2 – 2.4 which also show which of the experimental designs was used for each fire.

Design one was utilised on a site on 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). Design two was used on Black Hill, Whitborough Estate, in the Pentlands outside Edinburgh (03°20'W, 55°51'N, Grid Reference NT 185625).

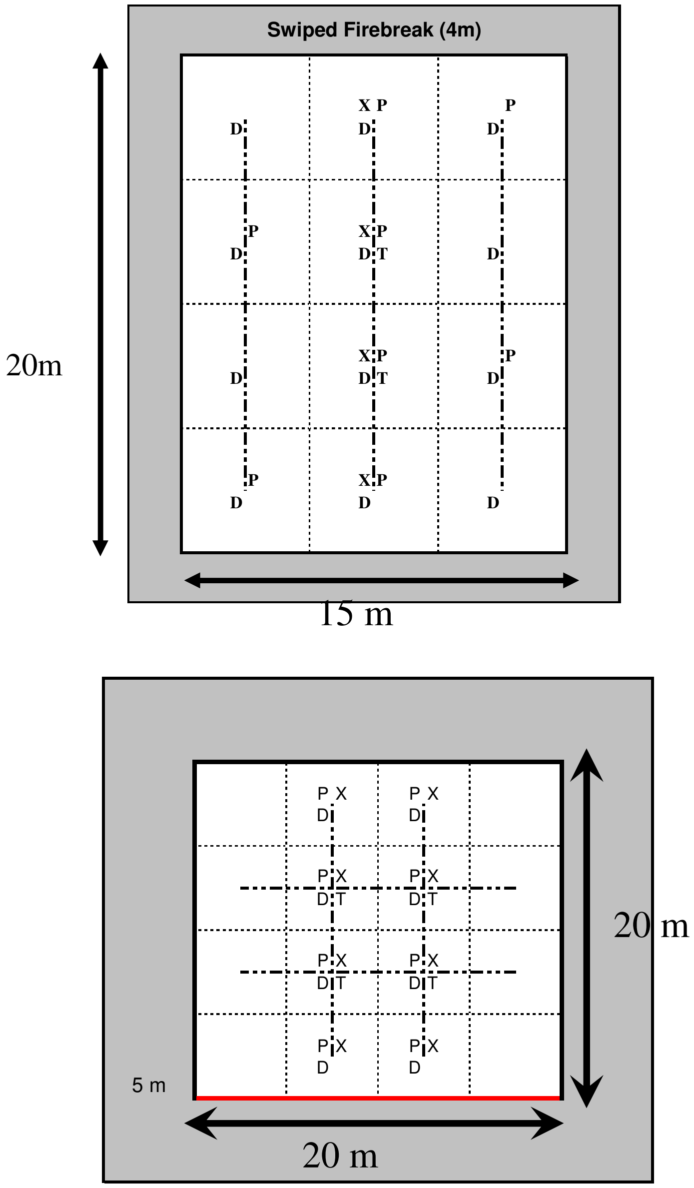


Figure 2.1: Plot and equipment layout for experimental designs one (top) and two (bottom). P is a thermocolour pryrometer, T a set of thermocouples, D a duff spike and X a flame height monitoring post. Thin dashed lines mark out 5 m x 5 m monitoring sub-plots. Thick dot-dash lines are FuelRule transects.

All plots were located on a slope of < 5 – 10 %. The vegetation of stands prior to burning was species poor, *Calluna*-dominated upland heath and comprising mostly closed stands of *Calluna vulgaris* with blaeberry, *Vaccinium myrtillus,* and cowberry, *Vaccinium vitis-idaea,* commonly occurring beneath the canopy (NVC[2] community H12, *Calluna vulgaris-Vaccinium myrtillus* heath, Rodwell 1991). Stands contained a mixture of coarse grasses and sedges with deer-hair sedge, *Trichophorum cespitosum*, wavy hair grass, *Deschampsia flexuosa,* and purple moor grass, *Molinia caerulea,* being frequent but never forming a significant proportion of the fuel load. Most stands of the building phase (Gimingham 1988) and older were underlain by more or less continuous mats of pleurocarpous mosses.

Plots were burnt with the wind as a headfire and ignited using a single ignition line from a drip torch or gas burner. Final responsibility for ignition pattern lay with the designated burn boss and the ignition pattern was altered for safety reasons on all of the burns on Black Hill using design 2 where, due to strong winds, the top or edge of a plot was lit first in order to strengthen swiped firebreaks. In these cases the fire characeristics (RoS and flame length) were measured before the headfire was deemed to have reached the zone of influence of the backfire.

Fuel Loading and Structure

Plots were surveyed using the FuelRule method (Davies et al. submitted) in order to estimate fuel loading, structure and stand heterogeneity. Monitoring points were located 2 m apart on either three or four, 15-m long transects giving a total of nine sticks per transect. Figure 2.1 shows the location of transects for the two plot designs. In addition, a single 50 cm x 50 cm fuel assessment quadrat was located in a representative area of the plot (near to an edge so the flow of fire was not disrupted). The primary objective of these harvested plots was to provide independent data to check the calibration of the FuelRule measures at the plot level. Each of the quadrats was harvested down to the moss/litter layer. Harvested material was sorted in the laboratory into the following categories: 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.

Fuel moisture samples

Fuel moisture content (FMC) samples were collected immediately prior to ignition and were dried in an oven at 80C for 48 hours (Brenner 2002) to allow calculation of FMC on a percent dry weight basis. For fires burnt as past of Davies' (2005) PhD four samples were taken of both live canopy shoots (containing live and dead foliage) and the top 2 cm of the moss/litter layer. For subsequent fires (2006 onwards) five samples of live canopy shoots, dead stems with foliage and the top 2 cm of the moss/litter layer were collected from the centre of randomly selected subplots (Figure 2.1). Fuel moisture samples were normally ca 10-15 g fresh weight (sufficient to three-quarters fill hermetically-sealed aluminium cans ca 4 cm diameter and 8 cm deep) but for dead fuel and litter samples were often only 5 g where material was scarce.

Weather data

A portable meteorological station (Skye Instruments Ltd, Llandrindod Wells) was located roughly 50 m to the rear of each fire. Wind speed was measured at 1.5 m above ground level which was judged to roughly equate to mid-flame height and would be equivalent to the height of a hand-held anemometer. Data logging began at least 15 minutes prior to ignition and on most days data was recorded as 10-second averages . Unfortunately the roving weather station proved to be somewhat unreliable and on one day (Burn Day 1) it was only possible to retrieve data at 10 minute intervals while for four fires (Plots 11, 14, 19 and 23) the data collected were corrupted and unusable. In

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[2] National Vegetation Classification

these cases hourly means for the required information were available from a fixed weather station (Campbell Scientific Ltd, Loughborough) located some 10 kilometres to the ENE (O.S. Grid Ref. NN 6995) at a similar altitude. Although less than ideal, none of the fires for which the remote weather data were used appeared to be outliers in the fire behaviour analyses. Wind speed data from the base station were calibrated for use at the experimental site by regression relationships established over two calibration periods when the two stations collected data at the same monitoring interval with the roving station located centrally within the experimental area. Details of the calibration procedure are given in Davies (2005). The weather stations recorded wind speed and direction, temperature and humidity.

Rate of spread

Rate of spread (RoS) was estimated using thermocouples located at ground level or below the heather canopy and by timing fire-front arrival at either a single or double line of flame height posts (see Figure 2.1) using a handheld stopwatch. Posts were located in the centre of the middle row of monitoring sub-plots, thus the first post was located 2.5 m from the bottom edge of the plot with subsequent posts 5m apart.

Rate of spread was also calculated from thermocouple traces by dividing the distance between the thermocouples (see Figure 3.1) by the time between their maximum temperature peaks. For fifteen fires one thermocouple estimate was available for fire spread between posts 2 and 3 whilst for 3 fires of design one thermocouple measurements were made at all four posts. Thermocouples were not operational for any of the fires burnt according to design two. A weighted mean rate of spread was calculated by taking the average of mean thermocouple and mean observed rates of spread. Rates of spread for fires without thermocouples were corrected using a regression of observed on the observed/thermocouple mean rate. The time for the fire to reach the first flame height post was omitted from calculation of rate of spread as fires have been observed to still be accelerating during this period (Davies 2005).

Fireline intensity

Fireline intensity (I) was defined by Byram (1959) as:

$$I = H\,w\,R$$

Where:
I = Fireline intensity (kW m^{-1})
H = Heat of combustion (kJ g^{-1})
w = Mass of consumed fuel (kg m^{-2})
R = Rate of spread (m s^{-1})

We calculate fireline intensity using a value of 20,810 kJ kg^{-1} for the high heat of combustion of live shoots of *Calluna* which is the mean of the values measured by Hobbs (1981) for *Calluna* shoots and woody stems (21, 350 kJ kg^{-1} and 20,270 kJ kg^{-1} respectively). This value was reduced by 1263 kJ kg^{-1} to account for latent heat absorbed by the vaporization of the water of reaction (Byram 1959) and by a further 24 kJ kg^{-1} per fuel moisture content percentage point (Van Wagner 1972).

As we are assessing fire intensity post-hoc we can define available fuel as the total amount of material burnt by the fire and so '*w*' is the same as consumed fuel. Fuel consumption was estimated by subtracting estimated unburnt fuel from pre-fire fuel loading. Post-fire biomass was estimated by destructively harvesting a number of 50 x 50 cm quadrats in each plot. Harvested material was divided into the following size classes, stems with foliage, stems < 2 mm, stems 2-5 mm and stems > 5 mm, before being dried in an oven for 48 hours at 80C and weighed.

Flame height
Flame height was estimated visually during the course of the fire. Three estimates of height were made when the fire reached each flame monitoring post. Cross beams at heights of 1 and 2 m allowed flames to be judged against a constant reference point. The data were used to calculate mean and standard deviations of flame height.

Data analysis
The aim of this analysis was to create predictive models for fire behaviour characteristics to inform both researchers and land-managers as well as to provide direction for the development of a fire behaviour prediction system for Scotland. Multiple iterations of best-subsets and stepwise regression analyses were used to model fire behaviour characteristics using a variety of transformed, untransformed and integrated prediction factors. The models selected were not just those that gave the best fit to the experimental data, but those which were also intuitive and consistent with previous research and theoretical constructions of the controls on fire spread. As dead FMC data were only available for subsets of the fires, regression analysis was first completed on all fires excluding dead FMC and vectors as inputs before being repeated including first dead FMC, and then wind vector data.

Prior to the regression analysis we used an ANOVA to test the similarity of weather conditions between burn days and of fuel load and structure between fuel groups. Redundancy analysis (RDA) was used to explore the relationships within and between control and response variables. Analysis was completed using Minitab 14, SigmaPlot version 9 and Canoco 4.5 (ter Braak & Šmilauer 2002). The Redundancy Analysis was completed twice once on all fires with dead FMC excluded and once on just those fires for which dead FMC data was available.

Results

Variation in burning conditions

Results of the ANOVA demonstrated that there was no significant difference in the weather conditions under which the different fuel load groups (High, Medium or Low) were burnt, but that there was significant variation in conditions between different burn days (Table 2.1). In contrast for two key fuel structure variables (fuel load and mean *Calluna* height) whilst there was a significant difference between fuel load categories there was, on average, no difference between individual burn days. Bulk density (total fuel load above the moss and litter divided by Mean Height) and CDI (Canopy Density Index, see Davies 2006) both demonstrated significant variation between both fuel load categories and between individual burn days (Table 2.1).

Fuel structural characteristics and weather conditions during individual fires are described in detail in Tables 2.2 and 2.3. Fuel load, fine fuel load, bulk density and mean height all varied considerably between the three different fuel load categories (Figure 2.2). The vast majority of the fuel in most plots was live, dead material making up only one fifth to one third of the total load. Particularly high proportions of dead fuel were found in a number of low loading plots and in older stands on the Black Hill experimental site.

Both live and dead fuel moisture content varied significantly. Live FMC ranged from around 55 % to nearly 100 % whilst dead varied from around 15 % to nearly 30 % (Table 2.3).

Table 2.1: Results of an ANOVA investigating the relationship between burn day and fuel category on key fuel structure and weather characteristics.

	Fuel Category			**Burn Day**		
Variable	**F**	**P**	**d.f.**	**F**	**P**	**d.f.**
Fuel load	18.08	<0.001	2	1.31	0.306	8
Mean height	31.71	<0.001	2	1.91	0.129	8
Bulk density	13.93	<0.001	2	7.09	<0.001	8
CDI	35.55	<0.001	2	8.70	<0.001	8
Wind speed	1.61	0.230	2	27.02	<0.001	8
Temperature	0.31	0.741	2	39.96	<0.001	8
Live FMC	2.00	0.167	2	5.56	0.002	8
Moss FMC	3.00	0.078	2	11.03	<0.001	8

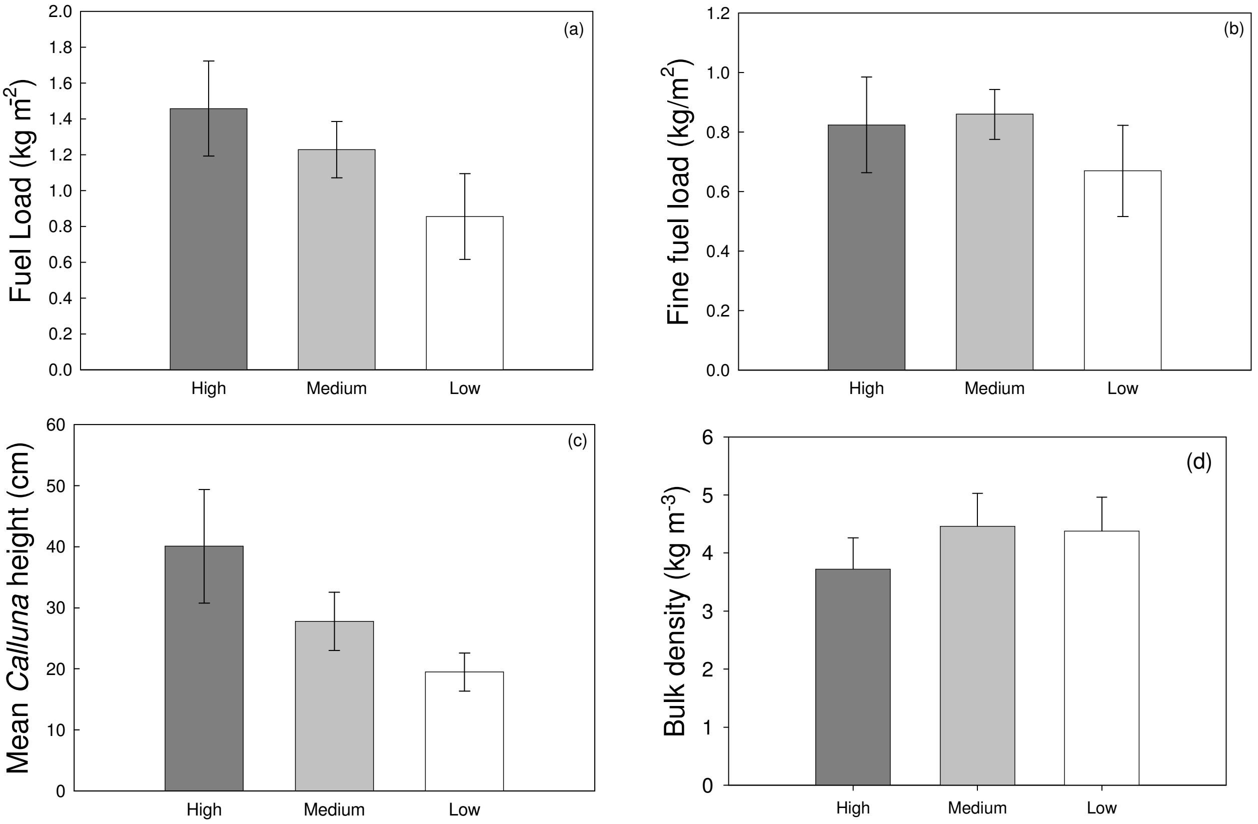


Figure 2.2: Bar graphs showing variation in the fuel structure of experimental plots. Graphs show mean total (a) and fine (b) fuel loads, as well as mean *Calluna* height (c) and fuel bulk density (d) for the three fuel load categories. Error bars are standard deviations.

Factors controlling fire behaviour

A wide range of fire behaviour was captured during the experimental burns with rate of spread estimated from just over half a metre per minute to over twelve metres per minute. Fire intensity also varied widely, ranging from less than two hundred to over four thousand kW m^{-1} (Table 2.4). One fire (BE2 P10) was located in an extremely low fuel loading and would not ignite despite several repeated attempts and successful burns in other fuel loads on the same day. There was significant variation in the behaviour of fires in High, Medium and Low fuel loading categories (Figure 2.3). The variability in both rate of spread and fireline intensity in High loading fires is particularly noticeable.

Redundancy Analysis
Redundancy analysis on the data available for all fires demonstrates the influence of a number of key variables on fire spread and intensity (Figure 2.4) which are very closely correlated. Rate of spread and intensity are closely linked to wind speed and mean height of vegetation. Given that mean height is a surrogate variable correlated with fuel load and both the horizontal and vertical structure of the *Calluna* canopy, this demonstrates the important roles of wind and fuel structure in determining fire behaviour. Wind speed explains a significant amount of the variation in the fire behaviour data (Monte Carlo permutation test, P = 0.016). The influence of mean height was only significant at the P = 0.10 level, but interestingly variation in flame height appears to be more closely linked to changes in fuel structure (including fuel height and heterogeneity) than to wind speed.

The standard deviation of CDI (Canopy Density Index) is highly significant in the ordination (Monte Carlo permutation test P = 0.001) with higher values being linked to slower moving less intense fires. Increases in live fuel moisture and bulk density are also important in dampening fire spread (Monte Carlo permutation test P = 0.023 and P = 0.016 respectively).

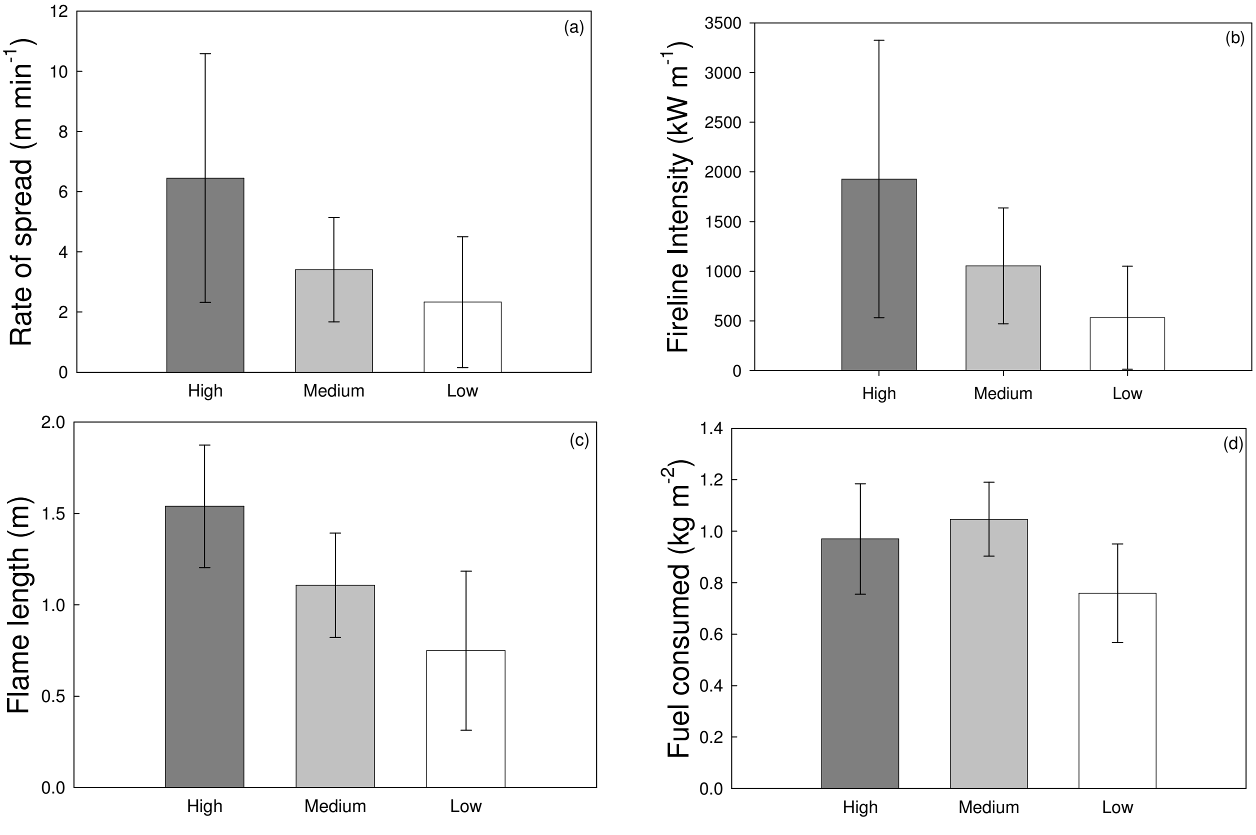


Figure 2.3: variation in fire behaviour characteristics within and between individual fuel load groups. Graphs show mean rate of spread (a), intensity (b), mean flame length (c) and fuel consumption (d). Error bars are ± 1 standard deviation.

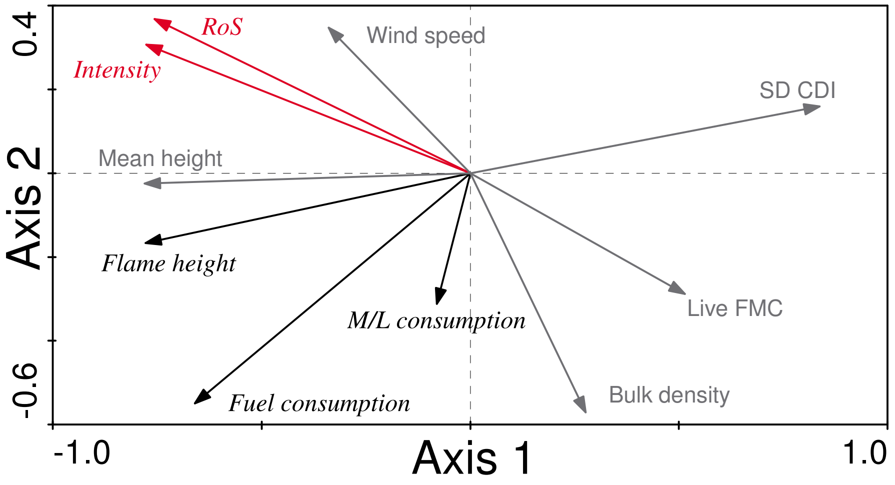


Figure 2.4: Results of a Redundancy Analysis on all fires with dead fuel moisture content excluded from the analysis. Axes 1 and 2 explain 44 % and 14 % of the variation in the fire behaviour data respectively. Redundancy analysis is a multivariate regression in which the first axis represents the axis of maximum linear association between the dependent and independent variables; subsequent axes represent the residual variation. Variables plotted with arrows pointing in the same direction are positively correlated within the plane of the first two axes – the length of the arrow indicates the strength of the association. Arrows pointing in opposite directions are negatively associated, while those are right angles are unrelated in this plane. M/L consumption is the consumption by the fire of the moss and litter layer; SD CDI is the standard deviation of the canopy density index.

When the Redundancy Analysis was repeated on just the twelve fires for which there was information on dead fuel moisture available (Figure 2.5) the only significant independent variable was fuel load (Monte Carlo permutation test P = 0.020) though relative humidity was close to being so (P = 0.057). Rate of spread and intensity were still observed to be positively influenced by wind speed and negatively affected by SD CDI. Both dead and live FMC were negatively correlated with rate of spread, fire intensity and flame length. Fuel and moss/litter consumption appeared to be positively associated with increased fuel moisture levels, though this was not the case on axis three (not shown) where they were strongly negatively associated.

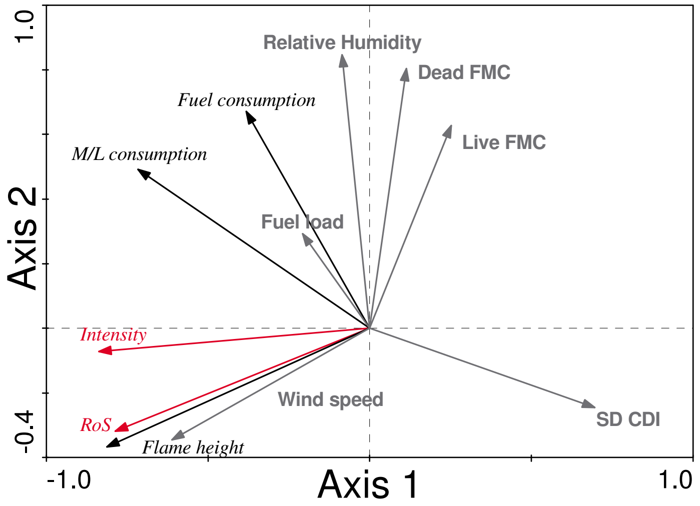


Figure 2.5: results of a Redundancy Analysis on the twelve fires for which dead fuel moisture content data was available. Axes 1 and 2 explain 53 % and 18 % of the variation in the fire behaviour data respectively. The only significant independent variable was Fuel load. See Fig 2.4 for the interpretation of Redundancy Analysis.

Table 2.2: Pre-fire plot fuel load and structural properties. Fires prefixed with BE2 were burnt on Crubenmore Estate, those with BH were on Black Hill outside Edinburgh. R indicates two high fuel-load plots with particularly rank heather. Fuel load, Fine fuel and Dead fuel are all measured above the moss/litter layer.

Fire Name	**Category**	**Experimental Design**	**Fuel Load (kg m^{-2})**	**Fine Fuel Load (kg m^{-2})**	**Dead Fuel Load (kg m^{-2})**	**Moss/Litter Load (kg m^{-2})**	**Bulk density kg m^{-3}**	**Mean height ± SD (cm)**	**CDI ± SD**
BE2 P1	High	1	1.67	0.80	0.33	1.50	3.68	45.4 ± 10.6	-0.22 ± 0.13
BE2 P2	Low	1	0.72	0.54	0.09	0.59	3.89	18.6 ± 8.5	-0.39 ± 0.26
BE2 P3	High	1	1.55	0.80	0.23	2.20	3.28	47.4 ± 8.9	-0.22 ± 0.13
BE2 P4	Medium	1	1.17	0.87	0.27	0.79	4.22	27.8 ± 6.5	-0.42 ± 0.19
BE2 P5	Medium	1	1.07	0.82	0.25	1.08	3.60	29.7 ± 7.1	-0.41 ± 0.17
BE2 P6	High	1	1.34	0.89	0.24	1.57	3.46	38.7 ± 10.1	-0.25 ± 0.13
BE2 P7	Medium	1	1.02	0.73	0.17	0.99	3.81	26.8 ± 8.1	-0.36 ± 0.22
BE2 P10	Low	1	0.42	0.40	0.16	0.52	3.59	11.7 ± 7.4	-0.72 ± 0.51
BE2 P11	High	1	1.49	1.06	0.30	1.84	3.35	44. 6 ± 9.1	-0.23 ± 0.13
BE2 P14	Medium	1	1.22	0.79	0.18	0.88	4.30	28.4 ± 5.3	-0.38 ± 0.17
BE2 P19	Low	1	0.86	0.67	0.14	0.79	4.08	21.2 ± 7.6	-0.60 ± 0.39
BE2 P20	High	1	1.32	0.76	0.24	1.82	3.86	34.3 ± 11.1	-0.35 ± 0.14
BE2 P21	Medium	1	1.27	0.91	0.20	1.04	4.36	29.2 ± 7.9	-0.44 ± 0.32
BE2 P23	Low	1	1.17	0.96	0.22	0.77	4.29	27.3± 12.0	-0.49 ± 0.37
BE2 P24	Low	1	0.76	0.62	0.10	0.76	3.82	20.0 ± 7.2	-0.47 ± 0.32
BE2 P8	High	1 (revised)	1.95	1.06	0.35	1.93	4.20	46.5 ± 14.8	-0.35 ± 0.22
BE2 P9	Medium	1 (revised)	1.40	0.86	0.32	1.38	4.64	30.3 ± 9.5	-0.46 ± 0.23
BE2 P16	Low	1 (revised)	0.86	0.67	0.13	0.65	4.65	18.6 ± 4.4	-0.60 ± 0.46
BH1	Medium	2	1.07	0.81	0.19	0.61	5.40	19.9 ± 5.4	-0.84 ± 0.42
BH2	Low	2	0.78	0.72	0.29	0.56	5.00	15.6 ± 3.9	-1.02 ± 0.54
BH3	Low	2	0.90	0.69	0.11	0.57	5.26	17.19 ±4 .9	-0.92 ± 0.35
BH4	High, R	2	1.34	0.81	0.39	1.17	4.50	29.8 ± 11.1	-0.49 ± 0.25
BH5	Medium	2	1.44	1.00	0.28	0.89	4.98	28.9± 4.3	-0.53 ± 0.23
BH7	High, R	2	0.99	0.65	0.24	0.99	4.30	23.0 ± 12.6	-0.41 ± 0.27
BE2 P15	High	1 (revised)	1.46	0.59	0.28	4.23	2.87	51.0± 10.9	-0.34 ± 0.19
BE2 P13	Medium	1 (revised)	1.39	0.95	0.25	1.11	4.83	28.9 ± 7.8	-0.48 ± 0.21
BE2 P22	Low	1 (revised)	1.22	0.76	0.33	0.79	4.84	25.7 ± 5.6	-0.61 ± 0.30

Table 2.3: Weather condition and fuel moisture recorded during experimental fires. Fuel moisture data are means for four or five samples taken from random subplots.

Fire ID	Wind speed ($m\ s^{-1}$)	Humidity (RH)	Temperature (°C)	Live FMC (%) DW	Moss FMC (%) DW	Dead FMC (%) DW
BE2 P1	9.9	65.0	3.09	80.7 ± 1.2	203 ± 65	-
BE2 P2	11.5	61.0	2.40	87.4 ± 2.0	248 ± 115	-
BE2 P3	4.7	64.0	5.06	55.2 ± 20.5	326 ± 45	-
BE2 P4	11.8	57.8	4.63	95.1 ± 6.0	179 ± 35	-
BE2 P5	4.7	62.3	3.95	63.3 ± 4.8	282 ± 53	-
BE2 P6	10.6	58.8	6.92	69.3 ± 9.1	411 ± 113	-
BE2 P7	11.2	52.3	7.50	80.2 ± 5.4	305 ± ??	-
BE2 P10	4.2	64.0	4.03	87.1 ± 9.0	231 ± 46	-
BE2 P11	6.6	78.7	2.30	60.9 ± 8.9	337 ± 51	-
BE2 P14	6.9	78.1	2.29	63.7 ± 7.9	245 ± 29	-
BE2 P19	8.2	74.8	1.99	93.5 ± 3.7	211 ± 52	-
BE2 P20	5.8	67.1	1.62	75.4 ± 9.1	170 ± 73	-
BE2 P21	7.0	62.5	2.36	73.9 ± 4.3	190 ± 12	-
BE2 P23	7.1	74.1	2.92	63.0 ± 13.6	321 ± 31	-
BE2 P24	9.9	59.3	5.77	71.4 ± 5.5	525 ± 107	-
BE2 P8	12.9	74.2	4.22	97.2 ± 5.4	552 ± 144	20.7 ± 2.0
BE2 P9	12.4	78.6	2.88	84.3 ± 12.3	501 ± 308	22.7 ± 3.0
BE2 P16	11.0	81.4	4.45	91.2 ± 6.8	422 ± 174	27.0 ± 4.1
BH1	3.8	42.7	4.31	63.2 ± 5.1	266 ± 77	18.2 ± 1.3
BH2	4.5	38.7	3.30	66.7 ± 7.8	256 ± 45	19.5 ± 12.0
BH3	7.3	55.4	8.75	72.9 ± 19.2	85 ± 18	14.9 ± 4.0
BH4	4.3	41.2	4.86	61.2 ± 10.4	268 ± 42	16.5 ± 1.4
BH5	7.3	61.1	9.03	66.8 ± 5.5	72 ± 19	27.6 ± 14.5
BH7	8.6	48.5	8.67	70.5 ± 10.0	167 ± 72	15.7 ± 1.0
BE2 P15	9.0	62.3	4.06	75.1 ± 4.8	361 ± 297	16.0 ± 1.7
BE2 P13	9.5	63.2	4.53	76.9 ± 6.3	123 ± 75	29.0 ± 24.5
BE2 P22	8.7	66.4	2.90	73.7 ± 5.4	182 ± 61	17.0 ± 1.7

Table 2.4: Variation in fire behaviour characteristics recorded during the experimental fires. * indicates plots where RoS and flame length were measured over a restricted length of the fire run so that the backburning of a firebreak did not interfere with the headfire.

Fire ID	**Date burnt**	**Category**	**Rate of spread ($m\ min^{-1}$)**	**Intensity ($kW\ m^{-1}$)**	**Flame length (m)**	**Fuel consumed ($kg\ m^{-2}$)**
BE2 P1	16/10/2003	High	4.37	1495.43	1.96	1.17
BE2 P2	16/10/2003	Low	3.19	575.59	0.92	0.62
BE2 P3	09/03/2004	High	12.64	4056.41	1.49	1.06
BE2 P4	16/10/2003	Medium	2.51	721.27	0.92	1.00
BE2 P5	09/03/2004	Medium	5.48	1498.60	1.32	0.91
BE2 P6	22/04/2004	High	11.71	3757.44	1.30	1.08
BE2 P7	22/04/2004	Medium	4.37	1141.22	0.58	0.89
BE2 P10	09/03/2004	Low	0	0	0	0
BE2 P11	05/03/2004	High	8.91	2979.97	1.63	1.11
BE2 P14	05/03/2004	Medium	2.98	923.76	0.94	1.03
BE2 P19	01/04/2004	Low	0.67	137.10	0.30	0.71
BE2 P20	01/04/2004	High	1.34	429.41	1.42	1.08
BE2 P21	01/04/2004	Medium	1.93	589.82	1.21	1.03
BE2 P23	05/03/2004	Low	0.54	155.38	0.38	0.95
BE2 P24	22/04/2004	Low	0.80	146.06	0.69	0.61
BE2 P8	14/10/2006	High	1.92	558.42	0.85	1.01
BE2 P9	14/10/2006	Medium	2.37	858.93	1.13	1.24
BE2 P16	14/10/2006	Low	1.78	401.58	0.43	0.78
BH1	04/04/2006	Medium	2.13	569.14	1.13	0.89
BH2	04/04/2006	Low	1.53	242.83	0.58	0.53
BH3	18/04/2006	Low	7.07	1593.47	1.23	0.76
BH4*	04/04/2006	High, R	3.00	452.41	1.88	0.50
BH5*	18/04/2006	Medium	6.76	2407.78	1.61	1.19
BH7*	18/04/2006	High, R	6.35	1598.06	1.76	0.85
BE2 P15	02/04/2007	High	7.85	2028.22	1.56	0.87
BE2 P13	02/04/2007	Medium	2.14	783.46	1.12	1.24
BE2 P22	02/04/2007	Low	3.05	1000.12	1.50	1.11

Developing fire behaviour models

Internal correlation between the predictor variables means that care must be taken when developing explanatory models. Where two variables are closely correlated, inclusion of one variable in a model removes most of the explanatory power of the second. However, this does not imply that the second variable is not important in the underlying process. In this section, rather than explaining the processes, we are attempting to develop simple models that can be used in the field for predicting fire behaviour. The use of best subsets regression picks the combination of predictor variables that gives the 'best' model (i.e. with highest R^2), but also gives alternative models using different combinations of independent variables that, while statistically less efficient, may none-the-less be more useable in practice.

Table 2.5 shows the correlations between the main weather and fuel moisture variables. Some of the internal correlations are to be expected (e.g. Standard deviation of temperature *v* standard deviation of relative humidity); other are less expected (e.g. live FMC *v* temperature which is discussed elsewhere). However, wind speed, which is picked out by the best subsets regression as the most powerful variable for predicting fire behaviour, has very little association with the other independent variables.

