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A flammability phenology for dry mixed heaths and its implications for modelling fire behaviour

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ABSTRACT

Background. Fires in temperate dry heaths burn dead and live fuels and are increasing in frequency. Models that describe these fuels and their contribution to fire behaviour is becoming of greater importance. **Aims.** We sought to identify variations in fuel moisture and flammability in dry heath fuel types throughout the year and assess the strength of phenological shifts to influence predicted fire behaviour. **Methods.** Six plant species from three dry heaths in the United Kingdom (UK) were collected throughout the year, their moisture content and effective heat of combustion measured. Data were used to parameterise a dynamic fuel model and undertake a sensitivity analysis using BehavePlus. **Key results.** Phenological changes in live fuel moisture had the greatest effect on predicted fire behaviour where variations between late winter–early spring and late spring–summer, led to a four-fold difference in fire rate of spread. Dead fuel moisture had an effect in the summer months but was dampened significantly by phenologically high live fuel moisture content. **Conclusions.** Phenological drivers of live fuel moisture in temperate shrubland fuels must be included in models that predict fire behaviour. **Implications.** Using the data presented, models such as BehavePlus can be adapted to include this variability to predict fire behaviour in temperate heathland ecosystems.

Keywords: fire behaviour, fire ecology, flammability, fuel moisture, heathlands, heat content, heat of combustion, shrub fuels.

Introduction

Heathland and shrub habitats account for over 280,000 km^2 of land in Europe and are the second largest plant-based land cover type in the European Economic Area. Their distribution across Europe ranges across climatic zones from as far south as 34.7° latitude (Southern Cyprus) to as far north as 71.2° latitude (Northern Norway). European dry heaths account for approximately 25,500 km^2 of this heathland area and occur on freely-draining, acidic to circumneutral soils that typically have a low nutrient content. Many United Kingdom (UK) dry heathlands are designated as Sites of Special Scientific Interest (SSSIs) or special areas of conservation (SACs) as they can be particularly biodiverse and host rare flora and fauna. In the UK these dry heathlands tend to be populated by dwarf shrub communities of the Ericaceae family including *Erica cinerea*, *Erica tetralix* and *Calluna vulgaris,* as well as the dwarf gorse species *Ulex gallii* (Fabaceae) and the grass *Molinia caerulea* (Poaceae) as the main fuel types, whilst other parts may be dominated by *Ulex europaeus* (Fabaceae) as the taller woody shrub component or *Pteridium aquilinum* (Bracken fern, Dennstaedtiaceae).

Heathlands and other dwarf shrub dominated communities are amongst the most fire prone landscapes in northern temperate climates. Between 2009 and 2021, 28,900 ha of ‘heath and bog’ land cover types burned in England (Forestry Commission 2023). Similarly other northern temperate regions are beginning to become more fire prone where for example, the Netherlands saw approximately 405 ha burnt between 2017 and 2022 (the majority of which was heathland) (Stoof *et al.* 2024). Whilst the scale and number of fires in these examples are not anywhere close to those felt in highly fire prone countries such as the United States (US), Canada, Australia and across the Mediterranean, the intermingling of dry heathland with both rural and urban infrastructure means that even relatively small fires can have significant impact not only on habitat but also on homes, businesses, utilities and transport networks. For example, a wildfire at Canford Heath in Dorset, UK, burned 17 ha of SSSI heathland in April 2022. As well has having significant ecological impacts on rare species this heath adjoins one of the largest housing estates in Europe and required 20 homes to be evacuated. Hence it is where fire prone landscapes intermix with significant infrastructure and homes that prediction and planning for fire behaviour becomes particularly critical.

It has been increasingly emphasised that accounting for ecophysiological controls on woody vegetation, such as shrubs, is important for prediction of fire behaviour (Scarff *et al.* 2021; Dickman *et al.* 2023). Ecophysiological effects will not only affect fuel moisture but will also influence the accumulation of structural carbohydrates and lignin (Poorter *et al.* 2009). For canopy fires, increased leaf-density associated with changes in phenological changes in foliar chemistry and carbon allocations has been shown to increase modelled crown fire propagation (Jolly *et al.* 2016). The complex interactions, of what has been coined pyro-ecophysiology (Jolly and Johnson 2018), in respect to fire behaviour and its ecological outcomes realistically require more complex modelling approaches than are useable at the operational level.

Heathland dwarf shrub communities contain a considerable volume of dead and live fuel, both of which can carry intense fires (Fig. 1). Whilst the response to variations in temperature and humidity and their impact on the ignition and flammability of dead fuels is relatively well understood, the variability in live fuel flammability is less well studied, yet it is the live fuel components that contribute considerably to fire behaviour in UK dwarf shrub communities (Davies and Legg 2008, 2010; Little *et al.* 2024*a*). Live fuel moisture, like dead fuel moisture, is strongly associated with plant ignitability (Xanthopoulos and Wakimoto 1992) and is particularly important in understanding fire behaviour (Catchpole and Catchpole 1991; Yebra *et al.* 2013; Rossa and Fernandes 2017; Pimont *et al.* 2019) especially in heathland shrubs (Davies *et al.* 2006; Little *et al.* 2024*a*). Live fuel flammability is strongly influenced by phenology, for example a 'spring window' for increased fire risk is noted in broad-leaved species in Canada just ahead of new leaf flush or 'green up' (Parisien *et al.* 2023). This is also observed in the UK where the largest total burned area (15,000 ha) of 'heathland and bog' in England occurs in the month of April (Forestry Commission 2023), when these dwarf shrubs hold leaves that are essentially dormant ahead of spring green up. In such mid and high latitudes phenology is primarily controlled by temperature and photoperiod (Myneni *et al.* 1997; White *et al.* 1997; Chuine and Cour 1999; Jarvis and Linder 2000; Schwartz and Reiter 2000; Peñuelas *et al.* 2004; Jolly *et al.* 2005). Regional water availability is also important and physiological drought in cold conditions can also be an important factor in controlling live fuel moisture in dwarf shrub communities (Davies *et al.* 2010).

Fig. 1. Example of the vegetation types for temperate dry mixed heath (*a*). Images of Woodbury Common, United Kingdom. In the dry heathlands herbaceous fuels such as *Molinia caerulea* grass vary between live (*b*) and dead state (*c*) at different times of the year and are interwoven through the otherwise mixed dwarf shrub dominated fuel load that burn intensely in live state. See also Supplementary Fig. S3 for more images this mixed heath fuel type throughout the seasons.

