Cross-landscape fuel moisture differences impact simulated fire behaviour

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ABSTRACT

Background. Predicting fire behaviour is an ongoing challenge in temperate peatlands and heathlands, where live fuels can form the dominant fuel load for wildfire spread, and where spatial heterogeneity in fuel moisture is important but not typically represented in fuel models. **Aims.** We examine the impact of fuel moisture variation on simulated fire behaviour across a temperate peatland/heathland landscape. **Methods.** We collected field measurements of fuel moisture content in *Calluna vulgaris* shrub from 36 sites across the North Yorkshire Moors, United Kingdom. We used these to define fuel moisture inputs within existing shrubland fuel models to simulate fire behaviour in BehavePlus. **Key results.** Simulated rates of spread varied with fuel moisture content; average mean variance of 23–80% from the landscape average rate of spread. The driest sites had simulated rates of spread up to 135% above the landscape average and the wettest sites up to 86% below average. Fuel model selection dramatically impacted simulated rates of spread by a factor of five. **Conclusions.** We need to constrain the role of live fuel moisture within temperate fuel models to develop accurate fire behaviour predictions. **Implications.** Capturing cross-landscape heterogeneity in fire behaviour is important for safe and effective land and wildfire management decision-making.

Keywords: BehavePlus, *Calluna vulgaris*, fuel models, heathlands, live fuel moisture, peatlands, rate of spread, sensitivity analysis, shrub fuels, temperate ecosystems.

Introduction

Fire is integral to many ecosystems. Wildfires are a natural component of the landscape and there is a long history of human use of fire to manage landscapes (McLauchlan *et al.* 2020; Shuman *et al.* 2022). Global climate and land use changes are promoting increased interaction between humans and changing wildfire behaviour, including increasing burned area in many regions globally (Doerr and Santín 2016; Shuman *et al.* 2022).

One facet of this is the increasing wildfire risk in regions that have traditionally been considered to be less vulnerable to extreme wildfires, such as the temperate peatlands and heathlands of northwestern Europe (Belcher *et al.* 2021). Temperate peatlands and heathlands are ecosystems of high conservation importance that have an extensive history of landscape fire through both wild and managed fire that maintain biodiversity and reduce fuel loads (Davies *et al.* 2022). These ecosystems contain globally critical carbon stores that are vulnerable to smouldering combustion during severe wildfires and can result in significant carbon emissions (Mickler 2021). High intensity wildfires and their spatial patterns across peatlands and heathlands can have important ecological impacts in terms of post-fire vegetation and peat soil recovery, and potential water quality, infrastructure, and societal impacts (Doerr and Santín 2016). High rates of spread affect the controllability of fires and may result in managed fires 'escaping' their burn areas (Davies *et al.* 2009). Alignment of fuel and weather conditions conducive to wildfires in temperate peatlands and heathlands promote increased wildfire activity and their associated ecological consequences (Kirkland *et al.* 2023). Moreover, the seasonal window for conducting burning to meet management objectives is decreasing

alongside changing policy and viewpoints on the use of fire to manage landscapes (Minsavage-Davis and Davies 2022; Pandey *et al.* 2023). Accurate fire behaviour predictions are therefore critical for safe, effective land and wildfire management decision-making. Understanding spatial variability in wild and managed fire behaviour is important for determining how fire risk may change across a landscape, including potential impacts on vegetation recovery and carbon stores. This has implications for determining suppression tactics and resource requirements within wildfire response operations, as well for determining suitable locations for burning to meet land management objectives while minimising the risk of out of control fires or failed ignitions (Minsavage-Davis and Davies 2022).

Modelling fire behaviour

Fire behaviour models use simplified inputs of fuel, weather, and topography to assess potential fire behaviour, including rate of spread (ROS), flame length, and fireline intensity. Rothermel's surface fire spread model is a fundamental model used to predict fire behaviour within surface fuels (Rothermel 1972). BehavePlus is a fire behaviour modelling system that provides a user interface to Rothermel's model (among others). BehavePlus is widely used to predict fire behaviour for different scenarios across fire management, prescribed fire planning, and research applications (Andrews 2014). It provides point-based fire behaviour metrics that can also be integrated with systems like FlamMap and FARSITE to model fire behaviour in space (Finney 1998, 2006). Wildfire Analyst operationalised fire spread models for real-time wildfire risk forecasting, wildfire spread predictions, wildland fire behaviour analysis, and risk mitigation planning in many regions (Monedero *et al.* 2019), including temperate regions such as The Netherlands (Cardil *et al.* 2021). BehavePlus has previously been used to predict surface fire behaviour in *Calluna vulgaris* (Davies *et al.* 2009) and was recently used by Minsavage-Davis and Davies (2022) to evaluate ROS models in heathlands.

Temperate peatland and heathland fuel models

Fuel models are used to describe fuel availability in fire behaviour models and exist for a range of fuel types, including shrubland fuels (Scott and Burgan 2005). These are designed for non-specific vegetation types and rely on user selection. The choice of fuel model is important in determining the proportion of live to dead fuels and therefore sensitivity to fuel moisture changes. Dead fuel moisture content is the water content of dead vegetation and is important for the initial ignition of fuels. Because dead fuels respond mainly to changing weather conditions, there are simple models that can be used for predicting dead fuel moisture content. For example, the Fosberg model uses air temperature and relative humidity measurements to predict 1-h fine

fuel moisture, making adjustments for time of year, slope, aspect, and shading of the vegetation (Fosberg *et al.* 1971). Live fuel moisture content, the water content of living vegetation, is different as it can regulate drying through ecohydrological and plant physiological controls (Dickman *et al.* 2023).

In the dwarf shrub *Calluna vulgaris* L. Hull. (hereafter *Calluna*) that dominates peatland and heathland landscapes, both dead and live fuel moistures are important for wildfire behaviour (Davies *et al.* 2009, 2010). Despite increasing wildfire risk associated with climate and land use change, predicting fire behaviour continues to be challenging within these environments (Cardíl *et al.* 2023). Intense fire behaviour has been observed in temperate shrublands during fire weather conditions that are considered to be low risk in forested landscapes (Davies *et al.* 2019; Pepin and Wotton 2020). This questions whether existing fuel models are able to incorporate the role of live fuel moisture content that can drive spring-time wildfires in peatlands and heathlands (Jolly and Johnson 2018). This is an ongoing challenge for temperate landscapes even within traditionally fire prone countries (e.g. Canada (Pepin and Wotton 2020)) in addition to emerging fire prone temperate regions like northwestern Europe (Cardíl *et al.* 2023). We need to understand fuel moisture dynamics to constrain functioning fuel models for key fuel types in temperate peatlands and heathlands.