Table 2.5: Pearson correlation matrix for weather and fuel moisture variables. Values of $r > \pm 0.5$ are in bold.

	r M C	*r M C*	*r M C*	*e m p*	*e m p*	*H u m*	*H u m*	*Sp ee d*	*Sp ee d*	*Di re c*	*Di re c*
Dead FMC	1.00										
Live FMC	0.36	1.00									
M/L FMC	0.04	0.14	1.00								
Temperature	0.36	**0.68**	0.38	1.00							
SD Temp	-0.15	**-0.56**	**-0.52**	**-0.70**	1.00						
Rel Humidity	**0.50**	0.31	0.31	0.36	**-0.68**	1.00					
SD Rel. Hum.	-0.03	-0.44	-0.37	**-0.57**	**0.95**	**-0.57**	1.00				
Wind Speed	-0.06	-0.15	-0.15	0.10	0.12	-0.45	0.00	1.00			
SD Wind Spd	-0.09	-0.24	0.13	-0.06	0.39	-0.43	0.33	0.40	1.00		
Wind Directn	**0.57**	0.29	0.46	0.10	0.39	0.22	**0.56**	**-0.75**	-0.26	1.00	
SD Wind Dir.	-0.06	**-0.57**	-0.10	**-0.65**	**0.64**	**-0.50**	**0.64**	**-0.57**	0.02	**0.56**	1.00

Rate of spread

When all fires were analysed, excluding dead FMC data, a number of possible equations were developed (Table 2.6). The first of these (1) uses just the simple inputs of wind speed and heather height and has an R^2 (adj) of 0.56:

$$R = 0.792 + 0.000792 \times \mathbf{h^2} \times \mathbf{U} \tag{1}$$

Where: R = rate of spread (m min^{-1}), h = *Calluna* height (cm) and U = wind speed (m s^{-1})

Equation 2 demonstrates the significant effect of live fuel moisture (P = 0.008) and has an improved R^2 (adj) of 0.66:

$$R = 8.30 + 0.000728 \times \mathbf{h}^2 \times \mathbf{U} - 0.0970 \times \mathbf{M_l} \qquad (2)$$

Where: R = rate of spread (m min^{-1}), h = *Calluna* height (cm), U = wind speed (m s^{-1}) and M_l = live fuel moisture content (%)

The final equation includes the product of the standard deviations of mean height and CDI, a somewhat complex term but one that improves the R^2 (adj) to 0.72 and gives the best agreement between observed and predicted rates of spread (Figure 2.6):

$$R = 9.55 + 0.000662 \times \mathbf{h}^2 \times \mathbf{U} - 0.08272 \times \mathbf{M_l} - 0.992 \times \mathbf{S} \qquad (3)$$

Where: R = rate of spread (m min^{-1}), h = *Calluna* height (cm), U = wind speed (m s^{-1}), M_l = live fuel moisture content (%) and S = the product of the standard deviations of mean height and CDI

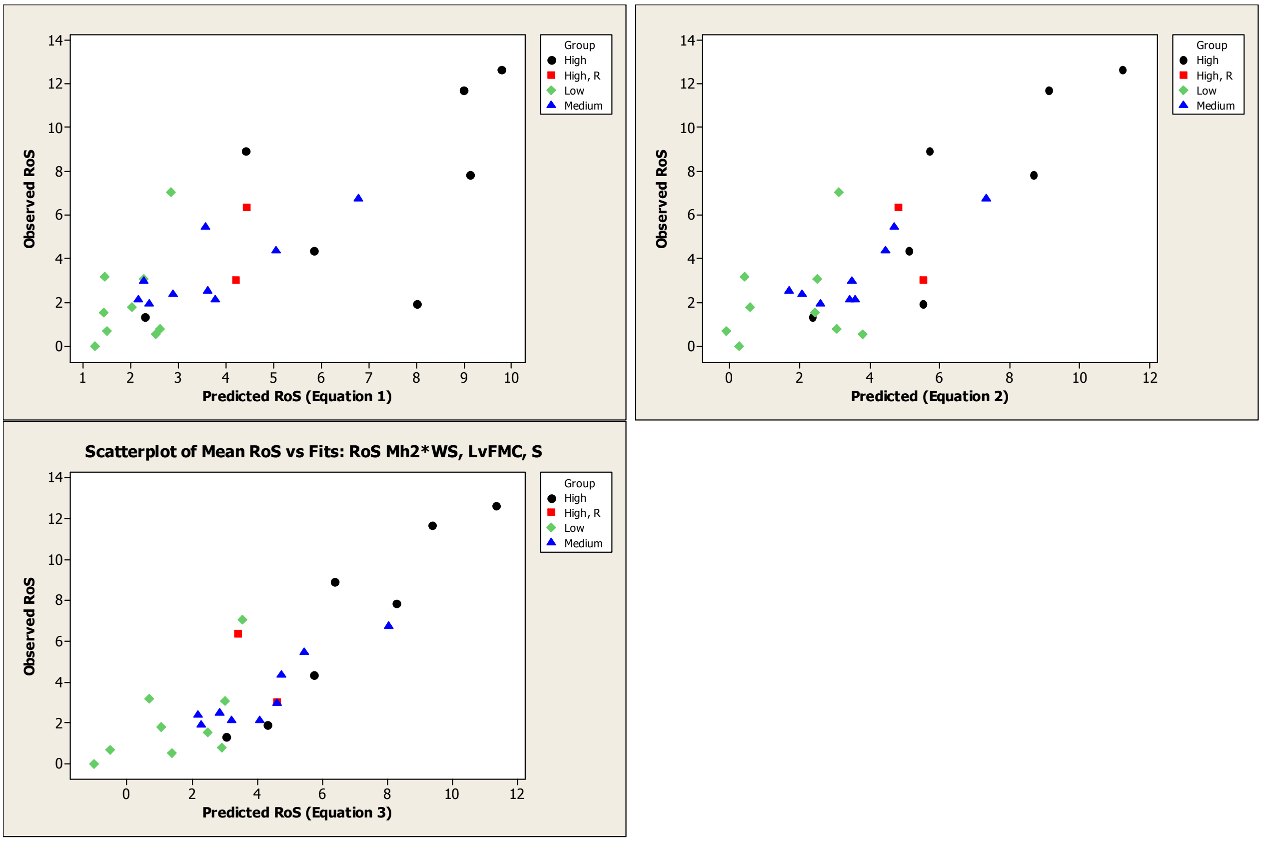


Figure 2.6. Observed v expected plots for regression equations (1) – (3). The outlier in equation 1 is plot BE2 P8.

A number of plots had particularly high values for the final predictor in Equation 3 (Figure 2.7), the reasons for this and its relevance to fire behaviour are dealt with in more detail in the discussion below. It is noticeable that the equations above will yield negative predictions of rate of spread where live fuel moisture and/or the standard deviations of mean height and CDI are very high. Log transformation of rate of spread prevents the problem of negative spread prediction, though the fit of log-linear models was not as good (Table 2.6).

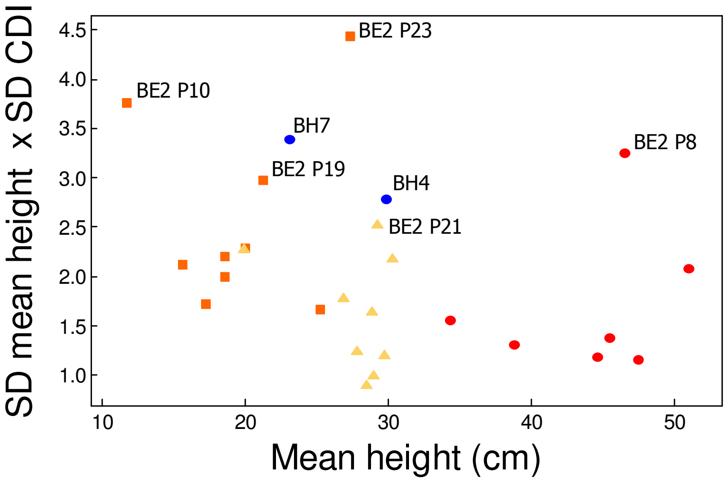


Figure 2.7: A plot of the regression equation variable "S" against mean *Calluna* stand height. Several of the fires (labelled) had particularly high values. Symbols indicate fuel loadings Low (orange squares), medium (yellow triangle) and high (red circles). Two plots with a high loading of particularly rank heather are blue diamonds.

Analysis of the fires for which dead FMC data was available produced similar results (Table 2.6, Equation 7) though a number of important differences are evident: Firstly that wind speed alone is the best single predictor. Second, mean height rather than mean height squared is included as the second predictor. Third, dead rather than live FMC is included in the model with the latter never appearing as significant despite the fact that dead and live FMC are not significantly correlated (correlation analysis: r = 0.36, P = 0.26). Finally it is important to note that mean height and dead FMC did not become significant in the regression until the product of the standard deviations of mean height and CDI was included as an input.

Fireline intensity

The relatively constant amount of fuel consumed in our fires (Figure 2.3d) means that rate of spread and fireline intensity are very closely linked (Figure 2.8). Unsurprisingly then the predictors appearing in equations for fire intensity are similar to those for rate of spread. Log-linear models were again used to prevent the prediction of negative fire intensities at high moisture contents and in very heterogeneous fuel beds (Table 2.6). Fires for which information on dead FMC was available were analysed separately though neither live nor dead FMC ever appeared as significant predictors in any of the regression equations.

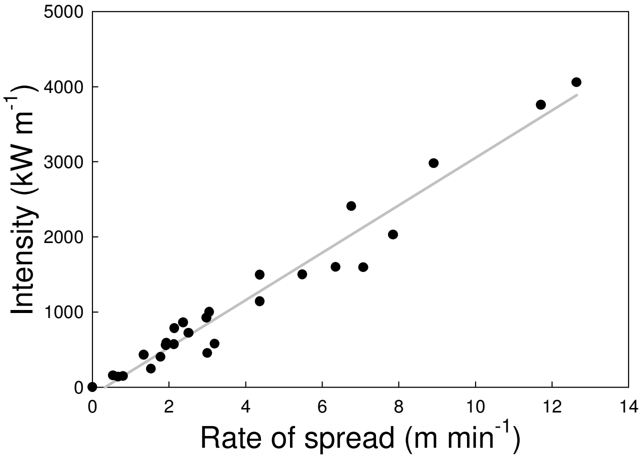


Figure 2.8: There is a very close relationship between fire rate of spread and intensity due the relatively constant amount of fuel consumed.

The role of wind speed

Examination of the equations developed above reveals that the models which best explain variation in fire RoS and *I* tend to be those including the product of wind speed and the square of mean height. This means that wind speed will have a much bigger effect at in high fuel. Figure 2.9 shows the relationship between RoS and wind speed for separate fuel groups and that High and Medium and Low fuels appear to have different relationships with wind speed with high loadings responding much more strongly. Additionally two High loading plots (shown in blue) burnt on the Black Hill site in very heterogeneous stands appear to behave differently from other members of the High group. It is possible that some of the higher than expected rates of spread may be associated with localised gusts of wind that may have undue effect on the rate of spread in relatively small plots; larger plots would be less susceptible to this effect.

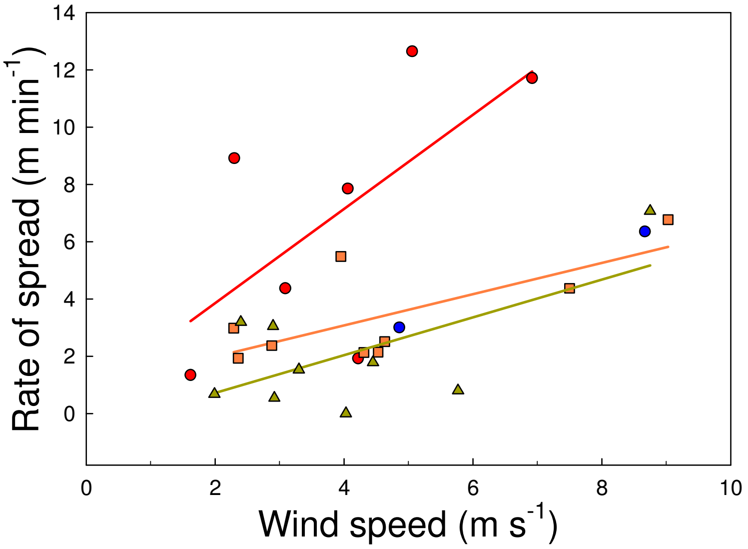


Figure 2.9: The effect of wind speed on fire rate of spread. Fires in High, Medium and Low fuel groups are shown in red circles, orange squares and yellow triangles. The lines show the regression of rate of spread on wind speed for each of the fuel groups. These had R^2 values of 0.42, 0.52 and 0.41 for High, Medium and Low fuels respectively. The two High loading plots (blue circles) burnt on Black Hill appeared to behave differently to others in the group and were excluded from the regression.

Separate fuel groups

Given the differences in behaviour between the different fuel groups demonstrated in Figure 2.9, and the fact that the different developmental growth stages can be recognised qualitatively in the field, it would seem sensible to try and develop models for High loads separately from Medium and Low loads. The High loading fires from Black Hill were excluded from this process as they appear to behave differently from other High loads plots and though they appear from Figure 2.9 to respond similarly to Medium and Low plots the reasons for their weaker response to wind are likely to be different as is discussed below. Log-linear modelling was used to remove the possibility of negative confidence intervals and predictions.

The results of the process (Table 2.6, Equations 11 – 14) show that whilst it was possible to construct a relatively robust model for High fuel load plots, results for Medium and Low plots were less so. Neither of these models include fuel moisture as an input as there was no strong relationship evident, indeed when live fuel moisture was added to the equations for Medium and Low fuels it appeared to have the effect of increasing fire spread.

Table 2.6: Regression equations developed to predict rate of spread (R, m min^{-1}) and fireline intensity (I, kW m^{-1}) where h = mean *Calluna* height (cm), U = wind speed (m s^{-1}), M_l = live fuel moisture content, M_d = dead fuel moisture content and S = the product of the standard deviations of mean height and CDI. “Fuel” denotes the fuel group and “N” the number of fires on which the equation is based. Terms shown in bold are significant in the regression ($P < 0.05$).

Number	Fuel	Characteristic	Equation	R^2 (adj)	N
4	all	Ln (R)	$0.381 + 0.000174 \times \mathbf{h^2 \times U}$	0.41	27
5	all	Ln (R)	$0.810 + 0.000655 \times \mathbf{h^2} + 0.196 \times \mathbf{U} - 0.0164 \times M_l$	0.51	27
6	all	Ln (R)	$1.51 + 0.000551 \times \mathbf{h^2} + 0.182 \times \mathbf{U} - 0.0121 \times M_l - 0.420 \times \mathbf{S}$	0.68	27
7	all	Ln (R)	$1.55 + 0.0256 \times \mathbf{h} + 0.196 \times \mathbf{U} - 0.0618 \times \mathbf{M_d} - 0.391 \times \mathbf{S}$	0.84	12
8	all	Ln (I)	$5.85 + 0.000203 \times \mathbf{h^2 \times U}$	0.44	27
9	all	Ln (I)	$5.45 + 0.0487 \times \mathbf{h} \times 0.191 \times \mathbf{U} - 0.521 \times \mathbf{S}$	0.71	27
10	all	Ln (I)	$6.28 + 0.0475 \times \mathbf{h} + 0.183 \times \mathbf{U} - 0.500 \times \mathbf{S} - 0.0108 \times M_l$	0.72	27
11	High	Ln (R)	$0.826 + 0.000144 \times \mathbf{h^2 \times U}$	0.75	7
12	High	Ln (I)	$6.20 + 0.000186 \times \mathbf{h^2 \times U}$	0.88	7
13	Med, Low	Ln (R)	$0.960 + 0.0109 \times \mathbf{U \times h} - 0.572 \times \mathbf{S}$	0.61	17
14	Med, Low	Ln (I)	$6.80 + 0.0103 \times \mathbf{U \times h} - 0.649 \times \mathbf{S}$	0.53	18

Flame length

Flame length and fireline intensity are closely linked and a model of the form proposed by Byram (1959) (derived from the regression of ln(Flame length) on ln(Intensity) then inverted) fits the data relatively well (Figure 2.10):

$$I = 753 \times L^{2.56} \qquad (15)$$

Where: I = intensity (kW m^{-1}) and L = flame length (m)

Our model differs significantly from Byram's as well as from that developed by Thomas (1963) in similar fuels.

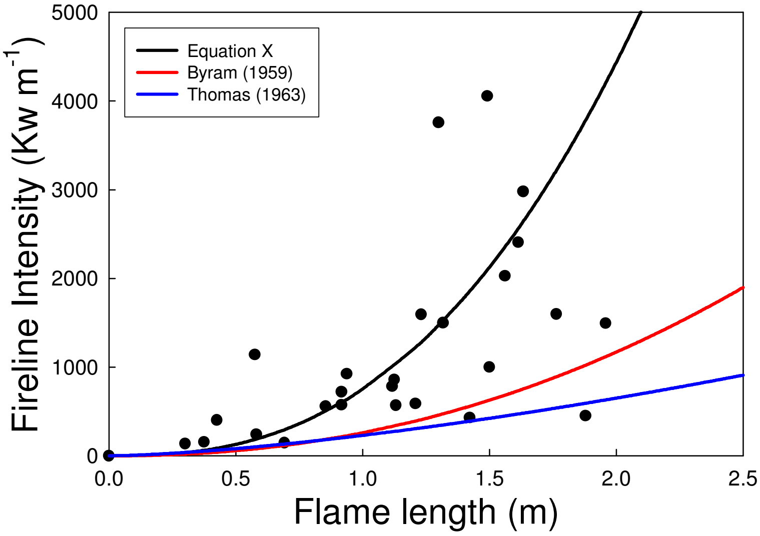


Figure 2.10: Relationship between flame length and fireline intensity. The R^2 of Equation 15 is 0.52.

Flame length was estimated visually in this study using marker posts as a reference point. Comparison of these estimated with those obtained from photographic monitoring of the plots suggests that observers may tend to consistently underestimate flame length (Figure 2.11), but visual estimates were used throughout in the modelling as this is what would normally be used by practitioners in the field.

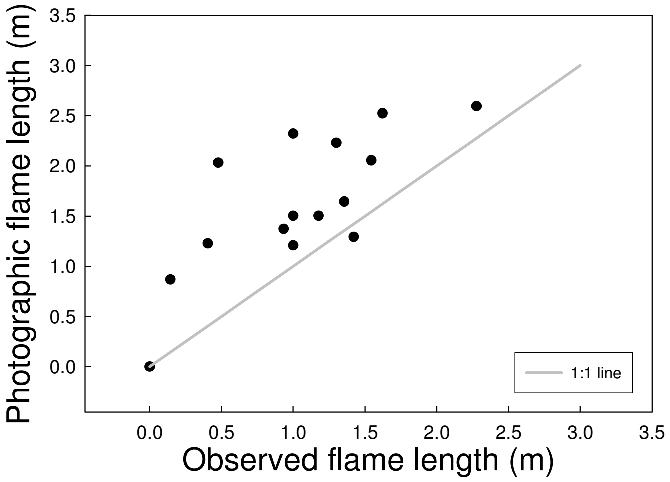


Figure 2.11: The relationship between flame length estimated visually against marker posts and from still photographs of the fire.

Discussion

There have been few studies of fire behaviour in Scotland and those that do exist have been primarily concerned with documenting and modelling temperatures (e.g. Whittaker 1961, Kayll 1966 and Hobbs & Gimingham 1984) so we have few studies with which to compare our results. As Van Wagner & Methven (1978) point out, maximum flame temperatures can occur as "in a single burning needle as readily as in a crown fire" and such a variable actually contains little information of management or ecological interest. Though he devised models for fire temperatures rather than RoS or *I*, Hobbs (1981, published as Hobbs and Gimingham 1984) nevertheless conducted a fairly rigorous programme of experimental fires. While the fire intensities we recorded are similar to his our rates of spread cover a much greater range and there seems to be an upper ceiling of 2 m min^{-1} on his RoS data. Davies (2005) demonstrated that this was probably due to problems with the way he used thermocouples to measure rate of spread. Our spread rates and intensities compare favourably with those recorded by Molina & Linares (1998), De Luis et al. (2004) and Fernandes (2001) in Mediterranean shrubland experimental fires. Our intensity values are however around half the highest recorded by Bruce & Servant (2003) in open moorland where the *Calluna* was both old and of extremely high loading.

The aim of this section of the report is to present relationships between fire behaviour and its controlling factors and we have used regression modelling to achieve this, presenting a series of predictive equations. It could be argued, however, that it is one thing to draw a line through a series of points but quite another to understand the processes governing the defined relationships. Those which we have developed, together with further analysis *via* RDA, and the results of similar studies (e.g. Hobbs & Gimingham 1984, Catchpole *et al.* 1998, Molina & Llinares 1998, Fernandes 2001, Bilgili & Saglam 2003), allow us to begin to understand the factors which influence fire behaviour.

Fireline intensity and rate of spread are intrinsically linked in our study due to the relatively constant amount of fuel consumed in our fires and it is difficult to discuss the controls on one with out consideration of the other. Equations 1 to 14 demonstrate that similar predictors can be used for both of these variables: mean fuel height, wind speed and the standard deviations of mean fuel height and CDI. The role of fuel moisture is, unfortunately still not particularly clear.

The role of fuel structure

Vegetation height is important as it is not only correlated with total fuel and fine fuel loading (though the relationship is not simple) but the height of the canopy above the ground may govern the degree of aeration of the fuel and thus oxygen supply for combustion. Old stands with heterogeneous canopies also have greater surface roughness which leads to turbulent air flow, greater penetration of air movement into the canopy and thus drying of fuels as well as an improved supply of oxygen for combustion. This process will be particularly important in governing the FMC of dead fuels. In older canopies there is, therefore, not just a continuous oxygen supply but also significantly less heat and time is needed to evaporate water before pyrolysis and combustion can begin. Although Rothermel (1972) described the behaviour of shrubland fires as types of surface fires, several authors (e.g. Fernandes et al. 2000, Alexander & Sando 1989) consider that shrubland fires have more in common with crown fires in that the existence of litter is not required for sustained fire propogation and that the fuel is aerated from below. . The importance of mean height rather than fuel loading is demonstrated by the High fuel load fires on Black Hill where large areas of the old, overgrazed heather canopy had collapsed producing stands with a very high fuel load but significant fuel discontinuities and a relatively low loading of fine fuels. Mean height therefore captures the mechanism producing reduced fire spread in these collapsed mature stands as well as the effect of reduced fuel load in Low stands. In Medium *Calluna* loads bulk density is the limiting factor which is also related to mean height.

The use of 'Mean h' squared rather than untransformed values when creating relationships for all fires/fuel groups together demonstrates the importance of fuel load in determining fire behaviour: the range of fire behaviour varies enormously over a relatively small range of stand heights/structures with an exponential increase in RoS and *I* as stands age. This contrasts interestingly with the work by Marsden-Smedley *et al.* (1999) who used the square root of vegetation height meaning spread rates become more similar as stands age and young stands have comparatively low fire intensities. The button-grass moorland in which they worked is likely to have rather little material to carry a fire and be composed of isolated tussocks when young preventing rapid fire spread; changes in height will have a big effect in relatively short stands where it correlates with an increase in fuel continuity resulting in rapid increases in rate of spread. In older stands the height will no longer relate so strongly to fuel continuity.

It is interesting to note that the RDA identified bulk density as having an important dampening effect on fire behaviour. This result, that suggests that sparser fuel beds burnt faster and more intensely (Figure 2.4), may seem counter-intuitive at first but agrees with the semi-physical models presented by Thomas (1971), Rothermel (1972) and Drysdale (1998). In open fuel beds RoS is known to decrease as the bulk density of the fuel increases though of course there must be some fuel there to begin with. This indeed may explain the failure of BE2 P10 to burn as it comprised extremely short young, green heather of a fuel load that was never great enough to allow the development of a sustaining fire. The influence of live FMC may be even greater in particularly dense heather stands when one considers that the attenuation of energy caused by evaporating moisture will reduce flame temperatures while the steam itself may have a smothering effect (Pompe & Vines 1966, Catchpole & Catchpole 1991).

Whilst decreases in fuel bulk density may, in general, allow for faster fire spread this appears to only be the case up to the point where decreases in density are linked to the presence of significant gaps that may disrupt the flow of the fire, slow its spread, reduce its intensity and in some cases cause it to go out all together if the gap is big enough. Particularly large gaps have been observed to lead to the breaking up of the head fire to form a series of smaller less intense parts. The importance of such factors is demonstrated by the inclusion of the standard deviation of CDI in the RDA as well as the almost ubiquitous presence of "S" in the regression equations. This term, which is the product of the standard deviations of height and CDI may seem a little obscure but it performs an important function. Standard deviations of CDI are generally greatest in shorter heather stands, probably relating to sparse open areas in young heather where regeneration has failed. The opposite trend is true however for the standard deviation of mean height which is greatest in old stands where smaller scale variation is caused by the differential growth of adjacent heather plans as well as by the collapse of some older bushes. Both of these terms are significantly correlated with height but multiplying the two together removes this influence and creates a variable that combines the influence of large canopy gaps with smaller scale variation in height. Examining Figure 2.7 it is clear that there is no relationship with height, the Y axis however picks out a number of fires with high values of "S" and a closer examination of these suggests this makes sense (Table 2.7).

"S" as a variable is not particularly useful from a practical viewpoint because of the effort required to measure it. However, it will relate closely to gappiness of *Calluna* which is a well recognised field character that could be applied qualitatively. Future analysis should explore the potential of a qualitative indicator of canopy heterogeneity.

The role of wind speed

The effect of increased wind speed on RoS is well documented and understood (Pyne *et al.* 1996). Greater wind speeds lead to flatter flames and increased reception of radiative energy by the fuel bed ahead of the fire front thus allowing a greater degree of preheating and drying. Such processes may also lead to greater fire front depth (a wider combustion zone) which increases both the radiative heat output per metre of fire-front and rate of spread. The interacting effects of several, correlated measures of stand fuel loading and structure and wind speed on *I* and RoS is demonstrated well in Figure 2.5. The negative effect of canopy gaps is also clearly evident.

Table 2.7 Experimental fires with high values of 'S' – the product of the standard deviations of height and CDI.

Fire ID	S	Significant heterogeneity?
BE2 P23	4.43	Fuel equivalent to a "High" load in one corner of the plot and a significant area dominated by grasses and sedges.
BE2 P10	3.76	Very short, young *Calluna* with a number of bare patches and grass dominated areas. Would not light despite repeated attempts.
BH7	3.39	Degenerate/rank *Calluna*. Canopy very broken with prostrate stems, large moss dominated open areas, many dead *Calluna* bushes as well as very dense patches where *Calluna* stems had "layered".
BE2 P8	3.26	Significant areas of dead material and prostrate *Calluna* stems. Canopy extremely gappy in places as a result.
BE2 P19	2.98	Many grass/sedge dominated patches with a significant amount of *Tricoporum cespitosum*. Fuel equivalent to a "High" load in one corner. The plot was crossed by a relatively wide sheep-track.
BH4	2.88	A mixture of very dense areas of layered heather between prostrate patches of overgrazed, "drumstick" form *Calluna*.
BE2 P21	2.52	A number of significant open areas in the *Calluna* canopy and a distinctly higher loading in one corner of the plot.

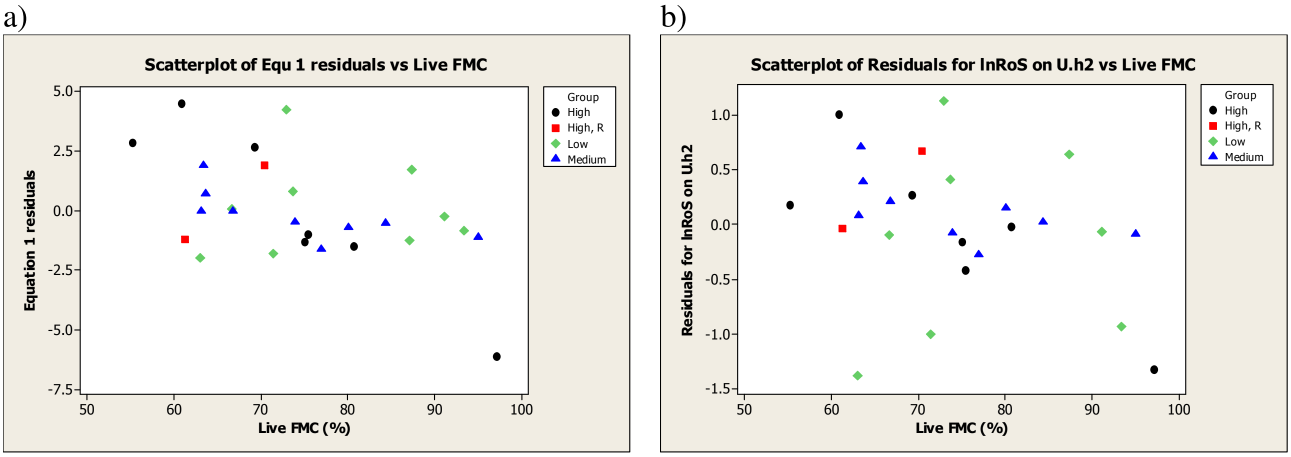
Greater variability in behaviour within and between fires in 'High' plots is possibly due to an increased sensitivity to wind speed in more 'gappy' stands. Many older *Calluna* stands contain significant canopy gaps which may, at low wind speeds, interrupt fire flow as there will be a greater distance between the radiative heat source of the flames and the next combustible area of *Calluna*. Higher wind speeds flatten flames allowing them to bridge gaps thus increasing heat transfer and fire intensity and spread through what is already generally speaking a better aerated, drier fuel bed with a low bulk density. In Low and Medium fuel loads increases in wind speed are possibly mitigated to some extent by reduced fuel loads and increased bulk density respectively which both serve to limit increased fire spread. Reduced fuel loads will reduce fire heat output whilst increased bulk density may create a situation where the fire is oxygen-limited. Both Low and Medium fuel loads also essentially sit on the ground surface, rather than being raised up above it as in High loads, further reducing fuel bed aeration. Such factors explain the importance of using the square of mean height in the regression models, High loads are able to spread much faster for a given increase in wind speed. Such effects are of course negated to some extent where there is significant heterogeneity in the fuel bed as accounted for by the "S" term.

Higher wind speeds also force convection columns closer to the ground with hot smoke plumes sometimes forced to travel over and through fuel beds for considerable distances. The effect of convection is not considered in many simple, theoretical models of fire spread but may play an important part at high wind speeds or where convection columns collapse and fires begin to generate their own winds, sucking in oxygen rich air from the surrounding atmosphere.

The role of fuel moisture

One of the key objectives of this piece of work was to try and clarify the role of fuel moisture in fire behaviour in *Calluna*-dominated heathlands. Previous work (Davies 2005, Davies et al. 2006) had failed to find a significant relationship between fuel moisture and fire behaviour although only "live" fuel moisture was measured. The moisture content of separate live and dead fuel components is in fact almost impossible to determine for *Calluna*. The structure of the plant with a canopy made of small shoots bearing tiny imbricate leaves makes separating the components totally impractical in a field setting. The live fuel moisture in this study is in fact a mixture made of live shoots inevitably bearing a variable amount of dead foliage. To try and resolve such problems and address questions about the role of dead fuel moisture in "driving" fire behaviour we completed further test fires collecting both "live" and purely dead material in a more intensified sampling regime than that used by Davies (2005). Unfortunately, whilst some questions appear to have been answered, yet more are posed.

The results of the RDA (Figure 2.5) and linear regression modelling (Equations 1 – 3) when all fires were included (and dead FMC data was thus excluded) both suggest that live fuel moisture has a significant negative effect on fire rate of spread and intensity. This was not however the case when rate of spread was log transformed as although there was still a sensible relationship with rate of spread and intensity, fuel moisture was no longer significant in the regression. Examining Figure 2.12 below shows that, after removing the effects of wind speed and height of vegetation, live FMC does play a very real role in dampening fire spread, particularly in the high fuel load plots, and that its inclusion in all the regression models is logically valid.


a)

b)

Figure 2.12: Scatter plots of the residuals of (a) Equation 1 and (b) Equation 4 against live fuel moisture content. These graphs show the relationship with moisture after removal of the effects of wind speed and height of vegetation.

When we examined the behaviour of fires for which we have information available on dead fuel moisture things apparently get even more complicated as not only does live FMC not appear as a significant predictor, but dead FMC appears as important instead. Its influence on fire behaviour is logical, despite the fact that dead fuels only make up a small proportion of the fuel load (Table 2.2). Dead fuels probably play an important role in fire behaviour due to their significantly lower moisture content, essentially allowing them to act as kindling for live material, preheating, drying and raising it to combustion temperature. The exact importance of dead moisture content is likely however to vary depending on the status of live fuel components. On dry days in early spring when live FMC can be as low as 40% the effect of dead fuel moisture may be less important whilst in the autumn when live FMC is generally higher, or in marginal conditions soon after rain, its status may be crucial. This is borne out to some degree by casual observations of fires spreading through the lower half of the *Calluna* canopy in marginal burning conditions. Here, self-thinning of lower-canopy shoots from the shade of the dense canopy above meant there was a greater proportion of dead material (see Table 2.2) and the live material above reached flaming combustion noticeably later. A fine balance is likely to exist between the relative amounts of dead and live fuel and their respective moisture contents and the exact nature of such a relationship is likely to only become truly clear after further experimental work. Smaller scale investigations like the ignition experiment described later may prove valuable in identifying go/no-go points for fires as well as the relative influence of dead and live fuels.

Even more troubling than the confusion about the relative importance of dead and live material was the fact that when we attempted to construct models for separate fuel groups (High, and Medium and Low combined) fuel moisture did not emerge as significant in the behaviour of High loads and apparently had a *positive* relationship with Medium and Low loads. We know of course that this is physically impossible and the apparent observed trend can fairly confidently be narrowed down to an artefact of the reduced data-set. If we examine the residuals from Equation 13 in relation to live FMC (Figure 2.13) it seems that relatively few fires are responsible for defining a relationship where otherwise none really exists. This highlights the problem of trying to create empirical relationships based on a small number of observations and strengthens the case for conducting further fire tests in a wider range of conditions.

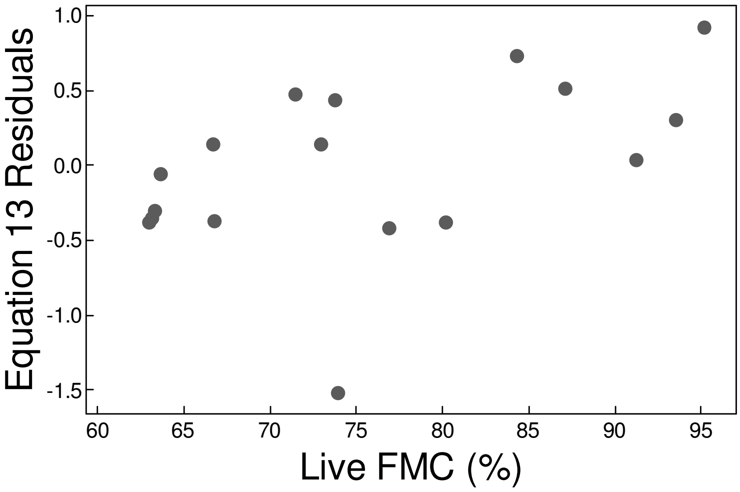


Figure 2.13: Residual from Equation 13 (see Table 2.6) in relation to live fuel moisture content.

Implications and further actions

In summary although we have been able to make some serious advances in our understanding of the factors controlling fire behaviour in *Calluna*-dominated habitats further work is probably still required if we are to be able to build truly robust models of the factors affecting fire behaviour. The models presented in Equations 1 – 15 are a good start and a sensible next step would probably be to make them available in the form of simple nomographs or on the web in order that collaborators can assess how well they perform in the field.