As well as both dead and live shrub fuel moisture varying with phenology, it is also likely that the energy content held within fuels varies seasonally. The heat content of plant material not only varies between species but also with plant parts (de Dios Rivera *et al.* 2012), this energy (heat) content of the plant material links to the energy (heat) released during combustion (Andrews 2018). The phenological period of growth of dry heathland plant species must also impact the heat content the material holds, due to variations in carbon allocation through the seasons. To date the energy content of different dry heath fuel types (both of herbaceous and shrub fuels) has been relatively unexplored and how this might vary throughout the year within species has not been considered.

Information on vegetation phenology is increasingly integrated into fire occurrence, behaviour and effects modelling (Dickman *et al.* 2023). Satellite observations of vegetation greenness have been successfully used to estimate wildfire danger in northern boreal forests (Leblon *et al.* 2007) and also appear to correspond to fire occurrence in the UK (Nikonovas *et al.* 2024*a*). Additionally, the National Fire Danger Rating System (NFDRS) of the US has been improved by including a new live fuel moisture model that includes a growing season index, derived from a meteorologically generalised phenology model (Jolly *et al.* 2005). This modification was designed to reflect within and between season live fuel conditions, including green up and herbaceous curing and dormancy phases, highlighting the importance of these factors on flammability and fire behaviour. Traditionally non-fire prone countries such as the UK and others that host northern temperate heathlands, currently tend to have low operational wildland fighting budgets. Therefore, adaptation of existing computationally inexpensive fire behaviour predictions models is of real value if they can be well tuned to these land cover types. The low cost and useability of models based on the coupling of the Rothermel (1972) fire spread and the Albini (1976) fireline intensity equations such as Behave released in 1984 (Burgan and Rothermel 1984), with subsequent iterations of, e.g. BehavePlus (Andrews 2018) through to the newly released Behave[7], are particularly useful and simple to apply. As this is free to use software and the model code has been made available, it has been re-coded and expanded in the wildfire analyst (WFA) software developed by TechnoSylva, Inc. (San Diego) (Ramirez *et al.* 2011; Technosylva, Inc. 2024), and in FireInSite (Nikonovas *et al.* 2024*b*), a web-based app designed for the UK and developed by a consortium of UK Universities and stakeholders.

Minsavage-Davis and Davies (2022) and Minsavage-Davis *et al.* (2024) recently developed a set of fuel models that describe dwarf shrub (*Calluna*) dominated habitats. All of these fuel models are static fuel models, meaning there is no transference of live to dead fuels as a consequence of phenology. Dry heathland communities often have seasonally large live herbaceous fuel loads, therefore using these models in static state for dry heathlands means that fire behaviour predictions, using the Behave family of models, won't allow for understanding of how live grass or bracken dynamic curing (linked to the approach of a fire front) will interact with the live woody components in terms of fire behaviour due to phenology-related variables. Here we explore the flammability phenology of UK dry heathland fuels by collecting fuel samples from three dry heathlands throughout an annual cycle for a range of heathland plant species and assessing their flammability on the same day as collection. Our aim is to identify the overall variability in phenological factors that influence flammability in UK dry heath fuel types and explore the significance of seasonal variations in influencing fire behaviour. This is contrasted to the seasonal occurrence of fire in the region via a satellite-based analysis. We then explore how the measured phenological variability in dead fuel moisture, live fuel moisture and heat content influence fire behaviour predictions made by the BehavePlus modelling system (Heinsch and Andrews 2010), including enabling dynamic curing during the fire of the lower moisture live herbaceous fuel components. Our aim being to provide novel data and an improved understanding of phenological fuel model dynamics for this fuel type when used to predict fire behaviour in accessible low-cost systems based around BehavePlus.

Materials and methods

Fuel sampling

Three lowland dry heathlands in the southwest of the UK were studied for 12 months between March 2021 and the end of February 2022, to understand the overall seasonal phenology of fuels. Two were located in Dorset (Hardown Hill (50°44′41″N, 2°50′38″W); Duddle (50°43′53″N, 2°22′22″W)) and another in Devon (Woodbury Common (50°40′57″N, 3°21′38″W)). All three heaths included a mixture of dwarf shrub fuels including *Erica cinerea*, *Erica tetralix*, *Calluna vulgaris* and *Ulex gallii* with interspersed *Molinia caerulea* grass (Fig. 1) and *Pteridium aquillinum* and *Ulex europeaus* at the edges and in patches.

Vegetation samples were collected from *Ulex gallii, Ulex europeaus, Erica cinerea, Calluna vulgaris, Molinia caerulea* and *Pteridium aquillinum* every 2 weeks over the 12-month period. The samples were taken in the morning between 11:00 am and 11:30 am on the same day at all sites (on days where there was not precipitation). This sampling time was selected to allowed sufficient time for all samples to be tested for their flammability the same day in the laboratory. Dead fuel moisture is known to vary throughout the day, being typically wetter in the early morning and drying throughout the day. To ensure that our sampling timing of between 11:00 am and 11:30 am was not significantly biasing our results to wetter fuels we collected samples of both dead and live *Ulex europeaus* hourly on a July day (5 July 2021). This indicated that the sampling period between 11:00 am and 11:30 am fell after the early morning peak and that the fuel moisture sampled was reflective of the drier parts of the day (Supplementary Fig. S1).

Dead and live fuel samples were taken if both were present, but this varied between species and throughout the year. Dead and live fuel samples were present all year from both *Ulex* species. The health of the *Erica* and *Calluna* was good, with few dead specimens or high volumes of dead branches or leaves in all three heathlands, such that only live fuel samples were collected. However, during the winter to early spring samples were live but dormant compared to live and green in the summer months. *Molinia* and *Pteridium* varied between live fuels and dead fuels depending on the season but it was possible to collect both in their dead fuel state throughout the year.

Approximately the top 15 cm of the shoots of the shrub fuels (*Ulex* sp., *Erica* sp., *Calluna vulgaris*) were sampled. For *Molinia caerulea*, whole grass blades were taken, whilst for *Pteridium aquilinum* each frond was cut into sections of approximately 10 cm × 10 cm such that they would fit in the flammability testing apparatus. To retain field level fuel moisture, the samples were placed into pre-weighed polyethylene storage bags, sealed and transported to the lab at the University of Exeter for analysis the same day. A Kestrel Fire Weather Meter (F400 Fire Weather Pro, Kestrel instruments, USA) was used to record the air temperature (°C) and relative humidity (%) at each sample location (Fig. 2).

