Ivison *et al. Fire Ecology* (2026) 22:39
https://doi.org/10.1186/s42408-026-00478-4

Fire Ecology

ORIGINAL RESEARCH

Open Access

Landscape can play a role in the moisture content of temperate fuels

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Abstract

Background Fuel moisture content (FMC) is a critical component of wildfire risk. The spatiotemporal patterns of FMC of many key live, dead and surface-level temperate fuels (e.g. heather (*Calluna vulgaris*), gorse (*Ulex europaeus*), bracken (*Pteridium aquilinum*), moor grass (*Molinia caerulea*), litter, organic soil layers) are largely unknown and unravelling the drivers of FMC is challenging. Current models designed to predict FMC, principally of dead fuels, generally consider only weather variables. However, landscape variables (such as elevation, slope, aspect, soil type) affect water retention and availability of moisture within soils, and are therefore likely to influence FMC of live and organic ground fuels. We carried out a large-scale fuel sampling campaign from 2021–2023 of eighteen different fuel types across 43 sites through six different climate regions of the UK. We implemented a two-stage modelling approach to determine the influence of weather, phenological, and landscape variables on FMC.

Results We found that landscape influences the FMC of eleven fuel types, particularly for the organic soil layer, followed by live gorse stem and live bracken leaves. The FMC of all surface fuel types (moss, litter, organic layer and twigs) and six of the seven live fuels were influenced by landscape. Only one dead fuel type was influenced by landscape variables. Of the landscape variables, soil type, land cover and elevation significantly influenced fuel FMC. Slope and aspect did not influence the FMC of any fuel types. Weather influences the FMC of most fuel types, and phenology largely only influences the FMC of live and surface fuels.

Conclusions We have shown that landscape variables are important to consider when developing fuel moisture models, but that this is mainly important for live fuels and organic ground fuels. We therefore recommend tailoring models to each fuel type to yield the best performance.

Resumen

Antecedentes El contenido de humedad de los combustibles (*Fuel Moisture Content* en inglés o su acrónimo FMC, que usaremos de ahora en más), es un componente crítico del riesgo de incendios de vegetación. Los patrones espacio-temporales del FMC de muchos combustibles clave de regiones templadas, tanto vivos, muertos, y superficiales (i. e. brezo (*Calluna vulgaris*), retamo espinoso (*Ulex europaeus*), helecho águila (*Pteridium aquilinum*), masiega (*Molinia caerulea*), la broza, y los horizontes orgánicos superficiales), son prácticamente desconocidos, y el descubrir las variables conducentes a sus respectivos FMC es todo un desafío. Los modelos corrientes diseñados para predecir el FMC, principalmente de combustibles muertos, consideran solo variables meteorológico-ambientales. Sin embargo, variables a nivel de paisaje (como elevación, pendiente, orientación, tipo de suelo) afectan la retención de

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agua y su disponibilidad dentro de los suelos, y es probable, por lo tanto, que tengan influencia en el FMC de combustibles vivos y en el material orgánico del suelo. Condujimos una campaña de muestreo de combustibles a gran escala desde 2021 a 2023 en dieciocho tipos de combustibles diferentes en 43 sitios representado seis diferentes regiones del Reino Unido. Implementamos luego un modelado de dos etapas para determinar la influencia de variables meteorológicas, fenológicas y de paisajes sobre el FMC.

Resultados Encontramos que el paisaje influencia el FMC en once tipos de combustibles, particularmente para el horizonte orgánico superficial, seguido por tallos vivos del retamo espinoso, y hojas vivas del helecho águila. El FMC de todos los tipos de combustibles superficiales (musgos, broza, el horizonte orgánico, y ramitas pequeñas), y seis de los siete combustibles vivos, fueron influenciados por el paisaje. Solo uno de los combustibles muertos fue influenciado por variables del paisaje. De estas variables del paisaje, el tipo de suelo, la cobertura del suelo y la elevación influenciaron significativamente el FMC. La pendiente y la orientación no influenciaron el FMC en ningún tipo de combustible. Los factores meteorológicos influenciaron la mayoría de los tipos de combustibles y la fenología, por mucho, sólo influencia el FMC de los combustibles vivos y superficiales.

Conclusiones Hemos demostrado que las variables del paisaje son importantes a considerar cuando se desarrollan modelos de humedad del combustible, pero que esto es particularmente importante para combustibles vivos y aquellos que componen el suelo orgánico superficial. Recomendamos entonces confeccionar los modelos de acuerdo a cada tipo de combustible para obtener la mejor performance.

Keywords Fuel moisture, Wildfire, Landscape, Peat, Live fuel, Dead fuel, Calluna

Background

Due to changing climates and land management, wildfires are increasing in both frequency and size, resulting in human mortality, economic losses, and environmental change (Bowman et al. 2020). Although not typically prone to large or severe wildfires, wildfire incidence has increased in temperate regions such as the UK (McCarty et al. 2020; Fernandez-Anez et al. 2021; Jones et al. 2022).

In the UK, many of the largest wildfires occur in heathland, peatland and coniferous forests (Forestry Commission, 2023) dominated by flammable fuels such as heather (*Calluna vulgaris*), gorse (*Ulex europaeus*), moor grass (*Molinia caerulea*) (Davies and Legg 2008) and bracken (*Pteridium aquilinum*) (Holland et al. 2022). Dead twigs, litter, moss and the organic layer of soil beneath the ground's surface also contribute to potential fuel loads in these ecosystems. Each fuel contributes to fire risk in different ways. For example, the vegetative structure of heather influences the fire rate of spread (Davies et al. 2009); moor grass may ignite at low temperatures (Ganteaume, 2009); gorse can burn at a high rate of spread (Anderson & Anderson 2010); bracken has been associated with higher fire temperatures (Adie et al. 2011); low FMC in the organic layer may result in more severe wildfires (Grau-Andrés et al. 2018). In these and other ecosystems, fuel moisture content (FMC) is an important determinant of wildfire risk and plays a key role in influencing ignitability, flammability, consequent fire behaviour and associated severity of wildfire impacts (Davies & Legg 2011; Rossa and Fernandes 2017; Grau-Andrés et al. 2018; Scarff et al. 2021).