Some previous research has focused on the influence of live fuel moisture content of *Calluna* on flammability, fire ignition, and ROS (e.g. Davies and Legg 2008, 2011; Santana and Marrs 2014; Log 2020). Ecological research on the life cycle of *Calluna* (e.g. Kayll and Gimingham 1965; Gimingham 1988) provided the foundation for understanding differences in fire behaviour between pioneer, building, mature, and degenerate growth phases, leading to the development of empirical ROS models and later fireline intensity and flame length for these different growth phases of *Calluna* (Davies *et al.* 2009, 2019). Cardíl *et al.* (2023) used Visible Infrared Imaging Radiometer Suite (VIIRS) remotely sensed hotspots to derive the ROS for wildfires across northwestern Europe. Understanding the response of fire behaviour models to the range of live fuel moisture conditions across a landscape is critical in addressing scenarios where models may underestimate fire behaviour. Phenologically-driven declines in live fuel moisture at the end of winter and into spring are particularly important drivers of wildfire risk in *Calluna*-dominated landscapes, which are critical to capture in fire behaviour predictions (Davies *et al.* 2010; Log *et al.* 2017).

Impact of fuel moisture spatial complexity on fire behaviour

Fuel loadings and fuel moisture are represented by single values within fuel models yet are highly spatially variable in reality (Jolly 2007). We recently conducted an intensive fuel moisture measurement campaign to capture the magnitude

of cross-landscape fuel moisture differences in a temperate peatland/heathland landscape. We found that this variability created spatial discontinuity in the availability of fuel for sustained ignition of live fuels and in the potential for smouldering combustion in organic soils Little *et al.* (2024). However, the influence of cross-landscape fuel moisture differences on simulated fire behaviour, particularly live fuel moisture, is still largely unknown.

Fire behaviour within emerging fire prone environments like the temperate peatlands and heathlands of northwestern Europe can be affected by small-scale heterogeneity in landscape and fuel characteristics. Some previous research has examined the sensitivity of fire behaviour models using hypothetical live fuel moisture scenarios (Jolly 2007; Minsavage-Davis and Davies 2022). Jolly (2007) systematically varied live fuel moisture content across existing standard fuel models, finding high sensitivities to live fuel moisture depending on the fuel model used. Minsavage-Davis and Davies (2022) evaluated different ROS models against observed ROS from experimental burns in *Calluna* heathlands. They found that various implementations of the Rothermel surface spread model could adequately predict ROS observed in *Calluna* heathlands. Both studies reported a lack of sensitivity in existing fire behaviour models to live fuel moisture content (Jolly 2007; Minsavage-Davis and Davies 2022). However, there are no studies that have evaluated fire behaviour predictions using a cross-landscape range of direct live and dead fuel moisture content measurements. These field-based fuel measurement campaigns are needed to develop robust fuel models for temperate fuel types that inform fire behaviour predictions.

Research questions

We examine the impact of cross-landscape fuel moisture variation on simulated rate of spread across a temperate peatland and heathland landscape utilising direct fuel moisture content measurements in BehavePlus. We address the following specific research questions: (1) To what extent does landscape-scale fuel moisture variability impact simulated fire behaviour? (2) How is cross-landscape simulated fire behaviour influenced by existing fuel models used for temperate shrubby fuels? (3) Does cross-landscape simulated fire behaviour change when different live and dead *Calluna* fuel layers are used? (4) Can existing operational dead fuel moisture models adequately capture cross-landscape predicted fire behaviour?

Methods

Study region

We measured cross-landscape variability in the fuel moisture content of *Calluna* within the North Yorkshire Moors

National Park, United Kingdom (Fig. 1*a*). The North Yorkshire Moors are dominated by extensively managed *Calluna*-dominated temperate peatland and wet heathland ecosystems (Simmons 1990). The landscape has been traditionally managed largely by rotational burning to create a mosaic of mixed-age homogenous *Calluna* plots for grouse habitat and fuel management (Glaves *et al.* 2020; Davies *et al.* 2022). Between the different life stages of *Calluna,* this mosaic creates spatial differences in potential wildfire behaviour and impacts. As such, the plots enabled a clear factorial experimental design to be constructed across the diversity of landscape characteristics within the regional oceanic climate.

Sampling design

The following sections outline the field sampling design and fuel moisture measurements collected. We recently used these data to examine the landscape and micro-meteorological controls on cross-landscape fuel moisture variation, and full details on the field experimental design can be found in Little *et al.* (2024). Briefly, we established 36 plots of 20 × 20 m homogenous *Calluna* across the landscape, with each plot comprising a unique combination of soil textures, slope, positions, aspects, and canopy ages that make up the diversity of the North Yorkshire Moors. We distinguished canopy age using time-since-last-burn records from land managers. 'Building canopy' plots were burned in the last 5–10 years and averaged 30 cm height with an accumulated moss/litter layer depth of 2.5 cm. 'Mature canopy' plots burned 15–20 years ago and averaged 60 cm in height with an accumulated moss/litter layer depth of 5 cm.

Field measurements

We collected fuel samples during hot, dry fire weather conditions between 11:00 and 17:00 local time, randomising the order of plots visited as much as logistically possible (see Little *et al.* 2024 for full details). Briefly, we collected three sets of samples during a 1-week period of drying in April, and two further sets in June and July to capture the peak spring and summer wildfire seasons of 2021. We sampled seven fuel layers in each plot to capture the vertical variation in fuel moisture: *Calluna* live canopy, live stems (<2 mm diameter), dead canopy, dead stems (<2 mm diameter), surface moss (top 2 cm), litter (top 2 cm), and the organic layer beneath the *Calluna* (top 5 cm of organic material above mineral soil). Of these seven fuel layers, BehavePlus only uses the live and dead fine fuel moisture inputs to model fire behaviour, so only the live and dead *Calluna* canopy and stem fuel layers are described further in this manuscript. We collected sprigs of live and dead *Calluna* following the protocol of Little *et al.* 2023. Briefly, ~10 sprigs with stem diameter <2 mm were collected from
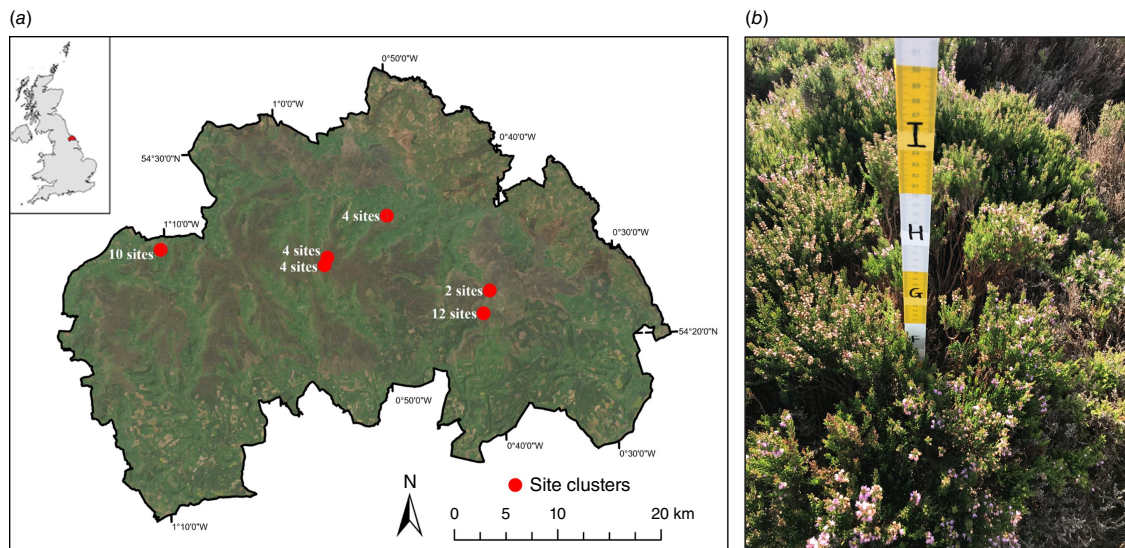
Fig. 1. Study region of the North Yorkshire Moors, UK reproduced from Little *et al.* (2024) (*a*). Live and dead *Calluna* fuel samples were collected from a total of 36 sites across the landscape on 5 days in spring and summer 2021. Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community. © Natural England copyright. Contains Ordnance Survey data © Crown copyright and database right 2022. Image of *Calluna* at one of the sites visualising the dominant live fuel load compared to fine dead fuel load (*b*). Image credit: Kerryn Little.