Flammability analysis

A total of 799 fuel samples were analysed on the same day as they were collected to avoid effects of changes in fuel moisture. Two sub-samples were used for flammability testing and a third from each species from both dead and live fuel was weighed and dried in a drying oven set at 40°C until dry for 2 weeks and checking that a constant weight was obtained before reweighing and calculating fuel moisture content. Fuel moisture was calculated as follows:

$$\text{Fuel Moisture} = ((\text{Fresh weight} - \text{dry weight}) / \text{dry weight}) \times 100$$

Samples were tested in duplicate using an iCone Calorimeter (Fire Testing Technology, East Grinstead, UK). Equal volumes of fuel were placed in a mesh basket and placed under a heat flux of 50 kW/m^2 (equivalent to ~750°C, chosen based on measurements taken in the field during dry heathland fires in Dorset UK, by the team). The time to ignition (s), peak heat release rate (max fire intensity) (kW/m^2) and the effective heat of combustion (MJ/kg) were measured for each sample. All samples were given 4 min of heating to assess whether ignition would occur. For the samples that ignited the rate of heat release was analysed until flaming ceased.

Wildfire observations

To identify when fires tend to occur in dry heathlands in the South and Southwest of UK, we used the satellite based active fire detection dataset from the visible infrared imaging radiometer suite (VIIRS) sensor (VNP14IMGML; Schroeder *et al.* 2014). The detectable fire size depends on fire intensity (which VIIRS observes as anomalies in brightness temperature) and background conditions. During daytime overpass (~1:30 pm local time) the algorithm has approximately 50% probability to detect fires of approximately 40 m^2 in size. While during night-time overpass (~1:30 am local time) the same detection probability applies to fires <10 m^2. (Schroeder *et al.* 2014), highlighting that this algorithm is suitable for detection of the relatively small scale of vegetation fires in the UK. Data were isolated for the South and Southwest UK and assessed between 2012 until 2023. Vegetation fire sources were separated from other heat sources (e.g. oil refineries) by selecting fire detections that occurred in vegetated land cover types. Each VIIRS fire detection was matched to a UK Centre for Ecology & Hydrology (UKCEH) land cover type (Morton *et al.* 2020) and 'events' that occurred in urban/suburban land, bare land and water were removed, following the methodology outlined in Nikonovas *et al.* (2024*a*).

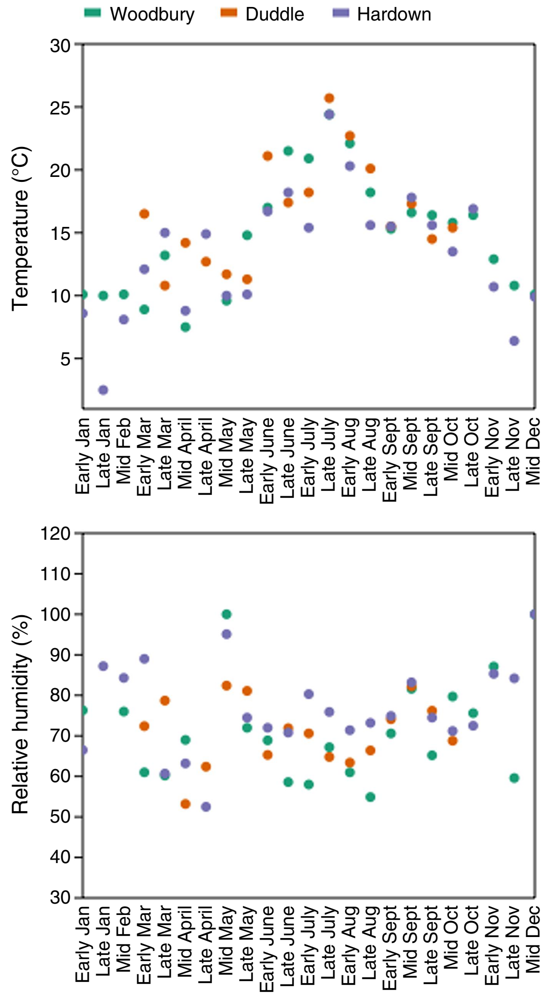

Fig. 2. Temperature and humidity measurements taken at ~11:30 am for the three study heathlands.

Fire behaviour and phenology driven model sensitivity analyses

To run the surface fire module in BehavePlus the fuel has to be described numerically in a fuel model. Environmental variables of dead fuel moisture (%), live fuel moisture (%), wind speed (km/h) and slope angle (%) are also included. Using these parameters, the rate of surface fire spread (m/min), flame length (m) and fireline intensity (kW/m) can be estimated. BehavePlus does not currently contain any fuel models directly tailored to UK heathlands. We chose the Minsavage-Davis and Davies (2022) fuel model to provide the baseline model for the sensitivity analysis as it contains a considerable herbaceous fuel content, reflective of the presence of *Mollinia caerulea* and *Pteridium aquilinum* in this habitat types (see Fig. 1) We made some modifications to this fuel model (Table 1a). Firstly, switching this from a static to a dynamic fuel model allows dynamic curing and transfers a fraction of the fuel load of the live herbaceous for moisture ranges between 30 and 120% (see Burgan 1979; Andrews 2018). Secondly for the mixed heath communities the surface area/volume (SA/V) of the live herbaceous component is smaller than that described Minsavage-Davis and Davies (2022) so this was shifted from 8810 to 5906 accordingly. As the fuel models are tailored towards generating realistic fire behaviour based on fire behaviour observations, rather than absolute measurements fuels, we tested the performance of this new fuel model by generating example BehavePlus predictions for three prescribed heathland fires as well as the Canford Heath wildfire (April 2022) (all in Dorset, UK) using the measured weather parameters for the fires. This indicated that the edited fuel model provided realistic outputs based on the observations of the fires. The results are shown in the Supplementary Tables S1 and S2.