Direct measurements of fuel moisture content are time-consuming and resource intensive. In contrast, fuel moisture simulations offer the capability to characterise current and future FMC at a range of spatial and temporal scales for diverse applications including wildfire management scenarios (Matthews 2014) or wildfire danger rating assessments (Van Wagner 1987; Matthews et al. 2019). Various models have been developed to predict FMC in different ecosystems (see Viney (1991) and Matthews (2014) for comprehensive reviews). Some link FMC only to temperature and humidity, investigating fuels such as *Pinus ponderosa* needles (Anderson et al. 1978; Nelson 1984), *Pinus elliottii* needles and *Quercus falcus* leaves (Nelson 1984) in North America. Van Wagner and Pickett (1985) presented more complex formulas incorporating temperature, precipitation, humidity and wind speed data to predict fine fuel and duff moisture content within pine forests in Canada. More widely used is the Canadian Fire Weather Index (FWI), which forecasts periods of increased fire risk (Van Wagner 1987) and includes several different indices that provide estimates of fuel moisture, including the Fine Fuel Moisture Code (FFMC) and the Duff Moisture Code (DMC). Other notable examples include the US National Fire Danger Rating System FMC equations (Cohen and Deeming 1985) and the Australian Fire Danger Rating System models (Matthews et al. 2019).

All of the aforementioned studies solely consider weather variables and were developed for fine dead fuels. However, different fuel types may experience different controls on their moisture content. For example, live fuel moisture content can be affected by phenological

(Davies et al. 2010) and physiological (Pivivaroff et al., 2019); Scarff et al. 2021) traits. Predictive models for live FMC therefore include remote sensing of vegetation indices (Dasgupta et al. 2007; Danson & Bowyer, 2004) and measurements of plant traits (e.g. specific leaf area; Griebel et al. 2023).

Landscape variables may also play a crucial role in controlling fuel moisture content (Little et al. 2024). Topography controls water retention and drainage flow paths, therefore influencing soil moisture and facilitating water uptake by live plants (Easton and Bock 2016) or surface litter via capillary flow (Nyman et al. 2015; Slijepcevic et al. 2018; Zhao et al. 2022). Landscape characteristics like aspect may also influence microclimates, thereby altering how weather might affect fuel moisture (Brown et al. 2022). Further research is needed to disentangle the potential influence of landscape characteristics for the control of live and dead fuel and soil moisture, particularly in non-forested ecosystems and fuels that have received less attention, in order to develop robust fuel moisture models.

In terms of heathland ecosystems, research has been conducted to characterise the spatial and temporal variability of heather FMC (Davies and Legg 2008; Davies et al. 2010) and flammability thresholds (Davies and Legg 2011), and on the moisture content and flammability of moor grass in central England (Santana & Marrs 2016). For example, it is known that the moisture content of live heather is largely controlled by phenology and season and therefore increases with the summer green-up (e.g. Davies et al. 2010). However, weather-based modelling approaches alone do not simulate fuel moisture contents effectively within these emerging fire regions. The ability of the FFMC of the Canadian FWI to predict gorse moisture content, a fuel commonly found in wildfire-prone regions in the UK, has been observed to yield poor results (Anderson & Anderson 2010). In terms of wildfire activity, which is strongly linked to FMC (Davies & Legg 2011), the performance of the Canadian FWI indices to predict wildfire occurrence differed greatly between regions of Scotland and no components of the Canadian FWI performed well in summer (Davies and Legg 2016). Little et al. (2024) measured cross-landscape fuel moisture variation in heather, finding that landscape variables (soil texture, heather canopy age, slope and aspect) generally controlled the spatial variation of live and dead fuel moisture beyond micrometeorological variables at the landscape scale. These studies suggest that models considering only weather may not effectively predict the moisture content of fuels typically found in the UK, and that other variables, such as landscape variables, are important to consider. To build on this work, we need to not only broaden the spatial and temporal scope of study for the UK's key fuels, but investigate how incorporating these landscape variables affect or improve predictive models essential for assessing wildfire risk.

In this study we aimed to address some of the knowledge gaps concerning the impact of landscape variables on FMC by answering the following questions: 1) What is the relationship between FMC, weather and phenology? 2) How does the influence of landscape on FMC vary across fuel types? 3) Which landscape variables have the most influence on FMC?

Methods

Study sites

Fuel moisture monitoring sites were established at 43 peatland, heathland, grassland and forest locations across Great Britain (Fig. 1). Sites were chosen to incorporate combinations of the key landscape variables (land cover type (acid grassland, bog, heathland, coniferous forest plantations comprising pine (*Pinus spp.*) and fir (*Abies spp.*) species; Marston et al. 2022), soil type (coarse to fine textured)) that vary within temperate ecosystems, and were spread over six of the Met Office's (Kendon 2014; Met Office 2024) key climate districts (hereon referred to as regions) in the United Kingdom: South West/South Wales, South East, Peak District, East Anglia, the North York Moors and the Scottish Highlands. For a summary of the landscape characteristics associated with each site see Table S1.

Data collection

We collected fuel samples at each site on a fortnightly basis (monthly only from November to March) during 2021 and 2022, and infrequently between February and June 2023 (Supplementary File S1). We sampled fuel moisture content following a modified protocol from Norum and Miller (1984) that has been used for other fuel moisture campaigns in UK peatlands and heathlands (Little et al. 2024). Briefly, we established a 20 m transect at each sample site for each of the following fuel types: live heather, dead heather, live gorse, dead gorse, live bracken, dead bracken, live moor grass, dead moor grass, moss, litter, organic layer and twigs. Hereon, moss, litter, the organic layer and twigs will collectively be referred to as 'surface fuels'. See Table 1 for a breakdown of the number of samples per fuel type and where they were sampled from. For above-ground vegetation sampling, clippings were taken at ca. 10 points randomly along these transects, and for heather, gorse and bracken the stems and canopy/leaves were then split and stored separately. Moss samples were taken by pinching the top two cm of moss from the soil surface, and litter samples were taken by pinching the top two cm of litter from the soil surface, both at ca. 10 points randomly along the

