Developing a live fuel moisture model for moorland fire danger rating

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Abstract

Fuel moisture plays a crucial role in determining fuel flammability and fire behaviour but most models of fire hazard only refer to dead fuel assuming that it is the most important component driving fire behaviour. In a number of fuel types, particularly shrublands such as *Calluna*-dominated heathlands, live fuels can form a significant or even dominant proportion of the total available fuel. Understanding variation in their moisture content is a crucial first step in developing a robust fire danger rating system. An existing system based on the CWFIS has been implemented for the UK but does not perform well for shrub fuels. Live *Calluna* does not always follow obvious patterns of variation in FMC with particularly low values encountered in spring in cold or freezing conditions. We review the need for and development of a fire danger rating system and the role of live fuel moisture. We describe the first stages in the development of a physiological model that accounts for seasonal variation in leaf conductance, water viscosity, freezing conditions and rates of water uptake.

Keywords: Calluna vulgaris, heather, fire behaviour, Canadian Wildland Fire Information System, stomatal resistance, viscosity of water, Penman-Monteith equation, physiological model.

1 Introduction

Wildfires are a significant problem in the United Kingdom despite our oceanic climate and the impact of climatic change is likely to make them not only more frequent, but also more intense and severe. Wildfires are most significant in upland regions where flammable fuels such as heather (*Calluna vulgaris*), gorse (*Ulex europaeus*) and purple moor grass (*Molinia caerulea*) dominate. Fires can

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spread over large areas causing significant ecological damage and, in particularly bad years such as 2003, they can place a real strain on the resources of the Fire and Rescue Services. Wildfires are also common in the heathlands of southern England, in grain crops and grass and in areas of gorse adjacent to urban or suburban areas. The uplands of the UK are unusual in that large areas of them are managed using traditional prescribed burning (muirburn as it is known in Scotland) that is particularly associated with the management of heather-dominated moorlands. It is used to provide habitat suitable for red grouse *(Lagopus lagopus scoticus*) for shooting, for red deer (*Cervus elaphus*) and the grazing of domestic stock. The importance of grouse shooting to the economy of large areas of rural Scotland and northern England means the majority of fire behaviour research has been carried out in such habitats, though there are some notable exceptions [1–3].

There is growing evidence to suggest that carefully controlled burning can have a positive effect on biodiversity and benefit a range of organisms [4, 5]. In the UK however there is growing concern about the sustainability of regular burning on peatland areas particularly with regards to its impact on drinking water quality, carbon sequestration and the impact of wildfires that occasionally originate from escaped management burns. Despite the controversies there is growing acknowledgement in many areas that burning can be used to achieve a multitude of management objectives such as forest regeneration 6, prevention of scrub encroachment [7] and fuel management 8 whilst fire is being re-introduced in several other countries where heathlands are recognised as threatened and valuable habitats [7, 9, 10].

For a country where fire is an important ecological factor it is perhaps surprising that until very recently the UK lacked any form of fire danger rating system and records on wildfire events are still not collected on a systematic basis. This creates a real challenge for managers and researchers alike. Recent research [11] has revealed important information on the timing of wildfires in the UK and it is noticeable that the majority take place during early spring, a period that coincides with the legal period for burning in the UK (this lasts from October to April with variations according to country and altitude [12, 13]) rather than a meteorologically defined hot, dry fire season as experienced in many areas of the world.

2 Developing a fire danger rating system

The introduction in 2005 of the Met Office Fire Severity Index (MOFSI) [14] was an important first step towards providing land-managers and the fire service with a fire danger rating system. There are however acknowledged problems with this system which is an almost direct implementation of the Canadian Wildland Fire Information System (CWFIS, [15]) that uses the daily “FWI” rating to calculate a five point scale of fire “severity”. The system was designed for a very specific task in response to the Countryside and Rights of Way (CROW) Act that designated areas of Open Access Land where the public had freedom to roam. As part of this legislation land-owners were given the right to suspend access in "exceptional" conditions when damaging fires were likely. MOFSI was calibrated such that a value of 5 relates to weather conditions that would normally be expected once every four to five years – severe drought conditions when intense and severe fires that ignite peat and are difficult to control are likely. The ratings of one to four by contrast are ill defined and have relatively little useful meaning. The system was calibrated against periods of known high fire frequency and against land-managers perceptions of fire risk, but was not based on any direct observations of fire behaviour.. A second major problem is that as the CROW Act only applies to Wales and England and the system is not currently operational in Scotland where, ironically, heather and grass vegetation susceptible to wildfire cover a much greater area of land.

