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Original Article

Fuel moisture and flammability of leaf litter in British forest plantations and their implications for wildfire risk

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Abstract

The UK faces increased wildfire risk due to climate change, but efforts to improve forecasting of this risk are limited by a lack of data on fuel properties. We assessed tree leaf litter flammability and ground fuel (litter and duff) moisture in samples from six managed forest plantations across Great Britain over the course of one year. We sampled litter and duff monthly, from Scots & Corsican pine [*Pinus sylvestris* L. and *Pinus nigra* subsp. *laricio* (Poir.) Maire], Sitka & Norway spruce [*Picea sitchensis* (Bong.) Carrière and *Picea abies* (L.) H.Karst.], and Silver birch (*Betula pendula* Roth) plantations (representative of long-needled, short-needled, and broadleaved trees), measured moisture content, and used cone calorimetry to obtain data on leaf litter flammability. We examined relationships between rainfall, litter moisture, and flammability, and showed that cumulative rainfall over the previous 20–25 days most strongly influenced litter moisture, which in turn accounted for much of the variation in flammability. Silver birch maintained higher litter moisture than coniferous species throughout the year, which may be attributed to differences in leaf morphology, decomposition and phenology between broadleaves and conifers. All species reached minima of both litter moisture and duff moisture low enough to sustain burning during the year. While previous studies have often used artificially composed litter samples to demonstrate the effects of leaf properties (especially leaf shape) on flammability, our results using unmodified litter only partially confirm these effects. Interspecies differences in the peak heat release rate may be attributable to both structural properties and volatile content of the litter. However, differences in total heat release, previously attributed to leaf morphology, were evident only when measured on an areal basis, and not on a mass basis. Our data do not support the hypothesis that the morphology of broadleaves results in more ignitable litter beds. This study presents forest litter flammability data through an annual cycle for the first time, and the first extensive litter flammability data from the British Isles. It provides fuel moisture and heat content data that will contribute to the development of fuel models for UK forest environments, enabling forest management that is better informed about fire risk.

Keywords: flammability; cone calorimetry; forest fire; forest fuels; forest litter; heat release

Introduction

While forests contain several distinct fuel types, the litter bed plays a unique role in determining the risk of fire, including the key aspects of ignitability, heat release rate, and fire severity. This is because forest fires typically ignite in the litter layer, and spread primarily through surface fuels (litter, herbaceous vegetation, shrubs, and downed woody material). In closed canopy forests, litter tends to form a continuous layer that may allow fire to spread even where other surface fuels do not. Flammability properties of forest litter vary considerably with moisture conditions (Ferguson *et al.* 2002) and species (Curt *et al.* 2011, De Magalhães and Schwilk 2012), with much of the latter variation being determined by leaf size and morphology (Scarff and Westoby 2006, Santoni *et al.* 2014, Grootemaat *et al.* 2017, Ewald *et al.* 2025).

There is substantial research linking various properties of leaves and individual fuel elements to aspects of flammability (e.g. Papió and Trabaud 1990, Dimitrakopoulos and Papaioannou 2001, Murray *et al.* 2013, Grootemaat *et al.* 2015). However, these studies have sampled leaves directly from the plants, and cannot necessarily be taken as evidence of the flammability characteristics of leaf litter from the same species. Leaf morphology affects packing ratio, and therefore ventilation of the fuel bed (Santoni *et al.* 2014), and the resulting effects on oxygen supply to the fuel may override flammability variations of the individual fuel elements. In addition, leaves picked from a tree will differ in their chemical composition from those naturally abscised in the formation of a litter bed (Berg and Laskowski 2005).

Research into litter bed flammability has primarily focused on monospecific fuel beds (Varner *et al.* 2015, Belcher 2016), or used simple, artificially composed mixtures of fuel elements (e.g. Zhao *et al.* 2019), rather than field-sampled litter. A number of studies report nonadditive effects where fuel elements of different species are combined (e.g. De Magalhães and Schwilk 2012, Zhao *et al.* 2019, Gormley *et al.* 2020), underlining the necessity of studying

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actual litter compositions. Flammability studies on field-sampled litter have been carried out for a number of woodland ecosystems globally (e.g. Curt *et al.* 2011, De Magalhães and Schwilk 2012), but to our knowledge no such study has been conducted in the British Isles.

Although the UK has amongst the lowest proportions of forest cover in Europe, estimated at 13.5% of land area in 2024 (Forest Research 2024), this has grown during the 20th century from around 5% due to a policy of afforestation, especially from 1945 onward, the majority of it with conifers (Cannell and Dewar 1995). As a result, much of the UK's woodland consists of forest plantations, dominated by a relatively small number of species, often non-native, and usually in even-aged plantations. These features of the UK's forests render them atypical in terms of their combination of climate and species/age composition, highlighting the need for a region-specific analysis of litter flammability.

With the expectation of increased wildfire risk in the UK due to future climatic changes (Arnell *et al.* 2021, Belcher *et al.* 2021, Perry *et al.* 2022), and the desire to further increase forest cover as a climate change mitigation and adaptation measure, there is a pressing need for improved ability to forecast forest fire risk and predict potential fire behaviour. At present, the Met Office (the UK's national meteorological service) forecasts a 5-day Fire Severity Index (Met Office 2005, 2024a). The Met Office Fire Severity Index (MOFSI) assesses the potential of how severe a wildfire may become, but not the risk of wildfire occurrence, and covers England and Wales only, at a 10 × 10 km resolution. Predictions of 'exceptional fire severity' may result in restriction of access to some publicly accessible lands, while a nationwide assessment is also incorporated in the Daily Hazard Assessment provided to emergency services and government bodies by the UK's Natural Hazards Partnership (Hemingway and Gunawan 2018).

The MOFSI is an adaptation of the Fire Weather Index (FWI), which is the meteorological module of the Canadian Forest Fire Danger Rating System (Stocks *et al.* 1989). The FWI is calculated from observed and predicted weather data, using empirically derived relations between weather conditions and fuel moisture to infer 'moisture codes' as an intermediate step to the calculation of potential rate of fire spread and total amount of combustible fuel, and these are used to calculate the FWI. The FWI is then translated to descriptive fire severity categories on a five-class scale (very low, low, moderate, high, and exceptional). The translation to the final severity rating is informed by historical data specific to England and Wales (Met Office 2005), but the calculation of the FWI itself does not differ from the Canadian system, and as that system was originally developed for use in Canadian pine forests, it incorporates relationships between fuel moisture and meteorological conditions derived empirically in those environments (Van Wagner 1974). While the FWI was selected as the basis for the MOSFI on account of its superior ability to discriminate UK fire weather conditions compared to other indices available at the time (Met Office 2005), the FWI calculation is not adjusted to account for the different fuel conditions of UK environments. Therefore, there is a need to establish the drivers and variability in dead fuel moisture for UK fuels, including forest litter, to adapt this system for UK purposes.