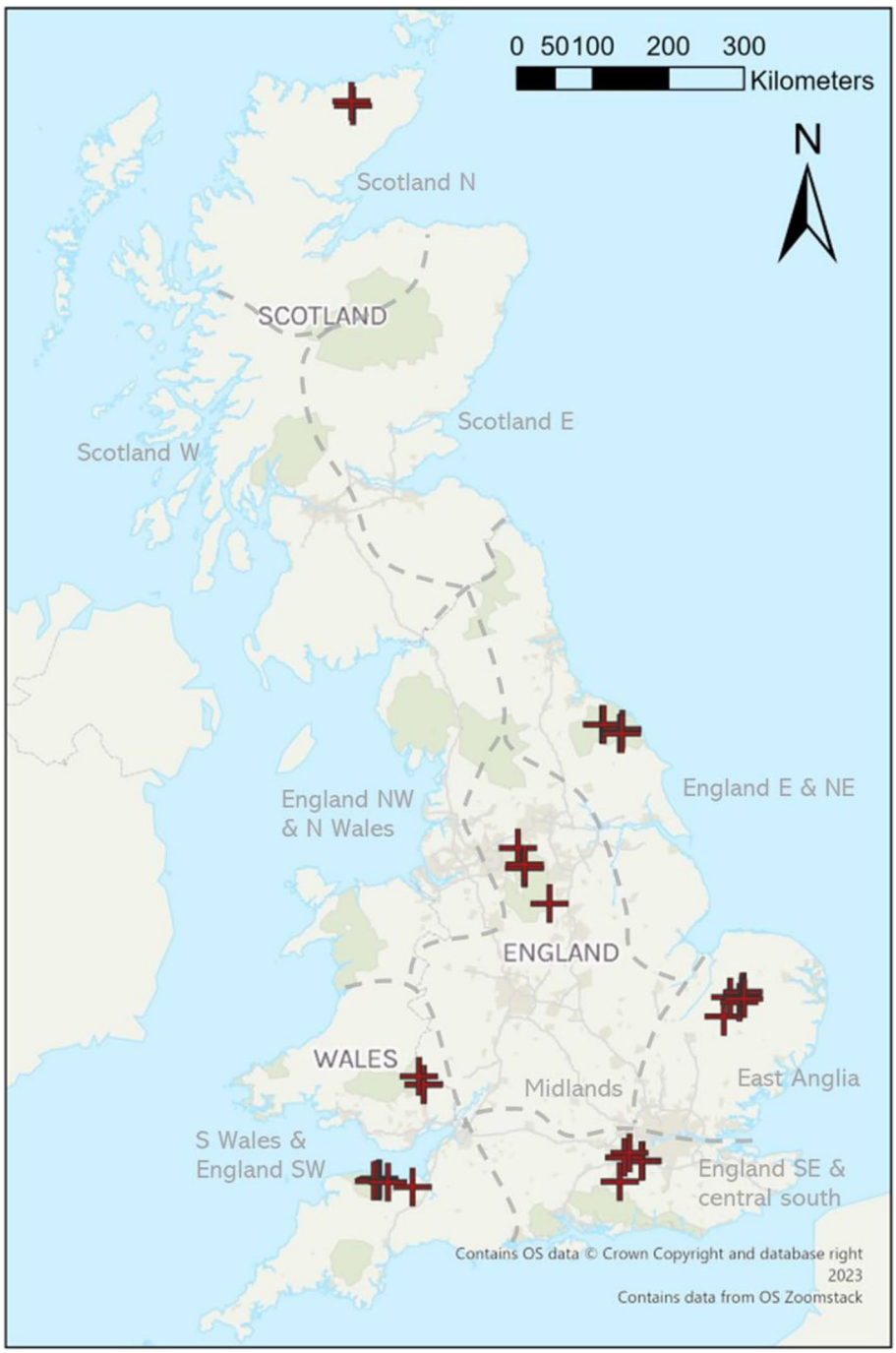


Fig. 1 Distribution of sample sites across the UK. Contains OS data. © Crown Copyright and database right 2023. Contains data from OS Zoomstack. Grey dashed lines and associated grey labels show climate regions (Met Office, 2024), one of the key variables considered when choosing sampling locations

transect. For the organic layer, we sampled the top 5 cm of organic material beneath the surface litter and above the mineral soil at four points along the transect. In forested sites, we collected twigs less than 5 mm diameter from fallen branches at ca. 10 points along the transect, only sampling those which were not touching the floor. We stored each fuel constituent in an aluminium screw-fit tin sealed with masking tape. For all fuel types, all 10 samples taken from a single transect were stored in the same tin resulting in a single sample per site that

Table 1 Number of samples and mean fuel moisture content (± standard deviation; %) for each sampled fuel type with the climate regions and land cover types where they were sampled

Fuel type	No. samples	Mean FMC (± SD)	Climate regions	Land cover types
Heather live canopy	389	105.6 ± 38.4	All (EA, NYM, PD, SH, SE, SW)	All (AG, B, CF, H)
Heather live stem	389	86.0 ± 30.5	All (EA, NYM, PD, SH, SE, SW)	All (AG, B, CF, H)
Heather dead canopy	374	27.0 ± 43.4	All (EA, NYM, PD, SH, SE, SW)	All (AG, B, CF, H)
Heather dead stem	379	24.5 ± 21.8	All (EA, NYM, PD, SH, SE, SW)	All (AG, B, CF, H)
Gorse live canopy	201	151.3 ± 55.2	EA, SH, SE, SW	AG, H
Gorse live stem	200	96.1 ± 38.8	EA, SH, SE, SW	AG, H
Gorse dead canopy	185	19.5 ± 30.4	EA, PD, SH, SE, SW	AG, H
Gorse dead stem	183	19.4 ± 14.2	EA, SH, SE, SW	AG, H
Bracken live leaves	156	253.5 ± 87.3	EA, NYM, PD, SE, SW	AG, CF, H
Bracken live stem	157	325.9 ± 139.5	EA, NYM, PD, SE, SW	AG, CF, H
Bracken dead leaves	323	28.6 ± 44.9	EA, NYM, PD, SE, SW	AG, CF, H
Bracken dead stem	316	43.2 ± 69.6	EA, NYM, PD, SE, SW	AG, CF, H
Moor grass live	122	163.1 ± 94.2	EA, NYM, PD, SE, SW	AG, B, H
Moor grass dead	193	32.7 ± 54.8	EA, NYM, PD, SE, SW	All (AG, B, CF, H)
Litter	805	105.9 ± 107.1	All (EA, NYM, PD, SH, SE, SW)	All (AG, B, CF, H)
Organic layer	667	144.8 ± 108.1	All (EA, NYM, PD, SH, SE, SW)	All (AG, B, CF, H)
Moss	541	173.5 ± 185.8	All (EA, NYM, PD, SH, SE, SW)	All (AG, B, CF, H)
Twigs	265	35.9 ± 28.9	EA, NYM, PD, SE, SW	CF, H