Three variable input values were explored in the sensitivity analysis. The first is the dead fuel heat content and sits within the fuel model itself (Table 1a). BehavePlus uses 'heat content' which is as measured from oxygen bomb calorimetry. In order to apply the measured effective heat of combustion (EHoC) values within BehavePlus we converted EHoC to heat content. To achieve this, we used a linear bivariate regression model (least squares) to assess the relationship between 32 matching plant species heat content and EHoC from the collated dataset of Vitali *et al.* (2022). This produced a strong positive correlation ($r = 0.81$) (Supplementary Fig. S2) and yielded a linear relationship:

$$\text{Heat Content} = 0.4383(\text{EHoC}) + 14.614 \quad (1)$$

Eqn 1 was used to convert the measured EHoC for each sample through the year to heat content for use in BehavePlus. Because the dry heathlands have several different species intermixed, we used the mean dead EHoC of all species for each date of measurement and applied a three-point average smoothing (Fig. 3). This resulted in a seasonal variability in modelled heat content, as shown in Fig. 4, that

Table 1. Fuel and environmental parameters used and edited within the fuel model for the sensitivity analyses.

	Units	Input values	Source
(*a*) Fuel model input variables			
Fuel model type		Dynamic (this study)	Modified from Minsavage-Davis and Davies (2022)
1-h fuel load	t/ha	2.5	
10-h fuel load	t/ha	0	
100-h fuel load	t/ha	0	
Live herbaceous fuel load	t/ha	8	
Live woody fuel load	t/ha	5.6	
1-h fuel SA/V	m^2/m^3	9560	
Live herbaceous fuel SA/V	m^2/m^3	5906	
Live woody fuel SA/V	m^2/m^3	1000	
Fuel bed depth	m	0.45	
Dead fuel moisture of extinction	%	30	
Dead fuel heat content	kJ/kg	Phenologically varied	This study
(*b*) Environmental input variables			
Dead fuel moisture	%	Phenologically varied	This study
Live fuel moisture	%	Phenologically varied	This study
Wind speed	km/h	16	Set value chosen
Slope steepness	%	5	Set value chosen

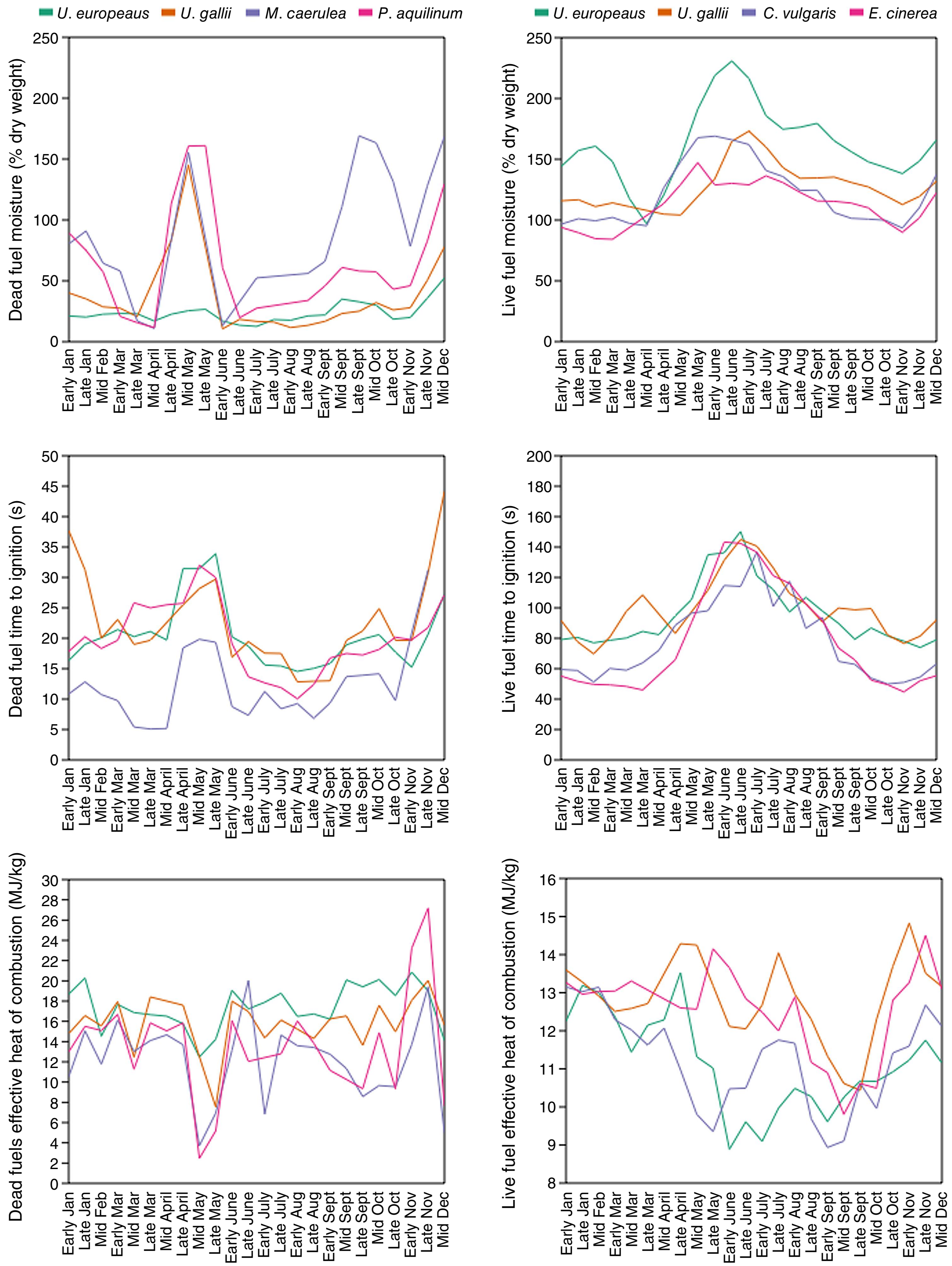

Fig. 3. Measured fuel moisture, time to ignition and effective heat of combustion for both dead and live fuels (mean for all heathlands).

were used as the variable 'heat content' input within the fuel model in trials to test the sensitivity of the model to the phenological variability in heat content.