Countries that have historically been more fire-prone than the UK have developed both more complex wildfire danger rating systems, and also fire behaviour prediction systems that combine weather and fuel moisture inputs together with data on differences in fuel properties between different ecosystems. As an example, the BehavePlus Fire Modeling System (Heinsch and Andrews 2010, Andrews 2014) has been widely adopted for prediction of wildfire behaviour, and planning of prescribed fires. However, the application of such systems in the UK is currently limited, in part due to lack of data on dead and live fuel moisture variability, and a lack of UK-tailored fuel models.

This study aims to characterise seasonal variation in litter and duff moisture, and in litter flammability, for five common forest plantation species, sampling from six locations around Great Britain on a monthly basis over the course of one year. Fuel moisture was measured for both duff and litter. Key flammability properties, including ignitability, peak heat release, and total heat release, were obtained by combusting the litter samples under realistic heating conditions in a cone calorimeter. We assess whether duff and litter moisture vary between species, how they are correlated with rainfall, and at what timescale. We then identify how key flammability properties for litter vary in relation to moisture content, season, and species. In order to utilise existing systems that allow estimation of fire behaviour, data are required to construct fuel models tailored to the UK. Our data will provide initial values for litter moisture and heat content to be incorporated in UK-specific leaf litter fuel models for systems such as BehavePlus.

Methods

We focused on forestry plantations of *Betula pendula* Roth, *Pinus sylvestris* L., *Pinus nigra* subsp. *laricio* (Poir). Maire, *Picea sitchensis* (Bong.) Carrière, and *Picea abies* (L.) H. Karst. We first determined variations in the moisture content of forest litter and duff for the five common plantation species, and their relation to precipitation and seasonality. We then examined the flammability of the litter samples by burning them in a cone calorimeter, to obtain measures of ignitability, rate of energy release, and total energy release. We sought to identify differences in flammability parameters between species, which may be linked primarily to leaf morphotypes, and to describe their seasonal variations, which may be linked to seasonal variations in moisture content or to phenology.

Litter and duff samples were collected from six managed forest plantations in different locations across Great Britain (Fig. 1, Table 1). At each plantation, litter was sampled each month from one stand of each genus, *Betula*, *Picea* and *Pinus*, for 1 year. All sampling areas were originally monospecific plantations, though at the time of sampling some also supported naturally regenerated species. Amongst the conifers, the Scots pine plantation at Thetford contained some other species, including birch (*Betula* L.), beech (*Fagus* L.), holly (*Ilex* Tourn. ex L.), and oak (*Quercus* L.) species, which were avoided during sampling. No conifer litter samples were observed to have any substantial components from other species. In the silver birch plantations, other tree species were more common, and some areas also contained substantial components of ground vegetation including bramble (*Rubus fruticosus* L.) and bracken [*Pteridium aquilinum* (L.) Kuhn]. As these conditions are a consequence of the naturally light canopy of the species (Hynynen *et al.* 2010), this is not considered to render the data unrepresentative, though the birch litter samples were more heterogeneous than those of the coniferous species.

Sampling was carried out monthly from July 2022 to June 2023, to obtain a full annual cycle at sufficient resolution to capture seasonal effects for each genus at each site. At Talybont, the annual cycle was taken from August 2022 to July 2023, and at Alice Holt Forest sampling could not be conducted during April. For each site, month and species, one litter sample was collected by removing ∼1 L of litter with a trowel or similar tool from a

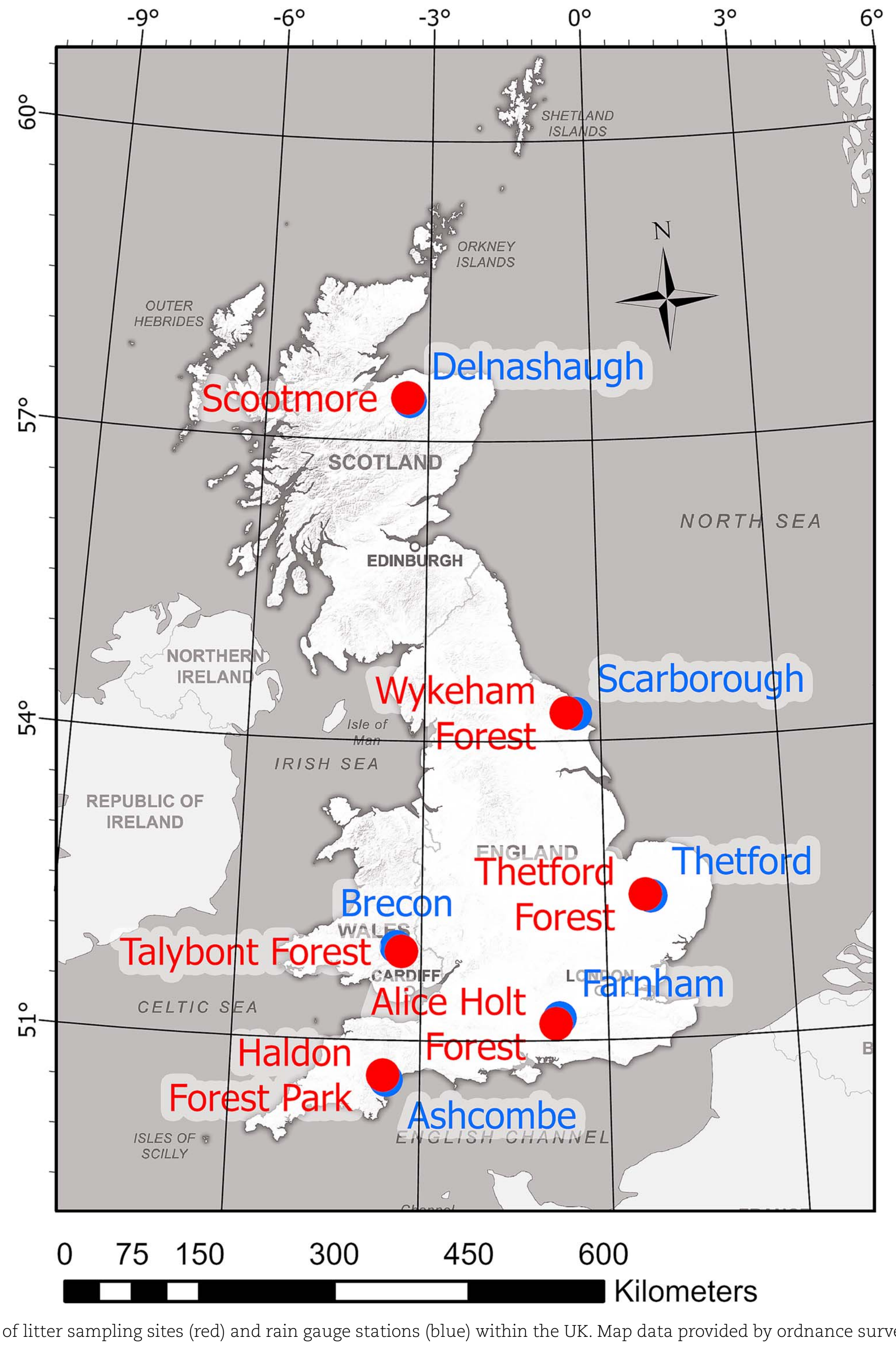

Figure 1. Locations of litter sampling sites (red) and rain gauge stations (blue) within the UK. Map data provided by ordnance survey. Contains public sector information licensed under the Open Government Licence v3.0.