It would seem that fire behaviour varies significantly in heather moorlands in relation to the age and structure of the fuel. It is becoming clear that what we have labelled Medium and Low loads behave similarly with respect to wind, albeit for different reasons: one shows reduced spread because of a small amount of available fuel the other because of its extremely high bulk density. High fuels respond to wind much more strongly due to their low bulk density and better aerated fuel beds but where such stands enter the degenerate phase (Gimingham 1988) and collapse forming extensive open areas as well as dense patches where layering (McDonald *et al.* 1995) has occurred behaviour is different again and more experimental fires are required in such habitats.

Further fires are required that:

- Further research the roles of dead and live fuel moisture in fire spread

- Examine fire behaviour in a wider range of fuel types, specifically in heather-grass mixtures and in rank heather, and on slopes
- Examine the behaviour of fires in summer
- Examine the effect of fire width on the behaviour of wildfires.

Section 3

Testing fire behaviour models

Introduction

The recent creation of the Scottish Wildfire Forum acknowledges the growing problem of uncontrolled wildland fires in Scotland and is a first step towards rectifying the situation. Against the backdrop of these developments three things are clear. First that both land-managers and the fire service would be aided by tools which help them to predict periods of high fire risk so burning operations may be conducted safely and resources deployed effectively during such times. Second, with increased public access to 'wild' land there is a need to ensure visitors are made aware in advance of periods of high risk and to allow land to be closed in extreme cases. Finally many tools and predictive systems are already in operation elsewhere, several of which have been tested for use outside their countries of origin (e.g. Fernandes *et al.* 2002, Sauvagnargues-Lesage *et al.* 2001, Willis *et al.* 2001). This section tests a number of fire weather and fire behaviour prediction models for upland heathland conditions in the UK.

The situation in the UK is unusual compared with most other countries because our peak period of fire risk is not necessarily related to a climatically driven fire season but rather to the variable availability of dead or dry fuel before spring growth (see Section 2), and the period of legal prescribed burning (1st October until the 15th April). Muirburning is generally carried out by gamekeepers and graziers whilst most wildfires are either accidental or the result of escaped management fires, a smaller proportion are the result of arson. Very few fires can be classified as originating from 'natural' ignition sources and conditions for such events remain infrequent, though they have been documented in the past (Allison 1954, Weatherall 1954). Concern is particularly high during the spring when winter damage to *Calluna* leaf cuticles caused by frost and wind abrasion (Grace 1990, Pitcairn *et al.* 1986) may combine with high potential evapotranspiration, frozen ground and xylem cavitation (Jackson *et al.* 1999) to produce unusually low live fuel moisture contents (Davies 2005, Davies *et al.* 2006).

Heathland fuels in the UK are also unusual in an international context and a number of points should be noted:

- *Calluna vulgaris* is by far the dominant fuel and, in building phase (Gimingham 1988) stands, often forms dense, continuous, mono-specific canopies through which fire can easily spread. Higher fuel loads in mature or uneven-aged stands are often associated with greater structural heterogeneity and may be very patchy with significant gaps in the fuel bed as well as fuel 'jackpots.' In older stands large stems lift the canopy up, away from ground level.
- The majority of fuel is live; indeed a key purpose of muirburning is to burn live heather shrubs in order to encourage, lush, vegetative regeneration. A typical 'Mature' *Calluna* canopy with a fuel loading of around 16 t ha^{-1} will only have 20% present as dead material. Older stands typically have a greater proportion of dead material in the canopy than younger areas (Table 2.2).
- Fuel moisture contents (FMCs) are typically rather low for live fuel (65-100 %) and may become very low in late winter and early spring (< 45 %), though these are still higher than dead fuels encountered elsewhere. Typical moisture values for the moss and litter layer are c. 150 to > 500 % and this material rarely burns during normal management fires, though may do so in wildfires during summer or periods of prolonged drought.
- In younger stands quantities of dead fuels retained in the canopy are small but even here may play an important role in 'carrying' the fire; being drier they ignite first and dry and preheat live fuels. As the majority fuel in heathland is live, and in summer and autumn

probably has a relatively constant FMC small variations in other factors such as this may be crucial. If the latter go unnoticed practitioners may be unprepared for periods of high fire risk, as the more common problem is getting a fire to ignite in the first place!

A number of models were selected for testing:

BehavePlus: The Behave family of fire prediction models are based on the Rothermel (1972) fire model which uses energy balance equations to predict RoS. A description of the system can be found in Andrews *et al.* (2005). Fuel structure/loading can be defined in BehavePlus either by pre-defined fuel models (Scott & Burgan 2005) or via the direct entry of stand descriptors. Key inputs include dead fuel load according to three fuel-moisture size classes: 1 hour, 10 hour and 100 hour fuels; live herbaceous and live woody fuel load, live and dead fuel moisture content, live and dead fuel heat content, the surface area to volume ratio of the different fuel types and the height of the stand. Wind speed and the slope of the site are also required.

The Canadian Wildland Fire Information System: The CWFIS was developed on the basis of empirical relationships between fire behaviour parameters and environmental control variables rather than on theoretical equations of heat transfer as in the American BehavePlus system. A full description of the Fire Weather Index (FWI) and Fire Behaviour Prediction (FBP) of the CWFIS can be found in Van Wagner (1987) and Forestry Canada Fire Danger Group (1992) respectively. The FWI provides a series of equations that link meteorologically defined indices related to FMC to fire risk and behaviour. In the FWI the Initial Spread Index (ISI) is driven by a combination of the Fine Fuel Moisture Code (FFMC), which reflects the moisture content of dead fine fuels, and windspeed. The Build-up Index (BUI) is defined by two codes, the Duff Moisture Code (DMC) and Drought Code (DC) which reflect the moisture balance of litter and deep organic matter respectively, BUI is weighted to give DMC a stronger effect. The FWI itself is an index of likely fire intensity. The ISI is used in the FBP to determine fire behaviour predictions for specific fuel types via relationships established between it, wind speed and the value in question for each fuel. Acronyms used in the model are summarized in Table 3.1. The structure of the CWFIS can be seen in Figure 3.1.

Table 3.1: Abbreviations used in the Canadian Wildland Fire Information System (CWFIS).

Abbreviation	Name	Description
FFMC	Fine Fuel Moisture Code	Moisture status of fine (dead) fuels on the forest floor. Short response time to drying conditions.
DMC	Duff Moisture Code	Moisture status of partly decomposed litter lying on the forest floor. Medium response time to drying conditions.
DC	Drought Code	Moisture status of deep organic layers below duff. Only changes gradually during periods of drought.
BUI	Build-up Index	Combines the DMC and DC to provide information on risk of surface and ground fires associated with long term drought.
ISI	Initial Spread Index	Combines information from the FFMC with windspeed to give an index of fire spread irrespective of fuel type.
FWI	Fire Weather Index	An index of relative fire intensity based on ISI and BUI.

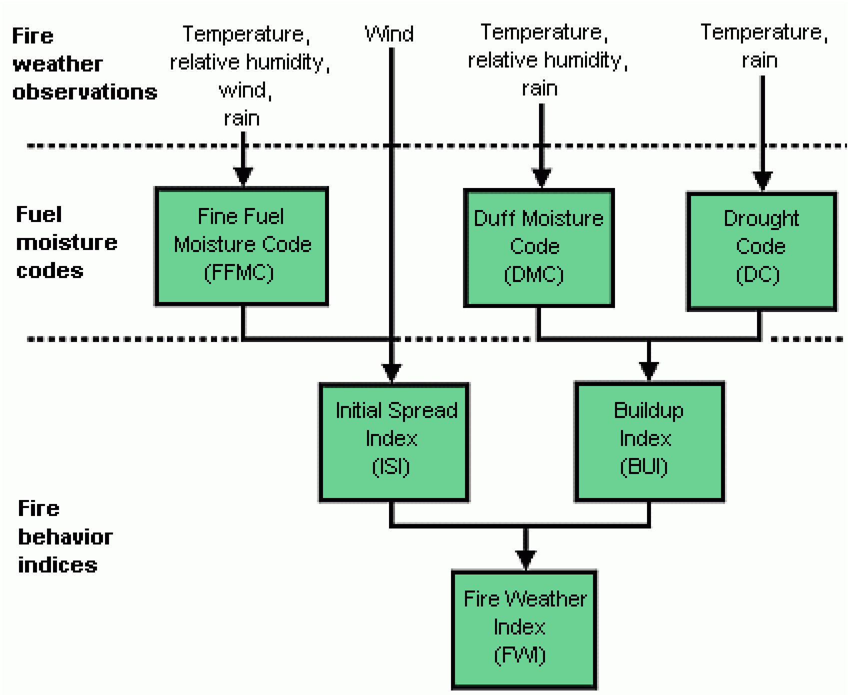


Figure 3.1: Structure of the Canadian Forest Fire Weather Index. From Canadian Forest Service Website: http://cwfis.cfs.nrcan.gc.ca/en/background/bi_FWI_summary_e.php [Accessed 30/11/2005].

The Met Office Fire Severity Index: MOFSI is the current model available for fire danger rating in the UK. It is described in detail in Section 1 and in Met Office (2005). It is a direct implementation of the Canadian Fire Weather Index system which uses the FWI to define five levels of fire danger from "Very low" to "Exceptional". Slightly different class boundaries are used in summer and winter with changeover months seeing a linear increase or decrease from one set of values to the other (Table 3.2). The system was implemented after a limited amount of ground-truthing (Met Office (2005) and is primarily designed to detect "exceptional" fire weather of the sort that would normally be expected once every few years. The driving force behind the implementation system was Open Access legislation in England and Wales (The Countryside and Rights of Way (2000) Act; Stationery Office 2000) which allowed for access land to be closed at times of exceptional risk. MOFSI probably detects the top end of fire risk well (Met Office 2005, Davies 2005, Davies *et al*. 2006) and an Exceptional rating may indicate that any fires that do occur are likely to be ecologically severe and extremely difficult to control. The meaning of the other bands is however less clear.

Table 3.2: Canadian FWI class thresholds used in the MOFSI during summer and winter.

MOFSI class	June – September	November – April
Very low	1.70	1.41
Low	5.30	4.10
Moderate	11.40	9.08
High	21.83	16.77
Exceptional	> 21.83	> 16.77

FireBeaters models: Several fire behaviour models were developed in Section 2 using inputs for which we have independent fires with the required information. Equations 1, 4 and 8 predict fire behaviour or intensity on the basis of *Calluna* height and wind speed, whilst Equation 2 includes the effect of live fuel moisture.

Table 3.3: Empirical models of rate of spread and intensity selected for testing

Equation no.	Variable	Equation
1	R	$0.792 + 0.000792 \times \mathbf{h}^2 \times \mathbf{U}$
2	R	$8.30 + 0.000728 \times \mathbf{h}^2 \times \mathbf{U} - 0.0970 \times \mathbf{M}_l$
4	Ln (R)	$0.381 + 0.000174 \times \mathbf{h}^2 \times \mathbf{U}$
8	Ln (I)	$5.85 + 0.000203 \times \mathbf{h}^2 \times \mathbf{U}$

Excluding the empirical relationships developed in Section 2, the fire behaviour models described above have been developed for fires in dead fuels of low moisture content, during a climatically defined fire season. British conditions may therefore challenge the performance of models and colleagues working in New Zealand for instance have experienced considerable difficulty in calibrating the Canadian Fire Weather Index in particular for use in shrubland fuels (REF). Despite such problems the CWFIS remains the most widely used system worldwide (REFS) and has been implemented in the UK in the form of the Met Office Fire Severity Index (FireBeaters Fire Danger Index). Previous research (Davies et al. 2006) has suggested that an implemented system based on the CWFIS may not adequately reflect variation in fire behaviour, though the Fire Weather Index may be able to reflect periods of extreme risk linked to low humidity and medium to long-term drought. Testing the model against further experimental fires may allow a better understanding of the relationship between the various indices of the FWI and fire behaviour as well as allowing a calibration between observed fire rate of spread and the Initial Spread Index of the sort that underlies the FBP component of the system.

The only other significant model in the context of this research is the **Special Hazard Rating Index** which currently used by the UK Forestry Commission (Kirby & Tantram 1999). The index uses observation of easily measured meteorological variables (rainfall, temperature, humidity and wind speed) and a series of tables and worksheets to calculate a hazard rating index ranging from 0 to 100. A detailed description of the method can be found in Rouse (1959). Even though this method has previously been tested for assessing fire risk on Dorset (SW England) heathlands (Kirby & Tantram 1999), Davies (2005) found that it did not reflect observed fire behaviour at all well. For this reason it has been omitted from testing in this study.

Aims and objectives

- To test the ability of existing systems and models to predict fire behaviour in *Calluna*-dominated fuels
- To attempt to calibrate the Initial Spread Index of the CWFIS for *Calluna* moorland
- To examine fire behaviour characteristics in relation to the Met Office Fire Severity Index
- To test the predictions of models generated in Section 2 against independent records of fire behaviour
- To test the performance of the models as if they were implemented in a system, i.e. running using Met Office NWP data for any weather parameters.

Methods

Test data sources

Data for testing the models came from three sources. For BehavePlus and the CWFIS the experimental fires described in Section 2 were used as the test data-set. When examining the performance of the models developed during the FireBeaters programme (Equations 1, 2, 4 and 8) actual fire behaviour data was available from three sources: the experimental fires described by Kayll (1966), Thomas (1971) and Bruce and Servant (2002) as well as a number of fire behaviour observations submitted to FireBeaters that included measurement of *Calluna* height, wind speed, rate of spread and in some cases live fuel moisture content. Unfortunately, these additional data sets did not have adequate weather data for testing the Canadian or BehavePlus models.

In addition to formal assessments of fuels, weather and fire behaviour as described in Section 2, the FireBeaters researchers also instigated a programme of simple fire record collection where collaborators, involved in prescribed burning, submitted a simple record of the fuels, weather and ease of ignition and control of the fires they were burning (Table 3.4).

Table 3.4: The one to five ratings of ease of ignition and control used by volunteer observers to record the behaviour of fires they lit.

Ease of ignition	**1** Fire would not light despite repeated attempts with backpack/driptorch
	2 Fire lights but repeated ignitions necessary to fill in holes in the line
	3 Backpack/drip torch easily establishes fire line, few re-ignitions necessary
	4 Backpack etc used to establish small line/spot fires which grow rapidly
	5 Fire can be easily lit with cigarette lighter alone, fires spread from spot ignitions
Ease of control	**1** No control necessary as fire self extinguishes
	2 Control easy with beaters alone, fire extinguished using beaters
	3 Control possible with beaters, sprayer held in back-up, backing fire spreads
	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

Although these records are relatively crude and the data is likely to be of low quality in comparison to fully monitored experimental fires, we were able to amass a relatively large number of records in a short space of time potentially giving a powerful test data source. These records were used to test the relationship between observed ignition and control ease in relation to rate of spread and intensity classes predicted using Equation 1 of the FireBeaters models, MOFSI values and FFMC, ISI and FWI classes.

Historical NWP data (see Section 1) and CWFIS index values were available for all bar three of our experimental fires whilst MOFSI values were available for all of them. NWP provided daily estimates of mean wind speed for the grid square in which fire occurred.

Testing model performance

All models were tested using both the best available data and assuming that the model represented a fire behaviour prediction system that had already been implemented. For the CWFIS this meant using the daily FFMC value and mean wind speed recorded during the fires to calculate a fire specific ISI as well as examining the relationship between rate of spread and intensity in relation to daily values of FFMC, ISI and FWI. We were also able to compare reported fire ignition and control ease from the simple record cards to daily values of the aforementioned indices.

For BehavePlus we first modelled fires using plot level fuel models (Table 3.7), obtained from the results of pre-fire plot monitoring (see Section 2), and mean wind speed recorded during the fire The process was then repeated with grouped fuel models for High, Medium and Low fuel load categories based on the median value of each BehavePlus fuel property we recorded for that category. In addition we used mean daily predicted wind speed as supplied by the Met Office. The fuel moisture inputs into the model were always the values recorded at the relevant fire. For fifteen of the burns no measure of dead fuel moisture content was available so we assumed a value of 21 %, which represented the mean value of all fire days for which we had a record. See Table 3.5 for sources of the fixed parameters used in BehavePlus

FireBeaters models were assessed in relation to independent fire records using parameters estimated from the experimental fires. When assessing performance in relation to simple records, the recorded Beaufort wind speed was transformed into a speed in m s^{-1}. Predicted versus observed values were also examined for the FireBeaters fires described in Section 2 with the wind speed input to the models coming from the NWP dataset. Where fuel moisture was required as an input we used the FMC value recorded prior to the relevant fire.

Table 3.5: Summary of static input values used in modelling with BehavePlus

Input Description	Value	Data Source
Surface area-to-volume ratio, foliage and stems < 2 mm in diameter	9 560 m^2 m^{-3}	EUFirelab (2002)
Surface area-to-volume ratio, foliage and stems < 6 mm in diameter	8 810 m^2 m^{-3}	EUFirelab (2002)
Surface area-to-volume ratio, stems ≥ 6 mm in diameter	1 000 m^2 m^{-3}	EUFirelab (2002)
Calluna heat of combustion	20 810 kJ kg^{-1}	Hobbs (1981)
Moisture of extinction	30%	Based on maximum observed FMC of Dead fuel of 29%

Where we examined the relationship between predicted and observed fire behaviour characteristics these were first assessed using simple scatter graphs. Where relationships existed between predicted and observed RoS two tests were used to define model performance. The first was to examine, using R^2 values, the scatter of points about a regression line between predicted and observed RoS thus allowing conclusions to be drawn over the strength of the relationship between the two, while showing variation in real fire data compared to modelled values based on fixed parameters. Secondly, where strong, significant relationships exist between predicted and observed values the deviation of the slope of the regression from the line of perfect agreement (LPA) is examined using:

$$t = (1 - b) / SE_b$$

where '*b*' is the coefficient of predicted values in the regression of observed on predicted rate of spread. An indication of the significance of deviation in the slope of the line from the LPA (P-values) can then be obtained by examining tables of critical *t* values for *n*-2 degrees of freedom. In those cases where there was no significant difference between the slope of the two lines, the placement of the LPA within 95% confidence intervals of the regression line is examined to give an indication of significant over or under-prediction.

The performance of models in relation to the simple records was examined using stacked histograms of ignition and control ease in relation to predicted rate of spread and intensity classes. Classes for rate of spread were created by dividing the range of values into more or less equal sections, whilst for fireline intensity we used class boundaries based on suggested limits of fire control using different tools (Table X, REF).

Results

A summary of the performance of BehavePlus and the FireBeaters equations shows they predicted rate of spread fairly well when using on-site weather and fuel data but both models struggled when tested as though implemented (Table 3.6). Behave seemed to consistently under-predict all fire behaviour characteristics, performing worst for fire intensity. The FireBeaters rate of spread equations seemed to consistently over-predict rate of spread although there was a strong relationship between observed and predicted values. There was a strong relationship between observed and predicted values for Equation 8 (fire intensity) but this deviated significantly from the line of perfect agreement. When the models were tested as if they were part of an implemented system all performed very poorly with no significant relationship between observed and predicted rates of spread and intensities apart from Equation four which included an on-site measure of live fuel moisture content in addition to stand height and wind speed.

Table 3.6: A summary of the performance of FireBeaters equations and BehavePlus for two different modelling scenarios. Method 1 used on-site weather and fuel characteristics whilst method 2 assumed an implemented system. For Behave this involved the use of group (High, Medium, Low loading) heather fuel models and Met Office predicted wind speed whilst for the FireBeaters models we used an on-site estimate of heather height and Met Office wind speed. The R^2 value describes the strength of the relationship between predicted and observed values; d.f. is the number of degrees of freedom; P is the P-value for testing whether the slope of the regression line is equal to 1; LPA describes whether the line of perfect agreement lies within (W), above (A) or below (B) the 95 % confidence intervals of the regression line.

Model	Test data	Method	Characteristic	R^2	b	d.f.	P	LPA
BehavePlus	FireBeaters	1	Rate of spread	0.31	0.80	25	0.39	W B
BehavePlus	FireBeaters	1	Intensity	0.12	3.63	25	0.14	B
BehavePlus	FireBeaters	1	Flame length	0.24	0.79	25	0.42	W B
BehavePlus	FireBeaters	2	Rate of spread	<0.01	0.62	22	0.54	W B
Equation 1	Independent	1	Rate of spread	0.41	0.66	20	0.05	A W
Equation 2	Independent	1	Rate of spread	0.58	0.99	16	0.97	W
Equation 4	Independent	1	Rate of spread	0.62	0.16	20	<0.001	A W
Equation 8	Independent	1	Intensity	0.99	0.32	6	<0.001	A W B
Equation 1	FireBeaters	2	Rate of spread	<0.01	0.62	22	0.54	W B
Equation 2	FireBeaters	2	Rate of spread	0.28	1.35	22	0.42	W B
Equation 4	FireBeaters	2	Rate of spread	<0.01	0.98	22	0.99	W B
Equation 8	FireBeaters	2	Intensity	<0.01	1.33	22	0.79	W B

BehavePlus

Fire-specific modelling

BehavePlus was first tested using fire specific values for fuel and weather characteristics (Table 3.7). For the first fifteen fires no measure of dead fuel moisture content was available so we assumed a value of 21 % which was the mean of the values recorded for all the other fires. Although the results were extremely noisy and Behave failed to predict the behaviour of individual fires with any great degree of accuracy the general relationship between predicted and observed results was sensible for rate of spread and flame length (Figure 3.2a and 3.2c). Fire intensity was predicted relatively poorly with the line of perfect agreement lying well outside the 95 % confidence intervals of the regression line which itself had a low R^2 value indicating a very weak relationship between predicted and observed intensities (Figure 3.2b). This may be due to problems with the way that intensity is calculated within the BehavePlus model where intensity is calculated through reaction time and reaction intensity.

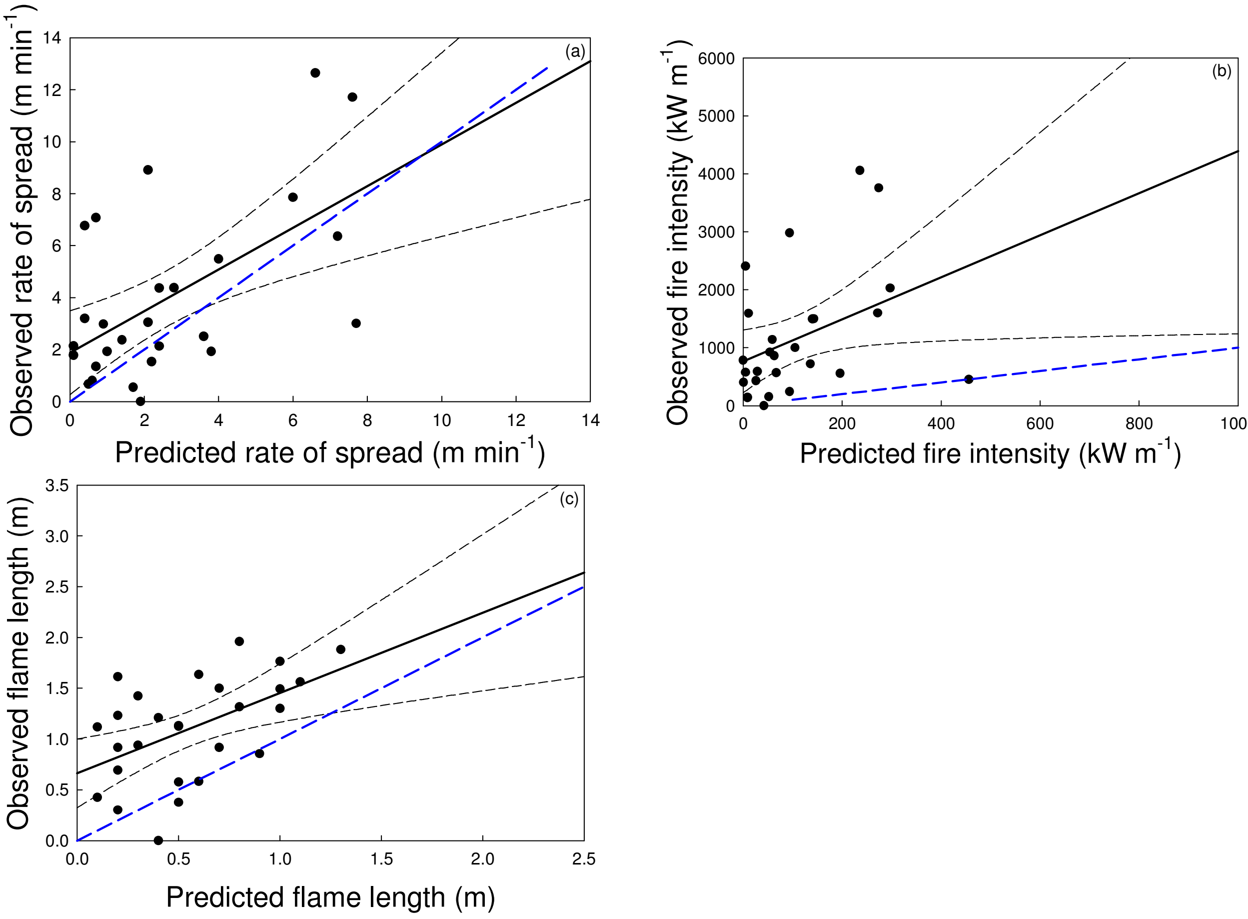


Figure 3.2: Observed values of (a) rate of spread, (b) fireline intensity and (c) flame length in relation to values predicted by BehavePlus using on-site weather data and plot level fuel models. The blue dashed line is the line of perfect agreement. Thin black dashes are 95 % confidence intervals.

Testing an implemented system

Grouped fuel models were developed based on the High, Medium and Low fuel categories as described in Section 2. Median values from each category were used for each of the four required inputs (Table 3.8).

The relationship between predicted and observed results was extremely poor; not only did the range of predicted values fall well short of those observed in the field but the R^2 of the regression was virtually zero (Table 3.6). Little difference could be detected between the slopes of the regression and the line of perfect agreement as the standard error of the regression coefficient was larger than the coefficient itself. Nevertheless predicted rate of spread does at least increase with observed rate of spread though Behave significantly under-predicts over the range of our data (Figure 3.3).

Table 3.7: Fire specific fuel and weather inputs for the first round of BehavePlus modelling. Dead FMC values marked with an asterisk are estimated based on the mean value for all the other fires.

Fire ID	1 hr fuels (t ha^{-1})	Live herbaceous fuels (t ha^{-1})	Live woody fuels (t ha^{-1})	Fuel depth (m)	Dead FMC (%)	Live FMC (%)	Wind speed (km h^{-1})
BE2 P1	3.3	8.0	8.7	0.4541	21*	81	11.12
BE2 P2	0.9	5.4	1.8	0.1855	21*	87	8.64
BE2 P3	2.3	8.0	7.5	0.4737	21*	55	18.22
BE2 P4	2.7	8.7	3.0	0.2778	21*	95	16.67
BE2 P5	2.5	8.2	2.5	0.2974	21*	63	14.22
BE2 P6	2.4	8.9	4.5	0.3870	21*	69	24.91
BE2 P7	1.7	7.3	2.9	0.2681	21*	80	27.00
BE2 P10	1.6	4.0	0.2	0.1170	21*	87	14.51
BE2 P11	3.0	10.6	4.3	0.4456	21*	61	8.28
BE2 P14	1.8	7.9	4.3	0.2844	21*	64	8.24
BE2 P19	1.4	6.7	1.9	0.2119	21*	93	7.16
BE2 P20	2.4	7.6	5.6	0.3426	21*	73	5.83
BE2 P21	2.0	9.1	3.6	0.2919	21*	74	8.50
BE2 P23	2.2	9.6	2.1	0.2730	21*	63	10.51
BE2 P24	1.0	6.2	1.4	0.1996	21*	71	20.77
BE2 P8	3.5	10.6	8.9	0.4648	21	97	15.19
BE2 P9	3.2	8.6	5.4	0.3026	23	84	10.37
BE2 P16	1.3	6.7	1.9	0.1859	27	91	16.02
BH1	1.9	8.1	2.6	0.1989	18	63	15.52
BH2	2.9	7.2	0.6	0.1564	20	67	11.88
BH3	1.1	6.9	2.1	0.1719	15	73	31.50
BH4	3.9	8.1	5.3	0.2983	17	61	17.50
BH5	2.8	10.0	4.4	0.2892	28	67	32.51
BH7	2.4	6.5	3.4	0.2300	16	70	31.21
BE2 P15	2.8	5.9	8.7	0.5096	16	75	14.62
BE2 P13	2.5	9.5	4.4	0.2885	29	77	16.31
BE2 P22	3.3	7.6	4.6	0.2526	17	74	10.44

Table 3.8: Grouped fuel models for BehavePlus

Fuel load category	1 hr fuels (t ha^{-1})	Live herbaceous fuels (t ha^{-1})	Live woody fuels (t ha^{-1})	Fuel depth (m)
High	2.5	8.0	5.6	0.4456
Medium	2.5	8.6	3.6	0.2885
Low	1.4	6.7	1.9	0.1859

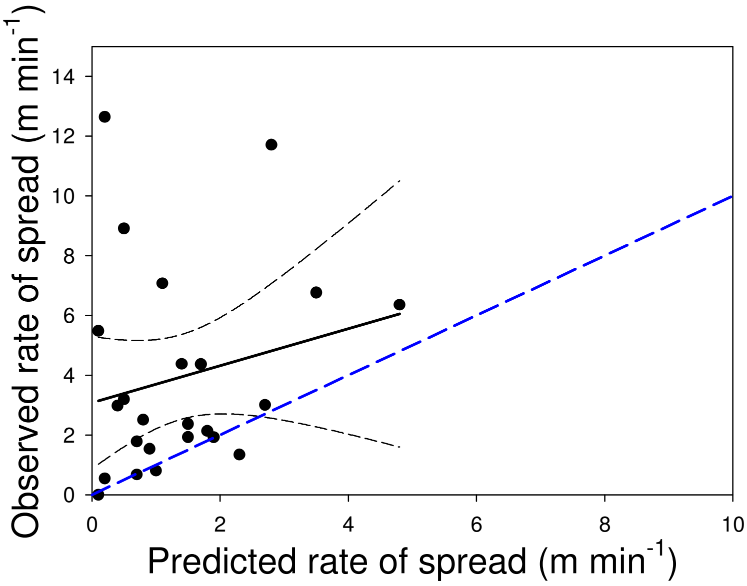


Figure 3.3: Predicted versus observed rate of spread using Met Office NWP daily mean wind speed and three group fuel models. The blue dashed line in the line of perfect agreement. Thin black dashes are 95 % confidence intervals.

The Canadian Fire Weather Index

Calibrating Initial Spread Index

We first sought to calibrate the ISI for heather fuels by using a daily FFMC value and wind speed recorded during the fire to calculate an on-site ISI value. No real relationship existed between the on-site ISI and observed rate of spread (Figure 3.4); any trend that can be seen is largely due to wind effect. The relationship between rate of spread and wind speed alone is much stronger than that with the modified ISI (Figure 3.5). All of our fires were burnt when ISI values were very low.

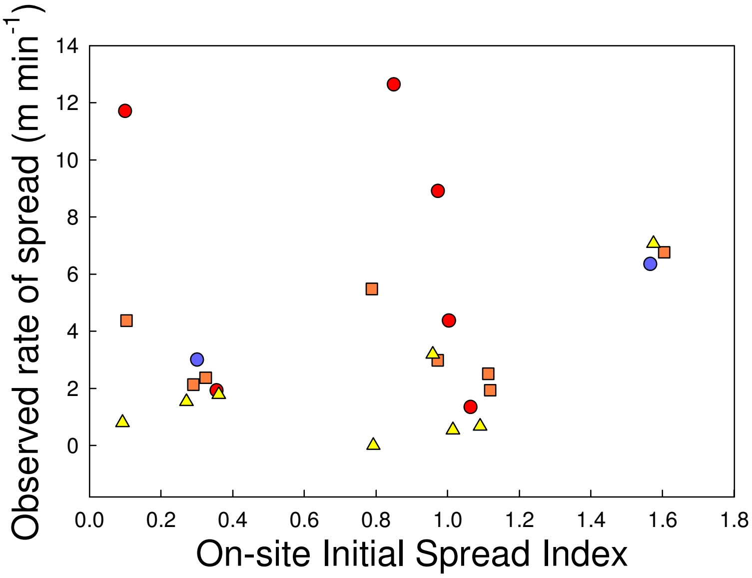


Figure 3.4. Observed rate of spread in relation to the initial spread index calculated using observed wind speed during the fire. High, Medium and Low fuel categories are shown in red, orange and yellow. Blue circles are High loads but had an extremely heterogeneous structure with many gaps.

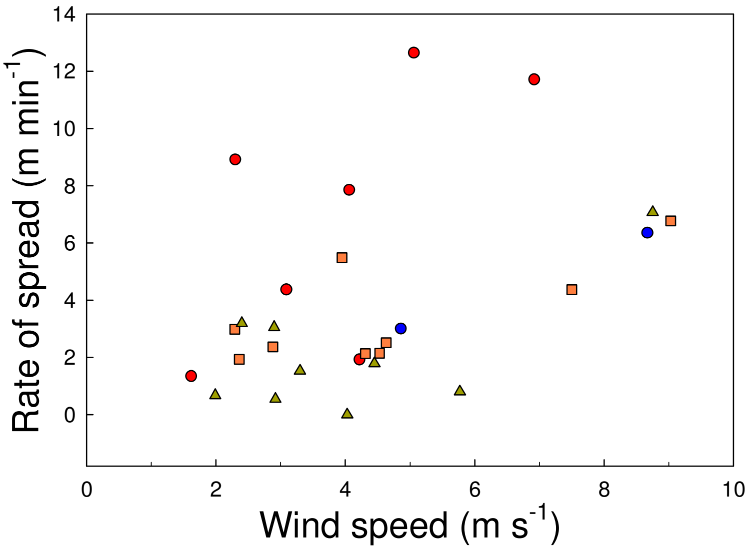


Figure 3.5: Rate of spread in relation to wind speed. High, Medium and Low fuel categories are shown in red circles, orange squares and yellow triangles. Blue circles are very heterogeneous, gappy fuel loads. A different relationship appears to exist between High loads and wind speed than for the other categories.

Testing an implemented system

We also examined the performance of relevant daily values of the CWFIS in relation to observed fire behaviour. No relationship existed between daily ISI and observed rate of spread or between daily FWI and observed fire intensity (Figure 3.6).

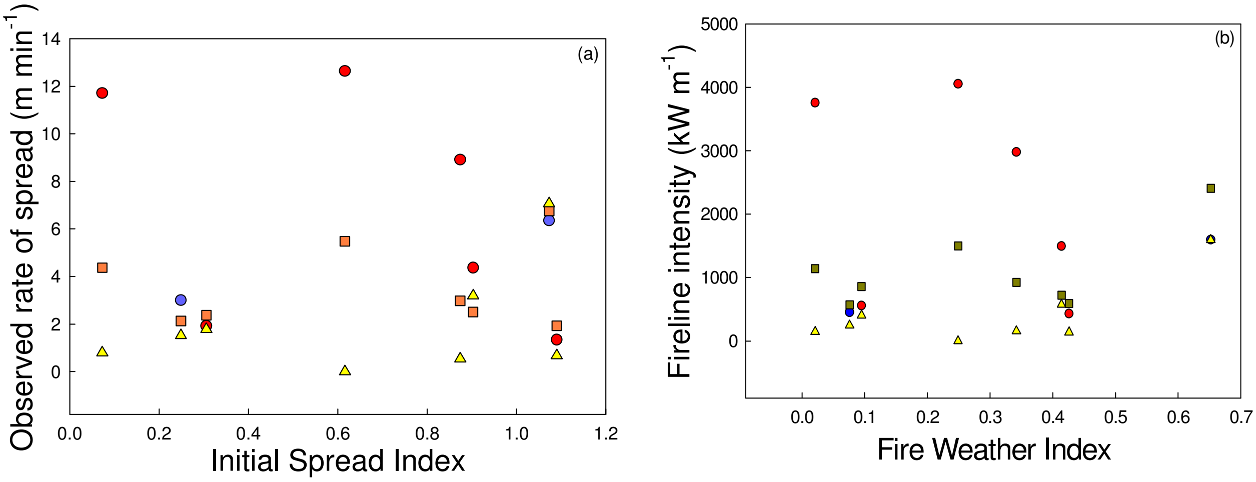


Figure3.6: Observed rate of spread and fireline intensity from 24 experimental fires in relation to daily values of ISI (a) and FWI (b) respectively. High, Medium and Low fuel categories are shown in red circles, orange squares and yellow triangles. Blue circles are very heterogeneous, gappy fuel loads.