The second and third variables for input into the model are the environmental linked input variables of dead fuel moisture and live fuel moisture (Table 1b) and varied

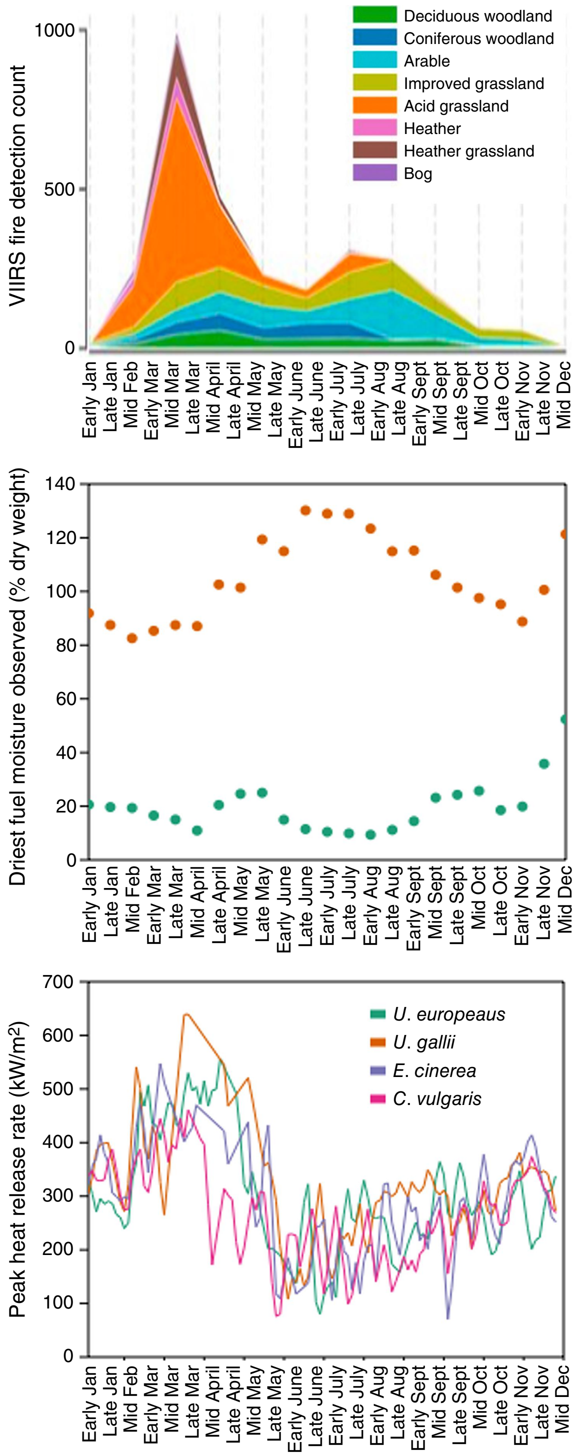

Fig. 4. Order from top, satellite observations of fire occurrence for the South and Southwest of the UK using the visible infrared imaging radiometer suite (VIIRS) sensor. Followed by mean phenological variability in fuel moisture, live fuel peak heat release rate and modelled heat of combustion.

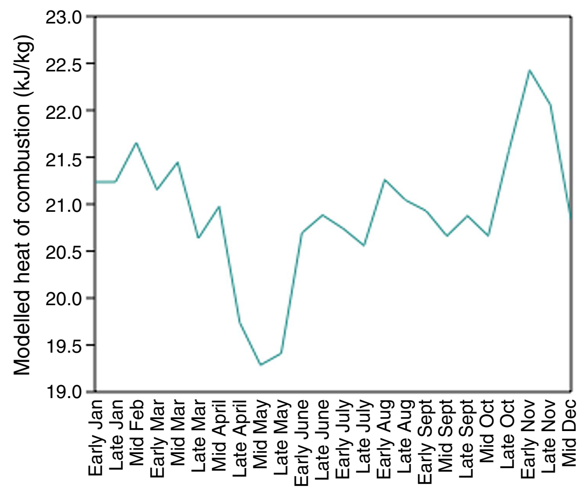

Fig. 4. (*continued*)

between the species (Fig. 3). The two weekly measurements from each species were translated to all-species dead fuel and live fuel means for input into the sensitivity analysis (based on the mixed heathland fuel type and co-existence of the species; Fig. 1). This allowed us to explore the typical variability in both dead and live fuel moisture across the seasons. Finally, BehavePlus requires an estimate of windspeed and slope angle, but because the effects of these were not being explored, we kept these values constant for all model runs (Table 1b). The wind speed chosen for all model runs was the average observed (16 km/h) for the Canford Heath fire, Dorset, UK, April 2022, measured by Fire and Rescue Services.

Three sets of model runs were undertaken using BehavePlus version 6 as part of the phenological sensitivity analysis. The first varied only heat content with dead fuel and live moisture content set static at 16 and 103% respectively (median values for the baseline dataset). The second varied only dead fuel moisture with heat content and live fuel moisture set static at 21,003 kJ/kg (the median for the dataset) and 103% respectively. Finally live moisture content was varied with heat content set at 21,003 kJ/kg and dead fuel moisture set as 16%. Each run produced values for surface fire rate of spread (m/min), surface fireline intensity (kW/m) and surface fire flame length (m) (all model run input data is provided in a Supplementary Datafile S1). All plots and statistical analyses presented were undertaken using PAST (Hammer *et al.* 2001).

Results

Observed flammability trends

The changes in temperature and relative humidity throughout the year were broadly similar between the three heathland sites (Fig. 2). The lowest temperatures were found throughout January and December and the highest temperatures in late July. The lowest relative humidities were found in late March and mid to late April, and the highest relative humidity occurred in mid May.

Dead fuel moisture and live fuel moisture in all species varied throughout the year (Fig. 3). Dead fuel moisture was found to be at its greatest (>150%) in late April through to the end of May and does not appear to be driven solely by high relative humidity. Late April had the lowest observed relative humidity but had the greatest dead fuel moisture, mid May shows the highest relative humidity, whilst late May appears to have a similar average humidity to the bulk of the year (Fig. 2). The period of highest dead fuel moisture coincides with our observations of the time at which live fuel moisture begins to increase due to the onset of green up of live fuels. Supplementary Fig. S3 shows images for some of the different seasons and shows a clear contrast in greenness between March and May. This observation is supported by satellite based enhanced vegetation index observations for 'heather' dominated landcovers in the southwest of the UK, where the mid-point of 'green up' occurs around the 140th day of the year (mid tolate May) (Nikonovas *et al.* 2024*a*). Fuel moisture increases through April and May and reaches a peak in live fuels during June in all fuels, except *U. gallii*, which peaks slightly later in early July (Fig. 3). The lowest fuel moisture in live fuels occurs in March and April (see Supplementary Fig. S3 and Fig. 3). Interestingly *U. europaeus* does not see such a high variation in dead fuel moisture as the other species and its live fuel moisture also sits apart from the *U. gallii*, *C. vulgaris* and *E. cinerea*. Supplementary Fig. S3 shows images of the varying phenological state of the dry heath at Woodbury Common, Devon, UK. Note the greenness in the images for May and July compared to those from March, August and October.