single point within the compartment (the exact point varying between months), avoiding edges and any areas that were visibly unrepresentative of the stand. The samples were double-sealed in zip lock polythene bags to preserve moisture content. The litter was not sorted in any way and no material was removed, and samples therefore consisted primarily of leaves, but frequently also contained cones, twigs, mosses, or any other material that was present. Duff samples were collected from immediately beneath the litter sampling point, and were sealed in 55 ml polythene tubes. Following Keane (2015), we define duff as material that has been sufficiently decomposed that its origin cannot be determined, and this characteristic defines the separation between the litter and duff layers. All samples were shipped to the Wildfire Lab at the University of Exeter, immediately after collection, and typically received ~24 h after posting. Due to the loss of two samples, a total of 211 litter samples and 213 duff samples were analysed.

Duff samples were used only for measurement of moisture content. Upon receipt at the laboratory, duff samples were

Table 1. Details of litter sampling locations and associated rain gauge stations.

Site	Coordinates	Species sampled	Planting year	Rain gauge location	Rain gauge coordinates	Annual rainfall (mm)
Scootmore Moray, Scotland	57.43°N, 3.39°W	Silver birch Scots pine Sitka spruce	1955 1955 1987	Delnashaugh	57.40°N, 3.36°W	769
Wykeham Forest North York Moors, NE England	54.28°N, 0.58°W	Silver birch Scots pine Sitka spruce	2010 1938 1996	Scarborough	54.27°N, 0.42°W	615
Talybont Forest Bannau Brycheiniog, Wales	51.89°N, 3.32°W	Silver birch Scots pine Sitka spruce	1989 1947 1986	Brecon	51.94°N, 3.40°W	1067
Thetford Forest Breckland, East Anglia	52.45°N, 0.66°E	Silver birch Scots pine Norway spruce	1951 1900 1988	Thetford	52.43°N, 0.74°E	634
Alice Holt Forest Hampshire, SE England	51.17°N, 0.84°W	Silver birch Corsican pine Norway spruce	1970 1989 1960	Farnham	51.23°N 0.77°W	886
Haldon Forest Park Devon, SW England	50.65°N, 3.58°W	Silver birch Corsican pine Sitka spruce	1988 1985 1983	Ashcombe	50.60°N, 3.53°W	1029

Annual rainfall is taken from 1 July 2022 to 30 June 2023.

weighed, then placed in paper bags in a drying cabinet at ~50°C (Hunt Jr *et al.* 2012, Davies *et al.* 2015), and dried to constant weight (taking between ~7 and 28 days) to determine their moisture content.

Litter samples were subdivided into three subsamples, two for flammability testing and one for moisture content measurement. As moisture is likely to become unevenly distributed during transit, each sample was turned over by hand to redistribute moisture immediately prior to subsampling. The subsample for moisture analysis was weighed, then placed in a paper bag in the drying cabinet at ~50°C, and dried to constant weight. The other two subsamples were immediately analysed for combustion characteristics in a cone calorimeter (iCone plus, Fire Testing Technology Ltd, East Grinstead, UK), following ASTM standard E1354 (ASTM International 2016).

Each litter sample for iCone analysis ($n = 422$) was placed into a perforated steel sample holder of 126 mm diameter and 30 mm depth (Schemel *et al.* 2008), and filled to the top of the container to give constant depth and volume. After weighing, the sample was placed beneath the element of the iCone, where the cone heater was set to 750°C, and the litter sample placed at 25 mm separation, to achieve a heat flux of 50 kW m^{-2} to the litter's surface. Thermal decomposition under radiant heating from the element releases pyrolysate from the solid fuel. An electric sparker positioned ~15 mm above the sample produced a continuous arc until the pyrolysate ignited, initiating flaming combustion of the sample. Time to ignition (TTI) and cessation of flaming were recorded manually. If samples did not ignite after 300 s, the test was discontinued, as these were considered non-ignitable in any realistic scenario. While this cutoff time is necessarily arbitrary, it was chosen as it is considered unlikely that a natural energy flux of 50 kW m^{-2} would be present as an ignition source for longer than this. In all other cases the test time was defined as ending 20 s after cessation of flaming.

Exhaust gases and smoke were drawn off at a measured flow rate, and the heat release rate calculated continuously from the flow rate and the O_2 content of the exhaust gases, following the principle of oxygen consumption calorimetry. The key calorimetric parameters are derived from the heat release rate. The peak heat release rate (PHRR) is the maximum rate of heat release attained during the test. The total heat release (THR) is the cumulative heat release per unit area of the fuel bed, and the effective heat of combustion (EHC) is the cumulative heat release per unit mass of the fuel.

Daily rainfall totals were obtained from the online data platforms (Environment Agency 2024, Natural Resources Wales 2024, Scottish Environmental Protection Agency 2024) for the closest location to each sampling site (<10.1 km). Relationships between antecedent rainfall and moisture content of each fuel type were assessed by calculating cumulative rainfall prior to sampling, for periods in 5-day increments, and calculating Pearson's correlation coefficient (r) for each pairing of fuel type and time period. Bonferroni corrections were applied to the resulting significance values to account for the 90 correlation tests performed. Fisher's z-transformation was applied to r to normalise the sampling distribution and stabilise variance. Fisher's z test was used to assess the significance of differences between correlations, with Bonferroni corrections applied to account for multiple comparisons.

Relations of litter moisture to flammability metrics (TTI, PHRR, THR, and EHC) were first assessed visually, then appropriate models fitted by least squares, and the optimal (exponential) models selected based on Akaike's information criterion (AIC). Spatial and temporal influences on flammability metrics were investigated by fitting of generalised linear models (GLM) to assess direct effects and interaction effects amongst species, location, and time. A separate model was derived for each metric (TTI, PHRR, THR, and EHC). We adopted a fixed effects design, as sampling was nonrandom across all predictor variables, and the aim of the models was to assess the effects of the predictor variables on flammability metrics within our dataset, rather than to derive models with wider predictive capabilities.