The basic records received need to be analysed with respect to the Fire Weather Indices, though this has not yet been possible at this stage.

MOFSI

There was no relationship between MOFSI value and either experimentally derived estimates of fire behaviour or practitioners rating of perceived flammability of fuels and fire controllability (Figure 3.7). All of the experimental fires were completed occurred at “Very low” fire danger levels.

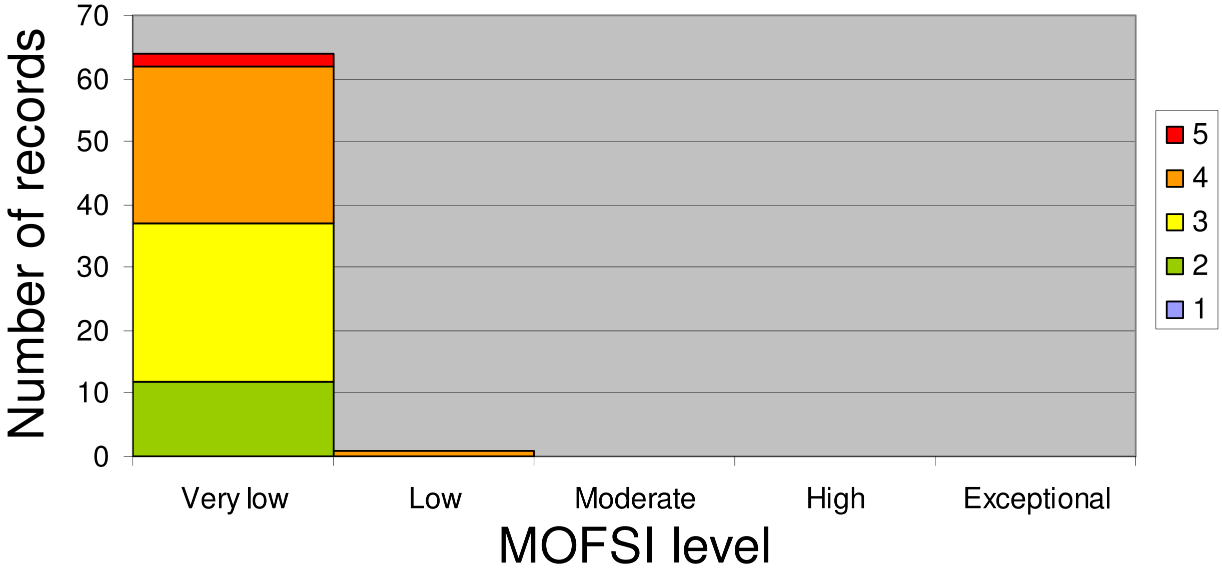


Figure 3.7: Met Office Fire Severity Index classes in relation to perceived fuel flammability based on the FireBeaters 1-5 rating of ease of ignition. MOFSI showed a similar relationship with ease of fire control.

FireBeaters models

Published data

Though we do not have many real fire behaviour records on which to base our tests it would seem that our models are able to predict observed rate of spread relatively well, though there are a number of significant outliers most of which are values reported by casual observers (Figure 3.8). For equations one and two there is a strong relationship between predicted and observed rates of spread (Table 3.6), whilst for equation two not only does the slope of the regression not differ significantly from the line of perfect agreement but the latter also lies within the 95 % confidence intervals of the regression over the range of our data. Both equations appear to over-predict rate of spread. Equation four appears to perform adequately for a subset of the data but the regression line is dominated by several outliers: it massively over-predicts rate of spread for the fastest fires recorded by Bruce and Servant (2002). The scatter of points for slower fires seems to more or less follow the line of perfect agreement. It should be noted that some of the Bruce & Servant fires were on slopes and slope has not been taken into account in any of our models.

The results for fire intensity are based on a very small number of records as values were only available from the work of Bruce and Servant (2002) (Figure 3.9). Although there is a strong relationship between predicted and observed values the slope of the line differs significantly from the line of perfect agreement and our model fails to predict the extremely high fire intensities recorded by Bruce and Servant (2002).

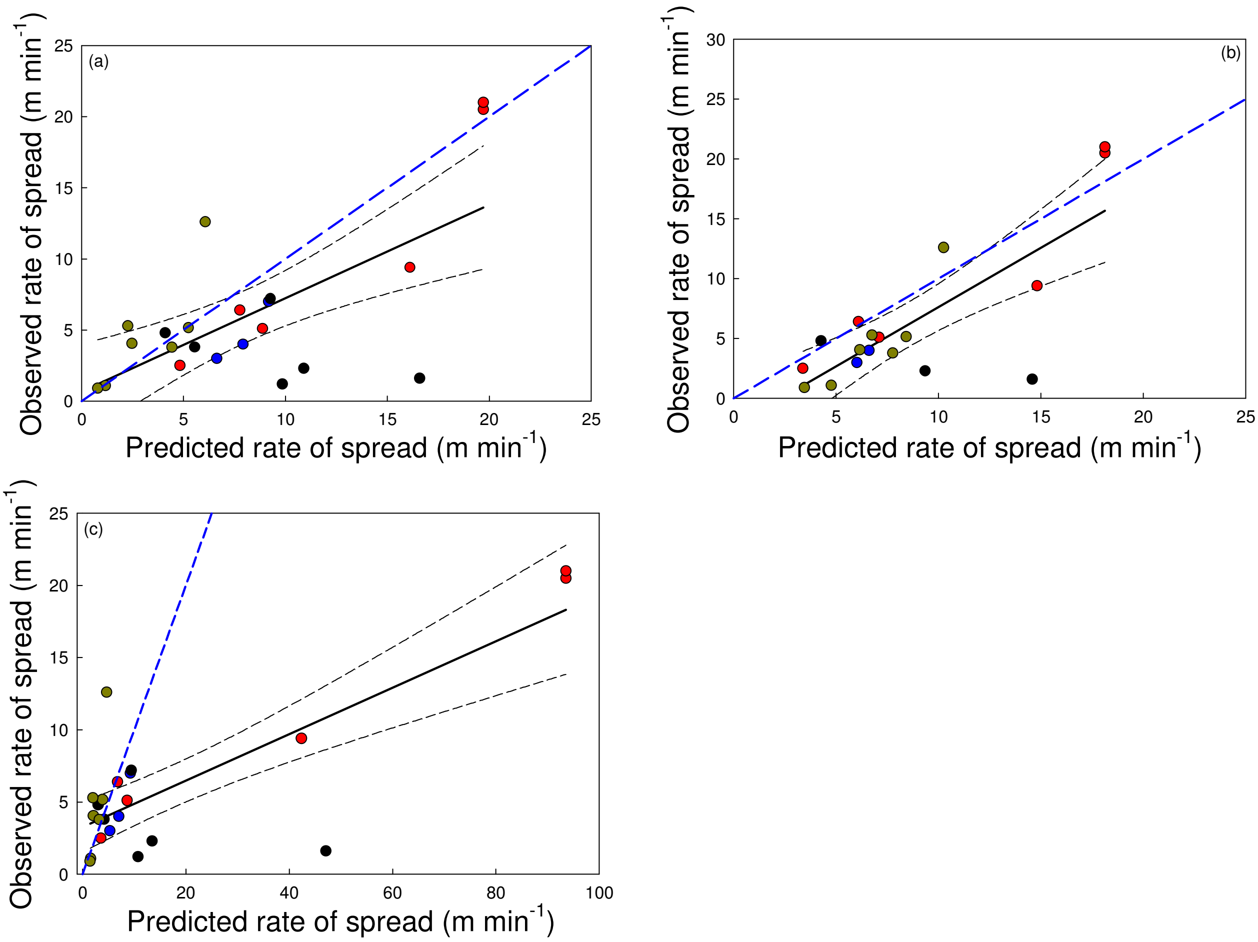


Figure 3.8: Predicted versus observed rates of spread using Equations one (a), two (b) and four (c). Blue dots are fires recorded by Kayll (1966), red by Bruce & Servant (2002) and gold by Thomas (1971). Black dots are records provided by volunteer observers when they submitted simple record cards.

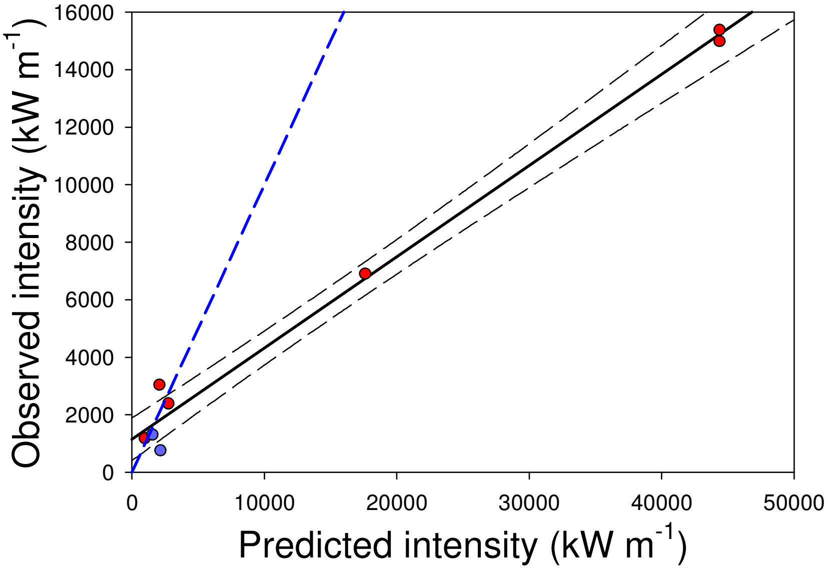


Figure 3.9: Predicted versus observed fire intensity using Equation 8. Red dots are fire burnt by Bruce & Servant (2002), blue dots by Kayll (1966). The blue dashed line is the line of perfect agreement and black dashes 95% confidence intervals.

Simple records

Our equations distinguish relatively well between different observed ignitions and control ease classes. There is a general trend of increasing average ignition and control ease with increasing predicted rate of spread (Figure 3.10a and 3.10b). Equation 1 successfully identified those fires reported as being easiest to ignite and most marginal burns (rated as 2 or below) were confined to the lower range of predicted spread rates. The equation performed less well for control ease with the most difficult and easiest fires to control lying in adjacent rate of spread classes. Predicted rates of spread at which ignition was reported as being relatively easy with hand tools alone (rated 3 or less) covered a wide range of spread rates reaching as high as at least 17 m min^{-1}. The relationship between predicted intensity and ignition and control ease was not as good with fires both unsustaining (1) and unmanageable (5) fires occurring in the range > 500 to ≤ 2000 kW m^{-1}. Fires predicted as occurring in higher intensity classes were, by and large, reported as easier to ignite and more difficult to control.

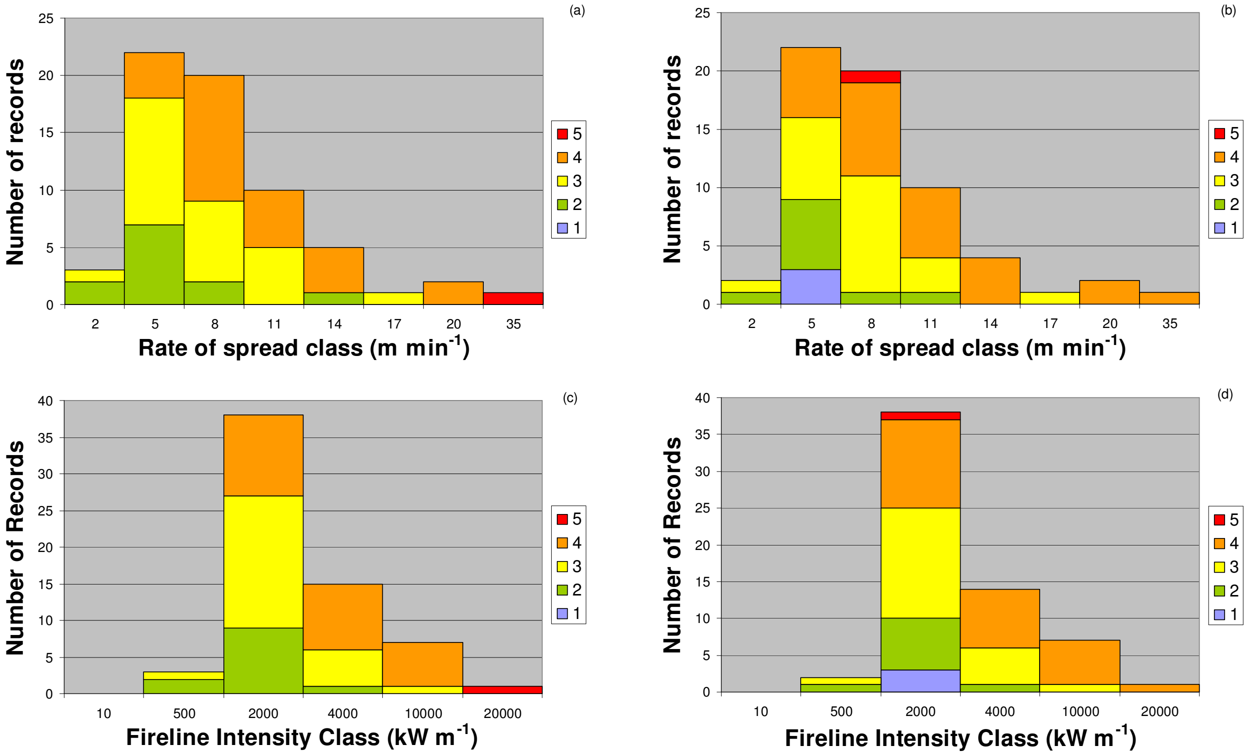


Figure 3.10: Reported ease of ignition and control in relation to predicted fire rate of spread (a and b respectively) and predicted fire intensity (c and d respectively).

Testing FireBeaters models with Met Office weather data

Unfortunately no independent data existed which would allow the FireBeaters models to be tested using Met Office NWP weather data so we were forced to back-cast onto the data used to build the models. Equations 1, 2, 4 and 8 were run using mean height and, for Equation 2, fuel moisture recorded in the field. The wind speed used was the daily forecast mean wind speed provided by the Met Office. The results are extremely poor (Figure 3.11) with no good relationship existing between predicted and observed rate of spread and intensities. Equation 2, which includes an on-site measurement of fuel moisture content performs marginally better than the others. These equations are clearly inadequate to predict the behaviour of individual fires (Fig 3.11), and show a tendency to under-predict both rate of spread and intensity.

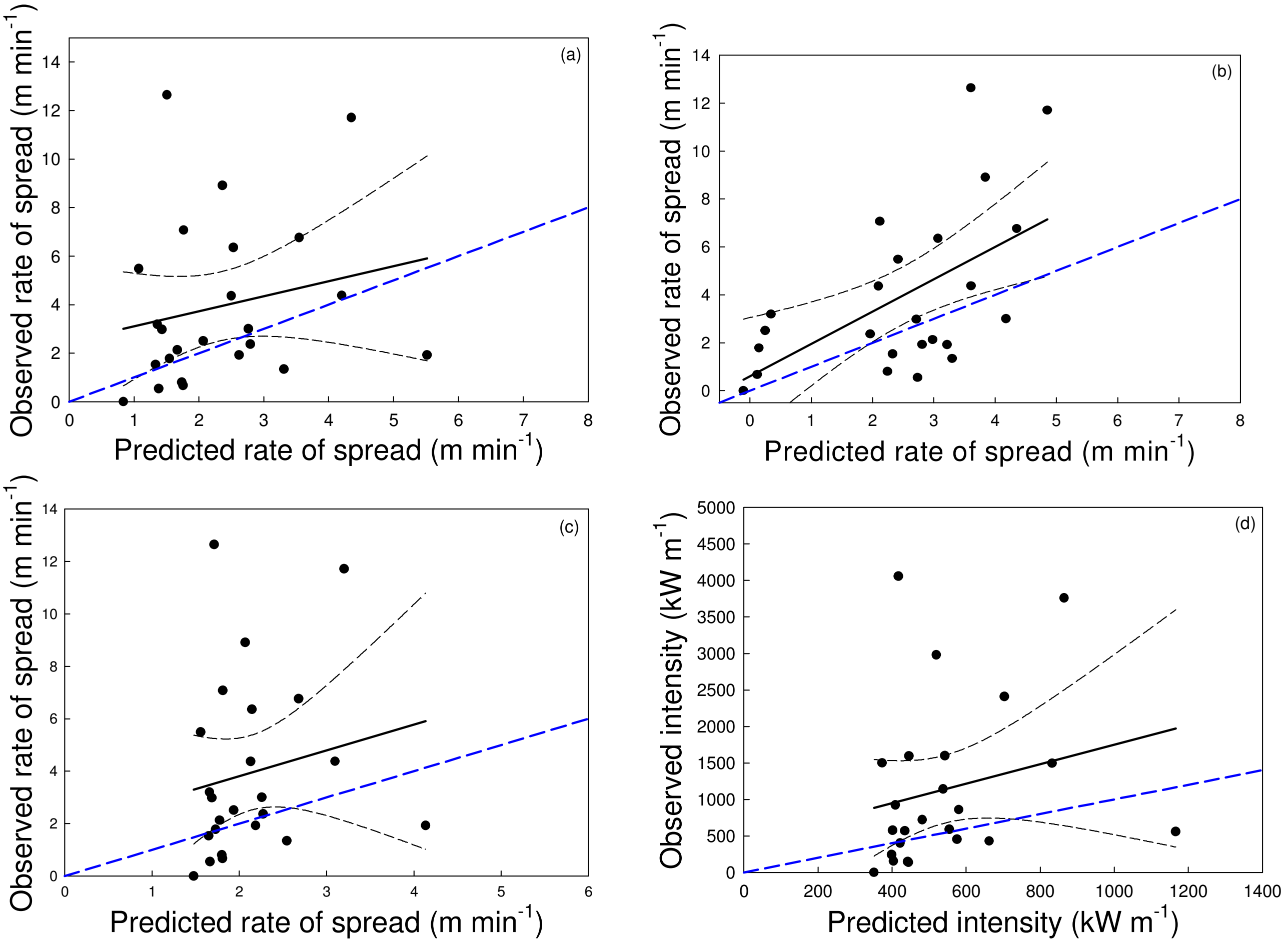


Figure 3.11: Predicted versus observed rates of spread using Equations 1 (a), 2 (b) and 4 (c) and fire intensity using Equation 8 (d). Site specific fuel height and moisture content measures were used but wind speed was the mean daily value forecast by the Met Office.

The residuals are all highly skewed except for Eq 2 suggesting that a square-root transformation of rates of spread may have improved the statistical analyses slightly.

Discussion

BehavePlus performed reasonably well for the fires of Davies *et al.* though this is to be expected since it is partly based on physical laws of heat transfer which do not vary according to location. It must however be borne in mind that a number of assumptions were involved in its use (dead FMC, moisture of extinction and surface area-to-volume ratio). Including measured values for these variables in future tests of the system may help to improve the accuracy of the predictions and this requires the determination of moisture of extinction and surface area-to-volume ratio for British *Calluna*.

Plot 10 stood out as having an extremely inaccurate prediction for its RoS. The fact that it would not burn is explained by its low fuel loading and high density of green, high FMC shoots. The apparently large quantity of dead material in this stand was irrelevant to fire spread as most of it took the form of larger stems (> 2 mm in diameter) which were killed but remained unburnt following a previous fire. Their large size, smaller surface area-to-volume ratio (compared to fine twigs and foliage) and the fact that they lay on the ground surface meant they were moist and not as readily flammable as fine dead material supported in the canopy.

It is interesting that the model predicted rate of spread and flame length relatively well but that the relationship with fire intensity was rather weak. There are a number of possibilities, the first is that the error lies in our estimation of fire intensity and we have acknowledged in the methods used that the value we give is likely to be an underestimate (see Section 2) but this should be systematic and should not cause such noisy results. The strong relationship with flame length makes the result even more odd and suggests, as does Figure 2.10, that there may be a different relationship between flame length and fire intensity from those on which the model is based. A question mark may exist over the ability of Behave to accurately predict that amount of fuel consumed in the fire. This may have been partly caused by the fact that the consumption of live fuel is not predicted correctly either due to a relatively high fuel moisture content or due to the value given for surface-area to volume ratio. We know from the results discussed in Section 2 that a relatively constant load of shrub fuel is consumed in heather management fires and thus if there is a good relationship with rate of spread there should be an equally strong one with fire intensity. Davies (2005) demonstrated the sensitivity of the model with regards to small changes in live and dead FMC and moisture of extinction and further sensitivity analysis of this kind would reveal the effects of assigning heather fuel categories to different areas of the BehavePlus fuel models as well as the impact of altering surface area-to-volume ratio. It would be wise to seek to measure both this and the moisture of extinction of *Calluna* before using the model further.

The Canadian FWI system (Van Wagner & Pickett 1985) as implemented here performed extremely poorly though this was probably to be expected given the results discussed by Davies et al. (2006) and Anderson (2006). The truth is that the system performs well around the world for habitats and fuel types similar to those for which was designed, mature lodgepole and jack pine forest, but that adaptation is needed before it will perform well in other fuel types (Fogarty et al 1998). The moisture regime and fire behaviour of shrub fuels which have frequently been observed to behave like mini crown-fires (Alexander & Sando 1989) cannot be equated easily with that of a layer of needles and moss on the forest floor. Live *Calluna* and dead material suspended in the canopy are not well represented by any of the moisture codes of the FWI (see Section 6). The attempt to calibrate ISI with rate of spread for heather fuels has been made along the same lines as that attempted by Alexander & Sando (1989) and was unsuccessful. Any vague relationship was an artefact of the influence of the site-specific wind speed on the index value. The relationship between rate of spread and wind speed alone is in fact much better.

All of our fires occurred over a very small range of extremely low ISI and FWI values and this is largely a product of the cold, humid and wet conditions experienced during much of the autumn and spring burning seasons. The fact that heather is flammable under such conditions is a remarkable product of the fineness of its fuel structure, the low fuel moisture of live material and the rapid drying of suspended dead fuel following rain. It may be that if we were to examine the behaviour of fires over a wider range of conditions and to measure fire behaviour in summer wildfires we would find that, at a coarse scale, the index is able to predict changes in rate of spread and intensity. Certainly this was found to be the case by colleagues working in New Zealand (Anderson 2006). Previous work (Davies et al. 2006) has indicated that the FWI may be suitable for predicting periods of extreme risk but if we want a system that can detect both wildfire risk in the summer due to drought and dry conditions and periods for the safe use of prescribed burning we will have to do better.

The fact that we have little idea of what fire behaviour does in the summer is a real problem in this context. Behaviour may well be extreme in dry conditions as dead fuel and the moss/litter, the moisture content of which is well predicted by FFMC (see Section 6), will both become available fuel. High FFMC in the summer reflecting dry moss/litter, may well indicate potentially high fire risk but how this relates to fire behaviour in the context of a heather canopy with a very high moisture content is difficult to know. Summer test fires are thus an immediate priority, though it should be noted that the current legal position means this is impossible in Scotland.

The models developed in Section 2 perform relatively well on the independent data we have available, seeming to represent both what colleagues have recorded experimentally and what fire managers are observing on the ground in terms of the ignitability and controllability of management fires. The performance of Equation four is weak and massively over-predicts rates of spread for Bruce and Servant's fires. These burns were lit in extremely tall heather well beyond the limited of any of our experimental fires. The height of these stands leads to large values of predicted Ln(rate of spread) and a larger still prediction for rate of spread itself. This highlights well the dangers of extrapolating empirical models beyond the range of the conditions they are based on and suggests that further fires are required in a wider range of fuel types if we are to build truly robust models.

Equation 8, which predicts fireline intensity, yielded rather strange results. There was a very strong relationship between predicted and observed values, albeit based on a very small number of data points, but the equation seriously underestimated the intensities recorded by Bruce and Servant. Again it is important to point out that the fires were burnt in a heather fuel load that was significantly different from any of those burnt during our experimental fire programme. The fires burnt by Bruce and Servant spread considerably faster than many of those we recorded and also consumed a much greater quantity of fuel. These burns occurred in very tall stands of a high fuel loading and were also much larger in extent than our experiments. This suggests both that we need to extend the range of fuels for which we have good records of fire behaviour as well as to understand the relationship between fire width and behaviour. Previous research (Cheney *et al.* 1993) has demonstrated that larger fires spread faster and burn more fiercely and we need to understand such scale influences if we are to be able to relate the behaviour of our burns to that of wild fires. The records we have from volunteer observers suggests that predicted fire intensity classes do not match up well with observations on the ground. We need to assess whether this is because the quoted suppression method intensity limits are not correct or whether our equations are not predicting behaviour accurately.

Using models for forecasting

The results of testing all of the models as "implemented systems" revealed the difficulties in predicting the behaviour of any one individual fire with any confidence, though the models that performed well using on site data (BehavePlus and Equations 1 and 2) generally showed sensible general trends. We already know from previous work (Davies et al. 2006) that BehavePlus doesn't work for *Calluna* dominated fuels when we use grouped fuel models and even less so when a single general fuel model is used. The significantly different relationships that exist with wind speed for our "High" loads and all the others meant we decided that, for the purposes of fire behaviour prediction, separate models would be sensible. If the objective were to predict general coarse trends in fire danger then a single, well defined model may well be enough, differences due to variation in fuel type can be taken into account by experienced practitioners.

For a model that relies heavily on wind speed for the prediction of fire behaviour it is a significant problem that the mean daily NWP wind speed values are significantly lower than those recorded during individual fires as peaks and troughs will be flattened out. Spatial variation in wind speed and direction is significant, particularly in mountainous areas and it is questionable whether data at a resolution of 5 km^2 is sufficient for accurate fire behaviour prediction. Forthcoming changes in the resolution of the NWP to provide data at a finer scale may make a significant difference and the impact of this needs to be assessed.

Despite the inability of the models to give an accurate, site-specific prediction of fire behaviour the models may well yet prove suitable for giving a general impression of regional changes in fire danger. The scope and range of data on which the empirical models are based needs to be improved however, and none of the models should be used to create publicly available fire behaviour forecasts. More fires in wildfire-type conditions of the sort completed with Northumberland Fire and Rescue Service would be useful in helping us determine the effect of fire size on fire behaviour. Though two such burns were completed and we were able to learn a significant amount about the behaviour of large fires, as well as how to monitor them effectively, equipment failures and complex burn patterns meant the majority of the information collected was not usable and that which was will take significant further effort to untangle.

The performance of the FWI was again poor and there was no relationship obvious between fire behaviour recorded either experimentally or observed by collaborators conducting prescribed burning. As was mentioned earlier the FWI system may be suitable for predicting certain periods of exceptional fire risk and, at a coarser scale, there may be a relationship between fire behaviour and FWI indices over the range from un-sustaining to wildfire-type conditions. Unfortunately for the two large fires on which we were able to record some information problems with the data supply from the Met Office also meant that it was not even possible to examine these fires qualitatively as we were unable to calculate FWI values from the data provided. Such knowledge and data gaps need to be addressed immediately. MOFSI code values seem to bare no relationship to changes in fire behaviour assessed either experimentally or subjectively by managers. It may be that some modification of the MOFSI class boundaries will allow it to detect some of the changes seen at the management fire level and still detect “exceptional” conditions for wildfires but while it remains based on an unmodified FWI this is doubtful.

The need to input fuel moisture values into BehavePlus and some of the empirical models of fire behaviour we have developed, as well as the fact the major problem associated with the FWI seems to be that it does not accurately represent the moisture of the fuel types of interest, means that the focus of future research must also be on the further development of fuel moisture models for live and dead fuels. The fact that live fuel moisture declines rapidly when soils are cold or frozen (Section 6) is an important factor in our fires that is not taken into account in these other models. Progress in this area could allow both the replacement of the FFMC index for heather, and possibly other shrubs, as well as the implementation of a fire prediction model based on Behave and/or our more complex models. The influence of live fuel moisture could also be included in any redevelopment of the FWI as has been done in other areas (Fiorucci *et al.* 2006).

Implications and further actions

The first obvious point we should make is that we currently lack a sufficient data-set with which to either build robust empirical models or with which we can tests those based on our experimental fires. A number of other projects have or are examining various aspects of fire in *Calluna*-dominated vegetation and it is imperative that we forge closer links, try to develop common methodologies and agree procedures for data-sharing. In the meantime we should aim to complete experimental fires in a wider range of *Calluna*-dominated fuel types and to examine the effect of fire size/width on behaviour.

The performance of the Canadian FWI with regards to heather fires asks questions about what we want and expect a fire danger rating system to do for us. If we want a system that merely detects infrequent “exceptional” conditions then MOFSI and the FWI on which it is based is possibly appropriate though we need to examine the relationship between large, ecologically damaging fires and FWI indices. A real fire danger rating system can however do much more than this and we should aim for a system which predicts the real ignition of wildfires and safe conditions for prescribed burning. For a system to be useful to the Fire Brigades and land-managers it is not good enough to have a model which predicts thresholds for extreme behaviour or impact but comes with a proviso that “wildfires can occur at any value of the Fire Danger Index”.

Our focus must now lie on better understanding the variation in fuel moisture of a range of different fuel types (e.g. live and dead heather and gorse, grass, peat) in order to test the applicability of the FWI indices in a way that allows us to develop new sub-models for the FWI for UK fuels or to allow the use of other systems such as BehavePlus or our empirical models. A model of fuel moisture provides information on fuel ignitability and it is this which should form a fire weather index with information on fuel type and other weather factors influencing behaviour providing information on potential fire behaviour. This combined with analysis of the spatial distribution of wildfires in relation to human population and access is what will provide a true measure of actual fire danger. The desirability of such a separation of fire weather from fire behaviour has been echoed by others working in shrubland fuels (Anderson 2006).

In summary, action points for us to consider include:

- Decide carefully what stakeholders want a fire model to do.
- Re-examine the MOFSI class thresholds on the basis of recorded fire behaviour.
- On the basis of the above point either consider whether/how we can adapt the already implemented CWFIS, or consider if the work needed to redevelop the moisture codes means that developing a fuel moisture model for use with Behave or our models might provide better results for the full range of fire behaviour.
- Expand our observer network and get volunteers to test our models either using a nomogram and/or model(s) published on a private area of the website
- Examine the implications of using NWP data for running models and the effects of the forthcoming change in resolution from 5 km^2 to 2 km^2 grid squares.

Section 4

Weather and fuel controls on sustained ignition

Introduction

Previous fire behaviour research in the UK (Davies 2005, Davies et al. 2006) has failed to adequately identify the role of fuel moisture content (FMC) on fire behaviour, and though the research presented in Section 2 takes things forward a little the relative importance of dead and live fuels and their FMC is still not understood. The fact that *Calluna*-dominated fuels mostly comprise a live, green component that displays significant seasonal variation in its moisture content and significant intra-seasonal variation on a diurnal basis (Davies 2005, Jackson *et al.*1999) during some periods makes predicting changes in the flammability of *Calluna* difficult. Large-scale experimental fires of the sort documented in Section 2 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 been focused on a restricted range of conditions when fires were likely to be sustaining.

Conditions during the legal burning period in Scotland (roughly speaking the 1st October until the end of April, see SEERAD 2001a) are extremely variable with weather ranging from sub-zero temperatures with deep snow cover to extended warm dry spells typically seen towards the end of the period. 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. Frequent periods of rain often interrupt suitable burning conditions and limited man power, on-top of such variable conditions, means that time spent trying to burn in non-sustaining conditions is a serious loss whilst fires may rapidly escape control in other conditions. 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-less winter that froze ground and allowed *Calluna* to become exceptionally dry (Davies et al. 2006). Understanding the ignitability of fuel is critical from the point of view of predicting the risk of accidental and malicious wildfires, and although societal factors may play an important role in governing where and when wildfires occur (McMorrow *et al*. 2006) the vegetation still needs to be dry enough for these to become anything other than minor incidents. Fuel moisture content combined with other weather conditions determines how easy fires are to control 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. Other authors (Marsden-Smedley et al. 2001, Tanskanen et al. 2005, Fernandes et al. 2002) 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, that combined ignition attempts with fine scale dead and live fuel moisture monitoring, information on fuel structure, on-site data on prevailing weather conditions and fire weather indices from the CWFIS was designed. 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 4.1). Below this self thinning leaves a layer of dead and live stems of various sizes but with little foliage. It was hoped that by sampling these layers individually as well as taking samples of purely dead material and the moss/litter layer it would be possible to get a better idea of critical fuel moisture levels for ignition and sustained burning as well as the role of the moisture content of live and dead fuels and structure of the *Calluna* canopy.

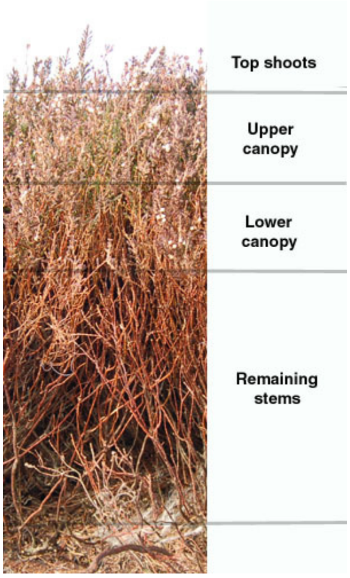


Figure 4.1: Cross-section through a closed *Calluna* stand illustrating the four stratigraphic layers harvested during FMC quadrat collection. For the remaining stems layer dead steams (grey) and live stems 2 mm or less in diameter (thin brown) were collected separately.

Aims and objectives

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

Methods

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, *Vaccimium myrtillus,* were locally co-dominant but such areas were avoided. Grasses, mainly moor matt grass, *Nardus stricta,* and wavy hair grass, *Deschampsia flexuousa*, 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. flexuousa* plants and a compacted layer of mosses. To the east the site was bounded by a wide gravel track.

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.

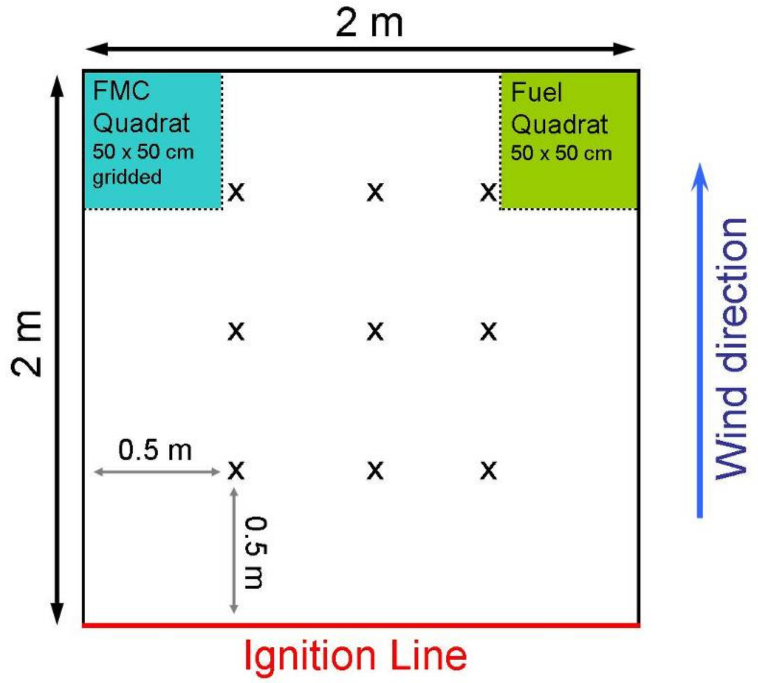


Figure 4.2: Layout of the experiment. X represents FuelRule measurement locations spaced 0.5 m from the plot edge and 0.5 m apart.