Heather, an evergreen dwarf shrub that forms dense and continuous canopies, is a very different habitat to those for which the CWFIS was designed. Recent research in Scotland [11, 16, 17] has demonstrated that MOFSI and the CWFIS do not provide an accurate representation of fire behaviour in *Calluna* fuels and similar problems have been noted with the system in shrublands elsewhere [18, 19]. Data on wildfires reported to the fire & Rescue Services from 2003-2006 for four regions in Scotland showed that MOFSI does not predict when wildfires are likely to occur, though the proportion of high-magnitude fires is somewhat greater when MOFSI is moderate to high (Figure 1).

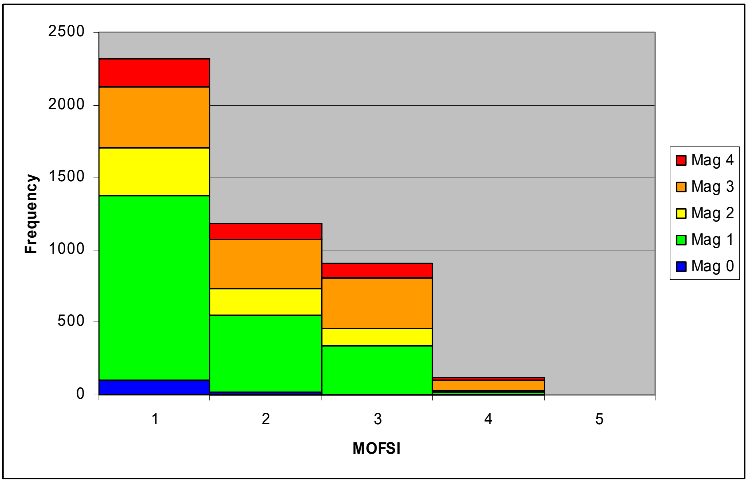

Figure 1: Number of wildfires reported in the five classes of the Met Office Fire Severity Index (MOFSI) for four regions of Scotland.

The data also demonstrate that days with exceptional conditions are likely to be exceedingly rare in some areas of the UK with no wildfires occurring in 'exceptional' conditions in this study. By contrast the Fine Fuel Moisture Code (FFMC) of the CWIFS,, which is designed to represent the moisture content of dead litter and pine needles, performed rather better as a predictor of fire risk (Figure 2).

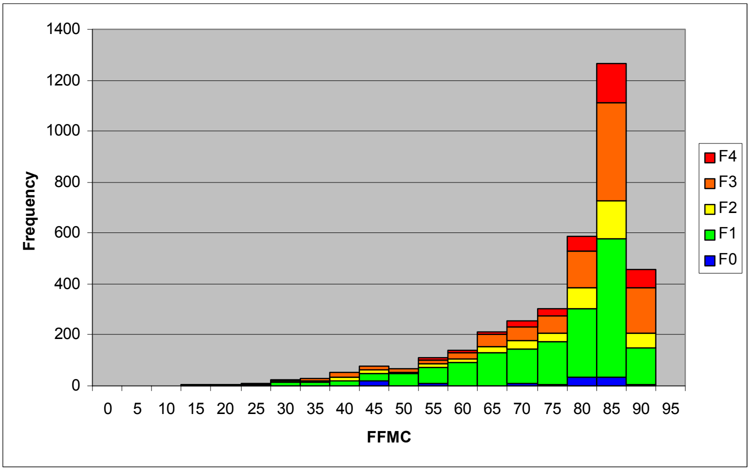

Figure 2: Number of wildfires recorded in four Scottish regions for different categories of the Fine Fuel Moisture Code (FFMC). Magnitude refers to the size of fire, its impact and difficulties in extinguishing it.