different plants along a 25-m transect to ensure fuel samples were representative of the entire plot area. We separated the leafy canopy material from the woody lower stems into separate 250 mL aluminium tins filled 3/4 full. We measured gravimetric fuel moisture content (mass of water per mass of dried sample, %, Eqn 1) by recording the wet weight of tinned samples, drying the samples for at least 48 h at 80°C, and reweighing the dried samples.

Fuel moisture content
$$= \frac{(\text{sample wet weight} - \text{sample dry weight})}{(\text{sample dry weight} - \text{container tare weight})} \times 100 \tag{1}$$

The 36 plots were spread across the landscape in pairs of building and mature canopy *Calluna*. At each pair of plots, we housed HOBO U23-001A PRO V2 (Onset Computer Corporation, Bourne, MA, USA) sensors in radiation shields to monitor 1.25 m air temperature and relative humidity at 15-min intervals.

Fuel models

We opted to use the shrub fuel models available within BehavePlus without any additional parameter customisation. We recognise that customised fuel models such as those developed by Davies *et al.* (2009) that tailor specific fuel physical and chemical parameters for *Calluna* are also available; however, we opted not to use these as they contain a high live herbaceous fuel load that was not representative of our study region. Of the preset shrub fuel models, we selected Scott and Burgan's (2005) SH3

and SH6 shrub fuel models as these best represented the range of shrub fuel load and fire behaviour scenarios for *Calluna*-dominated heathlands and are therefore suitable for examining cross-landscape differences due to fuel moisture content variation. The SH3 and SH6 models have both been used in temperate peatlands and heathlands: the SH3 fuel model in Northern Ireland and SH6 in the Netherlands (Stoof *et al.* 2020) and Nova Scotia, Canada (Pepin and Wotton 2020). The SH3 fuel model describes a moderate fuel load with a high live (1.39 kg/m²) compared to fine dead (0.10 kg/m²) fuel load and fuel height of 0.73 m. The SH6 fuel model describes dense shrublands where there is a higher fine dead fuel load (0.65 kg/m²) compared to fine live fuels (0.31 kg/m²) and fuel height of 0.61 m.

We used the live and dead fuel moisture categories in BehavePlus, which describe the fine (< 2 mm diameter) live and dead shrub fuel moisture contents, to input our measured fuel moisture content values. We used different combinations of measured live and dead *Calluna* fuel moisture content as the fuel moisture inputs in simulations to explore the response of the models to fuel moisture content (Tables 1, 2). In addition to using the canopy and stem fuel moisture inputs individually in simulations, we also used the plot-average combined fuel moisture content (the average of the canopy and stem fuel moisture contents for the plot). We calculated the landscape average fuel moisture content as the average of all the plot-average combined fuel moisture contents.

We also calculated dead fuel moisture content using the Fosberg model that uses plot relative humidity and

Table 1. Summary table of the main fuel moisture content (FMC) combinations used as inputs for predicting rate of spread (ROS) and referred to throughout the text.

Fuel moisture/ROS scenario name	Fuel moisture description	ROS dead fuel moisture input	ROS live fuel moisture input
Live canopy	Observed live canopy FMC	Average dead	Live canopy
Live stems	Observed live stem FMC	Average dead	Live stems
Live combined	Plot average of observed live canopy and live stem FMC	Average dead	Live combined
Average live	Landscape average of live combined FMC across all plots	Average dead	Average live
Dead canopy	Observed dead canopy FMC	Dead canopy	Average live
Dead stems	Observed dead stem FMC	Dead stems	Average live
Dead combined	Plot average of observed dead canopy and dead stem FMC	Dead combined	Average live
Average dead	Landscape average of dead combined FMC across all plots	Average dead	Average live
Fosberg dead unshaded	Predicted dead FMC from the unshaded Fosberg model using observed temperature and relative humidity measurements at time of sampling	Fosberg dead unshaded	Average live
Fosberg dead shaded	Predicted dead FMC from the shaded Fosberg model using observed temperature and relative humidity measurements at time of sampling	Fosberg dead shaded	Average live

Fuel moisture and consequent ROS scenarios are named by the fuel layer of the fuel moisture content that is varying in the ROS predictions. For example, the live canopy scenario utilises field measured variable live canopy fuel moisture content and landscape average dead fuel moisture content in BehavePlus to predict ROS. Each plot has field collected fuel moisture contents for the following layers: live canopy, live stems, dead canopy, and dead stems. The combined scenarios refer to the average of the canopy and stem fuel moisture content for each of the 36 plots, calculated separately for live and dead *Calluna*. The average scenarios are calculated as the overall landscape average of the 36 plots combined fuel moisture contents for live and dead *Calluna*.

temperature measurements at time of sampling for one case study each in spring (23 April 2021) and summer (22 July 2021). The Fosberg model is used to estimate fine dead fuel moisture content from relative humidity and temperature measurements and can be adjusted for canopy shading, elevation, aspect, slope, and season (Fosberg *et al.* 1971). The model has been incorporated into operational tools because of its simplicity and accessible data inputs, including look-up tables for predicting dead fine fuel moisture content and probability of ignition that are used within the National Wildfire Coordinating Group Incident Response Pocket Guide (NWCG 2022) and fire weather instruments, such as the Kestrel Fire Weather Meters (Kestrel Instruments, Boothwyn, PA). The Fosberg model was also integrated into Rothermel's surface fire spread model in the USA and associated fire prediction modelling systems (NWCG 2023).