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.

Fuel moisture monitoring was completed using a 50 cm × 50 cm quadrat gridded with 25 sub-quadrats, each 100 cm^2. Five sub-quadrats were randomly selected for harvesting. Within each sub-quadrat all *Calluna* was harvested in the following order: green shoots projecting above the top of the main canopy, the top half of the *Calluna* canopy 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.

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

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.

Results

Our initial intention had been to use the data collected from this experiment to develop logistic regression models that linked variation in fuel, fuel moisture and weather to the success or failure of ignition attempts. Poor weather during the Spring 2007 burn season meant that we were only able to complete tests on six days, giving a total of twelve fires. Met Office data supply problems meant that it was not possible to examine the results of the trials in relation Canadian FWI index values. Only a brief, initial analysis was therefore undertaken.

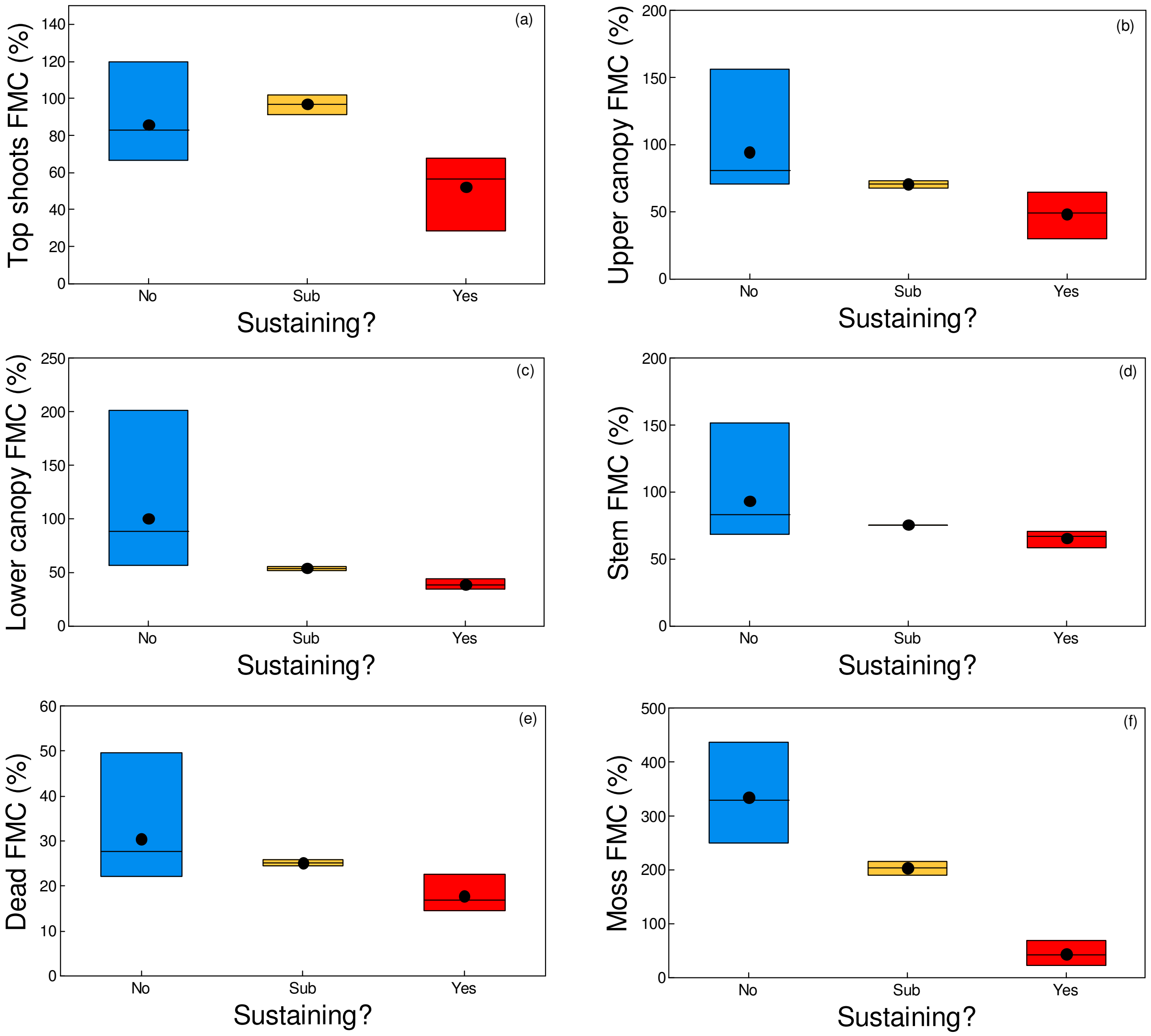


Figure 4.4: The range of moisture contents measured for six fuel components in fires initiated from spot ignitions and classified as non-sustaining (blue, four fires), sub-sustaining (orange, two fires) or sustaining (red, six fires). Black dots are the mean FMC value.

The days on which we attempted ignitions, although small in number, seemed to cross the threshold between sustaining and non-sustaining conditions quite nicely and one day had extremely low live fuel moisture contents of less than 40 % and was associated with frozen ground. For spot fires successful ignitions were associated with lower moisture contents of all fuel components whilst sub-sustaining fires were associated with intermediate values (Figure 4.4). Line ignitions were successful in a slightly wider range of conditions and fire established at higher moisture contents (Table 4.2).

A number of the ignitions took place on days when management fires were lit and recorded using basic fire record cards. Several of these larger fires burnt well despite failed ignition tests immediately beforehand.

Table 4.2: Maximum fuel moisture contents (% dry weight) at which spot and line fires developed into fully sustaining fires.

Fuel component	Spot	Line
Top shoots	68	102
Upper canopy	64	73
Lower canopy	44	55
Dead shoots	23	26
Live stems	71	75

Discussion

The brief analysis of the results above clearly demonstrates the role of fuel moisture in determining the sustainability of fires. The fact that spot and line ignitions were sustaining at different moisture contents is interesting and demonstrates the importance of scale to fire behaviour. For slightly wetter fuels a greater initial energy input appears to allow the fire to preheat, dry and spread to adjacent fuels while a small spot ignition simply does not release enough energy for this to occur. The success or failure of spot ignitions is important as understanding the relationship between the probability of success and fuel moisture content is important for assessing the risk of accidental ignitions from different potential sources such as discarded cigarettes, matches or embers from management burns or bonfires.

It is interesting that the difference between the maximum FMC of dead fuels for spot and line ignitions is relatively small compared to the differences seen in live canopy fuels. Subjectively, the moisture content of the lower canopy did seem to be particularly important. This fuel layer contains a considerable amount of the dead fuel found in *Calluna* stands but is attached to live stems and mixed in with a small amount of live foliage. Most of the fires were observed burning through this layer with the green, upper canopy igniting afterwards. The dead foliage attached to live stems is probably what ignites first and the combustion of this dries and ignites live stems and the predominantly live material above. Fires on the penultimate day were observed spreading through the upper and lower canopy more evenly and this coincided with extremely low live (upper canopy) moisture contents and a period of frozen ground. Frozen ground has previously been hypothesised to be an important control on live fuel moisture content in spring as it restricts plant access to water at a time when leaf cuticles are damaged due to over-winter wind and ice abrasion and stomatal closure is less effective at controlling moisture loss (Grace 1990, Davies *et al.* 2006).

It appears from our results that we can begin to define the critical moisture content of dead fuels as lying somewhere between 20 to 30 percent and that the moisture content of this material is crucial in determining whether or not it is possible to ignite any kind of fire. If ignition of dead fuels is possible the FMC of live fuels will be most likely to play a significant role in determining fire behaviour, particularly in spring when the moisture status of *Calluna* plants seems to vary significantly (Davies 2005). Extreme events such as periods of frozen ground or extended drought may allow live moisture contents to drop far enough for live material to fall close to the moisture of extinction significantly increasing flammability. The exact importance of dead and live FMC for fire behaviour is likely to be a combination of their moisture status and the relative amounts of each component. We can hypothesise that fires will establish only where there is enough dead material of sufficiently low FMC to be ignited, and that this releases enough energy to dry and cause pyrolysis of live fuel. The amount of energy required for the latter process will be controlled by the live fuel moisture content. Fire behaviour may therefore relate well to the fuel load-weighted average of dead and live moisture content.

For many accidental wildfires it may well be that it is the moisture content of the moss or litter layer that is crucial in determining ignition probability as discarded cigarette ends or falling embers will probably fall onto this fuel. Moss moisture content varied dramatically over the course of this study and on two of the days there was significant combustion of this layer which meant even these small fires require a concerted effort to extinguish. It would be interesting to examine the ignitability of heather stands in a moisture inversion situation when light rain after an extended dry period might allow a dry moss layer but wet heather canopy or even a relatively dry lower but wet upper canopy.

Implications and further actions

Even at a relatively early stage this experiment has yielded some important results and suggests that with further data we will be able to better understand the roles of dead and live fuel moisture on the flammability of *Calluna* stands. In comparison to full scale fire tests this experiment is relatively quick, easy to set up and complete and it would be useful to complete further replications in a wider range of conditions and in different *Calluna* fuel types. Further tests would also allow us to understand the importance, if any, of small scale variation in fuel structure, the ratio of dead to live fuels as well as the importance of weather variables such as wind speed. The latter may be important in determining the threshold for sub-sustaining versus sustaining fires. Linked to the development of models for dead and live moisture content the experiment could potentially provide empirical models that predict the probability of a spot or line fire establishing.

Section 5

Weather controls on wildfire occurrence

Introduction

Fire danger rating systems are used around the world to assess the probability of fire occurrence and the likely fire intensity and difficulty of control should a fire occur. In this section we examine wildfire records provided by the Fire & Rescue Services and other agencies and attempt to relate these to weather data provided by the Met Office.

Aims and objectives

To identify temporal and spatial patterns in wildfire records in Scotland

To assess the value of the Canadian fire weather indices in predicting the occurrence and magnitude of wildfire in Scotland.

Methods

Fire Records

Data for outdoor fires were received from Fire and Rescue Services for four regions of Scotland. To these were added records for the Peak District National Park from the Moors for the Future, for the Dorset Heaths from Dorset County Council, for the New Forest from the Forestry Commission, and the records for heath management fires described in earlier sections of this report. This gave a total of 6962 fires (Table 5.1).

Table 5.1. Total number of fire records received, and those between 16/3/2003 and 15/3/2007 used in this analysis. Basic fires are management fires for which a basic record card has been completed. Experimental fires are those with detailed monitoring of fire behaviour. FDR1 fires are those for which an insurance claim has been made; all other fire records for Highlands and Islands are FDR3. Urban fires are those within circles drawn round the 100 major towns and cities in Scotland and Dorset.

	Total	Used	Rural	Urban	
Experimental	39	39	39		Oct 03 – Mar 07
Basic muirburn	134	110	110		Apr 06 – Mar 07
Incl. New Forest (Forestry Commission)	90	67			
Peak District (Moors for the Future)	377	69			
Dorset Heaths	487	484	62	422	
Dumfries & Galloway	471	464	351	113	Jan 03 – Mar 07
Grampian	1155	840	624	216	Jan 02 – Jan 07
Highlands and Islands FDR1	101	63	58	5	Jan 03 – Mar 07
Highlands and Islands FDR3	1907	1805	1337	468	Jan 03 – Mar 07
Lothians and Borders	2201	1186	437	749	Jan 03 – Aug 06

The quality of these records is very variable and ranges from the detailed records of the experimental fires conducted as part of the FireBeaters project to simple records of date and location on which a fire occurred. The bulk of the records come from the Fire and Rescue Services, but the four regions use different criteria for describing the fire and resources used. Although most of these come with a descriptor of fuel type, the terminology used is very imprecise and inconsistent. Thus 'moorland fire' or 'heath fire' may include vegetation dominated by *Calluna* or *Molinia* and the term 'Grass fire' is frequently used for wildfires in general, including heather and gorse. The records also include crop and stubble fire, some woodland and forest, and 'bushes' and 'hedge' as well as 'gorse' or 'whin' (Table 5.2). The main classes of fuel used here were Heath, Grass and Gorse. The 'Other' category (including such fuels as 'Bonfires', 'Vehicles', 'Rubbish' or unspecified) were ignored from the analyses.

Table 5.2. The fuels recorded in wildfire data grouped into main fuel types.

Fuel type	Count
Other	749
Bog	6
Bracken	14
Brash	16
Bushes	508
Crop	9
Duff	3
Forest	292
Gorse	455
Grass	1812
Hedge	22
Moss	11
Peat	32
Straw	94
Woodland	71

For the purposes of analysis the fire records were restricted to those within the period between 1/01/2003 and 15/3/2007. This provides a minimum 30-day lead-in time for calculation of the Canadian fire weather indices for which Met Office data are available from 1/12/2002 – 15/3/2007. Where data were available the indices were calculated with a 100-day lead-in. This leaves 4509 fire records for analysis (Table 5.1). The data from the Lothian & Borders F&RS ran to August 2006 only, so the overall data set does not have equal coverage of all months.

The amount of information received about each fire varies considerably between the different datasets. The minimum information required for the record to be useful was date and location of the fire, but time of day was also available for most records except those from the Forestry Commission. Where time of day was recorded then those fires reported between midnight and 9.00 am were assigned to the previous day because it was assumed that fuel moisture would be more closely related to the previous day's fire weather indices. Hour of day could be included in more detailed analyses at a later date.

Information about the magnitude of the fire varied from estimates of the area burned to precise measures of the number of man-hours involved. The magnitude of each incident was scored by assigning a number from 0 – 5 for duration of the incident (between report time and all F&RS returning to base), the area burnt, the number of appliances in attendance, the number of 'resources' (assumed to be the number of F&RS people in attendance), 'Number in attendance' (it is not clear if this includes non-F&RS personnel) and number of man hours (Table 5.3). These different ways of scoring magnitude scores were well correlated except for duration of the incident, which is rather poorly correlated with the area burned or the number of appliances and resources deployed (Table 5.4). Because the different data sets presented very different types of information it was not possible to analyse these data directly so the maximum of the above values for any one fire was recorded as an overall measure of event magnitude. There were rather few fires with a maximum score of 4 so the final index referred to simple as 'magnitude') was created by merging classes 3 and 4. This formed an arbitrary 5-point scale where 0 indicates that the incident was small by all counts and 4 indicates that the incident was in about the top 10% with respect to one or more of duration, area burned or resources deployed.

Table 5.3. The magnitude of each incident was estimated from the measures listed in the table below where data were available.

Magnitude class:	**0**	**1**	**2**	**3**	**4**	**5**
Duration (hrs)	<0.25	<0.5	<1	<5	<10	10+
Area burned (ha)	<0.2	<0.5	<2	<20	<200	200+
No of appliances	0	1	2	3	4	5+
Number of resources	<5	5-7	8-9	10-11	12-15	16+
Manhours	<8	<12	<25	<50	<100	100+

Table 5.4. Pearson Correlation coefficient of the 'magnitude' scores for 4523 fires where data were available. Note that only two or three of the scores are available for most fires. * indicates inadequate data for the comparison to be made.

	Duration	Area	No appl	Resource	Tot at	Man hours
Area	0.051					
No appl	0.038	0.355				
Resource	0.044	0.420	0.879			
Tot in at	0.331	*	*	*		
Man hours	0.503	*	0.818	0.799	*	
Max Mag	0.619	0.439	0.583	0.707	0.601	0.712

Fires were roughly classified as urban or rural by drawing circles round the 100 largest towns and cities in Scotland and in Dorset; fires within the circle were classified as urban while for rural fires the distance to the nearest town (to the edge of the nearest enclosing circle) was estimated. A similar list of 18 towns was used to classify the Dorset Heaths fires. All fires from the Forestry Commission (New Forest) and Moors for the Future (Peak District National Park) were considered rural. While this classification is approximate, it gives a good indication of the main differences in characteristics between urban and rural fires. Some 75% of fire in H&I and D&G are classified as rural, though only 37% of those in L&B. However, 90% of the H&I FDR1 fires for which insurance claims were made are classified as rural.

Data received from Met Office

The following weather variables were received from the Met Office on a 5- or 15-km grid for NW Europe from the Faeroes to the Mediterranean. This represents some 140,000 maps in 68,900 individual data files (i.e. roughly 2 x 10^{10} data items). The sheer number of data files caused considerable number of handling problems in Windows and analysis proved very troublesome and time consuming. The variables received are listed in Table 5.5.

Table 5.5. Weather variables received from the Met Office.

	Res	Format	Units	kb	End date
Daily_meso					
3d cloud cover 0000-15km	15	i2	oktas*10	1158	17/1/07
(multi-layer data)					
3d wind 000_15km	15	i2	m/s*10	2316	17/1/07
(N & E vectors for 35 layers)					
Screen dewpoint 000_15km	15	i2	°C*100	294	17/1/07
Screen temp 0000_5km	5	i2	°C*100	294	17/1/07
MSLpressure 0000_15km	15	i2	mb*10	34	17/1/07
6hr_maxmintemp					
12hr max screen_5km (@ 2100 hrs)	5	i2	°C*100	294	15/3/07
12hr min screen_5km (@ 0900 hrs)	5	i2	°C*100	294	15/3/07
Both above for 900-, 1260-, 1620- and 1980-minute forecasts					
Daily_nim					
Cloud fc cloud base 0000_merged	15	i2	m	34	15/3/07
Cloud fc cloud cover 0000	15	i2	Oktas*10	34	15/3/07
Rain fc snow frac 0000	5	i2	%	294	15/3/07
Hourly_accum					
radar rain accum comp hour	5	i2	mm/32	294	15/3/07
Daily_soil					
Soil moisture	5	r4	kg/m^2	2347	15/3/07
(4 depths)					
Surf temperature rlumean	5	r4	K	587	15/3/07
Soil moisture def median	5	i2	mm/32	294	15/3/07
Sunshine*	5	i2	hr*100	294	Not readable
Evapouration	5	i2	mm/hr*695	294	5/8/03-15/3/07
Net radiation	5	i2	W m^2*10	294	7/8/03-15/3/07
Potential evapouration	5	i2	mm/hr*695	294	16/7/05-15/3/07
Soil evapouration	5	i2	mm/hr*695	294	16/7/05-15/3/07

(Res is resolution in km; i2 is two-byte integer; r4 is four-byte real; * the sunshine data were not readable and have not been used)

Data structure

Data were received in Nimrod format. This is a poorly documented format with a header section containing the data definition followed by a data grid. Data represent the predicted weather variable at the centre of a 5-km or 15-km grid-square on the Ordnance Survey National Grid.

Software was developed in Delphi (Pascal for Windows) to read these datafiles and to mask out all except the British Isles. The mask for identifying the British Isles was based on the Met Office soil moisture map which is clipped to land area, though the mask is quite tight and many coastal squares with a high proportion of land are not included in the data set.

Several data sets were received for multiple layers through the soil (e.g. soil temperature) or atmosphere (wind, cloud cover). Only the surface layers were used for wind (i.e. 10 m) and soil characteristics; the individual cloud layers were abandoned in preference to the combined cloud cover. The sunshine data proved unreadable and were not used.

Data with 15-km resolution were stored as 5-km resolution by linear interpolation between neighbouring data points.

The remaining data were then stored as Delphi records in data files with one file per weather variable and one record in that file per day. These files, each ca 74 Mb, are easily accessible for Delphi programs and can be used to extract data for all squares for any day with relative ease and speed.

Data quality

Several of the weather variables contain either small numbers of missing data for individual squares (or for large blocks of squares in the cloudbase data, Figure 5.1). These missing values were substituted by interpolation between data for the nearest non-missing square to the east and that to the west. Where there were no good data to one side (e.g. if missing values were on the coast with missing data in the sea) then all missing values were replaced with the nearest good value to east or west. If the band of missing data spanned from coast to coast (east to west) then no substitution was made.

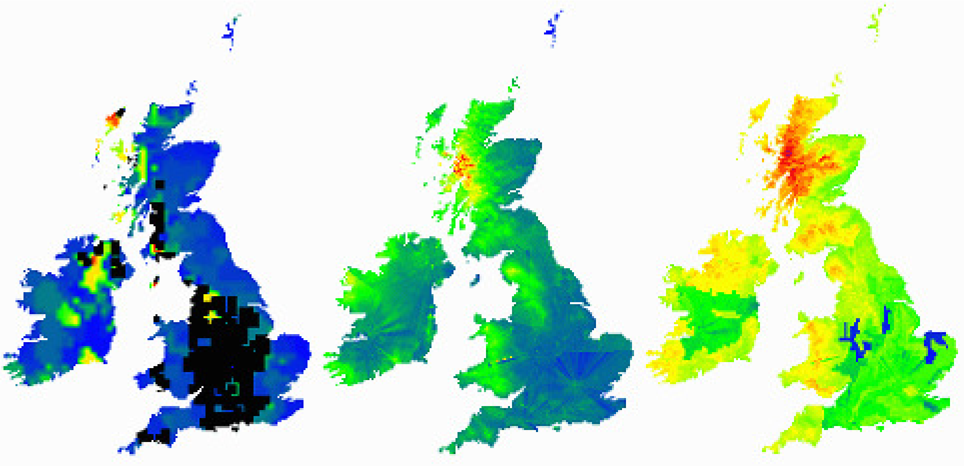

Cloudbase for 5/12/2002 **Average accumulated rainfall** **Average soil moisture deficit**

Figure 5.1. Examples of weather variables mapped for the British Isles showing missing data (Cloudbase), radar shadows (Average of accumulated rainfall) and other inexplicable patterns (Average soil moisture deficit).

There are many whole datafiles missing (ca 5% of the total apparently at random) representing whole days (or hours for rainfall data). When calculating accumulated rain and time since rain, missing values were considered to be ‘no rain’; this is conservative in that it will result in a slightly higher fire danger rating than any other procedure. In all other cases the missing data were interpolated linearly through time between the previous and the next good value for that square. Where the first or last datafile(s) are missing then the missing values are replaced by the nearest good value.

Rainfall data for Shetland were all received as zeros, apparently because the Met Office radar detection system does not cover the Shetlands. These data should have been converted to missing values, though this has not been done yet. This needs to be kept in mind if there are any fire records for Shetland.

Several of the weather variables show distinct spatial patterns that are clearly artefacts of the measurement or modelling system. For example, the radar rainfall data show radiating shadows of low rain and sharp boundaries between the rainfall estimates from neighbouring radar stations (Figure 5.1). Other areas show 'hotspots' of a few squares that are consistently higher rainfall than neighbouring squares which appear to be artefacts. The soil moisture and soil moisture deficit data also show distinct patterns with blocks of squares (e.g. in East Anglia or the Irish Midlands) with consistently about half the value of neighbouring areas. No attempt has been made to remove these patterns. Ideally some degree of smoothing or 'despeckling' would be appropriate.

Soil moisture deficit is also unstable through time with, for example, data for 5/5/2004 – 11/5/2004 an order of magnitude higher than before or immediately after (Figure 5.2). This means that the soil moisture and soil moisture deficit data are unlikely to prove useful for fire danger mapping. The 'hotspots' in the rainfall data are of more concern as this is likely to be a key variable in fire forecasting.

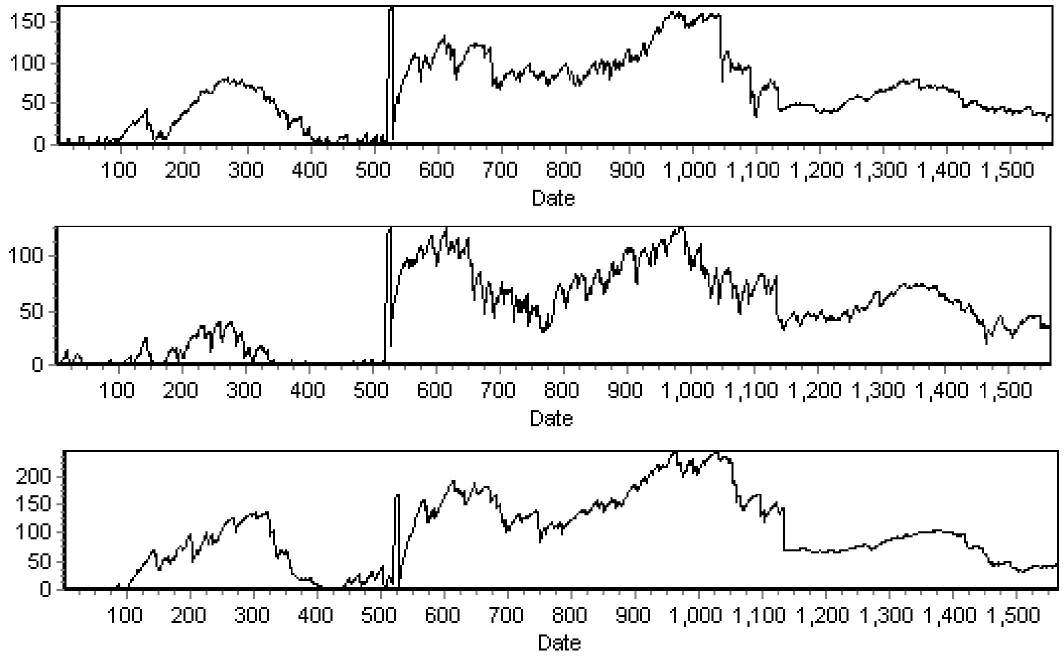


Figure 5.2. Graphs of soil moisture deficit against time for three locations in the East Highlands, the Isle of Skye and Dorset. Date is days from 01/12/2002.

The wind data were sent by the Met Office as vectors (assumed to be estimated noon wind speed). This was replaced by the mean wind vector.

Data from the Met Office were received as mean predicted values for 5 km x 5 km grid squares. The consequence of averaging over 25 km^2 is to reduce the variance of most variables relative to measurements at point locations from individual met stations but the mean remains unbiased. However, the effect of spatial averaging biases wind speed downwards and the frequency of rain will be overestimated. Ideally, the grid-based met data should have been calibrated against observational data to correct for these biases before calculation of the Canadian fire weather indices. In this case, however, the raw data were used as received from the Met Office which means that there will be some bias in the calculations, for example tending to underestimate ISI values.

Calculation of Fire Weather Indices

The six standard components of the Canadian Forest Fire Weather Index System (CFFWIS) were calculated using the equations given in Van Wagner & Picket (1985) with minor adjustments to match the rounding errors that are created by the Fortran 77 computer program given by Van Wager. The six indices are Fine Fuel Moisture Code (FFMC), Duff Moisture Come (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BUI) and Fire Weather Index (FWI). The Daily Severity Rating ($DSR = 0.0181.FWI^{1.77}$) and Fine Fuel Moisture Content after drying (*am*) as defined by Van Wagner & Picket (1985) were also calculated. The Met Office data used in the calculations may not exactly match the requirements of the CFFWIS (e.g. the maximum daily temperature was used in place of the noon temperature and the mean value for a grid square may not match point observations as discussed above), but the properties of the indices generated will closely match those of the CFFWIS.

The indices were calculated individually for the 5-km grid square for each fire record for that particular day. Because of the time lag built into the CFFWIS the calculations were based, where possible, on a 100-day lead-in before the time of the fire using the standard starting values given by Van Wagner & Picket (1985). The Met Office data were available from 01/12/2002 so the minimum lead-in time for fires in January 2003 was 31 days; for winter conditions it was assumed that the calculations would equilibrate relatively rapidly from the default starting values for these fires. The values calculated were the daily values – no attempt was made to calculate the round-the-clock hourly values (Van Wagner 1977) though this could be done at a later date.

The distribution of wild fires is non random in both time and space. In order to provide a set of 'typical' weather indices for non-fire days the CFFWIS indices were therefore calculated for a further set of 'control days' which had the same spatial and seasonal distribution as the wild fires. Thus for each fire, the CFFWIS indices were calculated for a control day in the same grid square on the same day of the previous year. For fires in 2003 the calculations were for the same day in 2006. This provides a base line of typical values for each index against which the characteristics of fire days can be compared.

Results

Management fires are legally confined between October and mid-April (see Basic and Experimental records in Table 5.6). The wildfire season extends from March to September often with a spring peak in April or May and a late summer peak in July or August (Table 5.6, Figure 5.2). 2003 was a particularly bad fire year with many wildfires in March and April as well as through the summer.

The majority of fires are reported during the afternoon but there is a secondary peak in the early evening (Figure 5.3a) and small numbers continue through the night. There is a slight increase in the number of reported fires at the weekend (Figure 5.3b). It is unlikely that the weather conditions are any more conducive to fires in the evening than the afternoon, or at weekends than weekdays, so it can be assumed that these peaks represent the human element either in fire occurrence or in fire reporting.

Roughly one third of all wildfires were classified as urban. The proportion of urban fires fluctuates somewhat from month to month being highest in January and lowest in September (Table 5.7), though it also varies from region to region with a much higher proportion of urban fires in the Lothians & Borders region (Table 5.7).

Table 5.6. Number of management and wildfires recorded in each data set by year and by month. All data excluding fuel type 'Other' and unspecified. The dash indicates data not received; a blank indicates no recorded fires.

Dataset	Year	Tot.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Basic	2001	9		6	1	2								
Basic	2002	14			14									
Basic	2003	12		4	8									
Basic	2004	10		4	6									
Basic	2005	12		1	11									
Basic	2006	36	1	5	9	10						10		1
Basic	2007	41			38	3	-	-	-	-	-	-	-	-
Exp	2003	3	-	-	-	-	-	-	-	-	-	3		
Exp	2004	12			6	6								
Exp	2006	9				6						3		
Exp	2007	15	0	2	8	5	-	-	-	-	-	-	-	-
D&G	2003	186	2	6	45	59	5	6	11	19	13	13	4	3
D&G	2004	62	1	10	6	6	16	12	5	3	2		1	
D&G	2005	107		2	8	14	11	6	24	13	23	3	3	
D&G	2006	93	1	6	13	19	8	14	16	3	2	4	4	3
D&G	2007	15	1	1	5	8	-	-	-	-	-	-	-	-
DH	2004	37			1	4	3	15	8	6				
DH	2005	11					1	1	1	2	1		3	2
DH	2006	14	2	1	1			1	1	8				
GR	2002	2	-	-	-	-	-	-	-	-	-	-	-	2
GR	2003	428		9	34	45	1	19	56	126	93	30	12	3
GR	2004	80	1	1	2	9	34	8	7	5	9		3	1
GR	2005	136		2	3	18	3	9	18	36	24	16	6	1
GR	2006	192	4	1	3	40	23	18	46	16	24	3	11	3
GR	2007	2	2			-	-	-	-	-	-	-	-	-
H&I FDR1	2002	1	-	-	-	-	-	-	-	-	-	-	-	1
H&I FDR1	2003	30		8	6	11			2	2	1			
H&I FDR1	2004	6				1	2	1		2				
H&I FDR1	2005	10				6	2	1	1					
H&I FDR1	2006	12			2		5		5					
H&I FDR3	2002	7	-	-	-	-	-	-	-	-	-	-	-	7
H&I FDR3	2003	742	3	116	134	204	16	42	47	78	45	25	28	4
H&I FDR3	2004	236	2	12	82	48	47	11	12	11	6	1	2	2
H&I FDR3	2005	282	4	14	30	101	42	15	34	16	10	7	3	6
H&I FDR3	2006	325	7	7	22	53	81	38	70	15	16	3	11	2
H&I FDR3	2007	3	1	2	-	-	-	-	-	-	-	-	-	-
L&B	2002	5	-	-	-	-	-	-	-	-	-	-	-	5
L&B	2003	233	1	4	32	38	13	12	16	36	36	22	18	5
L&B	2004	148	2	19	9	24	34	12	16	8	12	2	6	4
L&B	2005	128	2	7	3	18	15	8	21	18	17	12	2	5
L&B	2006	183	6	11	6	44	21	45	47	3	-	-	-	-

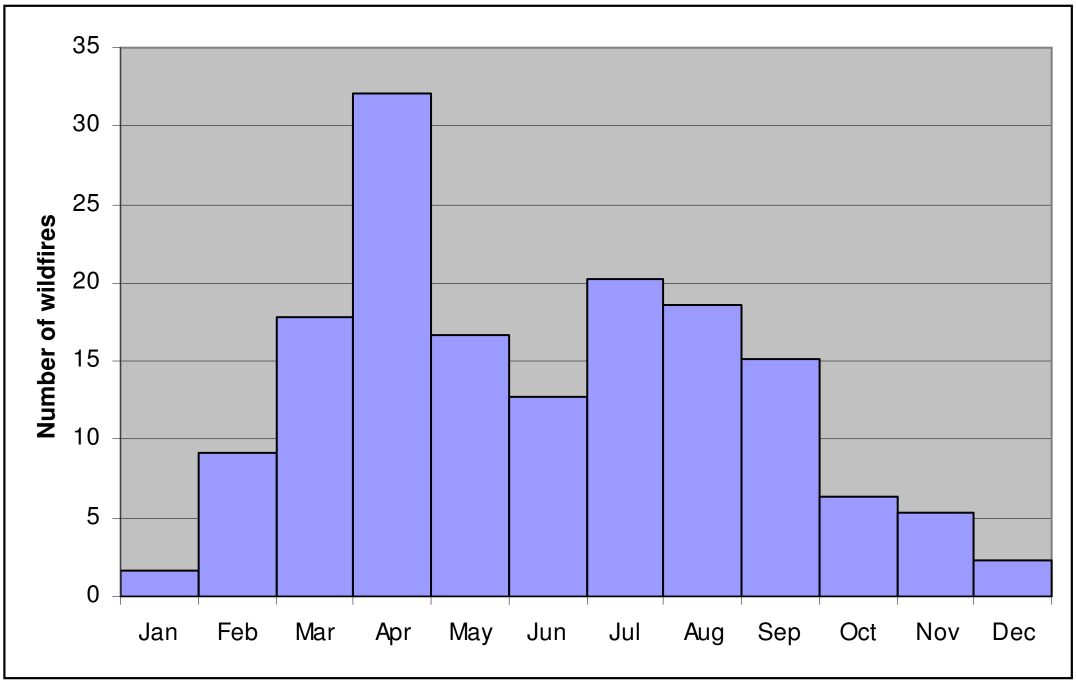


Figure 5.2. Seasonal variation in the mean number of wildfires reported by the Fire & Rescue Services and Dorset Heaths in any one month (all wildfires excluding fuel type 'Other').

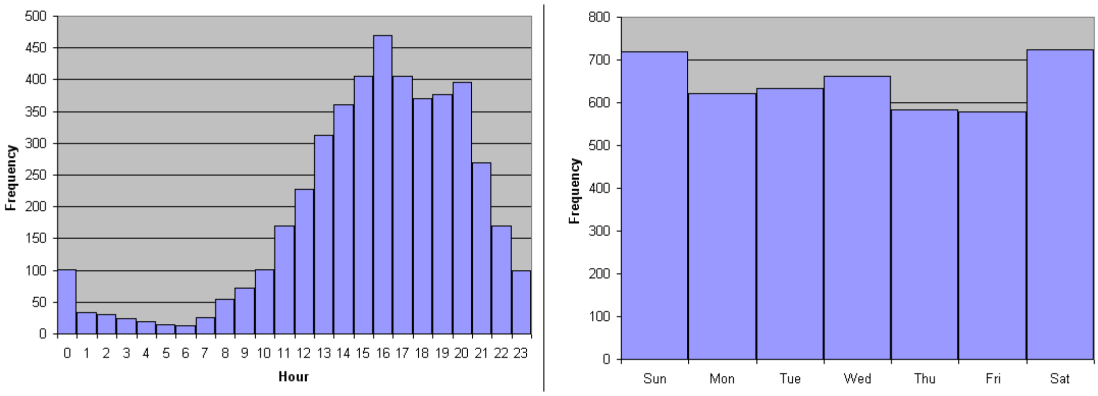


Figure 5.3. Wildfire frequency distribution with respect to (a) hour of the day and (b) day of the week.

Table 5.7. The number of wildfires (2003-2007) classified as urban and rural in each month (all wildfires excluding fuel type 'Other').