Climate regions: *EA* East Anglia, *NYM* North York Moors, *PD* Peak District, *SH* Scottish Highlands, *SE* Southeast England, *SW* South Wales/Southwest England. Land cover types: *AG* acid grassland, *B* bog, *CF* coniferous forest, *H* heathland

captured the within-plot variability along the transect. We calculated gravimetric fuel moisture content (mass of water per mass of dry sample, %) by weighing the collected samples, drying them for 48 h at 80 ˚C and then reweighing the dried samples.

Kestrel 3000 weather meters (Kestrel Instruments, Boothwyn, PA) were used to measure air temperature and relative humidity during sampling at each site. A limited number of temperature data were missing from samples early in the sampling period (early 2021) and humidity measurements were missing from the Scottish Highlands data. Missing weather data were filled in using the Met Office's MIDAS Open hourly weather data (Met Office 2019) and the Environmental Information Data Centre (Coyle et al. 2024) from weather stations close to each sample region (Table S2). Using air temperature and relative humidity, we calculated Vapour Pressure Deficit (VPD) which is commonly used in modelling fuel moisture (e.g. Jain et al. 2022; Griebel et al. 2023). Daily mean temperature and daily precipitation were downloaded at 0.25 degree resolution (roughly 27 km at the equator) for the grid cells containing sample sites from the E-OBS ensemble gridded dataset version 26.0 (Cornes et al. 2018). For each sample site, we calculated the long-term mean daily temperature of the site's associated grid cell for the 20-year period 2004–2023 to represent long-term climatology of the site and time of year. We calculated the number of days since rain to represent longer-term drying. Recent rainfall information was represented by calculating the sum of total precipitation of the sampling day and the 5 days prior to sampling.

Soilscapes (Farewell et al. 2011), which contains information about soil types across England and Wales, and the National Soil Map of Scotland (Soil Survey of Scotland Staff 1981) were used to assign soil types to each sampling location. Both datasets use a different method of assigning soil types, so Scottish soil types were assigned a Soilscapes classification according to their closest match. We grouped the Soilscapes categories into five groups to aid analysis, using the Soilscape descriptions: loamy & freely draining; sandy & freely draining; loamy & naturally wet; sandy & naturally wet; peaty & naturally wet (Table S3). The R package 'elevatr' (Hollister et al. 2022) was used to download elevation data, and the R package 'raster' (Hijmans & van Etten 2012) was used to download slope and aspect data. Finally, NDVI values were obtained from the MODIS Vegetation Indices (Didan 2021) via the Google Earth Engine in 16-day intervals, as fuel moisture content may be linked to plant phenology (Davies et al. 2010). NDVI was assigned according to the 16-day interval associated with the field sampling date.

Data analysis

We chose ten variables (see *Data collection* above; Table 2) to represent a range of weather, phenological

Table 2 Variables used in two-stage modelling approach

Variable	Units	Type of variable
Vapour Pressure Deficit (VPD)	hPa	Weather
Number of days since rain	Days	Weather
Total rainfall of sampling day and 5 days prior	Millimetres	Weather
Long-term (20 yr) mean daily temperature	° Celsius	Phenological
Normalized Difference Vegetation Index (NDVI)	NDVI	Phenological*
Time of day	Decimal time (e.g. 12:30 = 12.5)	
Sample year	One of 2021, 2022 or 2023	
Land cover type	One of: heathland, acid grassland, bog or coniferous forest	Landscape
Soil type	A variety of soil types characterised by Soilscapes (Table S3)	Landscape
Elevation	Metres	Landscape
Slope	Degrees	Landscape
Aspect	Degrees (0 = north-facing, 90 = east-facing, 180 = south facing, 270 = west-facing)	Landscape

* Although it varies over time, NDVI is linked to topographical factors (Kariyeva & Van Leeuwen 2011) so could therefore be alternately classed as a landscape variable. However, in the context of FMC we categorised NDVI as temporal as for live fuels as FMC is strongly linked to summer green-up (Belcher et al. 2021)

and landscape information. We grouped the variables like this because weather and phenological variables change over time, whereas landscape variables remain constant within each sample site. We note that canopy cover, which may play a role in moisture content (e.g. Tanskanen et al. 2005, 2006), was not included here because our sites either comprised heathland/bog/grassland sites, which did not have any canopy cover, and coniferous forest sites which had full or close to full canopy cover. Canopy cover would therefore be accounted for by the 'land cover' variable. We also acknowledge that some landscape variables (such as aspect, slope, elevation) may only influence FMC via their effect on meteorological variables such as solar radiation. However, in this study we are interested in the broader links between landscape variables and FMC rather than the mechanistic underpinnings. All of the variables included in our analysis are available on online resources (Soil Survey of Scotland Staff 1981; Farewell et al. 2011; Hijmans & van Etten 2012; Cornes et al. 2018; Didan 2021; Hollister et al. 2022; Marston et al. 2022; Coyles et al., 2024); Met Office, 2024). Although we measured the majority of air temperature and relative humidity data in situ, these may be obtained on an hourly timescale at a variety of locations around the UK using the Met Office's MIDAS Open hourly weather data (Met Office 2019) and the Environmental Information Data Centre (Coyle et al. 2024). Furthermore, the variables included have each been linked to FMC (e.g. Van Wagner and Pickett 1985; Belcher et al. 2021; Brown et al. 2022; Little et al. 2024) but have not been considered altogether or for such a variety of fuel types.