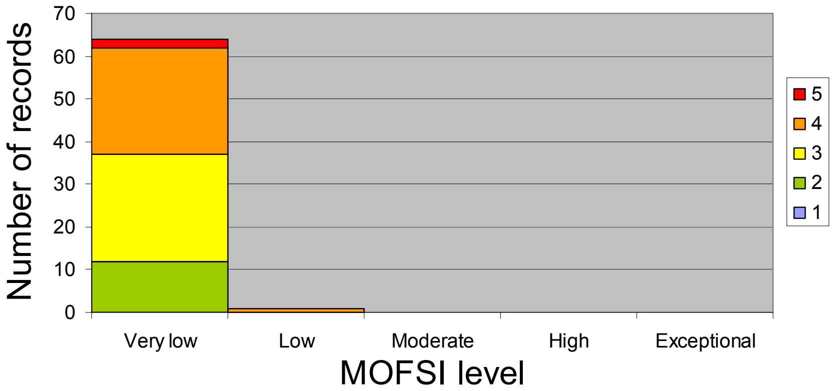

Figure 3: Ease of control of management fires in *Calluna* fuels as recorded by volunteer managers in relation to daily estimates of fire "severity" from MOFSI. 1 = not sustaining, 5 = fire displays extreme behaviour and escaped control.

The outputs of the CWFIS were further examined by comparing forecast Initial Spread Index (ISI) and Fire Weather Index (FWI) with the actual rate of spread and intensity of experimental *Calluna* fires though they showed little predictive value [17]. Furthermore the results of a participatory research exercise with land-managers revealed that the system did not represent the variation in fire behaviour they observed in the field (Figure 3).

Alternatives to the CWFIS do exist and are also being investigated, including the Behave model [20], based upon Rothermel's [21] fire spread equation which forms a central plank on the American National Fire Danger Rating System. Initial tests suggest it performs rather better than the CWFIS [11, 16, 17]. Legg et al. [11] developed empirical models of fire spread and intensity for fires in *Calluna* dominated fuels and, though simpler versions use just vegetation height and wind speed as inputs, predictions were considerably improved when live fuel moisture was included.

The precise role of fuel moisture in controlling fire spread in shrubland fuels remains unclear and there is an urgent need to untangle the relative importance of dead and live fuels. An on-going ignition experiment reveals that the main role of fuel moisture is to operate as an on-off switch determining fuel ignitability and that the moisture of both live and dead fuels are important (Figure 4). It is possible that fire behaviour responds in a non-linear fashion to changes in moisture content with critical thresholds of moisture relating to the ability of self-sustaining fires to develop and for fires to develop extreme behaviour. Further work is currently underway to clarify such factors.

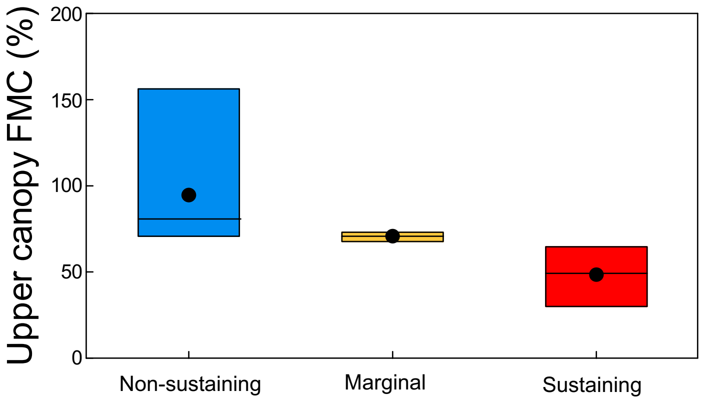

Figure 4: The effect of the moisture content of live fine fuel in the upper canopy of *Calluna* stands on the potential for the development of self-sustaining fires.