Fire behaviour simulations

We used the Rothermel surface ROS model in BehavePlus to simulate surface ROS at each of the 36 plots across the landscape on each of the five sampling dates, using the plot measured fuel moisture contents as fuel moisture inputs. We ran a series of different fuel simulations for each sampling date to address each of our research questions (Table 3). We kept all factors except fuel moisture constant, using 10 km/h midflame wind speed and 10% slope steepness to isolate the influence of fuel moisture content on ROS conditions. This scenario represented a

moderate wind speed and slope that could reasonably occur within the landscape without impacting the simulated fire behaviour by using high wind speeds and slopes. We used the SH3 model as the default fuel model as its higher live compared to dead fuel load is most representative of the high proportion of live to dead *Calluna* at the sample sites across the North Yorkshire Moors (Fig. 1b).

Existing fire behaviour models used operationally generally use a single live and dead fuel moisture content estimate to represent the average fuel moisture content for the region. We therefore calculated the landscape-average simulated fire behaviour as a null model to compare to the variability in simulated fire behaviour using the range of observed fuel moisture contents (Table 3, simulation 1). This simulation used the landscape average live and dead fuel moisture content inputs to produce a single average simulated ROS for the landscape. The main simulation of cross-landscape ROS variability uses the plot average canopy and stem fuel moisture content as the fuel moisture inputs to characterise the extent of landscape fuel moisture variability and its influence on simulated ROS (Table 3, simulation 2) as summarised in Table 2. We repeated the main simulation using the SH6 fuel model for comparison (Table 3, simulation 3). To assess the differences in simulated ROS using different fuel layer inputs, we ran the model using plot live canopy fuel moisture inputs while keeping dead fuel moisture constant as the landscape average dead fuel moisture content. We repeated this simulation for live stem fuel moisture and then plot average combined live fuel moisture (Table 3, simulation 4). This simulation setup was

Table 2. Summary of the measured fuel moisture content (FMC) variability used in the main BehavePlus simulations.

Date	Live combined range of FMC Mean (live canopy + live stem FMC) across the 36 plots	Average live FMC Landscape mean (live combined FMC)	Dead combined range of FMC Mean (dead canopy + dead stem FMC) across the 36 plots	Average dead FMC Landscape mean (dead combined FMC)
15/4/2021	51.8–76.3%	67.9% (s.d. = 5.1)	9.0–30.7%	14.8% (s.d. = 4.5)
18/4/2021	52.4–73.1%	63.3% (s.d. = 4.9)	6.7–35.5%	13.3% (s.d. = 6.5)
23/4/2021	42.0–71.2%	60.3% (s.d. = 6.5)	5.1–28.3%	11.0% (s.d. = 6.3)
13/6/2021	66.1–109.1%	88.9% (s.d. = 12.2)	9.3–20.1%	11.9% (s.d. = 2.0)
22/7/2021	66.5–123.4%	100.0% (s.d. = 14.6)	7.4–17.7%	12.3% (s.d. = 2.6)

The combined (plot average of canopy and stem FMC) range of FMC% and the landscape average FMC (calculated by averaging the combined FMCs) and standard deviations (s.d.) are given for both live and dead *Calluna* for each sampling date.

reversed, varying dead canopy, dead stem, and plot average dead fuel moisture content while keeping live fuel moisture constant as the landscape average (Table 3, simulation 5). Finally, we simulated ROS for the Fosberg modelled dead fuel moisture contents (Table 3, simulation 6).

Statistical analyses

For each plot, we calculated the percentage difference in the simulated ROS (Table 3, simulation 2) from the overall average ROS (Table 3, simulation 1) for each date. This metric was used to show how much simulated fire behaviour varied across the landscape (rather than using absolute values that vary day to day). We used Kruskal–Wallis non-parametric tests to test for statistically significant differences between the predicted ROS values calculated using canopy, stem, and combined fuel moisture content for both live and dead *Calluna* for each date (Table 3, simulation 4 and 5). We performed pairwise Wilcoxon tests where Kruskal–Wallis tests were significant to determine which fuel layers were different. We followed the same approach to compare predicted rates of spread between the observed and Fosberg modelled fuel moisture inputs (Table 3, simulation 6). We used Spearman correlations to compare fuel moisture predictions using the Fosberg model with observed dead fuel moisture content. We conducted all statistical analyses in R version 4.0.3 (R Core Team 2022), using packages stats (inbuilt), car (Fox and Weisberg 2019), and Hmisc (Harrell 2022).

Results

Cross-landscape fuel moisture variability

We observed high spatial fuel moisture variability across the 36 plots in the North Yorkshire Moors (Fig. 2, Table 2). Live combined fuel moisture (the plot average of live canopy fuel moisture and live stem fuel moisture) was least variable in April (overall variability from 42.0 to 76.3% across sampling dates). Live combined fuel moisture content increased in variability through June (66.1–109.1%) and July (66.5–123.4%). Conversely, dead combined fuel moisture (the plot average of dead canopy and dead stem fuel moisture) was least variable in June and July and most variable in April. The landscape average dead fuel moisture content showed little variation between the April (11.0–14.8%), June (11.9%), and July (12.3%) sampling dates.

Cross-landscape predicted ROS variability

Cross-landscape fuel moisture differences resulted in a 23–80% mean variation from average ROS predicted using single fuel moisture inputs (Fig. 3, Table 4). The driest plots predicted rates of spread up to 135% above the landscape average. The range of variation from average ROS between

Table 3. Behave Plus model inputs used to address each of our research questions.

Simulation description	Fuel model	Dead fuel moisture content input	Live fuel moisture content input	Number of runs
1: What is the predicted RoS for the landscape using only average FMC?	SH3	Overall average dead for each date (5)	Overall average live for each date (5)	5
2: How variable is simulated RoS across a landscape?	SH3	Dead combined FMC per plot (36) and date (5)	Live combined FMC per plot (36) and date (5)	180
3: How is predicted RoS impacted by the fuel model selected?	SH6	Dead combined FMC per plot (36) and date (5)	Live combined FMC per plot (36) and date (5)	180
4: What live *Calluna* fuel layers are important to collect?	SH3	Overall average dead FMC for each date (5)	A. Live combined FMC per plot (36) and date (5) B. Live canopy FMC per plot (36) and date (5) C. Live stem FMC per plot (36) and date (5)	540
5: What dead *Calluna* layers are important to collect?	SH3	A. Dead combined FMC per plot (36) and date (5) B. Dead canopy FMC per plot (36) and date (5) C. Dead stem FMC per plot (36) and date (5)	Overall average live FMC for each date (5)	540
6: Do existing operational tools perform just as well?	SH3	A. Dead combined FMC per plot (36) and date (2) B. Fosberg dead unshaded predicted FMC for each plot (36) and date (2) C. Fosberg dead shaded predicted FMC for each plot (36) and date (2)	Overall average live FMC for each date (2)	144