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Urban	44	148	266	524	260	250	294	344	188	102	84	46
Rural	40	330	628	1016	506	338	634	508	480	180	150	72

A comparison was made between the days on which fire was reported and their associated control days to test the power of the fire weather indices to discriminate those days on which fire was likely (Table 5.8). The mean difference between the weather index for fire and control days should be an unbiased estimate of the 'discriminating power' of that weather index that is independent of the sample size. The mean difference ('F-C' in table 5.8) can therefore be used to compare the discriminating power of an index between different vegetation types. It cannot, however, be used directly to compare the power of different indices because of the different scales of the indices. For this purpose therefore the mean difference was standardised by the standard error of the difference ('t-statistic' in Table 5.8). The t-statistic, which is dependent on sample size but independent of the scale of the index, permits comparison of the discriminating power of different indices within any one vegetation type. It is clear that FFMC, ISI, FWI and *am* are roughly equally good discriminators. DC is the least useful index and has no significant value for predicting days when bushes/gorse fire may occur.

Table 5.8. The mean value of each of the fire weather indices for control and fire days, the difference between them and the *t*-statistic for the paired comparison. Note that because of different sample sizes between fuel types the *t*-statistic can be used to compare the discriminating power of different indices within rows, but not between fuel types. Similarly, because of different scales for the weather indices, the difference between mean index value for fire and control days can be used to measure the discriminating power of an index between vegetation types, but not between indices. The *t*-statistic was calculated on transformed variables; FFMC was negatively skewed and therefore squared when computing the *t*-value; other indices were log(x+1)-transformed though some remain rather far from normal; statistical significance should be treated with caution.

Fuel type		N	FFMC	DMC	DC	ISI	BUI	FWI	DSR	am
Grass	**Control**	1055	63.6	13.1	293.5	0.8	22.5	1.6	0.1	49.1
	Fire		77.2	24.9	311.4	1.7	39.0	4.2	0.6	27.2
	F-C		13.6	11.8	17.9	0.8	16.5	2.6	0.4	-21.9
	t		24.1	25.0	9.0	25.1	23.8	26.0	19.5	24.4
Heath	**Control**	253	55.5	5.1	104.0	0.6	8.4	0.6	0.0	64.6
	Fire		70.8	8.8	115.3	1.2	13.1	1.6	0.1	37.9
	F-C		15.3	3.7	11.3	0.7	4.7	1.0	0.1	-26.7
	t		9.6	7.9	7.4	9.5	7.1	9.6	6.5	9.8
Bushes/ Gorse	**Control**	282	65.0	13.2	282.1	0.8	22.6	1.6	0.1	45.9
	Fire		75.7	19.5	289.7	1.5	31.9	3.3	0.4	29.1
	F-C		10.6	6.2	7.5	0.6	9.3	1.7	0.2	-16.8
	t		10.4	8.7	1.4	10.8	8.4	10.4	7.6	10.6
Forest/ Woodland	**Control**	208	64.1	14.8	303.4	0.9	25.3	1.7	0.2	48.4
	Fire		76.6	21.5	316.0	1.6	34.8	3.8	0.5	28.1
	F-C		12.5	6.7	12.7	0.8	9.4	2.0	0.3	-20.3
	t		9.2	9.0	3.6	9.8	8.8	9.6	7.2	9.4

The discriminating power of FFMC is displayed in Figures 5.4 and 5.5 showing that fires are much more likely to be reported when the FFMC exceeds 70 and the majority of severe fires with magnitude 3 and 4 are where the FFMC exceeds 80.

The mean FFMC for management ('Basic') and experimental fires in March and April is somewhat lower than that of wildfires attended by the F&RS suggesting that managers are avoiding days of high fire risk at this time. Similarly, wildfires in winter are, on average, at lower FFMC than summer fires. This does not imply that fires will not occur at low FFMC during the summer but rather that there are fewer opportunities for fire at high FFMC in winter.

It is disappointing that the other indices failed to identify days on which fires of higher magnitude occurred. For example, FWI forms the basis for the calculations of the Met Office Fire Severity Index (MOFSI) which might therefore be expected to relate to fire intensity. However the relationship between FWI and the index of fire magnitude calculated here was very poor (Fig 5.6).

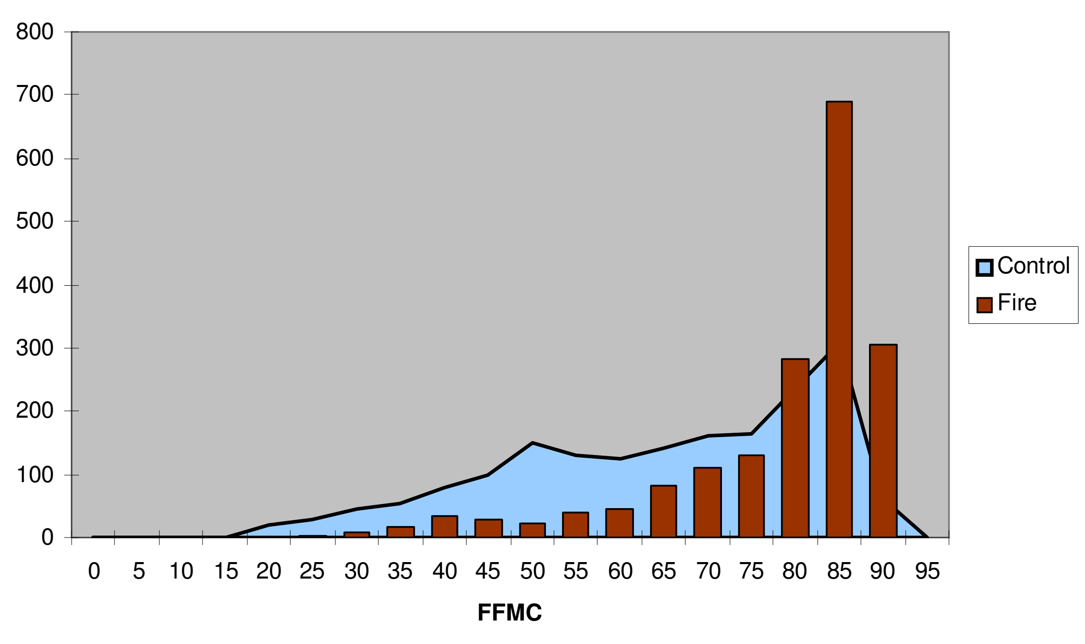


Figure 5.4. Frequency distributions of FFMC for control days (blue area) and reported wildfires with magnitude 2-4 but excluding fuel type 'Other'. Fires are much more frequent when the FFMC exceeds 70.

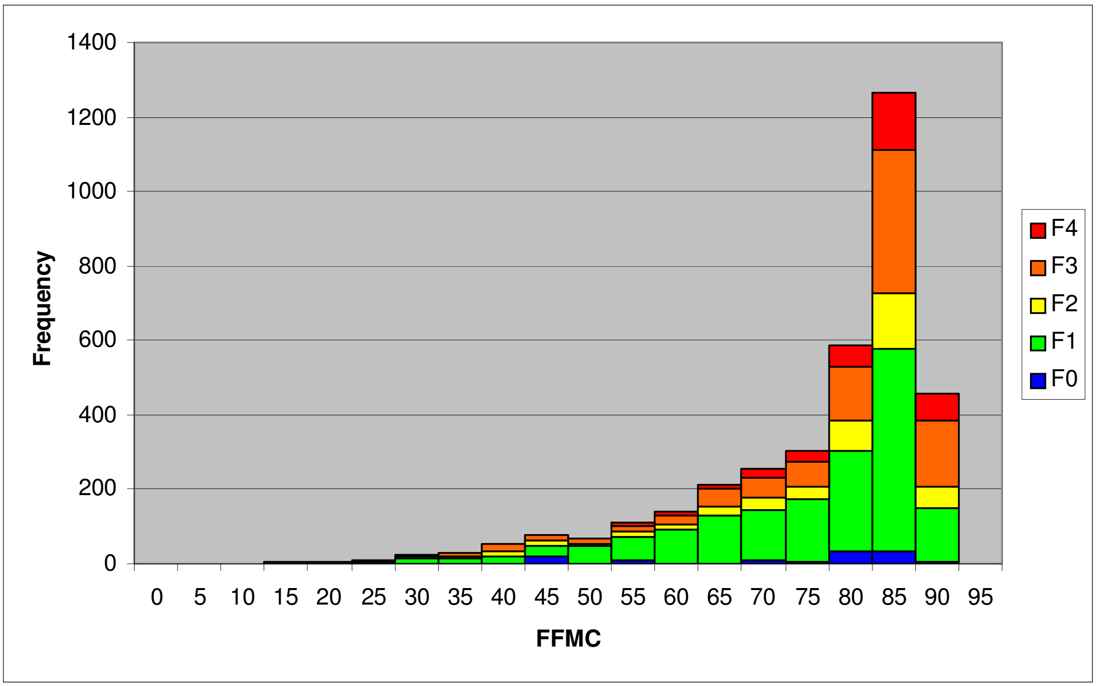


Figure 5.5. Frequency distributions of wildfires distinguishing the fires of different magnitude (F0 – F4) with respect to FFMC. The majority of fires of high magnitude occur when the FFMC is above 80.

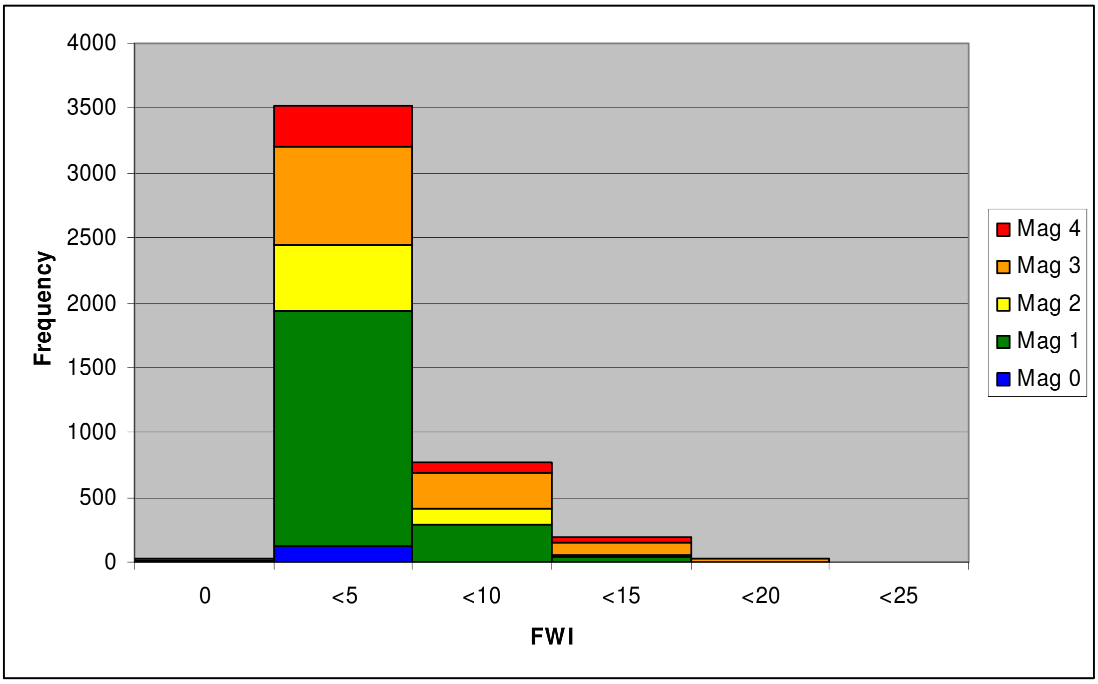


Figure 5.6. Frequency distributions of wildfires distinguishing the fires of different magnitude (Mag 0 – Mag 4) with respect to FWI.

This means that although fires on average occur on days when the MOFSI is higher than the average control days (Table 5.9), fires of high magnitude still occur when the FWI, and hence MOFSI are low (Figure 5.7).

Table 5.9. Cross-tabulation of the MOFSI index for days on which fires were recorded and control days.

		MOFSI of fire days					
		1	**2**	**3**	**4**	**5**	**Total**
MOFSI of control days	**1**	1987	900	557	44	0	3488
	2	235	194	217	40	0	686
	3	94	86	117	34	0	331
	4	1	3	12	1	0	17
	5	0	0	0	0	0	0
	Total	2317	1183	903	119	0	

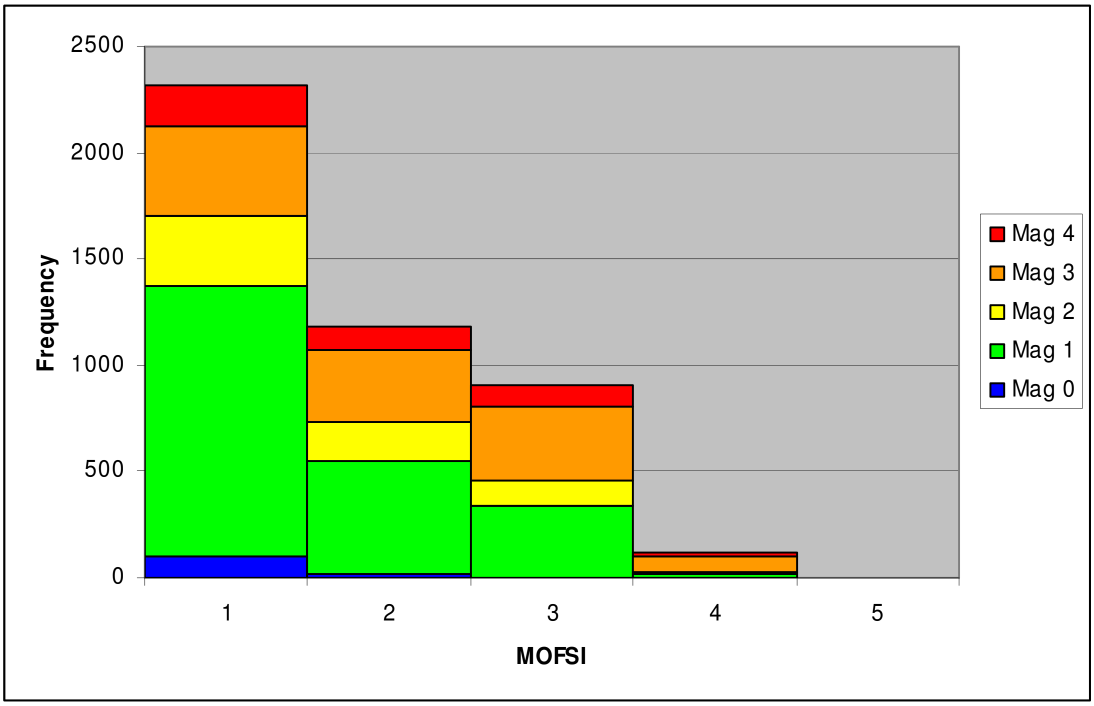


Figure 5.7. Distribution of fires of different magnitude (Mag 0 – Mag 4) with respect to the Met Office Fire Severity Index.

Correlation structure within the Canadian Fire Weather Indices

The Canadian fire weather indices were calculated for all of the 'Heath' fires stored within the database and for 'Control days' as described above. Fires with a Magnitude 0 or 1 were eliminated as insignificant leaving 206 fire records. The indices were then transformed to give a closer approximation to normality using log(x+1) except for FFMC which, being negatively skewed, was squared. The correlation structure of the fire weather indices for the control days was examined with PCA and Factor analysis. The first principal component accounted for 73.4% of the variation with the first three components representing 96.6% of the variation. This and a scree plot suggested that most of the variation could be represented in three dimensions; these were then rotated using Varimax (Table 5.8).

These analyses show the close association between FFMC, fuel moisture (*am*) and ISI on the first factor, DC, DMC and BUI on the second and DSR on the third. This suggests that there would be little information to be gained from more than three indices.

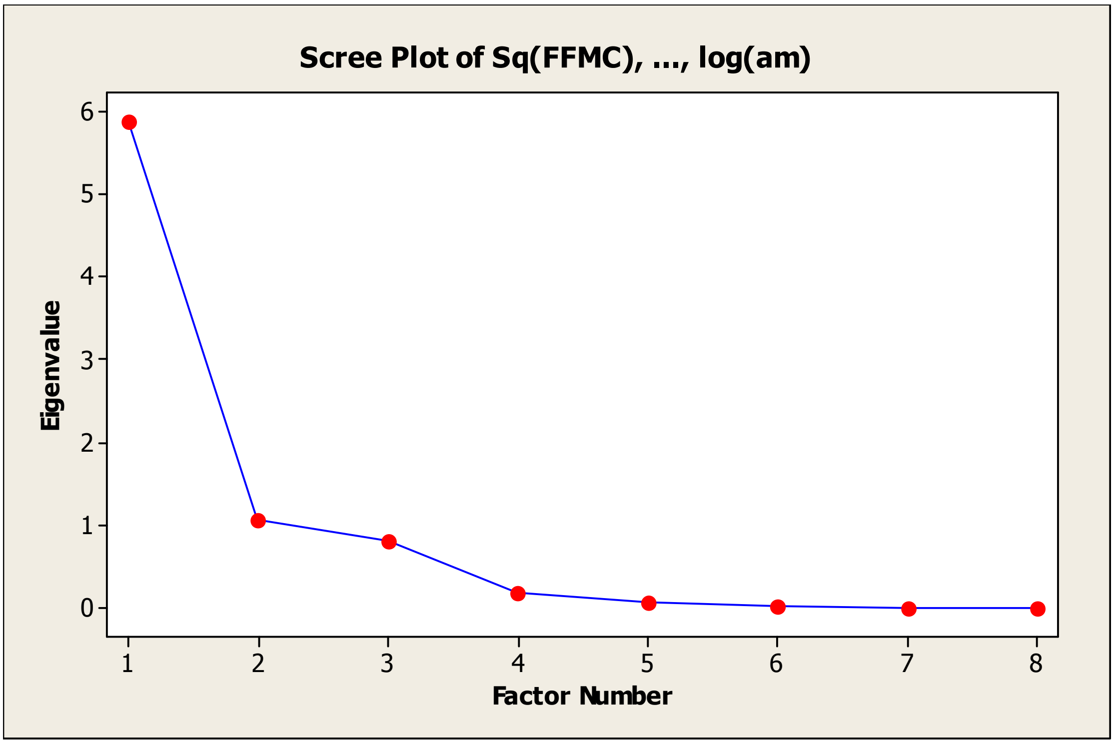


Figure 5.8. Scree plot of the principal components of the Fire Weather Indices for heath fires. The eigen values are as follows:

```
Eigenvalue   5.8685   1.0578   0.8014   0.1895   0.0546   0.0246   0.0023   0.0012
Proportion    0.734    0.132    0.100    0.024    0.007    0.003    0.000    0.000
Cumulative    0.734    0.866    0.966    0.990    0.996    1.000    1.000    1.000
```

Table 5.10. Factor Analysis of the transformed Canadian Fire Weather Indices: Sq(FFMC), log(DMC), log(DC), log(ISI), log(BUI), log(FWI), log(DSR) and log(am) with Varimax rotation of the first three principal components of the correlation matrix.

```
Variance of the unrotated axes:
       Variance    5.8685   1.0578   0.8014       7.7277
       % Var        0.734    0.132    0.100        0.966


Rotated Factor Loadings and Communalities
       Variable   Factor1  Factor2  Factor3  Communality
       Sq(FFMC)     0.935    0.294   -0.181        0.994
       log(DMC)     0.448    0.808   -0.303        0.945
       log(DC)      0.149    0.929   -0.136        0.903
       log(ISI)     0.892    0.256   -0.345        0.980
       log(BUI)     0.408    0.855   -0.274        0.972
       log(FWI)     0.519    0.465   -0.690        0.961
       log(DSR)     0.207    0.198   -0.949        0.982
       log(am)     -0.928   -0.305    0.191        0.990

       Variance    3.2321   2.7467   1.7489       7.7277
       % Var        0.404    0.343    0.219        0.966


Factor Score Coefficients
       Variable   Factor1  Factor2  Factor3
       Sq(FFMC)     0.439   -0.112    0.183
       log(DMC)    -0.046    0.351    0.052
       log(DC)     -0.214    0.568    0.169
       log(ISI)     0.373   -0.173   -0.012
       log(BUI)    -0.075    0.403    0.082
       log(FWI)    -0.024   -0.019   -0.429
       log(DSR)    -0.221   -0.190   -0.872
       log(am)     -0.428    0.105   -0.173
```

Table 5.11. Discriminant Analysis using linear response function to contrast the fire and control days using the fire weather indices: Sq(FFMC), log(DMC), log(DC), log(ISI), log(BUI), log(FWI), log(DSR), log(*am*).

```
Group classification:
                        True Group
Put into Group Control   Fire
C                  147     33
F                   59    173
Total N            206    206
N correct          147    173
Proportion       0.714  0.840


Squared Distance Between Groups
   Control     Fire
C  0.00000  2.87058
F  2.87058  0.00000

Linear Discriminant Function for Groups
          Control   Fire
Constant   -14644  -14641
Sq(FFMC)        2       2
log(DMC)      198     199
log(DC)        42      42
log(ISI)      624     627
log(BUI)     -166    -167
log(FWI)     -251    -252
log(DSR)      733     731
log(am)      5840    5838

Group means
                            Means for Group
Variable  Pooled Mean  Control     Fire
Sq(FFMC)       4747.1   3378.5   6115.8
log(DMC)       1.7063   1.3023   2.1103
log(DC)        3.7163   3.4603   3.9724
log(ISI)      0.61732  0.36062  0.87402
log(BUI)       2.0018   1.6005   2.4030
log(FWI)      0.57714  0.30649  0.84780
log(DSR)      0.08236  0.03586  0.12887
log(am)        3.5830   3.9992   3.1668

Group standard deviations
                       StDev for
          Pooled         Group
Variable   StDev Control    Fire
Sq(FFMC)    1665    2015    1218
log(DMC)  0.9189  1.0006  0.8292
log(DC)    1.513   1.678   1.329
log(ISI)  0.3237  0.3399  0.3066
log(BUI)   1.027   1.133   0.910
log(FWI)  0.5640  0.4792  0.6376
log(DSR)  0.1866  0.1422  0.2222
log(am)   0.5076  0.6077  0.3820
```

Discriminant function analysis was used to test the power of these indices to discriminate between days on which fire occurred and control days (with the same spatial and seasonal distribution, but in a different year) (Table 5.11). This analysis used the same transformed fire weather indices described above for the 206 heath fires with magnitude 2-4 and their control days. Sq(FFMC), log(DMC), log(BUI) and log(am) were highly correlated with other predictors, confirming the conclusion above. The discriminant function analysis correctly classifies 84% of fire days and 71% of control days. This seems a remarkably high proportion given that the control days have the same spatial and seasonal distribution as fire records.

Discussion

Fires reported to the Fire & Rescue Services are only a subset of the total number of fires that occur. The majority of fires in Scotland are controlled management fires and there are no national or regional records available that can give a good indication of the temporal or spatial distribution of these fires, although some estates may keep records of the numbers of fires burned on any one day that could be used in this sort of analysis in the future. It is possible that remote sensing may reveal the distribution of management fires in the near future, but present systems (e.g. MODIS) seem to miss a high proportion of small fires. Information about the timing of management fires and the association with weather variables must therefore remain based on a relatively small number of experimental fires as described in the earlier sections of this report.

It is also possible that a proportion of wildfires that occur on private estates are controlled and extinguished by the estate staff without reference to the Fire & Rescue Services. These fires (including many escaped management fires) are not recorded in any way. The records analysed here are reported fires only.

The quality of data recorded is also very variable and it is unfortunate that the Fire & Rescue Services do not have a standard method for recording the vegetation type and fire intensity or fire effects. The standardisation of fire records has been discussed by the Scottish Wildfire Forum but no action has yet been taken so far as we are aware and this should be a priority.

However, despite the lack of detail, the quantity of data should enable trends to be detected even though the data will be inevitably noisy.

Variation in the frequency of reported fires reflects both the weather component of fire danger and also the human aspects. The human component is revealed in the higher frequency of reported fires at weekends than during weekdays and the peak in fires in the early evening. There may also be a seasonal component that is associated with escaped fires and management burning during the legal burning season, though it is more difficult to identify from these data. It would be interesting to relate the seasonal distribution of fires to land use, or to see if the frequency of heath/moorland fires decreases at weekends during the main muirburn season. There has been no attempt to do this so far, though this factor is likely to be relatively minor relative to the effects of seasonal variation in fuel quality

The main trends to emerge from the data are the two peaks in frequency of reported fires, the main peak in April and a second in July/August. The fire frequency is therefore determined primarily by the seasonal variation in characteristics of the vegetation, rather than simply by weather.

The analyses of the wildfire records presented here have demonstrated that the FFMC is potentially valuable in identifying days where there is a higher than average probability of wildfire. FFMC relates to the ease of ignition of fine fuels in the initial phase of a fire and may also be expected to relate to the rate of spread. During periods of high FFMC wildfires might therefore be expected to spread more rapidly and take longer for the Fire and Rescue Services to control. No evidence has so far been found to relate the other fuel moisture indices (DMC, DC) to fire severity which might be expected to relate to the index of incident magnitude used here. It is possible that the fire conditions in the UK are such that the major incidents in terms of area burnt, duration and manpower required to control the fire are more closely related to rate of spread and fine fuel moisture than to the quantity of available fuel as indicated by the Buildup Index. The experimental fires reported earlier suggest that the quantity of fuel consumed is relatively constant in most fires;

this might contrast with forest fires where surface fires and crown fires differ in quantity of fuel consumed by orders of magnitude.

The experimental data reported in the next section of this report conclude that the Canadian fire weather indices do not successfully predict fuel moisture in *Calluna*. How is it, then, that FFMC does appear to be reasonably successful in discriminating between days when fires are likely to be reported to the Fire & Rescue Services? FFMC did correlate reasonably well with moisture content of the moss and litter layer. During summer and autumn the FMC of *Calluna* is relatively constant with the fuel dominated by healthy living green shoots. Summer fires are probably therefore dependent on a dry moss and litter layer for ignition. Indeed during autumn fires the flames can often be seen burning though the moss and litter ahead of the canopy fire such that the heat from moss and litter dries and pre-heats the live fuel before it will ignite. Dry moss and litter are probably also essential for ignition to occur accidentally or from a point source. Further analyses are necessary to determine whether FFMC fails to reflect the occurrence or magnitude of wildfires in spring when the live component varies widely in moisture content and has a much greater influence on fire behaviour. In gorse fires the initial ignition probably depends on the litter layer and is also well predicted by FFMC. In the case of grass fires, the dominant fuel is aerial foliage that will dry very rapidly – probably more rapidly than the FFMC predicts. A revised fuel moisture index may be appropriate for moorland *Molina* fires.

This complex dataset can be classified according to: fuel type, rural or urban, season and geographical region. It is likely that all of these factors will interact with the weather variables in determining fire occurrence and behaviour. The current research has only scratched the surface and further analyses are required. The first priority will be a more detailed analysis of the relationships between fire magnitude and the fire weather indices in the different fuel types and seasons. Our current understanding of the variation in live fuel moisture of *Calluna* and of leaf dynamics in *Molinia caerulea* suggest that spring fires in heathland should behave quite differently to summer and autumn fires, while the occurrence of fires in *Molinia* grassland will change quite abruptly as leaves die in autumn and green-up in spring. It is probable that leaf death in *Molinia* is determined by day length, rather than by drought. This means that grass-fire models developed in Mediterranean or semi-arid environments may work well for crop fires, but will need to be modified before application in the grass moorlands of north and western UK.

A considerable amount of extra information could be obtained by developing a GIS to overlay fire records and maps such as the Land cover classification and incorporating altitude and topography into the analyses. This should be a priority in future phases of the FireBeaters project.

Section 6

Explaining variation in heather moisture content

Introduction

Because of difficulties in establishing the research contract with the Scottish Executive the start of this project was delayed so that no work was possible during the summer months. We have not therefore been able to analyse data collected on fuel moisture variation through the summer. Work on modelling fuel moisture is on-going and a provisional model will be developed during Phase II. The following section is a very brief summary of the data that are available from the experimental fires and other sources and exploratory analyses that have been completed so far.

Aims and objectives

- Understand seasonal variation in the moisture content of live and dead *Calluna vulgaris* and pleurocarpous mosses
- Examine the relationship between the relevant fuel moisture indices of the CWFIS and *Calluna* fuel moisture
- Assess the potential for creating fuel moisture models for live and dead *Calluna*

Methods

The methods for estimating fuel moisture are as described in Section 2. Data have been collated from the experimental fires, ignition tests and data reported by O'Hara (2006). FMC records were combined by calculating the mean for each fuel type on any one day. The daily mean FMCs were then compared with the NWP data received from the Met Office and calculated fire weather indices for that location and date as described in the previous section.

Results

A correlation matrix between fuel moisture and weather indices revealed good correlations between moss/litter FMC and several weather variables (Table 6.1). While this may seem encouraging, this probably largely reflects the contrast between the small number of samples that were taken during the summer when the moss and litter were relatively dry and the high temperatures with associated low soil moistures (Figure 6.1d). The majority of samples were taken in autumn and spring when the moss and litter was damp and the temperatures low. Dead fuel suspended in the canopy shows very little correlation with either the weather on the day the sample was taken, or on the Canadian fire weather indices, though the sample size is small. Perversely, the live fuel moisture content is negatively correlated with the Met Office NWP prediction of fractional soil moisture and positively correlated with temperature.

These patterns are clearer when samples taken in spring, summer and autumn are considered separately (Figure 6.1 and 6.2). Live FMC is seen to decrease slightly with increasing FFMC in the spring, though the overall pattern is dominated by the high FMC of the summer samples.

Table 6.1: Selected results of a correlation analysis between the moisture content of individual fuel components, NWP weather data and relevant Canadian FWI indices. PET = potential evapotranspiration.

Fuel component	PET	Soil evaporation	Fractional soil moisture	Surface temperature	Dewpoint temperature	Mean temperature	Max temperature	Minimum temperature	am	FFMC	DMC	DC
Live	**0.56**	0.31	**-0.62**	0.37	0.43	0.42	0.40	**0.49**	-0.02	0.06	0.46	**0.58**
Moss	**-0.84**	**-0.72**	**0.62**	**-0.76**	**-0.64**	**-0.72**	**-0.74**	**-0.64**	**0.57**	**-0.60**	**-0.69**	-0.34
Dead	-0.25	-0.16	-0.13	-0.04	0.16	0.04	0.04	0.14	0.17	-0.21	-0.01	0.10
Dead (ground)			0.20	-0.44	-0.30	-0.38	-0.38	-0.29	0.07	-0.06	-0.10	-0.13

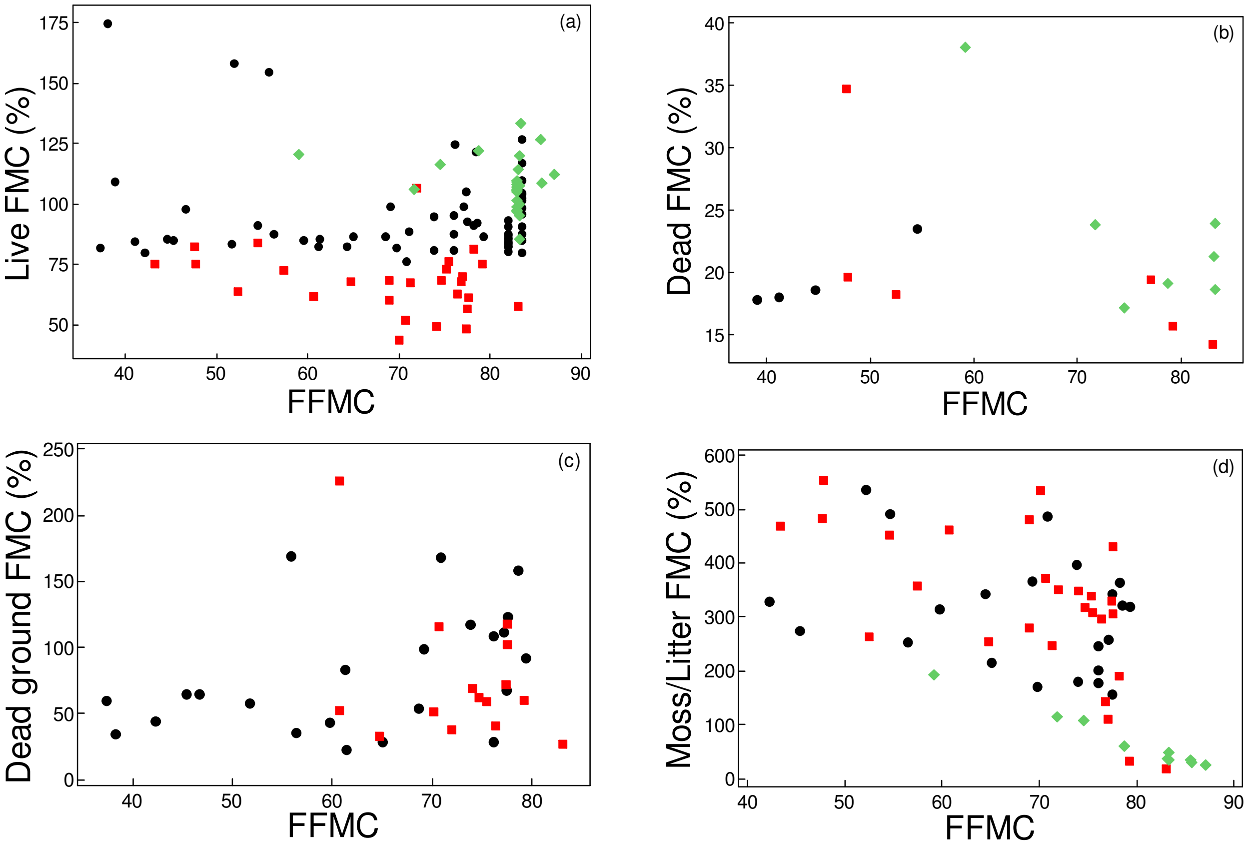


Figure 6.1: The performance of the Fine Fuel Moisture Code in relation to the fuel moisture of (a) live and (b) dead *Calluna*, (c) dead material lying in contact with the ground and (d) the top 2 cm of the moss/litter layer. Spring, summer and autumn are shown as red squares, green diamonds and black circles respectively.

The positive correlation between live FMC and temperature (Figure 6.2) appears to hold within the set of spring samples as well as between seasons. This supports the explanation presented earlier that cold or frozen soils inhibit the ability of the *Calluna* plants to take up water from the soil resulting in exceptionally low fuel moisture contents.