As the temporal variable of interest was seasonality (rather than any longitudinal effect), this was input as the absolute number of days from the nearest winter solstice. The initial model for each metric was specified with a linear response, with species and site as predictive factors, and seasonality as a covariate. Main effects and all two-way combinations of factors and covariate were considered, with a Type III analysis specified to avoid prejudging the relative importance of the predictors, and an intercept term included. Parameters were then varied by assuming a gamma distribution, appropriate to the continuous and positive nature of the response variables, and logarithmic link function. Both these and the linear models were then tested with each independent variable excluded individually to assess their contributions, and then with the addition of fuel moisture as a second covariate. Differences in model fit, adjusted for complexity, were assessed via AIC. As AIC indicated that site and species did not contribute meaningfully to the models for TTI, the process was repeated with only seasonality and moisture as predictors, and, due to the known correlation between these, single-predictor models for season and moisture were also considered. Based on minimisation of AIC, the heat-release metrics were best explained by including all parameters; PHRR and THR were best modelled by the gamma/log link models, but EHC (which had a noticeably more symmetrical distribution) by the linear model. The gamma distribution with identity link was also tested but produced poorer fits than with the log link. All GLM procedures were conducted in IBM SPSS Statistics version 29.0.2.0, and all other statistical testing was performed using PAST version 4.04 (Hammer *et al.* 2001).

A smoothing procedure was used to visualise the underlying seasonal trends in fuel properties, which may be obscured by unpredictable variation in weather conditions and spatial variation in seasonality. Time series of moisture and flammability parameters were obtained via a conservative smoothing method, to reveal seasonal variations at the spatial scale of Great Britain by averaging out the higher frequency and localised effects associated with meteorological conditions and intersite differences in timing of seasonal changes. Mean values of duff moisture, litter moisture, TTI, PHRR, EHC, and THR were calculated for each species, interpolated linearly to daily series, and then smoothed using a 59-day triangular window. The weighting of the smoothing function therefore decreases linearly both forward and backward in time, reaching zero at the 30th day. For each parameter, the daily smoothed value p_s is given by:

$$p_s = \sum_{d=-29}^{29} \left(\frac{p_d}{30} \times \left(1 - \frac{|d|}{30} \right) \right)_d$$

where p_d is the interpolated value at day d.

The applied smoothing window approximates the scale of geographic variation in seasonality across Great Britain (Broad and Hough 1993, Nikonovas *et al.* 2024), and is appropriate to the scale of weather episodes that are not annually recurrent. For the purposes of data smoothing, values for the 30-day periods prior to and subsequent to the year-long data collection period were substituted with the values from the following and previous year, respectively. Smoothed data were not used in any statistical testing.

Results

Fuel moisture and antecedent rainfall

Distributions of moisture content values for the whole year are shown for each fuel type in Fig. 2. Duff moisture ranged from 7% to 398% and litter moisture from 8% to 411%. Silver birch and Norway spruce had generally lower moisture in the duff than in the litter, while Sitka spruce had higher moisture in the duff, and for pine species litter and duff moisture distributions were similar.

Table 2 shows correlation coefficients (Pearson's r) and Bonferroni-corrected significance levels for correlations between moisture contents of all fuel types and cumulative antecedent rainfall up to 45 days prior to sampling, in 5-day increments. Figure 3 displays Fisher's z transformation of the coefficients. Relationships between litter moisture and antecedent rainfall were significant at $\alpha = 0.05$ for all species and all time periods. For each species, z_r increased with length of rainfall sampling period, to a maximum value of between 0.79 and 1.35 ($r = 0.66$–0.87) at 20 or 25 days prior to fuel sampling, and then decreased for longer time periods. Duff moisture content showed no significant correlations with cumulative antecedent rainfall at $\alpha = 0.05$ after Bonferroni corrections were applied.

Fisher's z statistics for interspecies differences in prior rainfall/fuel moisture correlations, for both litter and duff, are presented in Table S2. For each fuel type, a Bonferroni correction of $\alpha = 0.05$ to account for 10 interspecies comparisons results in a critical $|z|$ value of 2.81. For litter, this was not exceeded by any of the comparisons. For duff, the critical value was exceeded only by the comparison of Scots pine and Corsican pine at 5 days, though $|z|$ values were high (exceeding the critical value for uncorrected α) at all time periods, and at most time periods for Scots pine against both spruce species.

Fisher's z statistics for differences in the rainfall/moisture correlation between litter and duff, for each species, are presented in Table S3. Applying a Bonferroni correction to $\alpha = 0.05$ to account for five within-species comparisons resulted in $\alpha = 0.01$ and critical $|z|$ value of 2.575. Under this criterion, litter and duff of silver birch differed at all time periods up to 35 days, of Scots pine at all time periods up to 40 days, and of Sitka spruce between 20 and 40 days. Only Corsican pine showed no difference.

Seasonal changes in moisture content

Annual precipitation across the sites ranged from 615–1165 mm (Table 1), and the UK average of 1115 mm for the year July 2022–June 2023 was marginally drier than the 1991–2020 average of 1163 mm (Met Office 2024b). Notably, the usual month-on-month decrease in precipitation from December to April was interrupted by an unusually dry February, with a UK average monthly precipitation of 46 mm, compared to a 1991–2020 average of 96 mm, and with our sites averaging only 16 mm. Seasonal variations in rainfall for the sites are shown in Table S1.

Duff moisture content varied over the year for all five species (Fig. 4a). Conifers had generally low values from June to November (±1 month), and higher values from December (±1 month) to May. Spruce species had highest duff moisture in January, and also slightly raised values in April–May. Corsican pine had a more distinctly bimodal distribution, peaking in November and April–May, while Scots pine had higher values from December–May, with highest values in May. Silver birch had less distinct seasonal variation than the conifers, with a low around August and higher values November–March. Across the year, Norway spruce showed distinctly lower duff moisture than other species (Table 3).

Across all samples ($n = 410$), duff moisture content was quite weakly correlated with litter moisture content ($r = 0.34$, $P = <.001$). The moisture content of the litter (Fig. 4b) showed much more distinct variation than the duff, with consistent seasonal variation across all five species. Low values occurred from June to October. High values occurred from November to January, with a secondary peak between March and May depending on species. Birch litter