3 Forecasting live fuel moisture

3.1 The importance of developing a forecast

The work briefly reviewed above demonstrates a number of points: firstly that there are inconsistencies in the performance of MOFSI/CWFIS in that the FFMC code appears to forecast wildfire hazard relatively well but the ISI and FWI perform badly for fire behaviour, live fuel moisture plays an important part in determining fire establishment and behaviour, and finally that live fuel moisture is an important and necessary input in a number of existing models that could be developed into forecasting systems.

Examination of one of the models presented by Legg *et al*. [11] and the output of Behave demonstrates how significant the effect a reduction in live and/or dead could be (Figure 5). With relatively robust models of fire behaviour in place [11], and confidence that existing models either already work well or could be adapted for other important fuels such as moss and litter [16], suspended dead fine fuels or peat (Krivtsov *et al*. this volume), the development of a live fuel moisture model would allow significant improvement on our ability to forecast fire danger.

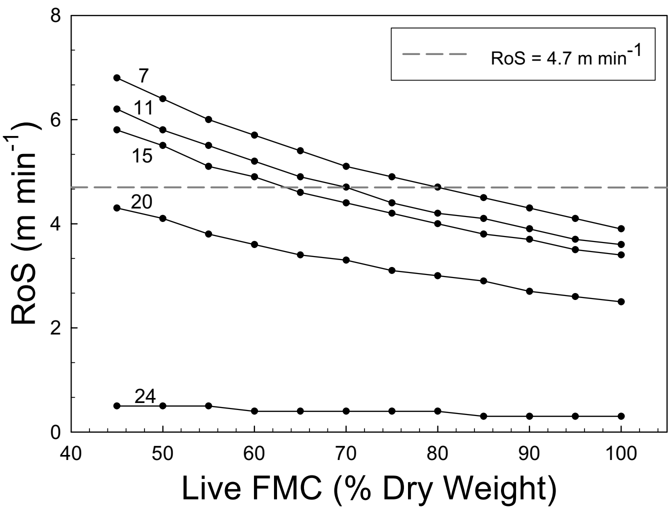

Figure 5: The effect of varying dead and live FMC on predictions from BehavePlus for Davies' [16] Plot 1 when all other inputs are held constant. Individual lines are different dead FMCs. The observed RoS (4.7 m min^{-1}) is shown on the graph.

3.2 Modelling efforts to date

One of the major problems with the CWFIS seems to be that its moisture indices do not accurately reflect changes in the moisture content of either dead or live *Calluna*. This is true both for the FFMC as well as the Duff Moisture Code (DMC) and Drought Code (DC) that have been shown to work relatively well for live FMC elsewhere [22, 23]. These latter two codes are rendered unsuitable due to the fact that, though in some environments they will represent the drying of live fuels due to drought and soil water depletion, in moorland environments peat soils mean that drought conditions rarely occur, though physiological drought may occur due to acid and waterlogged soils that are cold or frozen. The strong performance of the FFMC in forecasting wildfire occurrence may be because this code does seem to work well for the moisture content and ignition probability of moss and litter [11]. Many heather moorlands are underlain by layers of pleurocarpous moss and *Calluna* litter that dry out relatively rapid and are likely to be the relevant fuel for the initiation of accidental fires in the summer – cigarette ends and embers are likely to land in this fuel. Whilst dry periods may also occur in spring allowing these fuels to burn and contribute significantly to fire behaviour [16], such fuels are normally exceedingly wet (moisture content of > 200%) during this period. Many wildfires in spring, rather than starting from accidental sources and building up in the moss/litter layer are purposefully ignited and burn solely in the crowns of heather plants and thus resemble, in miniature, an independent crown fire.

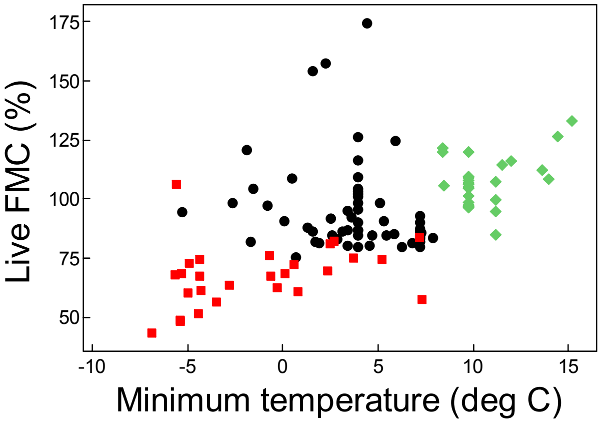

Figure 6: Variation in the moisture content of live *Calluna* with changes in mean minimum temperatures for three different seasons. Red squares = spring, back circles = autumn and green diamonds = summer.