Total number of unique runs = 1589 (simulation 6.A is a repeat of 5.A so does not contribute to the overall number of unique runs). The simulation description summarises the research question and the fuel model, dead and live fuel moisture content (FMC) inputs describe the set up of the BehavePlus simulation. Each simulation is run for every sampling date (5 runs) using either the landscape averaged FMC or individual plot FMC (36 runs). Simulation 1 is used to generate the null model of predicted rate of spread (ROS) using landscape averaged fuel moisture content.
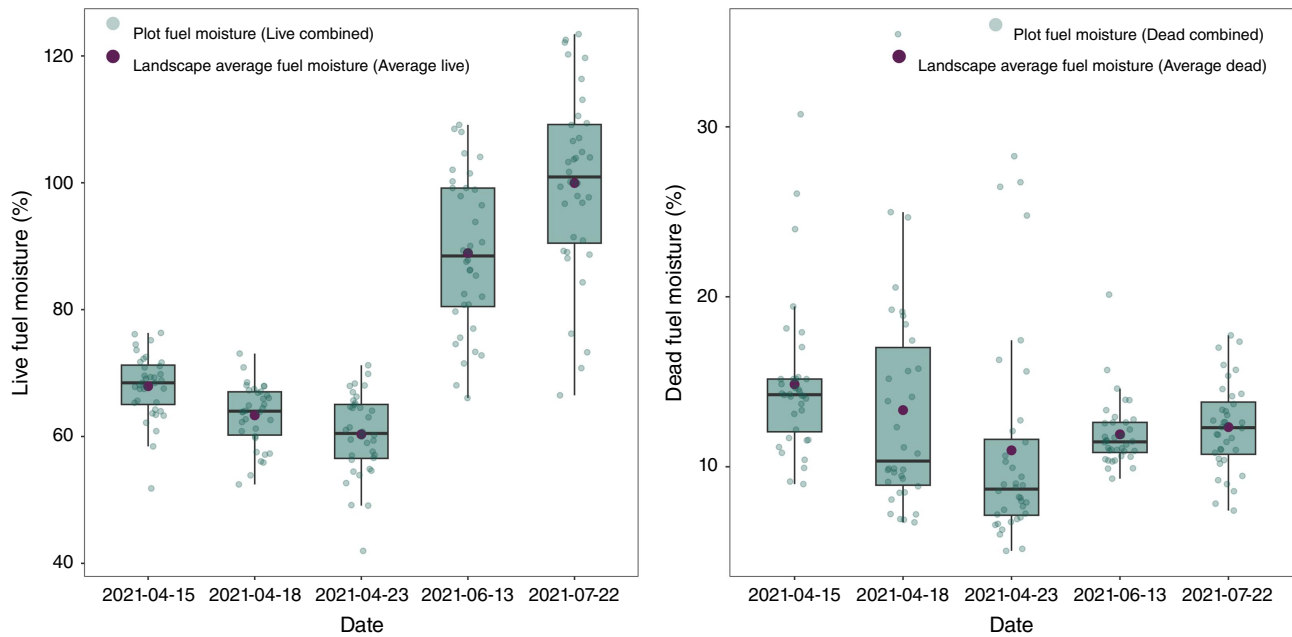
Fig. 2. Figure showing the range of cross-landscape live (left) and dead (right) fuel moisture variability for the 36 plots across the North Yorkshire Moors on each of the sampling dates. Green points depict plot combined fuel moisture content (average of canopy and stem fuel moisture content). Dark purple points show the mean fuel moisture content for the landscape overall (average of plot combined fuel moisture content), which is variable across each sampling date.
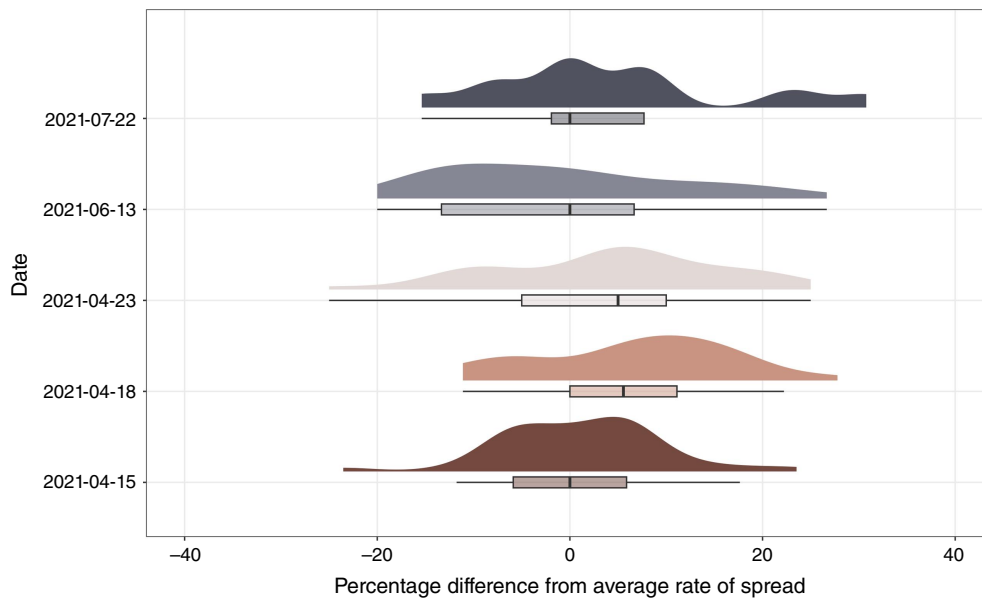

Fig. 3. Box- and half violin-plots showing the percentage variation from average rate of spread (ROS) across the 36 plots in the North Yorkshire Moors for each sampling date. The landscape average ROS is specific to each sampling date: 1.7 m/min (15/4/2021); 1.9 m/min (18/4/2021); 2.2 m/min (23/4/2021); 1.5 m/min (13/6/2021); and 1.4 m/min (22/7/2021).

the driest and wettest plots was between 46 and 160%. Predicted ROS variance and absolute ROS was highest in spring (Supplementary Fig. S1).

Simulated absolute ROS was significantly higher when the SH6 fuel model was used compared to the SH3 fuel model (Fig. 4). Average ROS was more than 5-fold higher overall when the SH6 fuel model was used to simulate ROS using the same fuel moisture content inputs. However, the mean ROS variance was comparable between the SH3 and SH6 simulations.

Table 4. Cross-landscape rate of spread (ROS) variation due to differences in plot combined fuel moisture content (average of canopy and stem fuel moisture content for each plot).