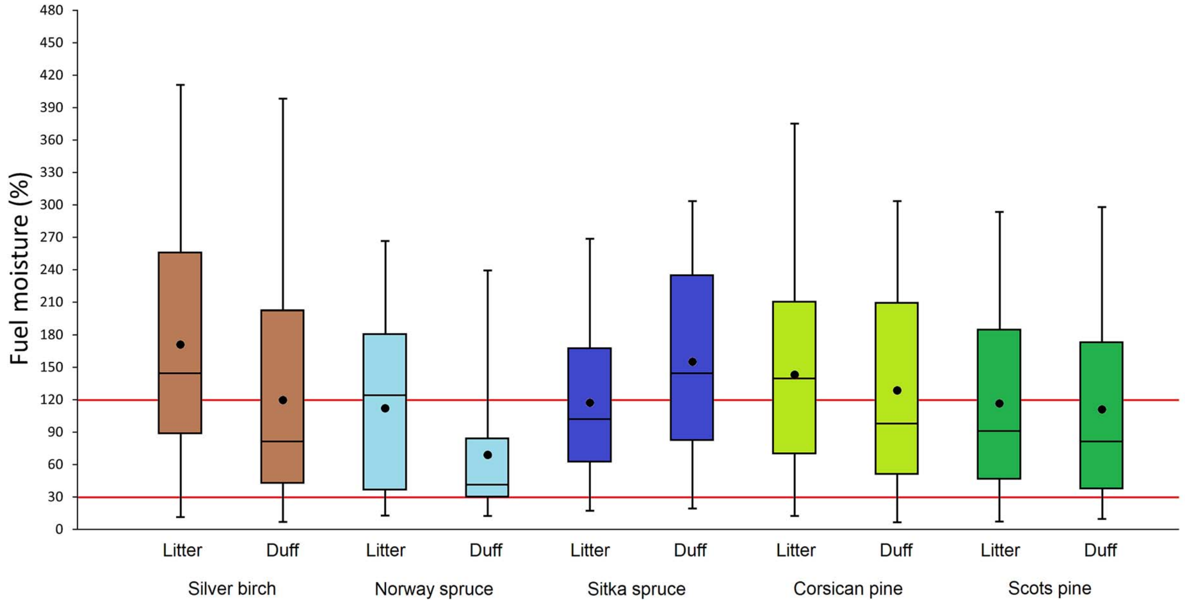

Figure 2. Distributions of fuel moisture content for litter and duff from five tree species over 1 year. Box plots indicate minima, first, second and third quartiles, and maxima. Dots indicate mean values. Horizontal lines crossing the box plots indicate moisture contents of 30% and 120% dry weight, which represent approximate thresholds for self-sustained burning (<30%) and non-ignitability (>120%) in duff.

Table 2. Correlation matrix for fuel moisture content and antecedent rainfall, showing correlations (Pearson's r) of 10 fuel types with cumulative rainfall over increasing time periods prior to sampling.

		5 days	10 days	15 days	20 days	25 days	30 days	35 days	40 days	45 days
Litter	Silver birch	0.45^{**}	0.54^{***}	0.60^{***}	0.71^{***}	0.67^{***}	0.62^{***}	0.59^{***}	0.55^{***}	0.52^{***}
	Scots pine	0.49^{*}	0.54^{**}	0.58^{**}	0.66^{***}	0.61^{***}	0.57^{**}	0.56^{**}	0.53^{*}	0.49^{*}
	Corsican pine	0.70^{*}	0.72^{**}	0.73^{**}	0.77^{**}	0.79^{***}	0.77^{***}	0.77^{***}	0.78^{***}	0.75^{**}
	Sitka spruce	0.53^{*}	0.62^{***}	0.72^{***}	0.79^{***}	0.79^{***}	0.74^{***}	0.73^{***}	0.70^{***}	0.66^{***}
	Norway spruce	0.68^{*}	0.76^{**}	0.77^{**}	0.83^{***}	0.87^{***}	0.85^{***}	0.82^{***}	0.81^{***}	0.78^{**}
Duff	Silver birch	0.03	0.14	0.11	0.15	0.19	0.16	0.18	0.17	0.17
	Scots pine	-0.21	-0.12	-0.14	-0.02	0.02	-0.06	-0.01	-0.02	0.00
	Corsican pine	0.51	0.51	0.49	0.53	0.58	0.56	0.56	0.57	0.55
	Sitka spruce	0.31	0.41	0.40	0.48	0.48	0.36	0.33	0.30	0.28
	Norway spruce	0.09	0.27	0.37	0.48	0.54	0.56	0.58	0.53	0.55

Strength of correlation is indicated by colour, from white ($r \leq 0$) to yellow ($r = 0.5$), to red ($r = 1$). Significance is indicated by asterisks, where $*$ indicates significance at $\alpha < 0.05$, $**$ at $\alpha < 0.01$, and $***$ at $\alpha < 0.001$, on the basis of Bonferroni correction for 90 simultaneous tests.

Table 3. Summary statistics for seasonal variation in duff moisture and litter moisture for five tree species.

	Duff moisture (%)					**Litter moisture (%)**				
	Silver birch	**Norway spruce**	**Sitka spruce**	**Corsican pine**	**Scots pine**	**Silver birch**	**Norway spruce**	**Sitka spruce**	**Corsican pine**	**Scots pine**
min.	7	13	19	7	10	12	13	18	13	8
max.	398	239	304	304	298	411	267	269	375	294
mean	120	69	155	129	111	171	112	117	143	117
Standard deviation	99	57	88	88	83	107	81	72	94	84

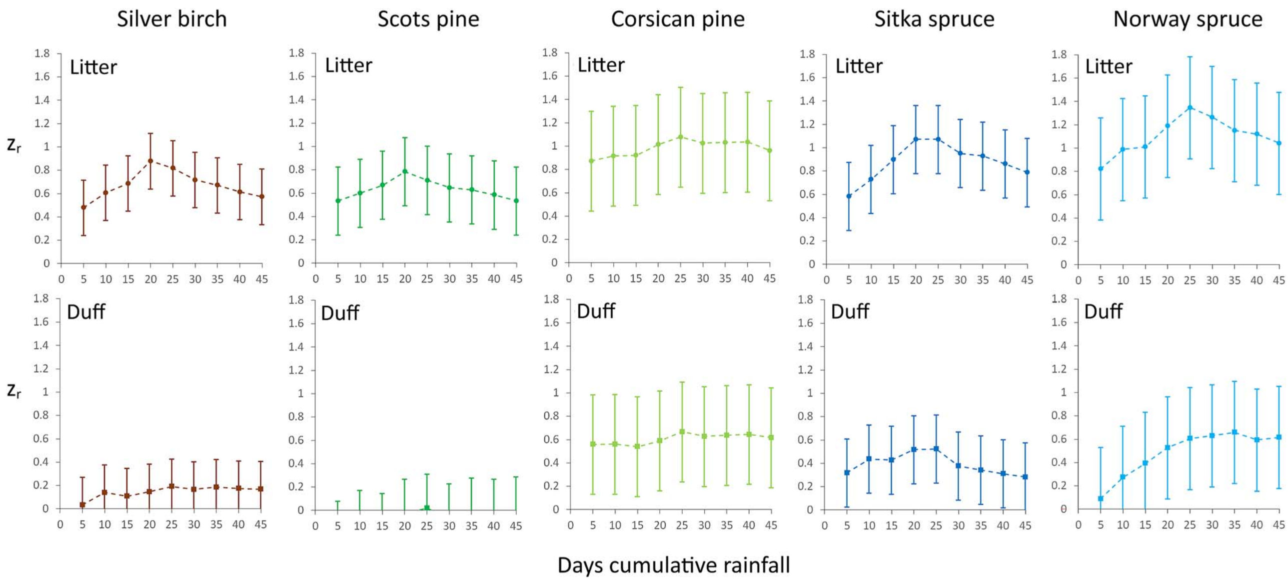

Figure 3. Strength of correlations between fuel moisture and antecedent rainfall, showing the Fisher transformation of the Pearson correlation coefficient (z_r) (omitting negative values), for 10 fuel types and cumulative rainfall between 5 and 45 days prior to sampling. Error bars represent 95% confidence intervals for z_r.