Observation of seasonal changes in *Calluna* live FMC reveal that values are lowest in spring and increase in response to the onset of plant growth and increased activity during the summer before declining over the winter months [16, 17]. In this respect it displays a trend similar to that observed in many other fuels. Bearing in mind the fact that live fuels form the majority of material burnt on *Calluna* fires [17], it is important to note that significant troughs in live FMC have been observed to occur [16]. In the spring of 2003 and 2007 live FMC was observed to drop from a "normal" spring value of around 80% to below 45% whilst dead and moss FMC remained relatively high. Davies et al. [24] demonstrate that these periods can be, at least qualitatively, linked to periods of cold or frozen ground with clear, sunny skies when root resistance to water uptake is increased but water loss continues due to damage to leaf cuticles. The relationship with, for example, temperature that this produces is significantly different from that found in most fuel moisture models (Figure 6) and explains some of the problems with the CWFIS where a rise in temperature always equates to drier fuel.

3.3 A physiological model of live fuel moisture

The difficulties described above mean our focus needs to be on the development of a relatively complex physiological model of plant moisture status if we are to build a system that is reliable and modifiable for habitat and environmental differences between different moor and heathland types. Fortunately a significant amount of work already exists, not just on plant physiology in general, but also specifically for *Calluna* on which much pioneering physiological work was done, e.g. [25–29]. In addition research aimed at quantifying plant productivity, activity and response to environmental variables has led to the development of several models and data-sets that could help to form the basis of a model. Though most of this focuses on changes in plant water status (e.g. leaf water potential) and at best relative water content (which can be related empirically to moisture content on a dry weight basis), it is sufficient for us to be able to at least outline a model and demonstrate some of the more interesting relationships we envisage it would include whilst highlighting current knowledge gaps that need to be filled.

3.3.1 Current status of the model

Our model is still at an early stage of development but we will base changes in moisture content on the pressure difference between air (vapour pressure deficit) and soil (soil water potential). Such models are already common in plant physiology and are used to estimate stem and leaf water potential, rates of photosynthesis and plant productivity. Importantly rates of water transport between the soil and the plant and the plant and the atmosphere need to be modified to account for changing resistance in the soil-air plant pathway caused by changes in weather and plant activity and here we focus on explaining important mechanisms that need to be understood.

3.3.2 Estimating water loss – the importance of leaf water conductance

Water loss is defined by a simplified version of the Penman-Monteith equation 16 that estimates water loss from leaves as a function of temperature, humidity, wind speed and solar radiation.

$$E = \frac{(s \times \Phi) + (\rho a \times cp \times ga \times \delta e)}{\lambda \times (s + \gamma \times (1 + ga / gl)}$$

where:
s = slope of the saturation vapour pressure curve (Pa K^{-1})
Φ = net incoming radiation (W m^{-2})
ρa = density of dry air (kg m^{-3})
cp = specific heat capacity of air (J kg^{-1} K^{-1})
ga = boundary layer conductance (m s^{-1})
δe = water vapour pressure deficit (Pa)
λ = latent heat of vaporization (J kg^{-1})
γ = psychrometer constant (Pa K^{-1})
gl = leaf/canopy conductance (m s^{-1})

Importantly the Penman-Monteith equation allows us to vary stomatal resistance and thus to include the effects of changing leaf conductance due to over-winter damage to leaf cuticles. Varying *gl* has a significant effect on transpiration rates (Figure 7). Unfortunately we do not currently have good data on exactly how *Calluna* leaf conductance changes over the course of an entire year though Miranda et al. [30] measured values of roughly 4 – 20 mm s^{-1} during the months of May to August. Obtaining estimates during early spring and understanding the rate of change in conductance over the course of the winter and spring is a priority.