We used a two-stage hierarchical modelling approach for each of the three fuel types separately to determine the effects of weather, phenology and landscape variables on FMC. We chose a two-stage modelling approach due to the temporal mismatch between temporally-varying weather and phenology variables, and temporally-static landscape variables. Firstly, we ran a mixed-effects linear model for FMC with fixed effects comprising weather variables (VPD, number of days since rain and the total rainfall of the sampling day and five days prior (hereon called five-day rainfall)) and phenological variables (NDVI and long-term mean daily temperature). Sample site was included as a random effect. Sample year and time of day were included as fixed effects to account for diurnal and interannual FMC variability. Within these models, we calculated the marginal R-squared values, which tell us the % of FMC variability explained by weather and phenological variables only (fixed effects), and the conditional R-squared values, which tell us the % of FMC variability explained by all variables including the site-level random effects. We extracted the random effect for each site and created a second linear model for these effect sizes with landscape variables (soil type, land cover type, elevation, aspect and slope) as fixed effects. We obtained adjusted R-squared values from these models which told us the % of FMC variability across sites explained by landscape variables. We then calculated the total % of all FMC variability explained by landscape variables as the % of site-level effects (i.e. the conditional R-squared—marginal R-squared from the first model) that were explained by landscape (adjusted R-squared). We calculated the importance of each landscape variable, represented by the variables' standardised

beta coefficients. For categorical variables (soil type, land cover type) we summed the standardised beta coefficients of each group within that category to obtain the overall variable importance. We ran all statistical analyses in R version 4.3.0 (R Core Team, 2023).

Results

Fuel samples

In total, we took 5,845 samples across 130 days from 2021–2023 (Supplementary File S1). For a breakdown of the mean FMC and number of samples within each region, land cover type and month see Tables S4–S6. For a full description of the raw data obtained in this study please see Ivison et al. (2024).

Relationship between FMC, weather and phenology

All seven dead fuels were significantly associated with weather variables but only one (dead heather stem) was significantly associated with phenological variables (long-term mean daily temperature, $p < 0.01$). Six of the seven live fuels were significantly associated with weather variables and six with phenological variables. All surface fuels (litter, moss, organic layer, twigs) were significantly associated with both weather and phenological variables (Fig. 2).

Of the weather variables, VPD was significantly associated with the greatest number of fuel types (fifteen), whereas no. days since rain was significantly associated with the least number of fuels (five). Five-day rainfall was associated with thirteen fuels. Of the phenological variables, NDVI was significantly associated with eleven fuels, and long-term mean daily temperature with only two fuels (Fig. 2). For full model summaries see Tables S7–S24.

Variance explained by landscape variables across fuel types

Eleven of the eighteen fuel types were associated with landscape variables, comprising all four surface fuels, six of the seven live fuels and only one dead fuel (dead bracken leaves). The organic layer was influenced most by landscape variables, which explained 34% of its FMC variability, followed by live gorse stem (14%) and live bracken leaves (5%) (Fig. 3; Table S25). Of the seven dead fuel groups, three had zero variance estimate for the site-level random effect, indicating that landscape played no significant role in the FMC variability of these fuels. A further three dead fuels had negative adjusted R-squared values (treated as zero in Fig. 3), indicating that, although there was across-site variability, this was not influenced by landscape variables included in our hypothesised model. Live gorse canopy also had a negative adjusted R-squared value.

Landscape variables with the most influence on FMC

The results of the second model within the two-stage model approach tell us, of the landscape variables, which had the most influence on the FMC variability observed between sample sites. Soil type was the most frequently associated with FMC variability and had significant relationships with the FMC of three fuels (live bracken stem, lower FMC in sandy & naturally wet soils (Table S10); live heather canopy, higher FMC in peaty & naturally wet soil (Table S16); organic layer, higher FMC for loamy & naturally wet and sandy & naturally wet soils (Table S23)). For two fuels (live bracken leaves, live moor grass), land cover type was significantly associated with FMC variation; specifically, FMC was higher in coniferous forests for live bracken leaves (Table S9) and lower in bog for live moor grass (Table S21). Elevation was only significantly associated with FMC variation for the organic layer, and this was the only fuel significantly associated with more than one landscape variable. The effects of aspect and slope were insignificant across all fuels (Fig. 4). See Figures S1–S15 for partial effect plots showing the relationship between each landscape variable and FMC of the fifteen fuel types with across-site variation.

Discussion

Do landscape variables influence FMC?

We investigated the potential influence of five landscape variables (land cover type, soil type, elevation, aspect, slope) on the FMC of eighteen different fuel constituents in the largest fuel sampling study carried out in the UK to date, both spatially and temporally. This is therefore the first time that the drivers of fuel moisture have been investigated for many fuel types directly.

Weather variables (VPD, five-day rainfall, number of days since rain) were associated with seventeen of the eighteen sampled fuel types. Weather variables affect FMC of many fuel types both in emerging fire-prone (Belcher et al. 2021) and fire-prone regions (Van Wagner and Pickett 1985; Matthews et al. 2019), particularly for elevated dead fuels (i.e. not surface litter) that are unable to draw water from the ground and are therefore controlled largely by their environment (Belcher et al. 2021). Phenological variables were associated with eleven fuel types, including almost all live fuels but no dead fuels. Previous studies have found that FMC for some live fuels, including heather in the UK (Belcher et al. 2021), is lowest in spring before the summer green-up (Jolly et al.