Table 4. Modelled relationships of calorimetric parameters with litter moisture content, for combined data from all species and sites, and associated coefficients of determination.

Calorimetric property (*y*)	Equation (where moisture content = *x*)	R^2	*P*
Time to ignition	$y = 178.23 * \exp(0.00201x) - 176.68$	0.46	<0.001
Peak heat release rate	$y = 358.55 * \exp(-0.0139x) + 53.70$	0.71	<0.001
Effective heat of combustion	$y = 16.24 * \exp(-0.0105x) + 2.01$	0.74	<0.001
Total heat release	$y = 42.28 * \exp(-0.00743x) - 3.13$	0.48	<0.001

generally had higher moisture content than the conifers year-round, with notably higher moisture content from November to January.

Moisture content and flammability

Ignitability was measured by both the average TTI, and the percentage of samples that did not ignite within 300 s. Across all sites and species ($n = 426$), occurrence of ignition under the test conditions was negatively correlated with litter moisture content ($r = -0.57$, $P < .001$). Of the samples that ignited ($n = 334$), TTI was quite strongly and positively correlated with moisture content ($r = 0.67$, $P < .001$). The proportion of variance in TTI accounted for by moisture content ($R^2 = 0.46$) will be underestimated by the model due to high values being excluded as non-ignitions. Key calorimetric properties of PHRR, EHC, and THR showed negative exponential relationships with moisture content (Fig. 5, Table 4).

Seasonal and species differences in flammability

Peaks in both TTI and % non-ignitions occurred between November and January, with a secondary peak April–May (Fig. 6). Silver birch and Corsican pine indicated low ignitability on both measures. Notably, Norway spruce had a high proportion of non-ignitions, but also low TTI for ignited samples. Scots pine showed low resistance to ignition on both measures.

Litter PHRR showed a distinct seasonal cycle (Fig. 7), with lowest values centred on December (±1 month) with the exception of Sitka spruce, which had the lowest values in April; and highest values centred on July (±1 month). Throughout the year, PHRR remained generally lower for silver birch than for the coniferous species.

For all species, litter EHC (Fig. 8) showed a similar seasonal pattern of low values from November to May, a sharp rise to a peak in June/July, and gradual decrease to winter values by November. A secondary peak around March was evident in Norway spruce and Corsican pine. There was little difference in EHC values between the species.

Litter THR (Fig. 9) shows the lowest values occurred around December (±1 month) except for Sitka spruce, which had its lowest values in April. Highest values for all species occurred around July (±1 month). A clear increase in values was evident in March for Corsican pine and Norway spruce. The spring increase was much more rapid than the autumn decrease.

THR varied less for silver birch seasonally than for the conifers. There was distinct separation between the species, especially in summer months (June–September). THR was lowest and least variable for silver birch, highest and most variable for spruce species, and intermediate for pine species (Fig. 9).

Based on AIC (Table S4), a four-parameter GLM (species, site, seasonality, and fuel moisture) was the best fitting of those tested for each of the three heat-release metrics (PHRR, THR, and EHC), with PHRR and THR best predicted by the gamma/log link models, and EHC by the normal/identity link (linear) model. For PHRR, species, seasonality, and fuel moisture were significant predictors (Table 5); site was not, except via an interaction effect with species, and moisture content also showed an interaction effect with seasonality. For THR, species and fuel moisture were

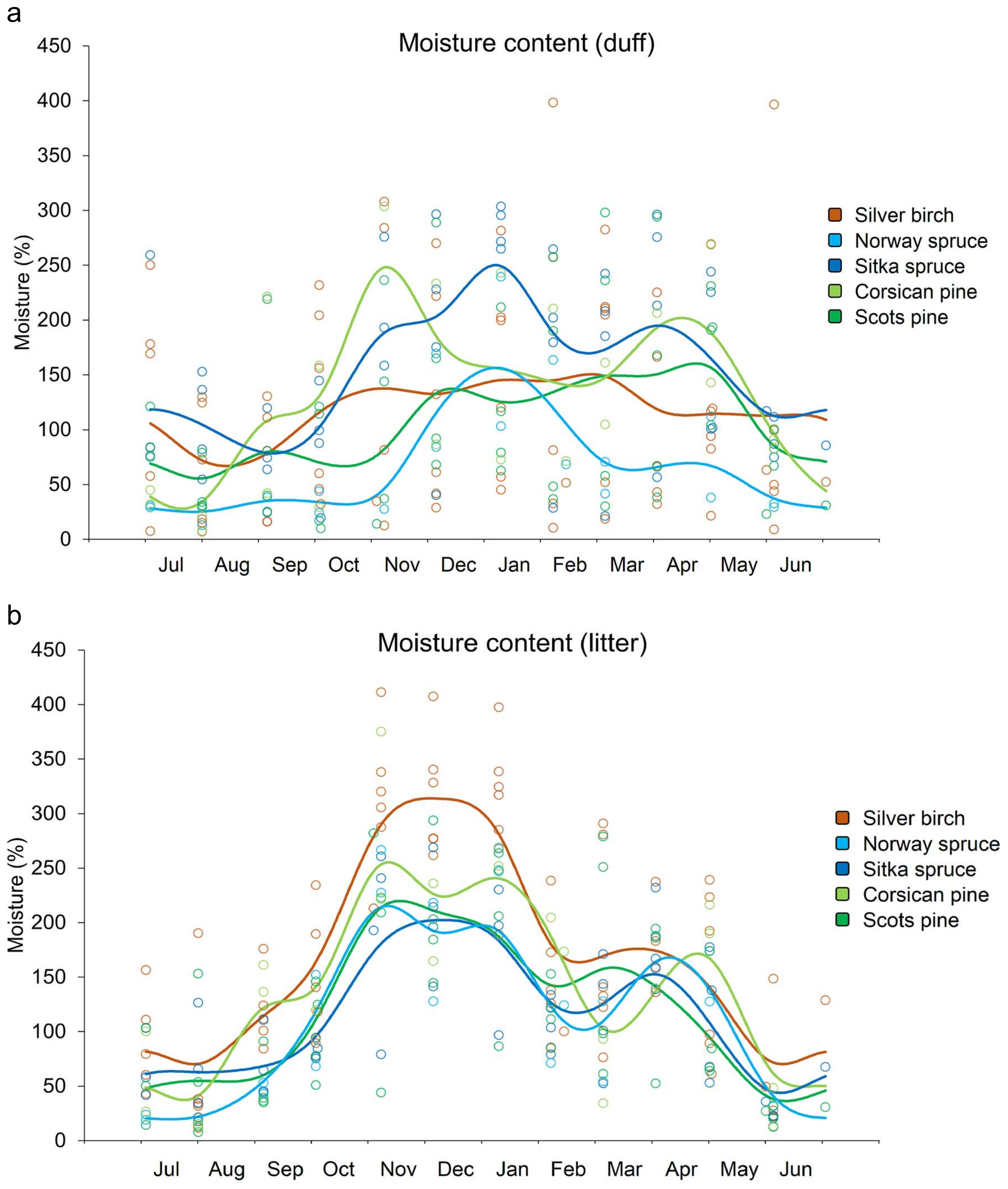

Figure 4. Annual variation in (a) duff moisture and (b) litter moisture for five tree species, showing each measured value and smoothed time series.