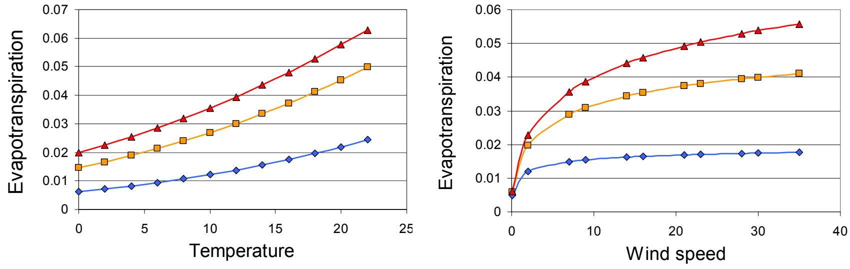

Figure 7: The effect of changes in stomatal conductance (diamonds squares and triangles are 4, 12 and 20 mm s^{-1}), temperature (°C) and wind speed (m s^{-1})on evapotranspiration (g m^{-1} s^{-1}) estimated using the Penman-Monteith equation.

3.3.3 Estimating water uptake – changes in root and stem resistance

At a very simple level the water status of leaves of a plant can be represented as a function of soil water potential, evapotranspiration and the resistance of the soil-leaf pathway:

$$\Psi l = \Psi s - E \times R$$

where:
Ψl = Leaf water potential
Ψs = Soil water potential
E = Evapotranspiration
R = Resistance of the soil-leaf pathway

Understanding the factors that affect *R* is critical to developing a robust model. As it stands, changes in soil water potential could be used to reflect the onset of drought conditions and reduced water availability for uptake but, as shown elsewhere [16, 24], significant reductions in live FMC can occur even on permanently wet peat soils but where the availability of water may be reduced due to cold or freezing conditions combined with high acidity and limited root development. We therefore need to understand the following impacts on resistance:

- The effect of increased viscosity of water with declining temperatures will reduce both water uptake through roots and transport within the xylem.

- Xylem cavitation (the formation of breaks in the water column) will occur when evapotranspiration is high but soil water availability is low. Such events have been recorded in *Calluna* in the context of drought conditions in summer [29] but need to be understood in the context of winter conditions. Cavitation will introduce an important feedback mechanism: where stomatal control has been lost cavitation will increase stem resistance, reduce water flow to leaves leading to further water loss, increased water demand and hence cause further cavitation.
- Rates of recovery from cavitation and refilling of plant vessels and leaves. Recovery from cavitation events may take place on a diurnal cycle but may also only occur at the onset of growth in early summer with the production of new vessels prior the green-up.
- The importance of precipitation in the recovery of water status. Direct rainfall as well as dew, mist and fog may provide an important mechanism by which plants recover their water status during spring. We also need to develop models of the potential of *Calluna* canopies to intercept ran and retain surface moisture.

Additional complications also exist in that at present leaf water potential is only empirically linked to relative water content [25] and a further regression equation links RWC to fuel moisture content on a dry weight basis. Both of these models are currently based on a limited amount of data collected solely during the summer months when FMC values are relatively high.

4 Summary

A physiological approach to modelling live fuel moisture content is valuable as it enables us to capture some of the important underlying mechanisms that affect changes in the moisture content of fuels during the spring and it helps us to understand the raised fire hazard in this period that in some years, like the recent outbreak seen in 2003, has resulted in extreme fire activity [16]. The model we have developed is in its early stages and a number of important mechanisms still need to be understood. The model is also currently based on a number of assumptions, such as continual soil water availability outside of freezing conditions, that limit its applicability to upland regions with significant peat deposits. Incorporating variation in soil type such that it can be applied for southern heathlands on sandy soils and other shrubs such as *Ulex* sp. is also important. Collaborative research involving fire scientists and plant physiologists on the links between plant water status and fuel moisture content will pay dividends for understanding fire behaviour and impact in shrublands globally.

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