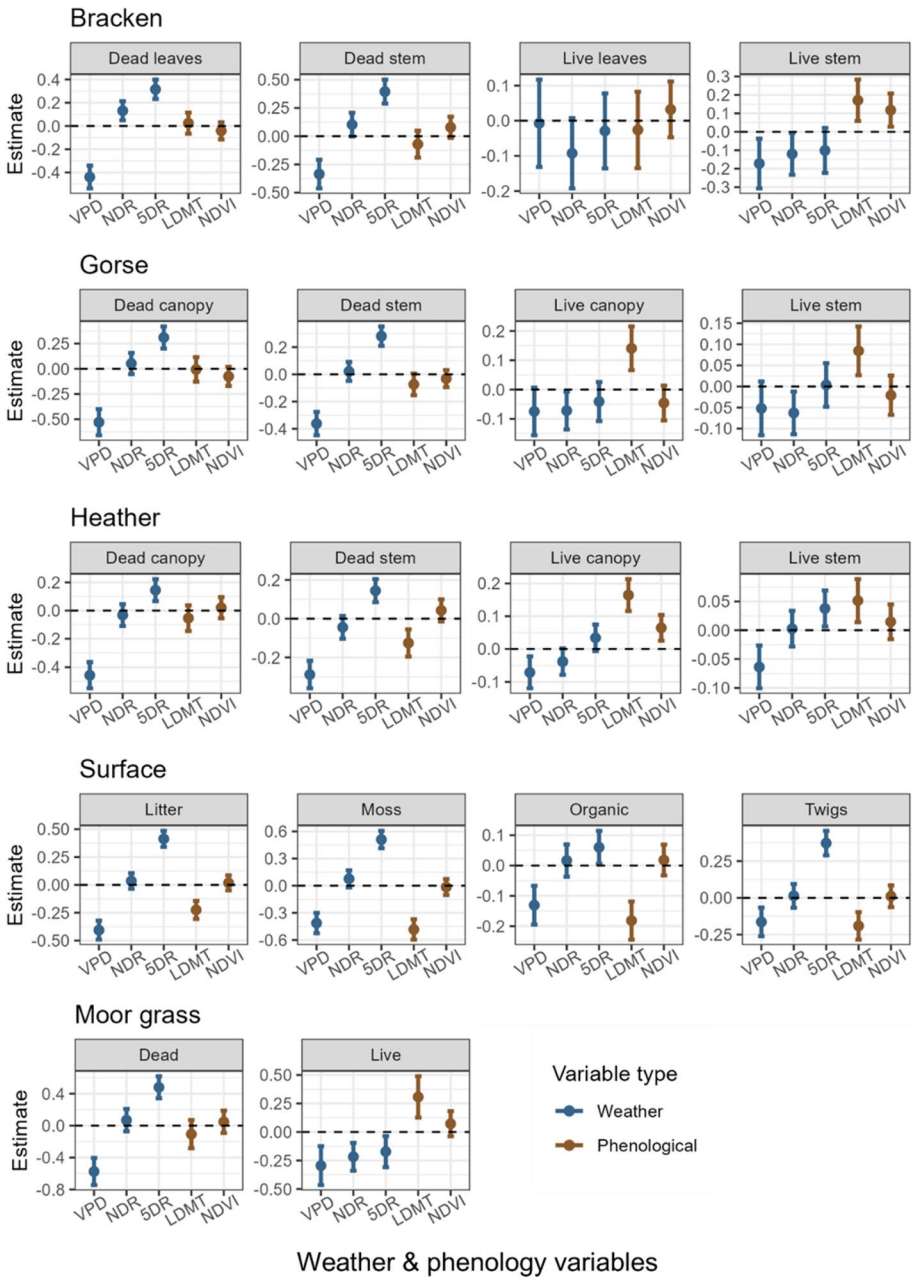


Fig. 2 The effect size (± 95% confidence interval) of weather and phenology variables on FMC for eighteen fuel types. VPD = Vapour Pressure Deficit, NDR = no. days since rainfall, 5DR = total rainfall of five days prior, LDMT = long-term mean daily temperature, NDVI = Normalized Difference Vegetation Index. Variables are considered significant if CI does not cross 0

2014), which is reflected in the relationship with NDVI found here.

Landscape variables influenced the FMC of eleven fuel types, comprising all surface fuels and most live fuels, and organic layer FMC had the strongest association with landscape. Understanding the organic layer's FMC is particularly relevant in the UK as many wildfire-prone ecosystems contain peat or organic-rich soils, and severe wildfires in these regions may result in smouldering combustion and the release of carbon stocks (Davies et al. 2013). The association of landscape variables on the organic layer is supported by other findings: for example, landscape position and surficial geology affect the depth of burn in peatlands (Hokanson et al. 2016); elevation has a significant effect on soil moisture in microclimate models (Walsh et al. 2017) and, combined with slope, can