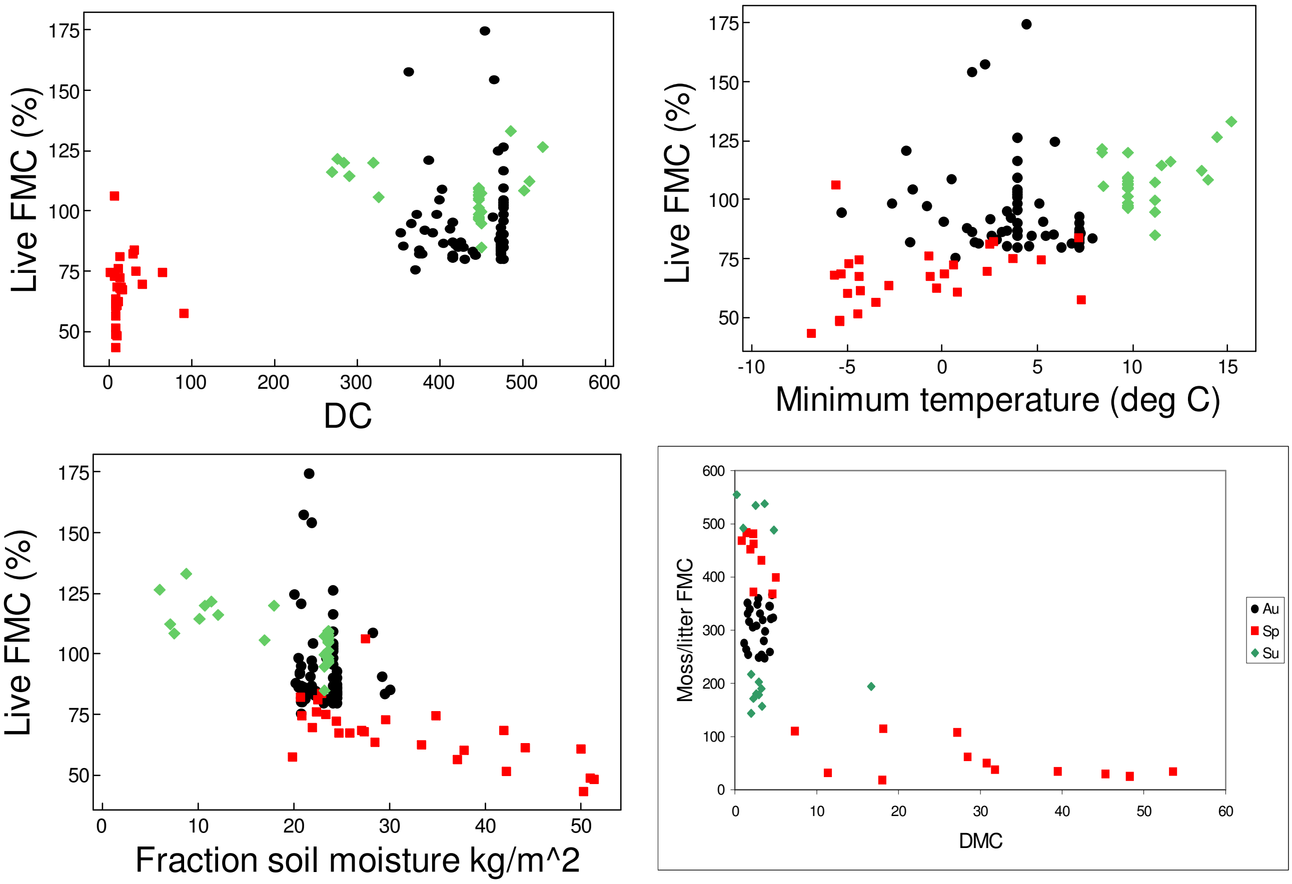


Figure 6.2. Relationship between live FMC and DC, minimum temperature and fractional soil moisture, and moss/litter moisture content and DMC. Spring, summer and autumn are shown as red squares, green diamonds and black circles respectively.

Discussion

These early results are dominated to some extent by the distribution of samples through the season. It is important that the within-season variation should be separated from the between-season patterns. The former are driven by weather conditions, but the latter are determined by the physiology of the plants as determined by the fresh growth in summer and the damage to leaf surfaces by frost and ice in winter. A priority for future research must be to gain a good quantitative understanding of these processes.

An outline of a physiological model of fuel moisture in *Calluna* has been developed (Figure 6.3) using the Simile modelling environment (Simulistics, undated). The full parameterisation of this model would require a considerable amount of time and effort, but would undoubtedly provide the key to understanding and modelling fire behaviour in the UK heathlands.

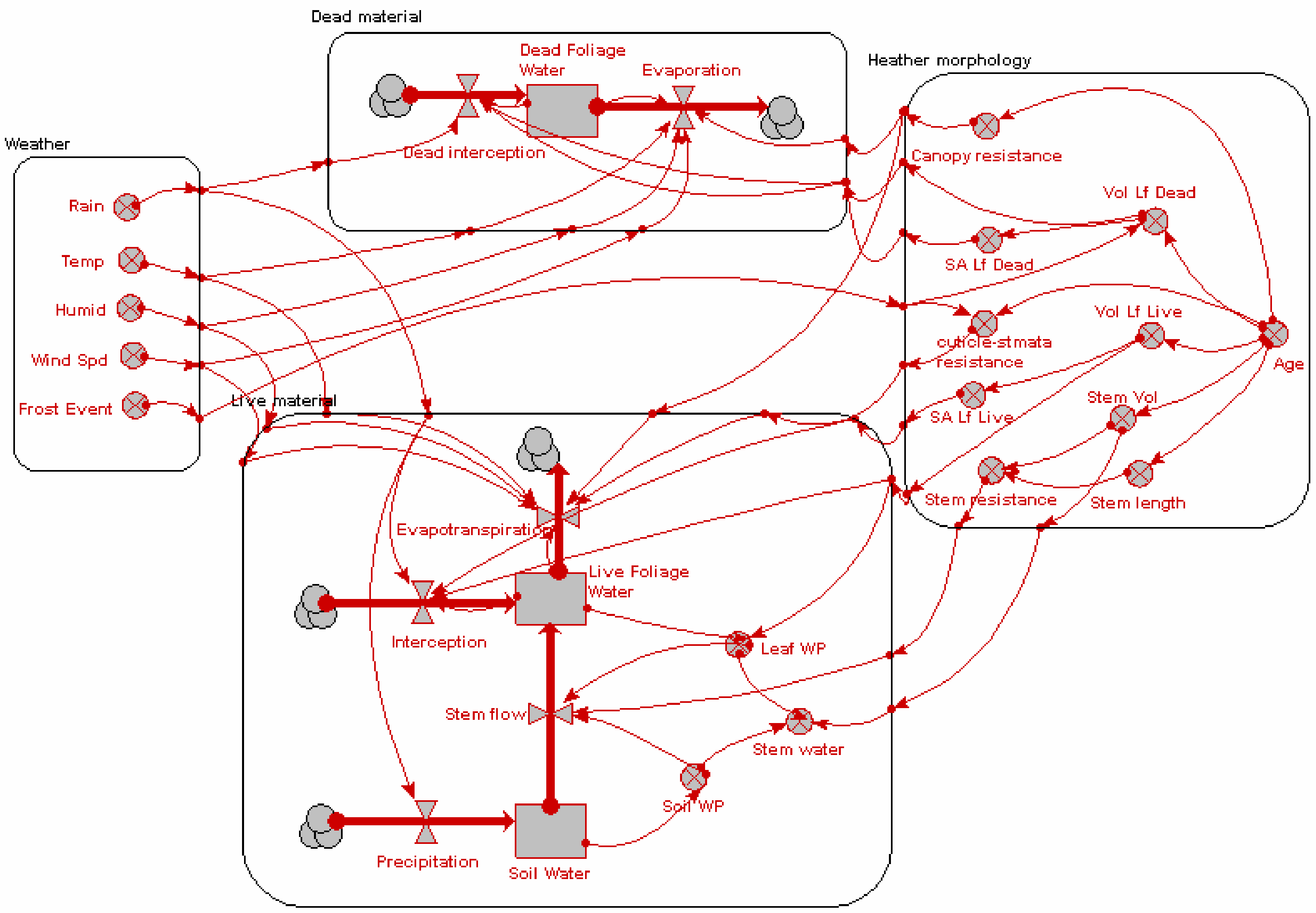


Figure 6.3. An outline for a physiological model of fuel moisture in *Calluna* developed in the Simile modelling environment

Section 7

Implementation and proposals for fire behaviour tools

A summary of the user requirement survey is given in Appendix 2 and though only small in scale it suggests that there is considerable appetite for computer models that predict or forecast fire behaviour, but in particular for simple tools like nomograms that are usable in the field.

An on-line fire behaviour calculator

An online fire calculator utilising Equations 1, 2, 8 and 15 will be developed, for registered users only, to provide feed-back of the performance of our models in a wide range of conditions.

A draft nomogram for heather

This may already provide a useful guide to potential fire behaviour, especially if combined with a copy of the ignition and control histograms for rate of spread (Figure 3.10) that allows users to assess the accuracy of the models on the basis of what their colleagues have observed. This will be made available to collaborators for evaluation.

A management fire forecast (histogram)

It is not possible to recommend any model for fire behaviour prediction at this stage as those that performed best require fuel moisture as an input. The research required to develop a fuel moisture model might well allow the Canadian FWI to become useful at the management fire scale as well as for predicting extreme periods when accidental wildfires are likely to be of high severity.

*NB We need to address the fact that these records may not include escaped management fires that are extinguished without the help of the fire and rescue services and this means publicising and promoting our wildfire data collection programme.

Wildfire forecast (histograms)

The large quantity of data received requires further analysis to separate out the differences in the distribution of fires in different vegetation types. We propose that a GIS approach using Landcover of Scotland maps should be used to provide more accurate vegetation information.

Until this has been completed, and on the basis of our analysis so far, it is not possible to recommend any of the underlying codes of the Canadian FWI system as providing significant added values to the information available from the MOFSI system.

A histogram of wildfire occurrence versus the MOFSI code may only serve to undermine public confidence in the system and add to the current confusion about what exactly it is supposed to forecast.

Conclusions and further actions

As a general summary the research to date suggests several key action points:

- Standardise the recording of wildfire data by the Fire and Rescue Services.
- Implement evaluation versions of our models and collect validation data and feed-back from volunteer land-managers.
- Use GIS to further develop our spatial analysis of fire records with regards to vegetation, altitude and topography.
- Develop a fuel moisture research programme examining in particular the effects of weather and canopy structure on live fuel moisture.
- Understand the factors controlling the curing and green-up of *Molinia caerulea* for predicting grass fires.
- Develop a Fire Danger Rating System specifically for UK conditions that builds on existing knowledge but which adequately accounts for fuel and climatic differences.
- Re-evaluate the first four MOFSI class thresholds on the basis of observed fire behaviour and wildfire occurrence.
- Conduct further market research on model development including possible commercial projects utilising GIS.
- Develop further calibration of NWP data against point observation, met station, data to allow harmonisation of field data and prediction models based on Met Office forecasts.

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Appendix 1: Summary of data collected

Experimental Fires

FireBeaters: 27 burns in a split block design: 3 fires burnt each day, 1 in each of a high, medium and low fuel loading.

Ignition Experiment: 12 records of small scale ignitability tests.

Published Data: a number of published sources are available totalling 38 fires documented but there are problems with some due to differing experimental designs and data quality issues.

Source	Fuel height	Fuel load	Dead load	Fine load	Fuel Rule	Bulk density	Fuel moisture	On-site wind speed	Slope
FireBeaters (27)	Y	Y	Y	Y	Y	Y	Y	Y	N
Bruce (6)	Y	Y		Y		Y		Y	Y
Kayll (3)	Y	Y		Y		Y	Y	Y	
Thomas (10)	Y					Y	Y	Y	
Hobbs (17)*	Y	Y	Y	Y		Y	Y	Y	Y

* Not usable due to data quality problems

Simple Record Cards

A total of 72 basic record cards were received. A number of individuals had recorded additional information such as rate of spread and fuel moisture

Wildfire Records

Lothian & Borders FRS	2201 records	Jan 03 – Aug 06
Highlands & Islands FRS	2008 records	Jan 03 – Mar 07
Grampian FRS	1155 records	Jan 02 – Jan 07
Dorset County Council	487 records	Apr 04 – Oct 06
Dumfries & Galloway FRS	471 records	Jan 03 – Mar 07
Moors for the Future	377 records	Jun 76 – Apr 06

Appendix 2: User requirements survey

The table below summarizes the results of the first user-requirements survey completed. A second survey was attempted but the response rate was very poor. Columns represent the occupation of the respondee: Conservationist, Land manager, Forester and Fire & Rescue Services.

1. What types of fire are of particular concern to you?

	All	**Conserv**	**Lnd Mngr**	**Forester**	**Fire Serv**
Moorland management fires	16	5	3	5	2
Wildfires					
Escaped management fires	20	7	3	6	3
Malicious/accidental fires	28	10	4	8	6
Peat fires	15	8	2	1	4
Forest fires					
Canopy	12	6		5	1
Surface	22	7	2	8	4
Urban	11	4		5	2
Bog	3	1	1		1
Juniper	1	1			
Grass	1				

2: What aspects of fire behaviour do you need to know about?

Fire behaviour					
Rate of spread	31	9	4	9	7
Flame length	9	6		1	2
Fireline Intensity	14	5	2	1	6
Ecological Impact					
Post-fire regeneration					
Heather	22	9	3	6	3
Grass	18	8	3	4	1
Trees	14	5	1	5	2
Moss/Sphagnum	1		1		
Soil damage					
Erosion	15	6	4	3	2
Hydrology	8	4	3	1	
Nutrient status	15	6	5	3	
Effect on animals populations					
Grouse	8	5	2	1	
Sheep	8	5	1	1	1
Deer	7	3		4	
Inverts	2	1	1		
Other birds	2		1	1	

	All	**Conserv**	**Lnd Mngr**	**Forester**	**Fire Serv**
Impacts on people					
Smoke	20	6	2	4	6
Recreation	19	7	3	5	3
Fire-fighter safety	25	7	5	5	7

3: What tools to predict fire behaviour would you use?

	All	**Conserv**	**Lnd Mngr**	**Forester**	**Fire Serv**
Portable weather kit	7	2	2	2	1
Fuel moisture model	10	4	2	2	2
Fuel photo-guides	11	6	1	2	2
Nomographs to predict					
Rate of spread	28	9	5	7	6
Head fire intensity	13	5	2	4	2
Flame length	7	3		2	2
Computer-based systems					
Intensity/Rate of spread	11	3	1	2	5
GIS spread models	13	5	1	4	3
Ecological impact	11	8	2		1
Fire danger rating	1		1		
Rules of thumb	1				
Total Number of Responses	34	10	5	9	7

Appendix 3: Activities: Publicity – talks, posters, papers

A considerable amount of effort has been put into publicising the project and disseminating knowledge to stakeholder groups. A number of workshops, training events and talks to stake holders have been given or are planned (see table below).

Table A3.1. Talks and posters presented, or to be presented, as part of the FireBeaters project.

	Event	Audience	Subject
Conference presentations	Conference presentation (GMD) Wildfire 2007 North Yorkshire	Various stakeholders	Developing prescribed burning as a management tool *and* FireBeaters: towards a management and wildfire forecasting system for the UK
	Conference presentation (GMD), Wildfire 2007 North Yorkshire (June 2007)	Various stakeholders	Developing a fire behaviour prediction system
	Conference presentation (GMD and KK), V International Conference on Forest Fire Research Portugal	Academic	Developing shrub fire behaviour models *and* Developing a fire danger rating system (see attached papers)
	Conference presentation (GMD), The Future of Biodiversity in the Uplands Battleby, Perth	Academics and land-managers	The future of fire management in the uplands. (see attached paper)
Poster presentations	Poster (GMD, CJL), International Heathland Conference	Conservationists, researchers, heathland managers	The FireBeaters project (see poster below)
	Poster presentation (GMD and others), Association of Applied Biologists	Research and academic	Phenological change, causes and consequences (see poster below)
	Poster presentation (GMD), Scottish Gamekeepers Association AGM	Gamekeepers and land managers	The FireBeaters project
Seminars and workshops	Seminar (GMD) School of GeoSciences University of Edinburgh	Academic	Fire behaviour modelling and prediction
	Seminar/Workshop (GMD) Kincraig, Cairngorms NPA	Local gamekeepers	Fire behaviour, fire management and prescribed burning
	Seminar (GMD) Forestry Commission Northern	Forest Research staff	Fire risk and management for forestry

Research Station		
Presentation (GMD) Braemar, Cairngorms NPA	Cairngorms NP board members	Fire management and prescribed burning
Presentation (GMD) Alnwick, Northumberland	Northumberland Fire Management Group	Fire danger rating, fire behaviour prediction and prescribed burning
Seminar (GMD, CJL), School of Engineering, University of Edinburgh, July 2007	Academic (Research and student)	The FireBeaters project
Seminar (GMD, CJL), University of Edinburgh, July 2007	Mixed audience	The FireBeaters project
Seminar series (CJL), Dumfries, Aberfoyle, Inverness, Scottish Branch of the Institution of Fire Engineers (September 2007)	Fire & Rescue Service personnel, foresters, land managers and general public	Wildfires: fire behaviour and prediction
Presentation (CJL), Service Delivery Advisory Forum, Falkirk (September 2007)	Fire & Rescue Services Scotland	FireBeaters project
Seminar (CJL), update on impacts of climate change on forestry, Institute of Chartered Foresters and Confederation of Forest Industries	Forester industry and forest research	Fire regimes in a changing climate

	Journal/Magazine	**Title**	**Status**
Published articles	Game Conservancy Trust Scottish Newsletter (GMD)	Taking the heat our of muirburn	Published
	Farm Woodland News Issue 9 (Autumn 2006) (GMD)	Developing a Fire Risk System for the UK	Published
	Proceedings of the V International Conference on Forest Fire Research, Portugal. Abstract published in the scientific journal: Forest Ecology & Management (GMD, CJL and others)	Developing shrub fire behaviour models in an oceanic climate: Burning in the British Uplands	Published Published
	Proceedings of the V International Conference on Forest Fire Research, Portugal. Abstract published in the scientific journal: Forest Ecology & Management (KK, PM, CJL, MB, GMD)	Developing a fire danger rating system for the United Kingdom	Published
	Journal of Environmental Management		Under review

International Journal of Wildland Fire (Based largely on GMD’s PhD thesis, but including material relevant to FireBeaters)	Accepted for publication
To be decided	In preparation

At the start of the project a mail-out was sent to all members of the National Gamekeepers Organisation providing them with basic record cards and a flier and letter publicising the project and encouraging them to join in. A targeted mail-out was also sent to individuals with a known interest in fire management. We also attended the Scottish Gamekeepers Association AGM where we distributed record cards, fliers and presented a poster (below) describing the project. We developed an e-mailing list of over 100 members who have been kept up-to-date with significant developments in the project.

We have endeavoured to make publicly available as many of our publications as possible. The five month report to the second steering group has been made publicly available on the web, as has a summary of the current fire management and wildfire situation in the UK (see the “Library of the FireBeaters website, http://firebeaters.org.uk).

We have also contributed to the recent consultation organised by Northwoods on developing a Wildfire Forum for the UK and attended a number of wild fire training events with Northumberland Fire Brigade. We were also instrumental in setting up the nascent UK Wildfire Research Group which has recently won a grant from the research councils NERC and ESRC to organise a series of four interdisciplinary seminars on fires and ecosystem services. The first of these seminars will be in Edinburgh in spring 2008.

Colin Legg and Matt Davies have been interviewed by the BBC Radio Scotland for the programme “Wild tracks” about the risk, impact and management of wildfires (July 2007). The programme is due to go on air in August 2007.

The FireBeaters team in Edinburgh were visited by Prof Anders Granström and Maria Johansson from the Swedish University of Agricultural Sciences (April 2007), and by Stuart Anderson from the ENSIS Bushfire Research Group, National Rural Fire Authority, New Zealand (July 2007).

Poster presentations

Flier sent out to NGO and SGA and other targeted individuals.

FireBeaters

http://firebeaters.org.uk

The UK Site For Wildland Fire Research

The Project

FireBeaters is a University of Edinburgh and Met Office project funded by the Wildfire Forum of the Scottish Executive and SNH. We are creating fire weather forecasts and a fire danger rating system for the UK. Our initial focus is on heather moorland and developing a muirburn forecast for Scotland.

Courtesy of the GCT

How will it be used?

- Land management: To plan where and when fires can be burnt safely.
- Fire prevention: To assess fire danger and design fire safety features into landscapes, plan firebreaks and undertake fuel-reduction burning.
- Public education: To provide a framework for informing the public of fire risk.
- Preparedness: Voluntary fire groups can be placed on standby at times of high risk and equipment primed for use. Professional fire crews and helicopter operators can deploy resources to areas of highest risk.
- Tactical fire suppression: To direct operations and avoid dangerous situations.

Get Involved

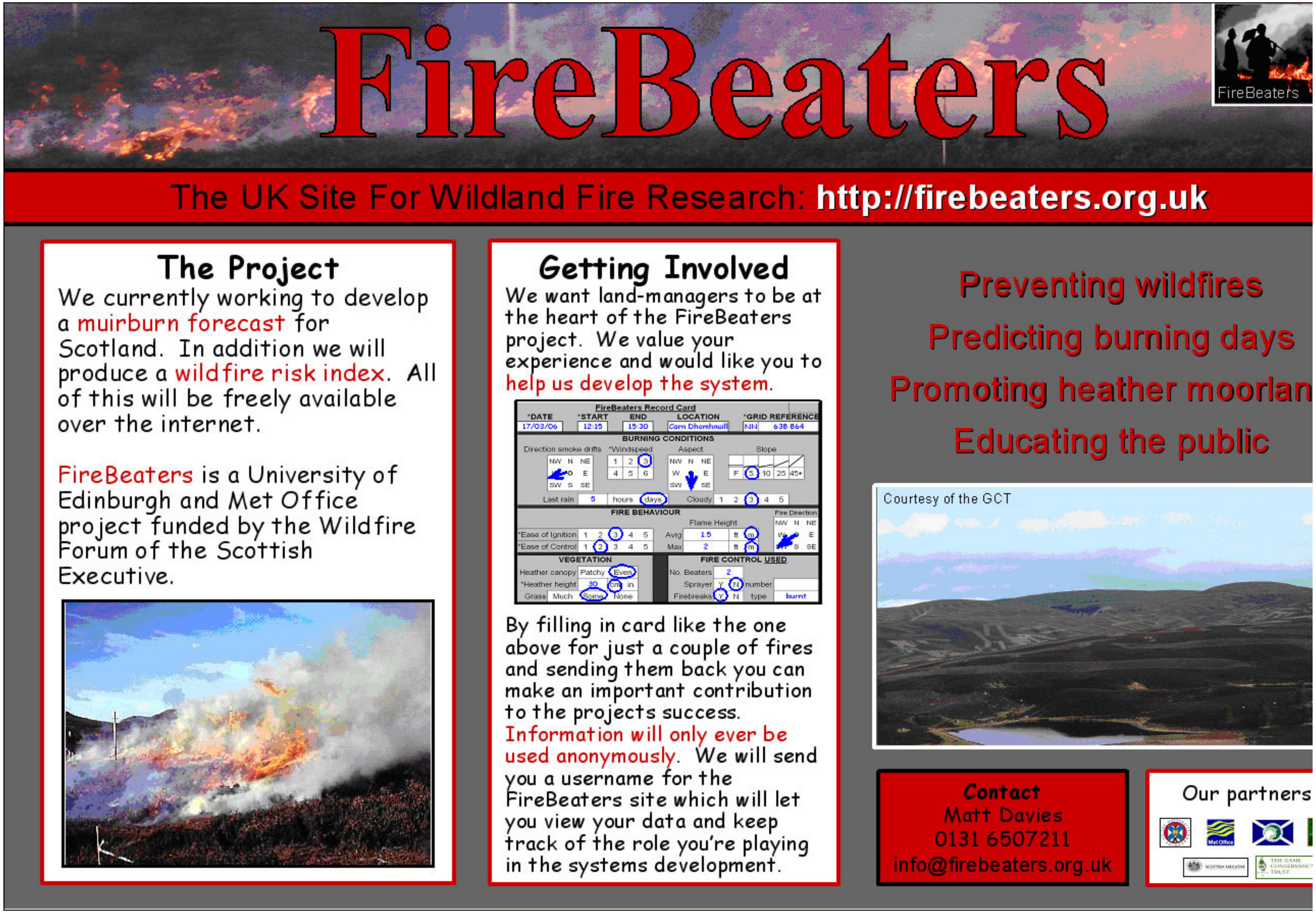
We want all those involved in land-management to be involved in the FireBeaters project. We would like to build on your experience and want you to help us develop the system.

We need data! By filling in a form for just one fire a season and sending it back to us you could make an important contribution to the projects success. If you have any questions get in touch.

Matt Davies
0131 6507211
info@firebeaters.org.uk

Some of our partners

The poster presented at the Scottish Gamekeepers Association AGM. Fliers and simple record cards were also distributed.



FireBeaters

The UK Site For Wildland Fire Research: **http://firebeaters.org.uk**

The Project

We currently working to develop a muirburn forecast for Scotland. In addition we will produce a wildfire risk index. All of this will be freely available over the internet.

FireBeaters is a University of Edinburgh and Met Office project funded by the Wildfire Forum of the Scottish Executive.

Getting Involved

We want land-managers to be at the heart of the FireBeaters project. We value your experience and would like you to help us develop the system.

FireBeaters Record Card

*DATE	*START	END	LOCATION	*GRID REFERENCE
17/03/06	12:15	15:30	Carn Dhomhnuill	NN 638 864

BURNING CONDITIONS
Direction smoke drifts: NW N NE W E SW S SE
*Windspeed: 1 2 [✓ 3] 4 5 6
Aspect: NW N NE W E SW S SE
Slope: F [✓ 5] 10 25 45+
Last rain: 5 hours [✓ days]
Cloudy: 1 2 [✓ 3] 4 5

FIRE BEHAVIOUR
*Ease of Ignition: 1 2 [✓ 3] 4 5
*Ease of Control: 1 [✓ 2] 3 4 5
Flame Height Avrg: 1.5 ft [✓ m]
Flame Height Max: 2 ft [✓ m]
Fire Direction: NW N NE W E SW S SE

VEGETATION
Heather canopy: Patchy [✓ Even]
*Heather height: 30 [✓ cm] in
Grass: Much [✓ Some] None

FIRE CONTROL USED
No. Beaters: 2
Sprayer: Y [✓ N] number
Firebreaks: [✓ Y] N type: burnt

By filling in card like the one above for just a couple of fires and sending them back you can make an important contribution to the projects success. Information will only ever be used anonymously. We will send you a username for the FireBeaters site which will let you view your data and keep track of the role you're playing in the systems development.

Preventing wildfires

Predicting burning days

Promoting heather moorlan

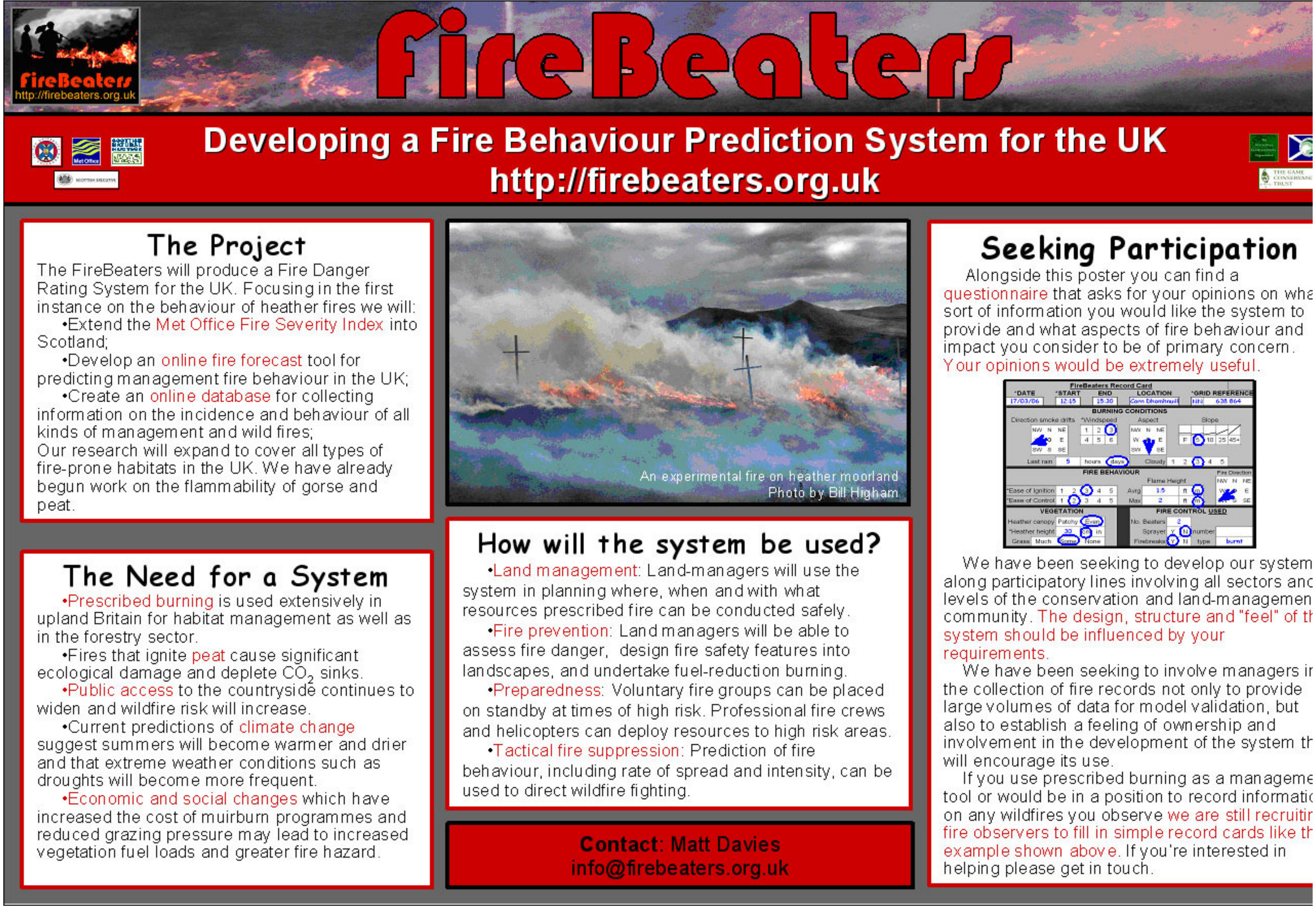
Educating the public

Courtesy of the GCT

Contact
Matt Davies
0131 6507211
info@firebeaters.org.uk

Our partners

Poster presented at the 9th National Heathlands Conference in Aberdeen. We also distributed a user requirement survey but the response was poor



FireBeaters

Developing a Fire Behaviour Prediction System for the UK

http://firebeaters.org.uk

The Project

The FireBeaters will produce a Fire Danger Rating System for the UK. Focusing in the first instance on the behaviour of heather fires we will:

- Extend the Met Office Fire Severity Index into Scotland;
- Develop an online fire forecast tool for predicting management fire behaviour in the UK;
- Create an online database for collecting information on the incidence and behaviour of all kinds of management and wild fires;

Our research will expand to cover all types of fire-prone habitats in the UK. We have already begun work on the flammability of gorse and peat.

The Need for a System

- Prescribed burning is used extensively in upland Britain for habitat management as well as in the forestry sector.
- Fires that ignite peat cause significant ecological damage and deplete CO_2 sinks.
- Public access to the countryside continues to widen and wildfire risk will increase.
- Current predictions of climate change suggest summers will become warmer and drier and that extreme weather conditions such as droughts will become more frequent.
- Economic and social changes which have increased the cost of muirburn programmes and reduced grazing pressure may lead to increased vegetation fuel loads and greater fire hazard.

An experimental fire on heather moorland
Photo by Bill Higham

How will the system be used?

- Land management: Land-managers will use the system in planning where, when and with what resources prescribed fire can be conducted safely.
- Fire prevention: Land managers will be able to assess fire danger, design fire safety features into landscapes, and undertake fuel-reduction burning.
- Preparedness: Voluntary fire groups can be placed on standby at times of high risk. Professional fire crews and helicopters can deploy resources to high risk areas.
- Tactical fire suppression: Prediction of fire behaviour, including rate of spread and intensity, can be used to direct wildfire fighting.

Contact: Matt Davies
info@firebeaters.org.uk

Seeking Participation

Alongside this poster you can find a questionnaire that asks for your opinions on wha sort of information you would like the system to provide and what aspects of fire behaviour and impact you consider to be of primary concern. Your opinions would be extremely useful.

FireBeaters Record Card

*DATE 17/03/06 *START 12:15 END 15:30 LOCATION Carn Dhomhnuil *GRID REFERENCE NN 638 864

BURNING CONDITIONS

Direction smoke drifts: NW N NE W E SW S SE
*Windspeed: 1 2 [✓ 3] 4 5 6
Aspect: NW N NE W E SW SE
Slope: F [✓ 5] 10 25 45+
Last rain 5 hours [✓ days]
Cloudy 1 2 [✓ 3] 4 5

FIRE BEHAVIOUR

*Ease of Ignition 1 2 [✓ 3] 4 5
*Ease of Control 1 [✓ 2] 3 4 5
Flame Height: Avrg 1.5 ft [✓ m]; Max 2 ft [✓ m]
Fire Direction: NW N NE W E S SE

VEGETATION

Heather canopy Patchy [✓ Even]
*Heather height 30 [✓ cm] in
Grass Much [✓ Some] None

FIRE CONTROL USED

No. Beaters 2
Sprayer Y [✓ N] number
Firebreaks [✓ Y] N type burnt

We have been seeking to develop our system along participatory lines involving all sectors anc levels of the conservation and land-managemen community. The design, structure and "feel" of th system should be influenced by your requirements.

We have been seeking to involve managers ir the collection of fire records not only to provide large volumes of data for model validation, but also to establish a feeling of ownership and involvement in the development of the system th will encourage its use.

If you use prescribed burning as a manageme tool or would be in a position to record informatic on any wildfires you observe we are still recruitir fire observers to fill in simple record cards like th example shown above. If you're interested in helping please get in touch.

Poster presented at the Association of Applied Biologists meeting *Phenological change, causes and consequences*

Using NDVI to Study the Curing of *Molinia* for Fire Management

Karin Viergever[1], Matt Davies[2] & Graham Russell[2]

Fire and *Molinia*

Fire is used extensively as a management tool in grasslands dominated by *Molinia caerulea*. Careful prescribed burning can be used to improve grazing for sheep and red deer and for biodiversity benefits though uncontrolled fires may cause significant damage. There is concern over the impact of burning on bog-building *Sphagnum* species and the effects of wildfire on carbon reserves in peat.

Fire in a mixture of *Calluna* and *Molinia*

Curing

The proportion of dead material in a stand grows over the autumn increasing the level of "curing" of the grassland. The proportion of dead fuel present is a crucial control on the fire hazard of such habitats. The risk of wildfires is greatest during dry spells in autumn and spring when little living material is present. Green-up in summer increases the proportion of live fuel, which has a higher moisture content, and dampens fire behaviour and risk.

The Phenology of *Molinia*

Molinia produces new leaves each spring which begin to die-back following flowering. There does not seem to have been a quantitative analysis of the factors responsible for the rate of progression of phenological change in terms of explanatory variables such as thermal time and day length.

1. June

2. August?

3. September

4. October

Images 1 to 4 show changes in a *Molinia* sward over the course of a year; from new shoots appearing through the previous years litter to the onset of curing in autumn.

A Role for Remote Sensing

A number of fire risk prediction systems, such as the National Fire Danger Rating System in the US include a relative green-ness index from satellite NDVI data for estimating flammability. Such techniques will be tested for the UK to determine if the degree of curing of *Molinia* can be detected and to investigate inter-annual and geographical variation in the timing of green-up and die-back due both to severe drought and phenological change. To test the idea we examined AVHRR FASIR NDVI data from 1996 to see if differences in NDVI values were visible between winter and summer for the west coast of Scotland. Results of the exercise are shown below. Although the images are at a coarse scale they suggest the technique could work providing funding can be found for higher resolution data.

NDVI February 1996

NDVI March 1996

NDVI data for winter (left) and summer (right 1996. Low values (red) indicate low chloropyll concentrations and a predominantly dead vegetation. High values (green) relate to an increased proportion of living plant material

NDVI July 1996

NDVI August 1996

For more information contact: info@firebeaters.org.uk

AVHRR FASIR data are provided courtesy of the NERC Earth Observation Data Centre (NEODC)

1: Institute of Geography, University of Edinburgh
2: CECS, University of Edinburgh

With thanks to Colin Legg

Article published in the Game Conservancy Trust Scottish Newsletter.

TAKING THE HEAT OUT OF MUIRBURN

Former GCT research student Matt Davies is heading up a new project aimed at reducing the risk of wildfires.


Experimental muirburn plots in the Scottish uplands (Colin Legg).

FIREBEATERS is a project being conducted by researchers at the University of Edinburgh working with the Met Office to predict the conditions in which wildland fires occur in the UK.

The project will use Met Office weather forecasts to calculate the fire behaviour in different habitats and in different areas of the country to develop a fire information system, available over the web, that gives land-managers both predictions of fire behaviour before they undertake vital prescribed burning activities and gives warnings of wildfire risk.

One of the leading figures in this project is Matt Davies, a former research student with the GCT's Upland Research Unit.