The time taken for the fuel samples to ignite broadly follows the patterns seen in dead and live fuel moisture throughout the year (Fig. 3). *Molinia* ignites the most rapidly in all seasons (the exception being late November and early December). The time to ignition in dead fuels is slowest in April through to the end of May, coinciding with the start of green up of live fuels. Time to ignition in live fuels increases (i.e. becomes slower) from late April and remains high throughout spring and summer, peaking in June (Fig. 3). The fastest time to ignition in dead fuels is observed in *Molinia* throughout mid to late March. The fastest time to ignition in live fuels is seen in *Erica* during the same period.

Seasonal variations in the EHoC were also apparent in both dead and live fuels (Fig. 3). Mean dead fuel EHoC for all species was found to have a broad range of values although the majority of values fell between 13,000 and 20,000 kJ/kg (Supplementary Fig. S2). The lowest EHoC in all dead fuels was seen during mid and late May, corresponding to slower times to ignition and increased dead fuel moisture, and high relative humidity with the start of green up. Live fuel seasonal variability in EHoC is included in Fig. 3. Live fuel EHoC falls to a low by late May in *C. vulgaris,* shortly followed by *U. europaeus* in early June. The lowest live fuel EHoC in *E. cinerea* and *U. gallii* are seen much later in the year during September where *C. vulgaris* also has a second minima.

Correlations with fire occurrence

The greatest number of active fire counts occurs in March, at the same time flammability tests indicate that this is the time of year when the peak heat release rate of the live shrub fuels was greatest (Fig. 4). In general, the highest peak heat release rates were found in plant samples collected between mid February and late April, which is the same time at which overall fire counts were greater than for the rest of the year. Both dead and live fuel moisture are lowest during this period, declining between February and mid April. The start of green up is marked by a clear fall in peak heat release rate in live fuels in mid May (Fig. 4), which is coupled to a large decline in mean HoC and a spring peak in dead fuel moisture (Fig. 4). This corresponds to a decrease in the probability of ignition against an overall rising trend (Fig. 4). Live fuel moisture increases from mid April and continues to increase until early June, and remains at its highest until early August when it starts to decline.

Sensitivity analysis of BehavePlus predictions to phenological shifts

As expected, predicted fire behaviour varied across different months/periods of the year and could be predicted based on each sensitivity analysis due to phenological controls (Fig. 5). All periods except for mid May, early June, late June, early July, late July, mid September and mid December had mean live fuel moistures that fell below 120% and therefore were subject to dynamic curing in model predictions.

Our sensitivity analysis of BehavePlus indicates that the relatively small shifts in phenological variations in mean heat content do alter the fire behaviour predictions, but that this impact is minimal when compared to phenological variability in fuel moisture (Fig. 5). The month of May overall had the lowest heat content and resulted in the lowest predictions of fire behaviour overall. Phenological variations in heat content alone were capable of leading to a maximum of 24% increase in predicted surface fire rate of spread however, the standard deviation of the predicted values was only 0.41 m/min. Therefore, the phenological impact of applying shifts in heat content alone using a dynamic fuel model in BehavePlus, was of negligible impact for predicting surface fire rate of spread in these habitats. The impact on predicted surface fire flame length was similar in terms of maximum percent increase (24%), but the standard deviation of 0.1 m is within the margins of error of reality for the BehavePlus modelling system. The impact of heat content alone on predicted surface fireline intensity had a maximum predicted increase in fireline intensity of 44% and an overall standard deviation of 71 kW/m.

Seasonal patterns did emerge in respect to varying only dead fuel moisture according to phenology (Fig. 5) and accounted for greater variability in estimates of fire behaviour than heat content alone (Fig. 5). The dead fuel moisture for

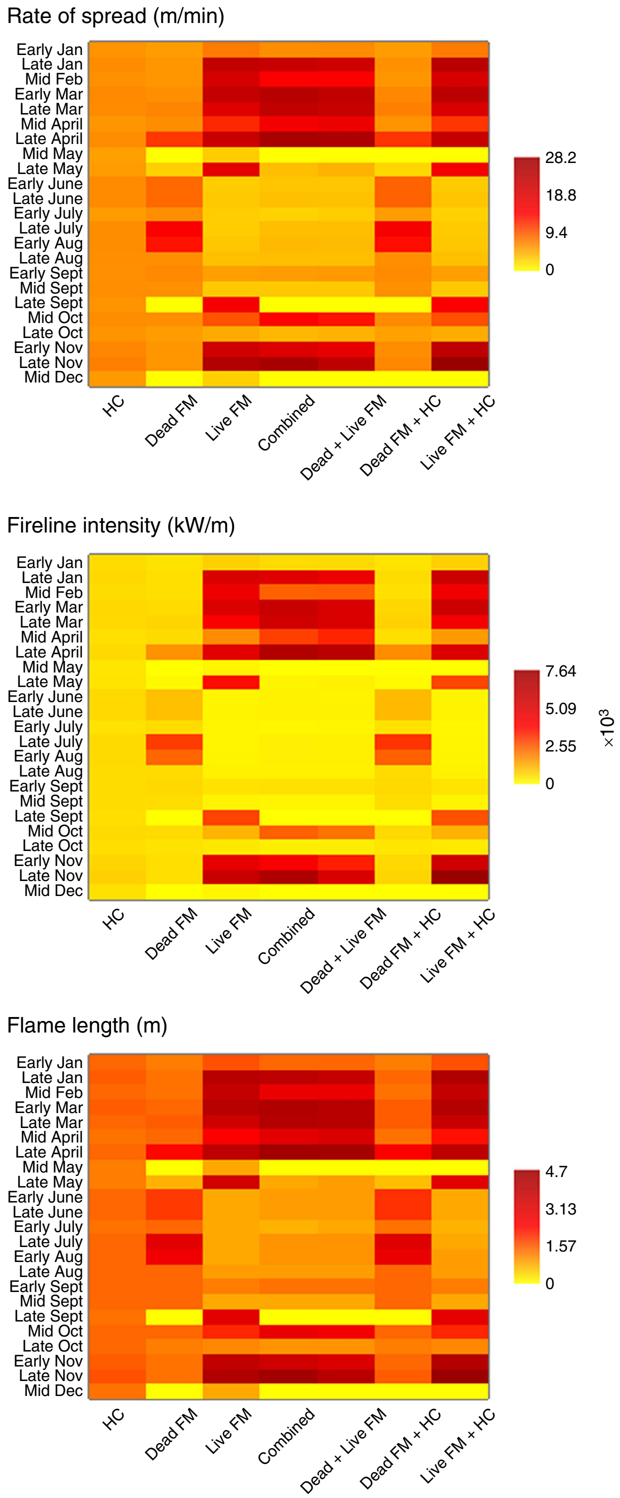

Fig. 5. Matrix plots of the results of the sensitivity analysis in BehavePlus showing monthly phenologically driven variations in fire behaviour predictions. The columns show which phenological driver or combination of drivers is being used to drive each sensitivity analysis. HC, heat content; FM, fuel moisture. Darker shades of red show greater fire behaviour predictions.