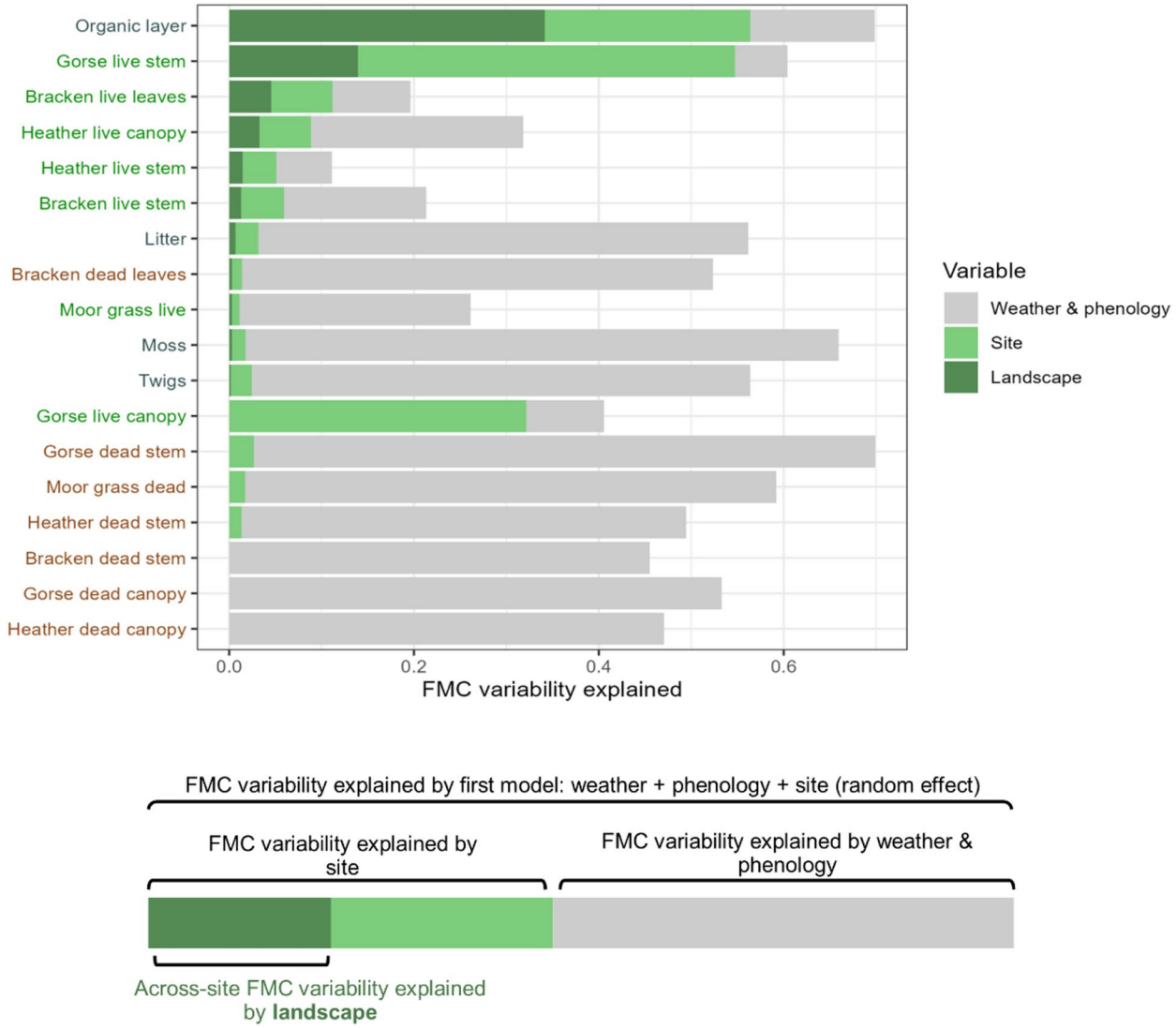


Fig. 3 The variability in FMC explained by a two-stage modelling approach. Total bar length denotes FMC variability explained by the first model comprising weather, phenology, and site as a random effect. Grey section denotes FMC variability explained by fixed effects of the first model (weather, phenology, sample year, and time of day). Green section denotes FMC variability explained by site, and darker green section denotes the proportion of this across-site variability explained by landscape variables (adjusted R^2 of second model). Fuels are colour-coded according to type; green = live, brown = dead, blue = surface fuels. For some fuels, site effect size was close to 0, so landscape models were not carried out; these have grey bars (depicting weather/phenology) only. Further fuels had across-site variability, but adjusted R^2 values were negative, indicating that landscape variables did not explain this across-site variability. Adjusted R^2 is treated as 0 for these fuels

affect surface fuel moisture (Holden and Jolly 2011) and therefore fire severity (Fang et al. 2018). However, opposing effects of elevation have been observed where in some regions, surface fuels at higher altitudes dry more quickly due to increased drainage (Fang et al. 2018 (Siberia, Russia)), whereas in others, fuel moisture was lowest at low elevations (Holden and Jolly 2011 (Montana, US); Sullivan and Matthews 2013 (Victoria, Australia)). In our study we found the latter trend of increased moisture with elevation (Table S23; Figure S14), which is likely due to the composition of soils in our study sites, where peaty soils were often located at higher altitudes (e.g. Peak District and North York Moors regions) and coarser, sandier soils were located at lower altitudes (e.g. East Anglia and the South East regions). Furthermore, aspect, which influences fuel moisture (Holden and Jolly 2011) due to the impacts on the water retention and drainage in soils (and therefore moisture) (Slijepcevic et al. 2018; Nyman et al. 2015), was not significant for the organic layer. Therefore, although landscape variables have been found