Date	Fuel model	Max ROS (m/min)	Min ROS (m/min)	Average ROS (m/min)	Max variation from average	Min variation from average	Mean variation from average
15/4/21	SH3	2.1	1.3	1.7	23.5	−23.5	23.5
18/4/21	SH3	2.3	0.9	1.9	27.8	−50.0	38.9
23/4/21	SH3	4.7	1.5	2.2	135.0	−25.0	80
13/6/21	SH3	1.9	1.2	1.5	26.7	−20.0	23.3
22/7/21	SH3	1.7	1.1	1.4	30.8	−15.4	23.1
15/4/21	SH6	12.3	7.2	10.4	57.7	−7.7	32.7
18/4/21	SH6	10.5	6.5	8.4	22.1	−24.4	23.3
23/4/21	SH6	15.1	1.6	11.4	31.3	−86.1	58.7
13/6/21	SH6	10.9	6.9	8.7	2.8	−34.9	18.9
22/7/21	SH6	10.1	6.2	8.0	3.1	−36.7	19.9

Absolute (m/min) and percentage variation from average ROS (%) results are shown, where average ROS is predicted from landscape averaged combined fuel moisture content under both the SH3 and SH6 fuel models (Table 2, simulation 1).
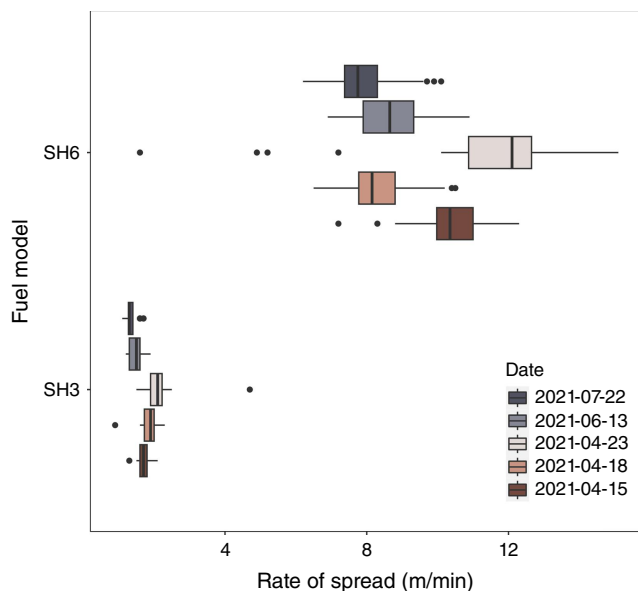

Fig. 4. Boxplots showing the range of variability in predicted rate of spread (ROS) due to variation in plot combined fuel moisture content (average of canopy and stem fuel moisture content for each of the 36 plots) between the SH3 and SH6 fuel models for each sampling date. The SH3 fuel model is the main model used in the simulations of Table 3, which has a moderate fuel load with a high live (1.39 kg/m²) compared to fine dead (0.10 kg/m²) fuel load. We compare these results to the SH6 fuel model that has a higher fine dead (0.65 kg/m²) to live (0.31 kg/m²) fuel load (Table 3; simulation 3) and may represent scenarios where there is a high proportion of dead fuel.

There were no statistically significant differences in predicted ROS when using dead canopy, dead stem, or combined fuel moisture contents. All live fuel moisture

Table 5. Kruskall–Wallis (KW) test for differences in predicted rates of spread (ROS) between different fuel layer fuel moisture inputs for each of the five dates.

| Fuel layer	Date	KW chi-squared	*P*-value
Live	15/4/2021	38.134	**0.000**
Live	18/4/2021	25.827	**0.000**
Live	23/4/2021	18.928	**0.000**
Live	13/6/2021	5.127	0.077
Live	22/7/2021	37.089	**0.000**
Dead	15/4/2021	0.269	0.874
Dead	18/4/2021	0.629	0.730
Dead	23/4/2021	0.015	0.993
Dead	13/6/2021	0.063	0.969
Dead	22/7/2021	1.908	0.385
Predicted dead	23/4/2021	6.546	**0.038**
Predicted dead	22/7/2021	0.756	0.685

Live fuel layers compare predicted ROS between live canopy, live stem, and combined live (average of canopy + stem) fuel moisture content measurement scenarios. Dead fuel layers compare predicted ROS in the same way but for measured dead fuel moisture contents. Predicted dead fuel layers use the Fosberg predicted shaded and unshaded dead fuel moisture contents as inputs. *P* < 0.05 differences are indicated in bold. Table 6 examines specific fuel layer differences for significant Kruskal–Wallis outcomes.

combinations led to significantly different ROS predictions, except for the June 13 field measurements (Tables 5, 6). Cross-landscape ROS predictions were more variable when live canopy *Calluna* fuel moisture values were used, leading to higher predicted rates of spread in spring and lower in summer (Fig. 5).

Table 6. Wilcoxon rank sum test pairwise comparisons for differences in predicted rates of spread (ROS) calculated using different fuel layer fuel moisture content inputs for each sampling date (Table 1).

Pairwise fuel layers	15/4/2021	18/4/2021	23/4/2021	13/6/2021	22/7/2021
Live combined × live canopy	**0.001**	**0.013**	**0.016**	0.357	**0.0025**
Live combined × live stems	**0.000**	**0.000**	**0.006**	0.289	**0.000**
Live stems × live canopy	**0.000**	**0.000**	**0.000**	0.089	**0.000**
Dead combined × Fosberg dead shaded	–	–	0.270	–	0.570
Dead combined × Fosberg dead unshaded	–	–	**0.000**	–	**0.000**
Fosberg dead unshaded × Fosberg dead shaded	–	–	**0.000**	–	**0.000**

Statistically significant differences (*P* < 0.05) are indicated in bold.
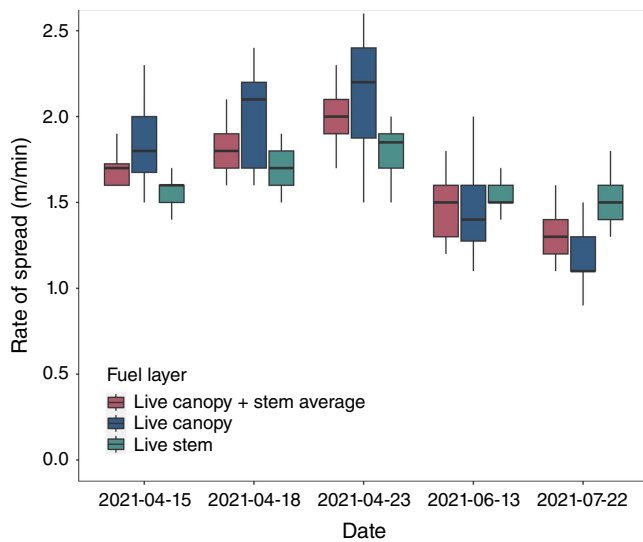
Fig. 5. Boxplots showing cross-landscape differences in predicted rate of spread (ROS) for each sampling date due to varying plot live fuel moisture content inputs. Live canopy and live stem scenarios describe predicted ROS due to plot live canopy and live stem fuel moisture content measurements, respectively. The live canopy + stem average scenario describes predicted ROS due to combined average live fuel moisture content for each plot. Dead fuel moisture content is kept as a single input of landscape-averaged combined dead fuel moisture content.