mid May was greater than the moisture of extinction in the model leading to no fire spread and for late May it was close to the moisture of extinction leading to predictions for rate of spread of just 2.6 m/min. The phenological links to dead fuel moisture in May appear to limit predicted fire behaviour during the phase of green up in dry heathlands. In contrast, the fire behaviour predictions based on dead fuel moisture alone are greatest in the UK summer months (late July and early August). However, for most months, phenologically linked dead fuel moisture had limited impact on overall predictions of fire behaviour. For example, the late winter early spring and through Autumn fire behaviour predictions, that used only dead fuel moisture, have standard deviations of 0.4 m/min for rate of spread, 0.1 m for flame length and 60 kW/m. The dead fuel moisture driven estimates of fire behaviour for these time periods are similar to the variability in outputs produced using heat content alone (Fig. 5).

Phenological variability in live fuel moisture had by far the greatest impact on the predictions of fire behaviour. The phenologically lower live fuel moisture in winter, early spring and again from early autumn produced the greatest fire behaviour estimates. The mean live fuel moisture for these periods was 88% (range 74–110%) whilst, that for the late spring and the summer months was 121% (range 88–136%). Therefore, in winter, early spring and autumn, a fraction of the live herbaceous load was dynamically transferred to cured state in the model. Whereas during the late spring-summer period only the mean live fuel moisture contents for late May, late August and early September allowed for dynamic curing of the live herbaceous load.

The predicted mean surface fire rate of spread for late January to late April were 19.5 m/min (range 12–23 m/min), mean flame lengths 3.6 m (range 2.4–4 m) and mean surface fireline intensity 4236 kW/m (range 1718–5269 kW/m). This contrasts to the mean predictions for the main growing season (May to September) where surface fire rate of spread was 4.7 m/min (range 2.8–17.7 m/min), mean flame lengths 1.1 m (range 0.8–3.4 m) and fireline intensities 536 kW/m (range 152–3626 kW/m). It should be noted the high ends of the ranges presented only occur in late May (during a period of drought in the UK, hence the average is a more valuable comparison). Therefore, phenological differences in live fuel moisture alone between late winter and early spring and late spring and summer appear capable of driving an average four-fold difference in surface fire rate of spread, a three-fold difference in flame length and an eight-fold difference in fireline intensity in model predictions resulting from BehavePlus.

When phenological variability in heat content, dead fuel and live fuel moisture are combined, as would be the case for complete model estimates, the seasonal pattern in fire behaviour predictions remains similar to those driven by live fuel moisture alone. Combining heat content and live fuel moisture variability tends to be additive in terms of the predictions for the late winter and early spring, however, the higher mean live fuel moisture in the late spring and early summer mitigates the impact of lower dead fuel moistures on fire behaviour during this period (Fig. 5).

Discussion

We found that fire occurrence generally peaks in dry heathlands in the early spring and late summer. This peak appears to be towards the end of the prescribed fire season, that runs October through to March in the region studied. It is not clear what the ignition causes of the early spring fires observed are. However, what is clear is that the spring peak occurs during the time in which live fuel is dormant (see also Supplementary Fig. S2) where the driest live fuel components are well below 100% fuel moisture (Fig. 4). Live fuel ignitability (time to ignition) is two to three times more rapid in live fuels at this time of year than during the summer months (Fig. 3). Similarly, the peak energy released from burning these dormant but live fuels is also greatest during this period (Fig. 4), highlighting their flammability. Our flammability (time to ignition) analysis supports the idea that phenological patterns in dead fuel moisture have the greatest influence in the summer (Fig. 3). The sensitivity analysis in BehavePlus also provides agreement, indicating that dead fuel moisture had its greatest impact on phenologically driven variability in predicted fire behaviour during late spring and summer (Fig. 5). This switches in importance in late winter and early spring such that predictions during this period are mostly driven by lower live fuel moisture (Fig. 5).

In late spring-summer modelled fire behaviour is enhanced by low dead fuel moisture but then dampened by phenologically higher live fuel moisture. This is because although both dead and live fuel components will receive the same heat flux from the burning fire front, the temperature that they receive will be different owing to the amount of moisture that can be driven off, thus dead fuel will reach ignition temperature more rapidly. Moreover, because the temperatures they reach will be different (a live fuel particle need not lose all its moisture before reaching ignition, see Rossa and Fernandes 2018) they will have different radiative heat losses and different net convective heat transfer, hence dampening initial propagation. Any remaining live fuel moisture will be driven off in the main combustion zone dampening the reaction and slowing the rate of spread (Catchpole and Catchpole 1991). It should be noted that the live fuel moisture influence on the rate of spread within BehavePlus is applied using a moisture dampening coefficient as the experiments used develop the fire spread model did not contain live fuels (Rothermel 1972; Andrews 2018). The moisture dampening coefficient interacts to determine the completeness and rate of fuel consumption as a ratio of reaction zone efficient to reaction time (Andrews 2018). So, whilst this makes some logical sense, predictions may be improved by the addition of parameters estimated from experimental burns that contain mixed dead and live fuels (Catchpole and Catchpole 1991).