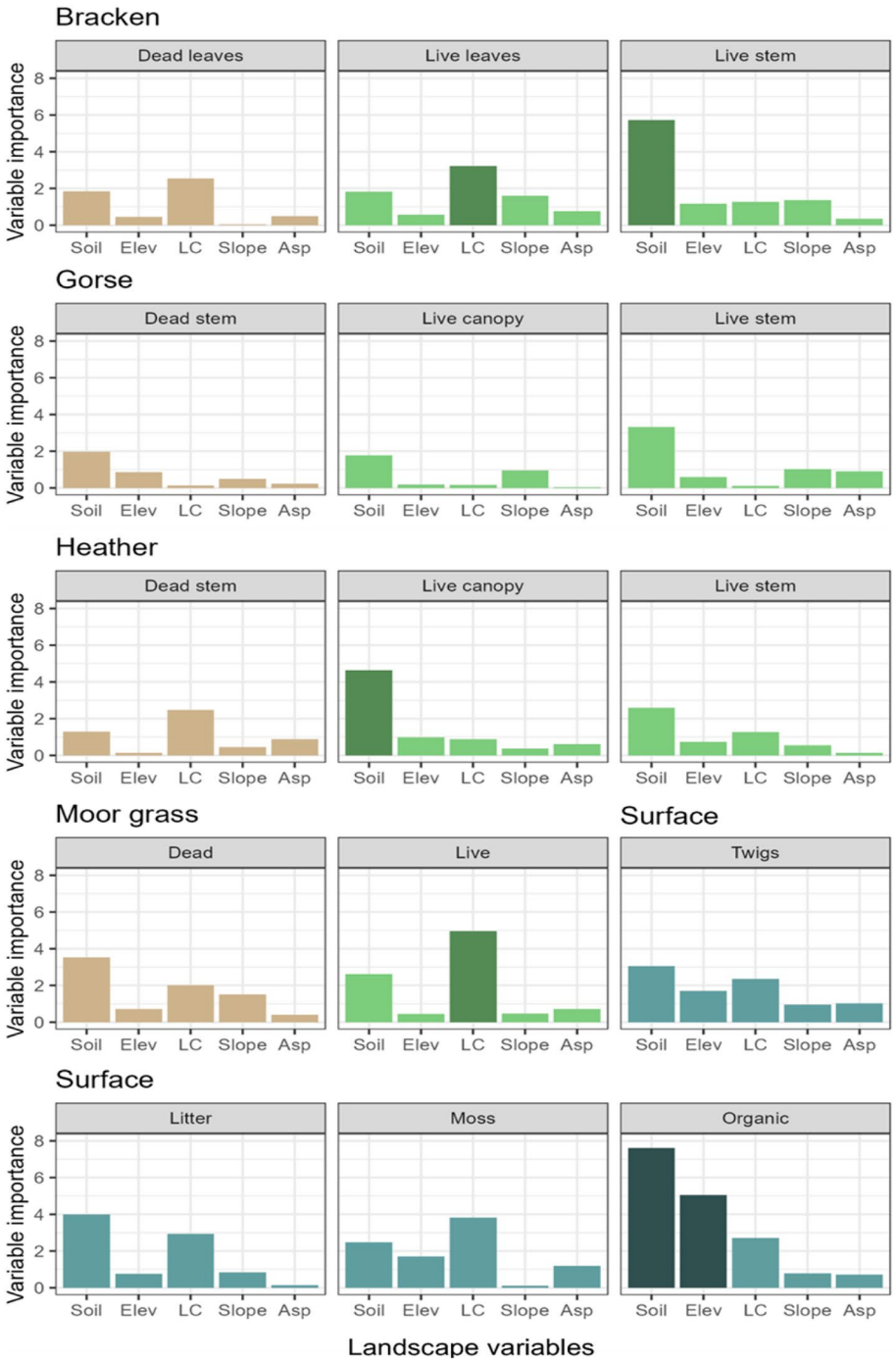


Fig. 4 The importance of each landscape variable on the variability in FMC observed between sample sites. Elev = elevation, LC = land cover, Asp = aspect. The variable importance for each group within categorical variables was summed. Dead fuels are plotted in brown, live in green and surface fuels in blue. Darker bars indicate variables which were significantly associated with FMC variability ($p < 0.05$)

to drive fuel moisture across a variety of ecosystems, the effects of each landscape variable may vary depending on specific site characteristics.

Landscape variables had little to no effect on the FMC of six of the seven dead fuels. This was either observed as a lack of across-site variability in FMC, where we were unable to run the second model of the two-stage modelling method, or as a negative adjusted R^2 value in the second model which indicated that, although there was some across-site variability, this was not explained by any

of the input landscape variables. This result is expected, as dead fuel moisture is controlled only by environmental conditions as it is unable to actively take up water from its surroundings (e.g. taking water from the ground or respiring water vapour) (Belcher et al. 2021).

Implications for fuel moisture modelling

These analyses inform our approach to FMC modelling. This is particularly pertinent for live FMC, where phenological or physiological patterns have been investigated (e.g. Pivovaroff et al. 2019; Davies et al. 2010) but the broader controls have so far been relatively unresolved and are consequently particularly difficult to predict (Jolly 2007; Ruffault et al. 2018). Landscape variables explained FMC variability to some extent for most live fuels and all surface fuels. However, for most dead fuels, FMC was widely influenced by weather only, and neither phenology nor landscape variables were significantly associated with FMC. Our work shows that, in order to yield the best results for applied predictive models, we should not include the same variables in models across all fuel types but should instead tailor them to the specific fuel. We have shown that landscape variables are important to consider for the organic layer, suggesting that further complexity in organic layer moisture modelling may be required compared to existing weather-driven models. Landscape variables do not have much influence on dead FMC in these ecosystems and could be discarded. Existing models to predict dead fuel moisture (e.g. Nelson 1984; Van Wagner 1987) are therefore likely to be sufficient without the need for introducing landscape. For live fuels, landscape is important to a degree; however, bringing landscape variables into models creates challenges in terms of model complexity, represented here by the two-stage approach required to incorporate temporally-varying (weather/phenology) and temporally-static (landscape) variables. Exploring the specific relationship between live fuel moisture and landscape is therefore a vital next step in fuel moisture modelling to assess whether this increased model complexity is necessary for live fuels.

Conclusions

Our work sheds light on the complex drivers of FMC and will help us understand the specific conditions under which wildfires may occur in different ecosystems. Previous research into the effects of landscape variables on FMC has investigated aspect (Holden & Jolly 2011; Nyman et al. 2015; Slijepcevic et al. 2018; Little et al. 2024), soil texture (Little et al. 2024), and elevation (Holden & Jolly 2011), but this is the first time that this variety of landscape variables has been studied across such a range of fuel types. Perhaps the most relevant finding for any future work is that landscape variables are important for some fuels but not all, and we therefore highlight the need for tailored predictive models of FMC for each fuel type. Our results are applicable to improving and developing robust fuel moisture models for different fuels and may help to inform the development of wildfire assessments.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-026-00478-4.

Supplementary Material 1.

Supplementary Material 2.

Acknowledgements

Thank you to Chloe Lewis, Lily Keyzor, Luke Everett, Erin Stoll and Niamh Dyer for their huge efforts sampling fuels for this study. We acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu).

Authors' contributions

NK, KL, AO and LJG designed the methodology; KL, AO and NK collected data; all authors devised the data analysis; KI analysed the data and led the writing of the paper; all authors revised the manuscript.

Funding

This project has received funding from NERC Highlight project NE/T003553/1. LJG was supported by the IIASA-NERC Research Fellowship NE/T009373/1.

Data availability

The datasets generated and analysed during the current study are available in the Figshare repository: https://figshare.com/projects/Landscape_factors_can_improve_the_predictive_ability_of_fuel_moisture_models_for_assessing_wildfire_risk/199327.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 21 March 2024 Accepted: 14 March 2026
Published online: 21 April 2026

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