The Fosberg models predicted lower dead fuel moisture content using temperature and relative humidity measurements (Fig. 6a). The predictions using the shaded position Fosberg model were closer to observed dead fuel moisture despite the plots technically being unshaded. Predicted shaded (correlation coefficient = 0.48) and unshaded (0.46) fuel moisture content was, however, positively correlated with observed fuel moisture for July 22 (Supplementary Tables S1, S2). These differences did not translate to significantly different ROS predictions between the Fosberg shaded and observed combined dead fuel

moisture simulations, but predicted ROS was significantly higher for the Fosberg dead unshaded simulations (Tables 5, 6). Predicted ROS was higher in spring than summer (Fig. 6b).

Discussion

Our research highlights the importance of including cross-landscape fuel moisture content differences in fire behaviour prediction models. This means it is also key that we collect fuel moisture content data and understand how its variability is controlled by landscape features. By comparing a null model with uniform fuel moisture content values to models that realistically represent the variability in fuel moisture across a landscape, our results show that the predicted fire behaviour differs significantly when incorporating natural variability in fuel moisture (Fig. 3, Table 4).

Landscape fuel moisture variability impacts simulated fire behaviour

Cross-landscape fuel moisture differences impacted predicted ROS by 23–80% on average, compared to predictions based on a single fuel moisture estimate for the entire landscape (Table 4). From an ecological perspective, the magnitude of variability in predicted fire behaviour will create spatial differences in the potential intensity and severity of a fire on the landscape and the consequent recovery of areas of the landscape to managed or wild fire. Understanding these differences may help to inform land management decision-making to minimise the potential impacts of managed or wild fire. Furthermore, while the absolute ROS predicted was low on the days we collected fuel samples and so cross-landscape variation would not likely cause concern, the magnitude of variation in expected fire behaviour may provide useful information for fire managers during more extreme scenarios, particularly where fire
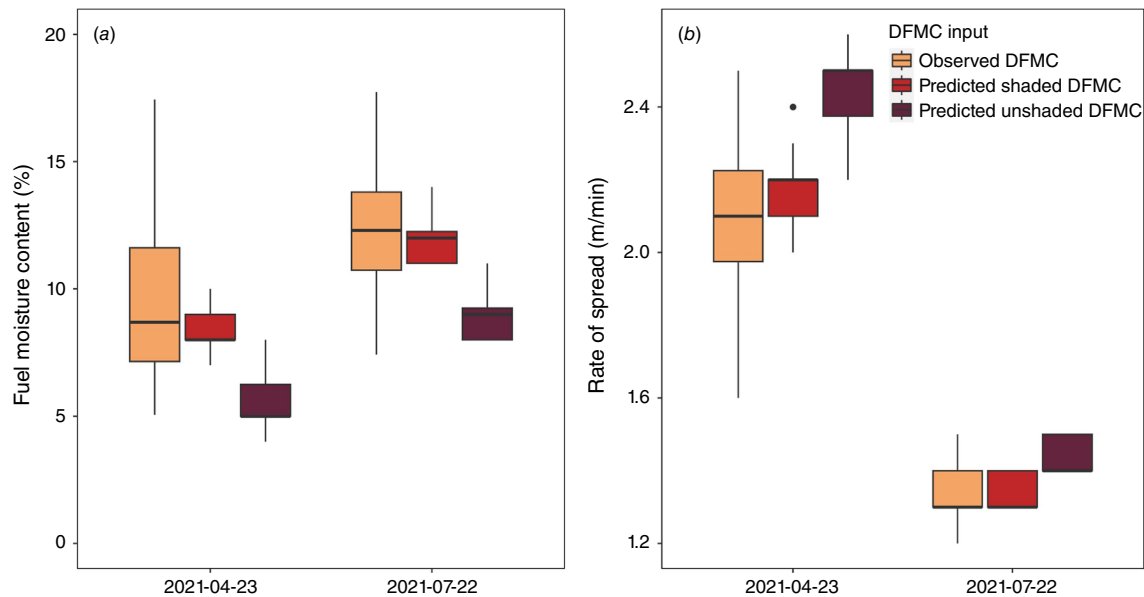
Fig. 6. Boxplots showing variation between observed combined dead fuel moisture content (average of dead canopy and stem fuel moisture measurements for each plot) and predicted dead fuel moisture content (DFMC) using the Fosberg model that calculates DFMC from air temperature and relative humidity recorded at each plot. We calculated the Fosberg DFMC for both shaded and unshaded scenarios for each plot (*a*). Boxplots showing the consequent variation in predicted rates of spread (ROS) due to observed and predicted DFMC variation for a spring (23/4/2021) and summer (22/7/2021) example (*b*).

behaviour crosses thresholds for the safe use of suppression tools and tactics. Similarly, points on the landscape where ROS is slower may provide Fire and Rescue Services with opportunities to focus suppression activities or create fire breaks.

This study contributes to existing model sensitivity studies as it utilises the measured magnitude of fuel moisture variation across a landscape on the same day and thus represents the range of differences in fire behaviour that could be expected in such a landscape. Fuel moisture content was more variable in our field campaigns than the observed fuel moisture ranges in previous experimental burns (Davies *et al.* 2009; Minsavage-Davis and Davies 2022). Spatial fuel moisture differences are dependent on preceding and concurrent weather conditions, which may explain some of the variation in field-measured fuel moisture content differences (Little *et al.* 2024). Absolute ROS tended to be lower than previous research has observed from experimental burns (Davies *et al.* 2009). This is likely due to differences in the specific parameters of the fuel models used that may not be fully representative of the fuel characteristics of *Calluna*. In particular, the SH3 and SH6 models both have a lower heat of combustion of 18.622 kJ/kg compared to customised models for *Calluna* based on field and laboratory measurements (Davies *et al.* 2009; Belcher 2023). Heat of combustion is known to be important for ROS (Madrigal *et al.* 2010) and the lower values used in the SH3 and SH6 models may have led to underpredicted

ROS. Understanding the ecological and phenological variability of *Calluna* and its impact on fuel moisture dynamics, fuel loads, and flammability will allow for the calibration of fuel models, such as those developed by Davies *et al.* (2009), for more accurate predictions of fire behaviour.