Detailed fuel moisture survey work by Little *et al.* (2024*b*) in a UK *Calluna* dominated moorland suggests that live canopy fuel moisture in *Calluna* is mostly too great during the summer (July) to overcome the live fuel threshold for sustained ignition (Taylor *et al.* 2021); however, the dead fuel moisture during the summer (July) always falls below that required for sustained ignition (Little *et al.* 2024*b*). Summer fires in the UK appear to occur during extra-seasonal shifts in fire weather, either in periods of drought or during heat wave conditions, which drive extremes in fire weather, superimposing greater variations in fuel moisture on top of baseline phenology (Kettridge *et al.* 2023). During the 2022 UK heatwave, live fuel moisture in *Calluna* fell from mean of 137% (non-drought July) to 81% (drought July) at Chobham Common in Surrey, South UK (measured by authors across the UK on the 18 and 19 July 22) which is a dry heath with similar fuel types to those studied herein. Whereas cured dead *Calluna* and *Molinia* fuels fell to ~3% fuel moisture at this site during the 2022 heatwave. Longer periods of drought, which need not be coupled to extreme weather, also tend to lower live fuel moisture in dwarf shrub ecosystems (Davies *et al.* 2010).

Reanalysis of a shrubland fire dataset by Pimont *et al.* (2019) has indicated that live fuel moisture effects fire behaviour when below 100% but is marginal above this threshold. Such thresholds should be further investigated for specific heathland fuel types particularly under heatwave scenarios. Currently BehavePlus allows dynamic curing at 120% in contrast to that suggested by Pimont *et al.* (2019), although between 120 and 100% live fuel moisture the transfer of live to cured is only 20% of the total live herbaceous fuel load, this progresses to 100% at 30% live fuel moisture (see Andrews 2018). Hence the ability of heatwave weather interactions that are observed to push summer live fuel moisture contents way below this value have clear implications, because it connects the period of year that typically has phenological low dead fuel moisture, with non phenologically driven lower live fuel moisture content. It has been noted that fuel effects on fire spread models are considered to be less important in periods of extreme fire danger, such that weather factors dominate the rate of fire spread (Cruz *et al.* 2022).

Although our exploration of varying heat content indicated that this has by far the least impact on estimates of fire behaviour using a dynamic fuel model in BehavePlus. It does hint that underprediction of fire behaviour in dry heath ecosystems may occur during seasons that have phenologically lower mean live fuel moisture (particularly late winter to early spring). The heat content used in the standard set of fuel models available for use in BehavePlus (e.g. Anderson 1982; Scott and Burgan 2005) of 18.622 kJ/kg is lower than the average for this, a mixed dry lowland heath fuel type (21.003 kJ/kg), so should be adjusted by the user. We note that the actual variability in heat content is greater than the mean smoothed version we utilised in the fire behaviour estimates we have presented. The maximum range seen across all fuel types throughout the year was 15,380–27,380 kJ/kg which would tend to expand the range of fire behaviour predicted. Therefore, we suggest that further exploration of phenological variation in heat content may be warranted, particularly under heat wave and drought conditions, particularly because EHoC which we measured directly and transferred to heat content (Eqn 1) is dependent on fuel moisture content (Madrigal *et al.* 2011).

Whilst our sensitivity analysis of using a dynamic fuel model for describing these dwarf shrub dry heathland fuels has shown promise in the adaptability of BehavePlus as a useful low-cost tool. It is to be reminded that BehavePlus treats shrubs as surface fuels and the results in this study are an output from the surface fire module. Shrublands really carry crown fires because sustained spread occurs throughout the canopy leaving little consumption of surface litter (Fernandes *et al.* 2000; Davies and Legg 2016). The predominant part of the fire, even in these dwarf shrub communities, is carried in elevated foliage and branches and is aerated from below. Recent work on *Calluna* dominated heathlands has noted that more realistic accounting for canopy live fuel moisture should lead to better estimates of fire behaviour (Little *et al.* 2024*a*). Moreover, differences in dwarf shrub canopy age influence both the proportions of live and dead fuel in the canopy where live fuel moisture has been observed to be lower in mature *Calluna* plant canopies that host a greater portion of old growth, whereas younger *Calluna* plants have a greater new growth to old growth ratio, leading to higher canopy fuel moistures (Little *et al.* 2024*b*).

Vegetation height in *Calluna* has been shown to be an important predictor of fire behaviour (Davies *et al.* 2009). Indeed, vegetation structure in shrub fuels has been noted as being particularly important where vegetation height and bulk density have strong effects on both apportioning of moisture within models and influence the effects of wind (Anderson *et al.* 2015). It is clear that seasonal variability in leaf investment will link to shrub crown fire propagation, and live canopy fuel moisture in shrub dominated ecosystems has been noted as being required to provide the most realistic fire behaviour scenarios (e.g. Catchpole and Catchpole 1991; Pimont *et al.* 2019). In the case of the dwarf shrub heathland fuels studied herein, that are intermixed with herbaceous fuels of a similar height and where the dominant shrubs have little dead fraction, some of these canopy differences may be less pronounced. However, areas of these heathlands dominated by *U. gallii*, which hosts significant portions of dead and live fuel throughout the year, is more like those dominated by *Calluna*, that has varying ratios of dead and live aerial fuels (Little *et al.* 2024*b*). It is clear there remains much to explore toward understanding the phenological interrelationship of live fuel moisture and its influence on dead fuel moisture within the shrub canopy if we are to improve predictive accuracy of fire behaviour in these fire prone dwarf shrub communities.

Conclusions

Here we have provided measurements of the variability in both dead and live fuel moisture, measures of flammability and the variability in heat content for a range of dominant heathland fuels throughout the year. These are well linked to observed changes in fire occurrence in the region. Our estimated fire behaviour sensitivity analysis indicates that phenological variability in dead fuel moisture, live fuel moisture and heat content shift in their importance in driving fire behaviour throughout the seasons. Live fuel moisture was the strongest phenological contributor to driving shifts in predicted fire behaviour. The mean live fuel moisture content across the year for this fuel type was just 105% (range 74–145%). However, the mean for late winter-early spring was 88%, and the mean for late spring-summer was 121%, where the shift between these led to a predicted four-fold difference in surface fire rate of spread and an eight-fold variation fireline intensity. The live moisture contents measured can serve as a guide of the typical seasonal live fuel moisture contents in these dry heathlands where information is not available. These could be used to better inform fire behaviour predictions in accessible modelling systems such as BehavePlus or within more complex models that seek to model these dwarf shrub communities as crown fuels. Similarly, this analysis has provided a realistic range of heat content information for these fuel types, which may aid further improvements to predictive capabilities.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study are available in the article and accompanying online supplementary material. Any other materials can be shared upon reasonable request to the corresponding author.

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