"Interest in the causes of wildfires and in fire behaviour in general reached a peak following the large number of wildfires across the UK in the spring of 2003," said Matt.

"Some of these fires burned for several days and destroyed many square kilometres of habitat. Although 2003 was exceptional, wildfires can still place a considerable strain on the resources of the Fire Services and private estates. Changes in the rural landscape due to climate change, reductions in browsing by sheep and deer and increased public access and outdoor recreation are likely to result in an increase in the risk of wildfires while there may be a reduction in suitable times for conducting prescribed fire."

How will the FireBeaters system be used?

- **Land management:** Land-managers will be able to plan where and when fires can be burnt safely.
- **Fire prevention:** Land managers will be able to assess fire danger and, with the knowledge of likely fire behaviour, design fire safety features into landscapes, plan firebreaks and undertake fuel-reduction burning.
- **Public education:** The FireBeaters Information System will provide a framework for informing the general public of fire risk.
- **Preparedness:** Voluntary fire groups can be placed on standby at times of high risk and equipment primed for use. Professional fire crews and helicopter operators can deploy resources to areas of highest risk.
- **Tactical fire suppression:** Prediction of fire behaviour, including rate of spread and ease of control, can be used to direct operations and avoid dangerous situations.

Seeking volunteer observers

Supported by The Game Conservancy Trust, Scottish Gamekeepers Association, National Gamekeepers Organisation, Ministry of Defence, the Fire and Rescue Services, the Scottish Executive and Scottish Natural Heritage, FireBeaters is seeking to work closely with practitioners and is currently recruiting people carrying out muirburn as volunteer observers.

"Muirburn, when carefully managed by experienced gamekeepers and other land-managers, is beneficial to both conservation and land use objectives but wildfires can be a very different matter," said Matt.

"Accidental or deliberate fires started by members of the public are not uncommon in high-risk conditions. Wildfires can have potentially devastating effects, destroying property and infrastructure and leaving habitats barren for decades. Where peat ignites significant amounts of carbon dioxide can be released contributing to global warming."

In the future FireBeaters will also be looking for people who can provide information on any wildfire outbreaks in their area or who are prepared to record additional details about their fires using a standardised methodology.

Matt continues: "Use of the system will be web-based and totally free of charge. Over the coming years we aim to produce simple field guides to fire behaviour and to ensure that the FireBeaters Information System becomes a valuable and reliable source of information that allows us all to ensure management fires continue to be used safely and sustainably during a time of environmental and climatic change."

For more information, please contact Matt: tel: 0131 6507211; email: info@firebeaters.org.uk

Article published in Farm Woodland News, The Newsletter for Participants in Farm Woodland Schemes, Scottish Executive, Issue 9 (Autumn 2006) pp 4-5. The original is available at: http://www.sac.ac.uk/consultancy/fbs/publications/fwn

Developing a Fire Risk System for the UK

Author: Matt Davies

At the University of Edinburgh we are working on a project with the Met Office to develop a system for predicting the risk of wildfires in Scotland. Our system will be web based, free of charge and provide a 5 day fire danger rating as well as site/vegetation specific predictions of fire behaviour. Combined with a growing number of Rural Fire Protection Groups we hope to ensure that damage from wildfires is minimised.

The system will provide prediction of likely fire risk for Scotland, and later the whole of the UK, and will have a number of possible uses:

- Land management: Land-managers will be able to plan where and when fires, including slash-burning and ground preparation fires, can be burnt safely.
- Fire prevention: Land managers will be able to assess fire danger and, with the knowledge of likely fire behaviour, undertake fuel-reduction burning and plan firebreaks.
- Public education: The FireBeaters Information System will provide a framework for informing the general public of fire risk.
- Preparedness: Voluntary fire groups can be placed on standby at times of high risk and equipment primed for use. Professional fire crews and helicopter operators can deploy resources to areas of highest risk.
- Tactical fire suppression: Prediction of fire behaviour, including rate of spread and ease of control, can be used to direct operations and avoid dangerous situations.

Fire is an inherent part of the landscape of the British Uplands and prescribed fire, or “muirburn” as it is traditionally known in Scotland, when carefully managed by experienced land-managers, is beneficial to both conservation and land use objectives. Wildfires are however a very different matter having potentially devastating effects, destroying property and infrastructure and leaving habitats barren for decades. Where peat is ignited significant amounts of carbon dioxide can be released contributing to global warming.

The image of wildfires sweeping through acres of forest, which we so often see from abroad, are thankfully something with which Scotland does not have to contend. Wildfires do however occur relatively frequently in the UK, can cover large areas and do considerable damage to both moorland and forest habitat. Although fires starting in woodland are relatively rare damage to forest can occur, particularly from wildfires spreading from adjoining areas of grass and moorland. Forest management also brings its own fire control issues, particularly with regard to slash and ground preparation burning, as well as new fire hazards such as thicket stage conifer plantation and areas of moorland set-aside for regeneration where a reduction in grazing and management burning can increase the amount of flammable vegetation.

Our research draws on support from the Scottish Executive and Scottish Natural Heritage but has already developed close links with the Forestry Commission, The Game Conservancy Trust, the Scottish Gamekeepers Association, the National Gamekeepers Organisation, the Ministry of Defence and the Fire Brigade. We are keen to engage with all sectors and levels of the land-management community to ensure that the way we develop our system is driven by potential users and integrates traditional knowledge and experience with new scientific understandings of fire.

Our principal stumbling block is getting hold of enough data on when and where fires occur. The experimental fires we burn provide us with an important source of high quality data on fire behaviour but these are currently focused on heather moorland and we need much better information on the incidence and behaviour of fires in all types of vegetation. We are currently seeking to recruit volunteers who are willing to send us information on any management fires they set and wildfires they observe.

If you would like more information about the project please contact Matt Davies: 0131 650 7211, matt.davies@ed.ac.uk. Our website is currently under preparation but should be up and running soon: http://firebeaters.org.uk

A surface fire in native pine woodland

Paper presented at the *V International Conference on Forest Fire Research*, Portugal.
Abstract published in the scientific journal: *Forest Ecology & Management*

Developing shrub fire behaviour models in an oceanic climate: Burning in the British Uplands

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Legg C.J.
The University of Edinburgh, Centre for the Study of Environmental Change and Sustainability, Edinburgh, EH9 3JN, Scotland, colin.legg@ed.ac.uk
Smith A.
The Game Conservancy Trust, Drumochter Lodge, Dalwhinnie, Inverness-shire, PH20 1BE, Scotland, asmith@gct.org.uk
MacDonald A.
Scottish Natural Heritage, 2 Anderson Place, Edinburgh, EH6 5NP, Scotland, ajmacdonald@treeline3m.freeserve.co.uk

Abstract: Prescribed burning of moorland vegetation in the UK is used to provide habitat for red grouse, a game bird, and to improve grazing for sheep and deer. The peak time of fire risk corresponds to the normal legal burning period of 1st November (1st October in Scotland) to 15th April rather than a meteorologically-defined fire season.

Moorland fuels in the UK are unusual. They are dominated by *Calluna vulgaris*, which forms a dense, uniform canopy (though as stands age gaps become more frequent), and in which live material forms the majority of “available” fuel. The moisture content of live fuel plays a dominant role in determining fire behaviour. Weather in the UK uplands can vary rapidly from cold and wet, to sunny with drying winds and low atmospheric humidity. Frozen ground can prevent plants from replenishing water lost by transpiration. Fire behaviour is difficult to predict and periods of significant wildfire activity can occur.

Data from fifteen experimental fires were used to build empirical relationships between rate of spread, windspeed and vegetation structure. Fires in the high fuel-loads responded much more strongly to increased windspeed. The high density of the fuel-bed in younger *Calluna* stands may have a limiting effect on the rate of fire spread. Redundancy Analysis highlights the importance of fuel moisture content and stand structural heterogeneity.

We tested the rate of spread predictions of BehavePlus and the Canadian Wildland Fire Information System (CWFIS). Predictions provided by BehavePlus were relatively good. The CWFIS was unable to predict rate of spread because the moisture content of live and dead *Calluna* was not accurately predicted by any of the moisture codes of the CWFIS. The system did detect a period of extreme risk associated with drought and wildfires during the spring of 2003. Multiple scales and causal factors of increased fire risk are discussed with reference to seasonal variation in the fuel moisture content of *Calluna*.

Keywords BehavePlus, ***Calluna*** *vulgaris*, CWFIS, fire behaviour, fuel moisture, fuel structure, muirburn, rate of spread, UK, windspeed.

Paper presented at conference: ***The Future of Biodiversity in the Uplands.*** **Battleby, Perth**

The Future of Fire Management in the Uplands

G. Matt Davies (University of Edinburgh), Colin Legg (University of Edinburgh),
Alistair Hamilton (Scottish Agricultural College) & Alan Gray (University of Edinburgh)

Fire has been a dominant force in the ecology of the uplands throughout the Holocene and human manipulation of fire regimes probably stretches back almost as far (Froyd 2006). The effects of both natural and anthropogenic fire have had enormous influence in shaping landscapes. Any cessation, decrease or increase in the amount of burning within the uplands will have significant effects. Though there is argument about exactly how much burning takes place (Yallop 2006), fire nevertheless plays a central role in carbon and nutrient budgets, landscape and patch biodiversity and has an influence on hydrology, erosion and water quality.

Environmental, social and climatic changes over the course of the next century are likely to cause changes in fire regimes. Decisions made in the next decade will be important in allowing us to manage these changes. Fires will happen regardless of management intentions and there is now a need for us to learn to live with fire and to manipulate fire regimes to our advantage.

Prescribed fire is a powerful management tool that can be used for multiple objectives and is not just suitable for grouse moor management. Wildfires can cause massive environmental damage, but through prescribed burning we can manipulate the fire regime of the British uplands to both maximise the ecological benefits of fire and manage the threat of wildfires. Defining future fire regimes will involve setting both strategic and local-level policies for fire risk management as well as targets for future landscape type that inform land-management strategy.

Observing that there is considerable variation in the quantity and quality of burning as a management tool in the UK we argue for an ecological basis for the use of fire. This should consider vegetation structure, flammability and plant traits to predict the impacts of burning *a-priori*. In many cases this will require further research. We seek to develop best-practice approaches to the management of fire including, where appropriate, complete protection from fire. Here we present three case study examples that describe how fire might be used in the future.

Moorland Management

Heather moorlands are a globally rare habitat type and there is growing concern at a Europe-wide decline in their area. Current management in the UK is based on 200 hundred years'-worth of controlled burning and grazing designed to increase the productivity of red grouse, sheep and deer (Figure 1). Traditional heather moorlands are an important part of the economy of the uplands and also support important animal populations (e.g. hen harriers, golden plover, curlew, mountain hare). Future research should identify fire-follower and fire-sensitive species in a UK context.

Figure 1: A traditionally managed grouse moor in the Scottish Highlands. Fire plays a key role in maintaining such characteristic landscapes. The network of different-aged burns promotes greater diversity at the landscape scale and breaks up extensive fuel beds into smaller areas (picture courtesy of the Game Conservancy Trust).

Fire on moorland needs to be managed in order to maintain the economic system, which funds the majority of land-management, whilst seeking to maximise the biodiversity benefits of burning. Traditional management techniques can be appropriate for managing threatened species such as hen harriers, results in greater diversity at the landscape scale and helps to ensure ecosystem robustness to environmental change.

Fire free areas will allow potential fire sensitive species to prosper and should help prevent steep slopes, gullies and scree from burning. Such areas will be protected from wildfire by the breaking up of the landscape by continued muirburn around them. Most effort should be placed on burning younger heather where regeneration is best and fires easier to control (Davies 2005). Moorland management plans should be drawn up identifying fire free areas and allowing the establishment of multiple fire regimes within individual management units.

Whilst continued burning will be valuable in mitigating the risk of wildfires managers should seek to engage local fire partnerships and to develop formal collaboration for fighting wildfires.

Forest Management

Fire can be used as a tool to develop diverse forest habitats, to reach conservation objectives as well as to maximise pine-wood regeneration (Hancock et al. 2005). Deciduous trees including birch and willow tend to sprout vigorously following fire.

Burning within forests can serve to promote beta level diversity and alter ground structure in a way that may be beneficial in managing endangered species such as Capercaillie. Such management will also help prevent fuel-build up and the risk of intense, stand-replacing wild and crown fires and should be used to protect specific features of interest where fire may not be desirable. This includes at the forest edge where there is a desire to prevent fire damage to trees from prescribed or wild fires on adjacent lands (Figure 2). This may be particularly relevant where young trees on regenerating areas have reached the thicket stage and the risk of crown fires is greatest.

Figure 2: A wildfire spreading from moorland into semi-natural pine forest. Fuel management at the forest edge can help to prevent such fires and reduce their intensity, decreasing the likelihood of crown-fire behaviour (picture courtesy of Michael Bruce).

Wildfire planning should be built into forest management and design including requirements for access and water for fire fighting but also through the manipulation of species balance. Larch for example can be used in plantations to suppress ground cover and to create fire-breaks whereas in semi-natural forests increased proportions of deciduous species will have a dampening effect on fire spread.

Carbon Management

The role of fire in the carbon balance of upland peatlands has been somewhat controversial and evidence as to its effects has been somewhat contradictory (Gray 2006). Fire can be used to promote peat-building species such as *Sphagnum capillifolium* and low intensity grass-dominated moorland fires can result in generally good recovery following burning (Hamilton 2000). Fire removes thick layers of *Molinia* litter, reduces shading thereby encouraging *Sphagnum* growth and avoids levels of fuel build-up that might lead to intense, damaging burns (Figure 3).

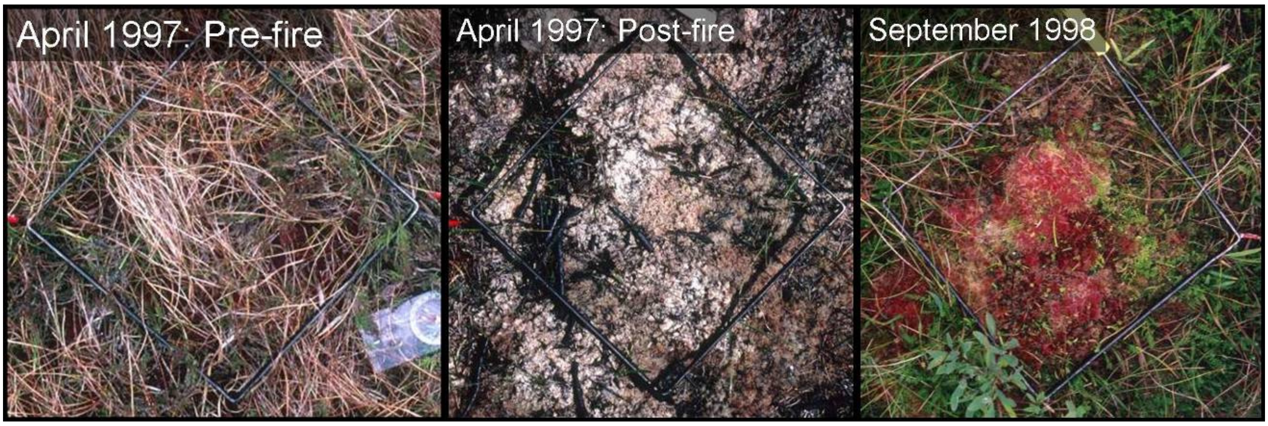

Figure 3: Recovery of *Sphagum capillifolium* following burning can be rapid where fuel loads are low and fires are of low severity (pictures by Alistair Hamilton).

The relationships between fire, drainage and grazing on bogs needs to be better understood. Manipulation of fire, water tables and grazing regimes is the only way to ensure that carbon is locked up in peat or that losses are reduced (Gray 2006). If burning declines on dry or degraded sites because of concern over carbon emissions it should be remembered that land-management is required to reduce the risk of severe wildfires. These fires can ignite peat, release large amounts of CO_2 and destroy carbon fixing vegetation. If forest invades or is planted this may lead to drying of peat deposits and further carbon losses both from slow oxidation and due to an increased likelihood of peat smouldering (Figure 4).

Figure 4: Extensive smouldering around the base of trees in a Douglas fir plantation following the spread of a wildfire from adjacent moorland (picture by Guillermo Rein).

Conclusion

Fire is a cheap and powerful management tool and an integral part of the ecology of the uplands. Fire should be an integral part of the ecologists' tool kit even when their primary goal is to minimise fire. A change in fire regimes will come to the uplands whether we like it or not and it is now up to us to decide whether we manage that change and manipulate it to our advantage or deal with the consequences of taking no action.

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Early Results from the FireBeaters Project

Matt Davies & Colin Legg

Introduction

For the last eighteen months the FireBeaters project based at the University of Edinburgh has been working towards the development of a Fire Danger Rating system for the UK. The project has its origins in research completed by the University, the Game Conservancy Trust and the Met Office and the exceptional number of wildfires that occurred during the Spring of 2003. Our aim has been to work with land-managers, conservationists and the Fire and Rescue Services to understand when conditions are suitable for heather burning (including both the "high" and "low" end of burning conditions) and when and why wildfires occur. Current predictions of climate change, increasing visitor numbers and changes in the economy of the uplands suggest the threat of wildfires and frequency of suitable conditions for burning may also change. A fire forecasting system will provide managers with additional information on which to base their decisions.

This article gives a taste of some of what we've been doing at FireBeaters a full version of our report is currently undergoing review and will soon be available on our website.

The Met Office Fire Severity Index (MOFSI)

FireBeaters has been examining the functioning of the Fire Severity Index, which was implemented by the Met Office in 2005 in England and Wales and was a direct result of the Countryside and Rights of Way Act. One of the first products of FireBeaters was an implementation of MOFSI for Scotland (available on our website http://firebeaters.org.uk) as it was the best, indeed only, fire danger rating system available for the UK.

The system was designed for a specific purpose – to predict periods of "exceptional" fire conditions (meaning those we'd normally expect once every three to four years) to allow the closure of open access land. It is based on the Canadian Fire Weather Index which has been widely used in other countries including New Zealand, Sweden, Fiji and Indonesia.

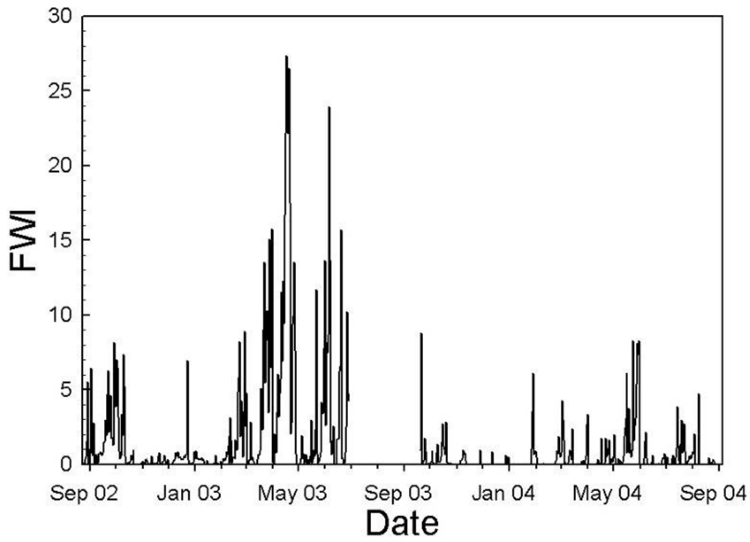

Figure 1: Fire Weather Index (FWI) for Newtonmore, Strath Spey, from September 2002 to 2004. The Met Office Fire Severity Index is based on bandings of the FWI with values greater than about 17 being "Exceptional" and greater than about 9 classified as "High" risk. The Spring of 2003, during which there were an unusual number of wildfires stands out.

For heather moorlands, our work suggests that while the system is good at predicting truly exceptional fire conditions (Figure 1) it does not necessarily provide information on when wildfires will occur and does not seem to relate well to the changes in fire behaviour that managers observe "on the ground" (Figure 2). Indeed, most of the management fires that were reported to us by volunteers using the report forms available from our Web site occurred while the MOFSI index was "Very low". We currently think the main problem with the system is that the Canadian models do not accurately reflect the way weather affects changes in the moisture content of heather fuels. We are hoping to recalibrate these in the next stage of the project as well as to test the system for other vegetation types. None-the-less, one would want to think very carefully before burning at MOFSI ratings of "High" or "Exceptional" - fire control tactics and resources would need to be prepared carefully in advance.

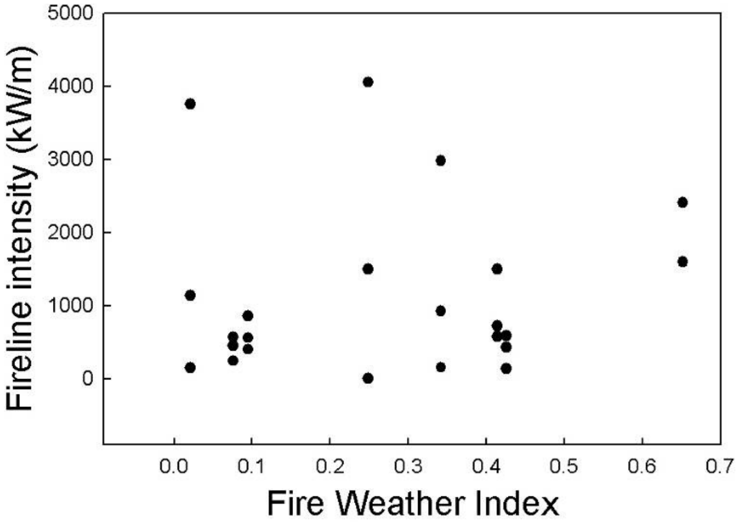

Figure 2: There is very little relationship between the intensity of heather fires and the Canadian Fire Weather Index. Fireline intensity relates closely to the ease with which a fire can be controlled – 500 kW m^{-1} is close to the limit of a heather fire that can be controlled with hand tools alone. For all of these fires the Met Office Fire Severity Index would be 'Very low'.

Fire behaviour

The second key part of FireBeaters has been our programme of experimental fires (Figure 3). By burning relatively small but intensively monitored fires we are able to get a good idea of the factors that control fire behaviour. The things that emerge as important may not be much of a surprise to most experienced managers but understanding the precise influence of each has allowed us to begin to develop simple models of fire behaviour (Figure 4).

Figure 3: Lighting an experimental fire on Crubenmore Estate. Swiped firebreaks have been placed around the plot and the downwind edge and flanks re-enforced with back burns. This lets us just sit back and watch the fire rather worry about trying to control it!

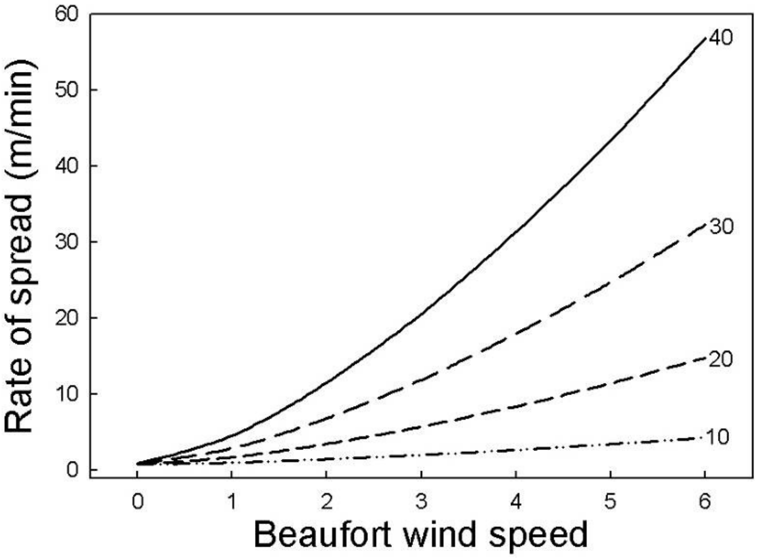

Figure 4: Predicted fire rate of spread of heather fires on level ground and normal weather conditions for four different heather heights (10, 20, 30 and 40 cm). Wind has a much greater affect on rate of spread in tall heather than in short. Rates of spread above about 10 meters per minute will be difficult to control using traditional hand tools. Factors such as the moisture content of the heather, the slope and aspect of the site will also affect rate of spread and the above is only a very rough guide. The horizontal axis is the Beaufort wind speed which can be estimated as follows: 0) No wind, smoke rises vertically; 1) Light air, smoke drifts but heather canopy still; 2) Light breeze, wind felt on face, grasses sway gently, heather still; 3) Gentle breeze, heather and small twigs show some movement; 4) Moderate wind, ash kicked up, exposed heather sways constantly; 5) Fresh wind, small trees sway all heather stems sway vigorously; 6) Strong wind, large branches move, heather thrashes about fiercely.

A number of managers got involved in our fire record collection programme, sending us information on fires they burnt. Despite that fact our most basic guide-line models (Figure 4) only take into account heather height and wind speed they seem to reflect what managers have observed on the ground relatively well, though there is obviously room for improvement. By building in the influence of factors like slope our predictions will hopefully improve; whilst understanding changes in heather moisture content will allow us to use high quality data from the Met Office to create forecasts of ignitability and behaviour (Figure 5).

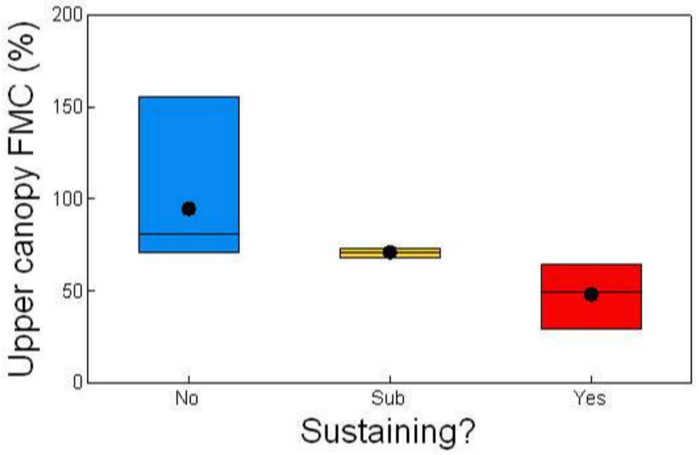

Figure 5: The heather canopy moisture contents of fires that are self extinguishing (No) or self sustaining ('Yes'). A clear threshold seems to exist above which it's not possible to get fires to ignite. A narrow range of conditions produced slow moving, patchy fires classified as sub-sustaining ('Sub'). At moisture contents below about 40% fire behaviour was getting difficult to control.

Further work

It is difficult, if not impossible, to reflect all aspects of fire risk and behaviour in a single number and more work is needed to enable the current MOFSI system to better reflect UK conditions. Some of this is already underway through a Met Office and University of Edinburgh project looking at how the system relates to the risk of peat fires. We believe that some components of the MOFSI system may relate well to the incidence of wildfires and be valuable for predicting when peat fires could occur.

Such relationships may enable us to implement test versions of a wildfire forecasting system relatively quickly but we need to be sure that we understand how the system works if we are to develop robust tools. A fire danger rating cannot be used to set limits when management fire will be safe; that depends very much on the local conditions. Rather, our system will enable the manager to make best use of the time and resources that are available. From a fire-control point of view there's not necessarily any such thing as the "wrong" time to burn but a fire danger rating could be valuable in indicating severe conditions where the tools and tactics need to be very carefully planned. We aim to provide managers and the Fire Services the information they need to plan ahead. All the work we've done so far suggests that understanding how the moisture content of vegetation changes is the key to doing this. Our main priority now though is demonstrating the value of a good understanding of fuel and fire behaviour and securing funding to further develop the system

Acknowledgements

FireBeaters was funded by The Scottish Executive, Scottish Natural Heritage, The Game Conservancy Trust and the Natural Environment Research Council. We are indebted to Glen Tanar Estate, Ralia Enterprises, Whitburgh Estates and the Scottish Agricultural College for access to their land and support for our burning programme. The Fire and Rescue Services from Dumfries and Galloway, Grampian, Highlands & Islands and Lothian & Borders provided use with huge quantities of wildfire data as did the Peak District National Park and Dorset County Council.

Papers presented to the *Wildfire 2007* conference, North Yorkshire (June 2007)

FireBeaters: towards a management and wildfire forecasting system for the UK

Davies G.M. & Legg C.J.

The FireBeaters project at the University of Edinburgh, together with the Met Office, is developing a fire behaviour forecasting system that will inform land-managers, the Fire Services and the general public about the suitability of conditions for heather burning and the risk of wildfires.

This talk briefly outlines the key controls on fire behaviour and examines the need for a fire forecasting system. We present the first draft of our management fire forecast as well as the results of testing various wildfire prediction systems including the Met Office FSI. We will outline further research and development towards improving FireBeaters and provide information about joining and using the system.

We seek stakeholder opinion on the FireBeaters project and invite collaboration in collecting data that can improve it.

Developing prescribed burning as a management tool

Davies G.M., Legg C.J., Hamilton A. & Gray A.

Traditional management burning plays a crucial role in the ecology of large areas of the UK. In the context of environmental, climatic and social change there is now a need to re-assess how this tool is used and to develop appropriate ecological and fire management strategies. Fire is an extremely powerful tool but should only be used with a thorough understanding of the controls on fire behaviour and impact.

This talk examines the role of fire in the management of the UK landscape and in controlling the risk and severity of wildfires. We examine three case study examples suggesting how prescribed burning could be used in the future in moorland management, forest and woodland management and in the protection of carbon deposits in peatland.

Appendix 4. Background to the Canadian Fire Weather Index (FWI)

The FWI system was completed in 1970 and has been implemented by Canadian fire management agencies since 1971. It has been adopted by a number of other countries including New Zealand another island nation and in other parts of the world as well.

- Provides a uniform method of evaluating fire weather
- Relates the effects of past and current weather on fuel flammability
- Provides numerical ratings of relative fire potential

The FWI system has a modular design and is composed of three moisture codes and three indexes of fire behaviour (Figure 1). There are four weather data inputs to the system: air temperature, relative humidity, wind, and rain in the preceding 24 hours. Weather data is collected at 12 noon and the system is calibrated to show the highest fire danger period in mid-afternoon.

There are two other key inputs. First the FWI is based on the assumption of flat terrain and a standard Canadian Jack Pine forest fuel type. There are other fuel models but the data provided is based on the standard Jack Pine fuel type. The system is designed to work on a broad area basis to give a general fire danger perspective. The system is built on the results from over 20,000 fire tests, prescribed burn results and wildfire case studies.

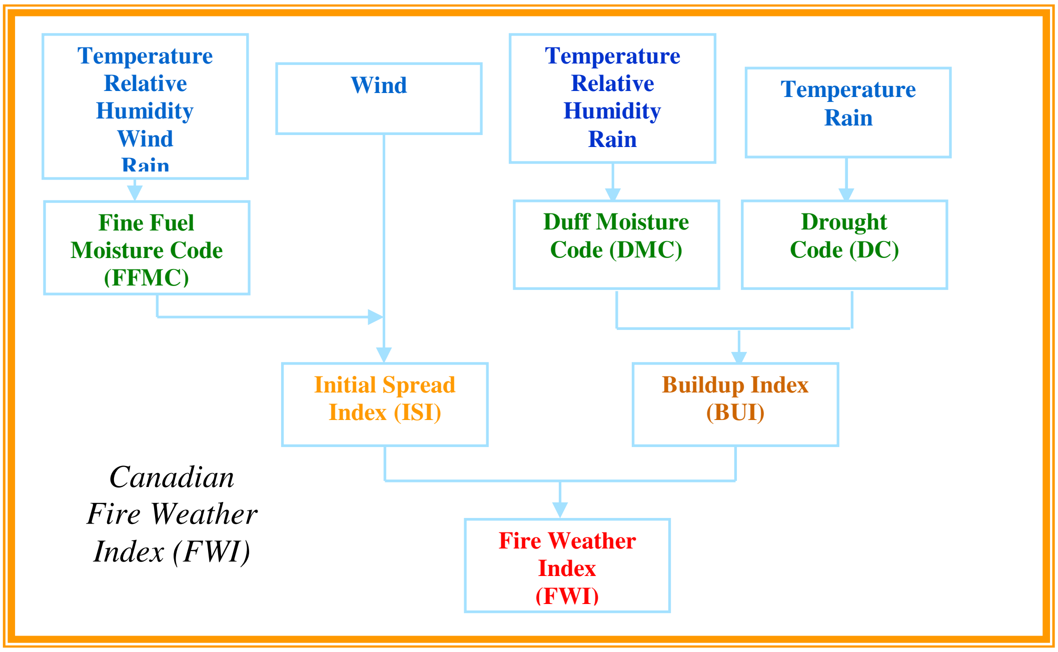

Figure 1: The Canadian Fire Weather Index System.

The definitions and descriptions of the FWI components can be seen in Table 1:

Table 1: The Canadian FWI System Components, Definitions and Descriptions

FWI fuel moisture code	**Definition and description**
Fine Fuel Moisture Code (FFMC)	The numerical rating of the moisture content of litter and other cured fine fuels. This code is an indicator of the relative ease of ignition and flammability of fine fuel. Depth 1.2 cm.
Duff Moisture Code (DMC)	A numerical rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-sized woody material. Depth 7 cm.
Drought Code (DC)	A numerical rating of average moisture content of deep, compact organic layers. This code is a useful indicator of seasonal drought effects on forest fuels. Depth 18 cm.
Initial Spread Index (ISI)	A numerical rating of expected rate of fire spread. It combines the effects of wind and FFMC on rate of spread without the influence of variable quantities of fuel.
Build Up Index (BUI)	A numerical rating of the total amount of fuel available for consumption that combines DMC and DC
Fire Weather Index (FWI)	A numerical rating of fire intensity that combines ISI and BUI. It is suitable as a general index of fire danger.

The FWI system also has functions relating to wetting and drying rates, for each fuel moisture code, that raise or lower the codes depending on the weather inputs. These functions are based on standard conditions and also take day length and other seasonal factors into account. The standard conditions are air temperature 21.1 degrees centigrade, 45% relative humidity, and a 13 kilometre per hour wind at noon in July. Under these conditions the length of time for most of the available moisture (2/3rds) to be lost is: FFMC within 1 day, DMC 15 days and DC 53 days. For FFMC to fully dry out takes around 3 – 5 days in the standard conditions.

The general “benchmark” fire behaviour implications of the various code and index values are as shown in Tables 2 – 7.

Table 2: FFMC Values and Fire Behaviour Descriptions:

Value	Fire Behaviour Description
74	Ignition threshold
80	Continuous surface spread
90	Spot fire potential
92	Extreme fire behaviour

Table 3: DMC Values and Fire Behaviour Descriptions:

Value	Fire Behaviour Description
20	Fuel layer becomes available for combustion
40	Fuel layer aids in spreading and intensity of fire, fire behaviour noticeably increases
60	Onset of extreme fire behaviour
150	Extreme fire behaviour

Table 4: DC Values and Fire Behaviour Descriptions:

Value	Fire Behaviour Description
15	Start-up value, 3 days drying after saturation
300	Onset of smouldering combustion
500	Sustained smouldering combustion, moisture reversal can occur, indicator of mop-up and extinguishment difficulty

Table 5: BUI Values and Fire Behaviour Descriptions

Value	Fire Behaviour Description
<30	Low intensity surface fire
>30	Deeper heavier fuels becoming involved in combustion with resultant increase in fire behaviour due to increase in available fuel
60	Threshold for continuous/extreme fire behaviour, safety concerns exist, mop-up problems will likely occur
90	Severe fire behaviour, more erratic fire behaviour, most fires will escape initial attack

Table 6: ISI Values and Fire Behaviour Descriptions

Value	Fire Behaviour Description
10	Threshold for onset of crowning in most conifer fuel types
20	Onset of extreme fire behaviour
70	Severe fire behaviour conditions, major conflagrations, rarely exceeds this value

Table 7: FWI Values and Fire Behaviour Descriptions

Value	Fire Behaviour Description
3	Threshold for sustained combustion and fire growth
25 - 30	Onset of crowning and extreme fire behaviour
70	Severe fire behaviour conditions, erratic fire behaviour, disaster fires.