significant predictors (Table 5); seasonality was not significant, and site was significant only via an interaction effect with species, which also showed an interaction effect with fuel moisture. The species/site interaction for both PHRR and THR, where no main effect of site was evident, is likely due to different species of pine and spruce being represented at different sites, entailing species differences across sites. For EHC, only seasonality and moisture, and their interaction, were significant predictors. For TTI, AIC indicated that site and species did not contribute usefully to the model, and the best-fitting model of those tested was the two-parameter model (seasonality and fuel moisture) with gamma distribution and log link. Seasonality, moisture content, and their interaction were all significant predictors ($P < .001$).

Discussion

Litter moisture

Litter is expected to be susceptible to burning at moisture contents below ∼30% (by dry weight), which approximates the moisture of extinction for dead woodland fuels (Keane 2015). Laboratory experiments indicate a moisture of extinction for pine needles of around 25% (Rego *et al.* 2021), which is not necessarily applicable to other litter types. In this study, all species had litter well below 30% moisture during the year, with minima ranging from 8% (Scots pine) to 18% (Sitka spruce), and all values <30% recorded between June and August. This indicates that litter of all five species reached low enough moisture contents to sustain burning at times during the summer. Although July–August 2022 and June 2023 were unusually warm in historical terms

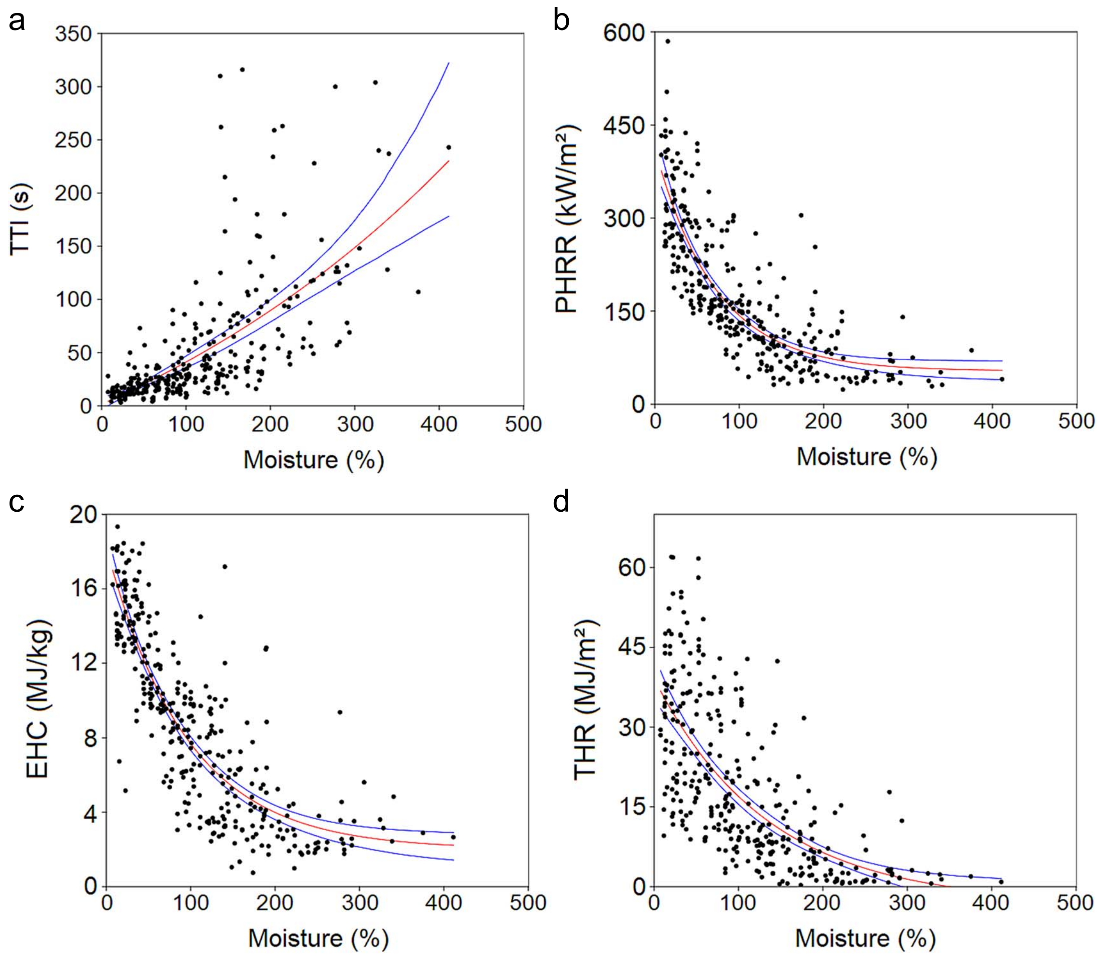

Figure 5. The relationships of (a) TTI (for samples that ignited within 300 s), (b) PHRR, (c) EHC, and (d) THR to litter moisture content, aggregating data for all five species and all months. Curves indicate exponential models fitted to the data, and 95% confidence intervals.