Simulated fire behaviour is impacted by choice of fuel layer and fuel model

Absolute ROS was significantly higher when the SH6 fuel family was used in place of the SH3 (Fig. 4). There are a range of fuel models that are used for temperate shrubby fuels (Scott and Burgan 2005), and we demonstrate that the choice of fuel model can dramatically affect predictions. Fine dead fuel load in the SH6 fuel model (0.65 kg/m^2) was six times higher than that of the SH3 fuel model (0.10 kg/m^2). We selected the SH3 model for the main simulations as our field measurements were collected in a high live fuel load landscape; however, under future climate change the proportion of live to dead fuel may change, and it is not unrealistic to think the higher dead fuel load SH6 fuel model may become more representative. A number of studies using climate projections point to future increased fire risk in the UK and northwest Europe due to increases in fire weather (Arnell *et al.* 2021; Perry *et al.* 2022). Moreover, the SH3 model contained a 0.67 kg/m^2 10-h dead fuel load (representing 6.35–25.4 mm diameter dead fuels), which is unrealistic within many *Calluna*-dominated

peatland and heathlands. As such, ROS is likely underpredicted in our simulations. In reality, a scenario somewhere between the SH3 and SH6 models would be most appropriate and highlights the importance of tailoring fuel models for robust predictions of fire behaviour.

Previous research has demonstrated fuel moisture differences between the different fuel layers of *Calluna* (i.e. canopy and stem fuel moisture differs for both live and dead *Calluna*) (Davies *et al.* 2010; Davies and Legg 2011). Predicted rates of spread were not significantly different when either dead canopy, dead stem, or a combined average was used. For simplicity, either material could be used from a fire behaviour modelling perspective. Predicted rates of spread were more variable for live *Calluna* canopy than stems or combined and predicted higher rates of spread in spring and lower in summer. Fire behaviour has proven challenging to model in temperate peatland and heathland fuels like *Calluna* where live fuel can form the dominant fuel load for fire spread during spring (Belcher *et al.* 2021). Moreover, previous experimental research found a strong relationship between *Calluna* canopy fuel moisture and variation in observed fire behaviour (Davies *et al.* 2009). In lieu of customised fuel models that specifically account for phenology, using *Calluna* canopy live fuel moisture for fire behaviour model inputs would help capture the role of phenology in influencing wildfire behaviour. Previous research has described fire behaviour in *Calluna* as akin to mini crown fires as sustained spread can occur through the canopy without consumption of the surface material (Fernandes *et al.* 2000; Davies and Legg 2016). As such, capturing *Calluna* canopy fuel moisture variation may provide the most realistic fire behaviour scenarios. These findings suggest that the underlying relationships that apportion the importance of dead and live fuel loads within the Rothermel family of fire spread models may need to be adjusted to better account for the importance of live fuel moisture in these fuel types.

Direct fuel moisture measurements are generally too time consuming to collect to be utilised in a wildfire response fire behaviour modelling capacity. In these scenarios we need to rely on modelled fuel moisture. The Fosberg model uses relative humidity and temperature to predict fine dead fuel moisture content. The ability to use a look-up table to generate quick predictions of fire behaviour is incredibly beneficial for response decision-making needs. These forms of fuel moisture models, like the Fosberg model, likely need to be customised for shrub fuel types that may not fully cure in the way grasses or litter do. Field-based measurements of fuel moisture in shrub fuels would allow for a correction factor to adapt existing models to temperate shrub ecosystems.

The Fosberg model was unable to capture the range of variability in fuel moisture content because factors beyond these meteorological controls also influence fuel moisture. While the unshaded model predicted lower fuel moisture contents and consequently higher ROS, the shaded model fuel moisture content was closer aligned to the observed dead fuel moisture despite a lack of shading effect from overstory forest canopy. The shaded Fosberg model simulated ROS that were not significantly different to those simulated using observed fuel moisture content (Fig. 6). This suggests that the density of *Calluna* canopy may shade understory fuels and make shaded fuel moisture predictions more appropriate to use, adding further weight to the narrative of *Calluna* behaving akin to a mini forest canopy.

Fire behaviour models are insensitive to cross-landscape live fuel moisture content

There is a broader issue of whether fire behaviour models are sufficiently sensitive to fuel moisture changes. While we measured high cross-landscape spatial fuel moisture variability (Fig. 2), the resulting variability in predicted ROS was much smaller (Supplementary Fig. S1). This is a reflection of the sensitivity of the Rothermel model to live fuel moisture. Previous experimental research has suggested that ROS is likely more sensitive to live fuel moisture changes than existing models predict, and this sensitivity increases with fuel aridity (Jolly 2007; Nolan *et al.* 2016; Pimont *et al.* 2019). This creates high risk scenarios in temperate regions where ROS may be underpredicted when live fuels are dry, such as at the end of winter and early spring when both managed burning and the main wildfire season are taking place in the UK's peatland and heathland landscapes (Davies *et al.* 2010). There is a need to constrain the role of fuel moisture, particularly live fuel moisture, within models to develop accurate predictions of fire behaviour in temperate environments (Dickman *et al.* 2023). One such avenue to achieve this would be to develop live fuel moisture models that capture plant phenological and physiological processes and constrain the sensitivity of fire behaviour models to live fuel moisture of temperate fuels.

Implications for fire management

In emerging fire prone environments like the temperate peatlands and heathlands of northwestern Europe, spatial heterogeneity in fire behaviour as a result of landscape characteristics is relevant to consider. Cross-landscape fire behaviour is important for fire management decision making, particularly where this variability may require changes in suppression tools and tactics employed or provide opportunities for suppression. Capturing cross-landscape fire behaviour variation would allow strategic decision-making for conducting burns to safely and effectively achieve management outcomes. Existing fire behaviour prediction tools based on a single regional average fuel moisture input could underpredict fire behaviour and create dangerous situations for those suppressing wildfires or increase the risk of escaped managed burns. Likewise, overpredictions could limit opportunities for managed burning and increase suppression costs associated with wildfire event turnouts.

As the risk from wildfires in these environments increases, availability of tools like BehavePlus to inform decision-making become increasingly important. These tools require user decisions such as choice of fuel model and fuel layer inputs, which can significantly impact predictions. Minsavage-Davis and Davies (2022) suggested fire behaviour modelling systems using Rothermel's surface fire spread model can be applied within *Calluna* heathlands but implored caution in interpreting predictions. While spatial variation in dead fuel moisture between *Calluna* fuel layers is not likely to impact predicted rates of spread, care should be taken in defining live fuel moisture inputs and emphasis should be put on capturing *Calluna* canopy fuel moisture. Our findings highlight the need to validate existing fuel models or develop tailored models that capture live fuel moisture dynamics and fuel loads in temperate shrub fuels.

Supplementary material

Supplementary material is available online.

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