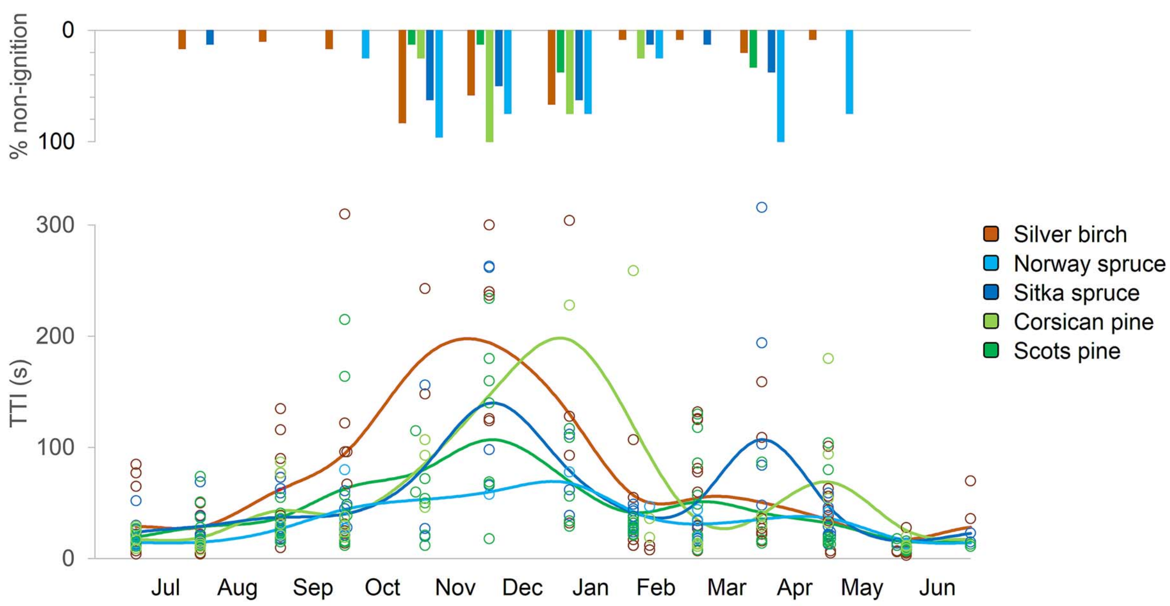

Figure 6. Annual variation in TTI and % non-ignition for litter of five tree species.

(Met Office 2024b), as was the full sampling period excepting December, the annual UK temperature anomaly for 2022 of +0.9°C (relative to 1991–2020) is predicted to represent an average year by around 2060, under the RCP4.5 (medium) emissions scenario (Kendon *et al.* 2023). For the year July 2022 to June 2023, the UK temperature anomaly was also +0.9°C (Met Office 2024b),

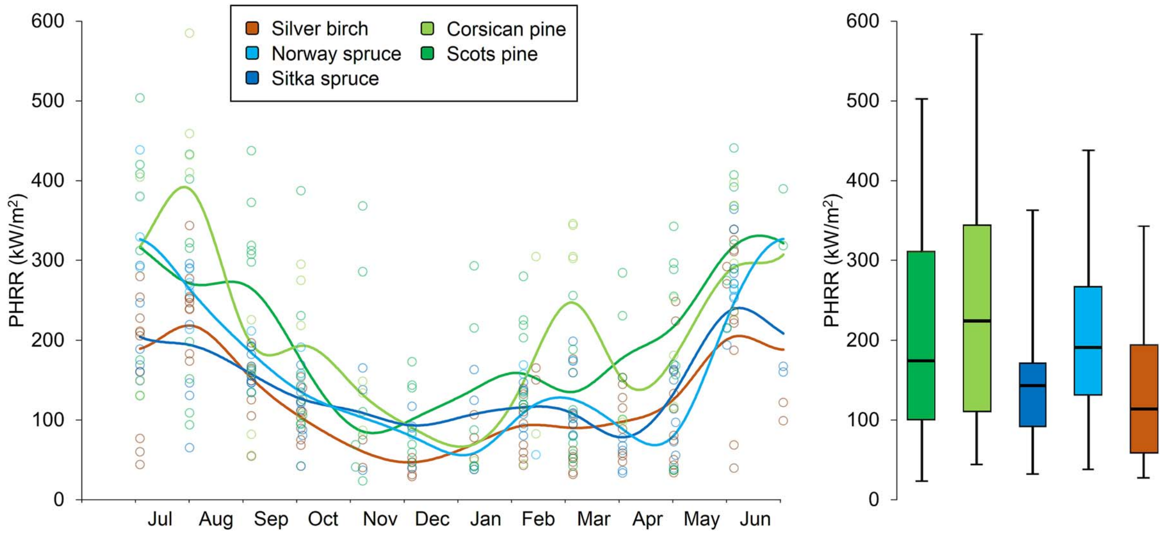

Figure 7. Seasonal variation in PHRR for litter of five tree species, showing each measured value and smoothed time series (left), and a boxplot of interspecies differences in PHRR when aggregated for all months and sites (right). Boxplots show minima, 1st, 2nd and 3rd quartiles, and maxima.

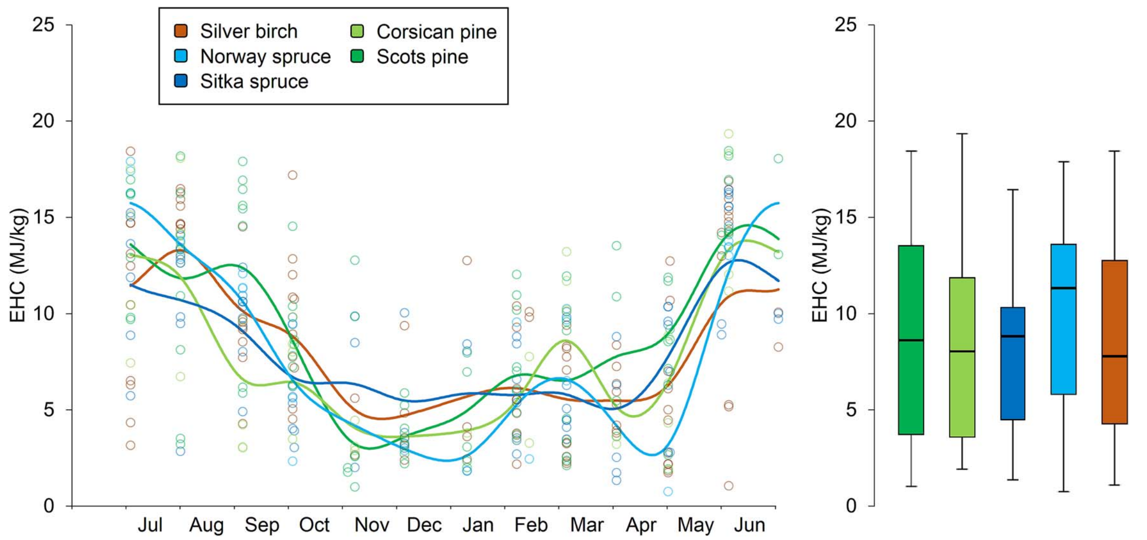

Figure 8. Seasonal variation in EHC for litter of five tree species, showing each measured value and smoothed time series (left), and a boxplot of interspecies differences in EHC when aggregated for all months and sites (right). Boxplots show minima, 1st, 2nd, and 3rd quartiles, and maxima.

Table 5. Significance matrix (*P*-values) for all predictor variables in the selected predictive models for four flammability metrics.

	TTI	PHRR	THR	EHC
Species	–	.013	.001	.511
Site	–	.491	.811	.142
Seasonality	<.001	<.001	.115	<.001
Moisture	<.001	<.001	<.001	<.001
Species ∗ Site	–	.006	.002	.103
Species ∗ Seasonality	–	.505	.275	.817
Species ∗ Moisture	–	.053	<.001	.158
Site ∗ Seasonality	–	.384	.989	.608
Site ∗ Moisture	–	.412	.094	.168
Seasonality ∗ Moisture	<.001	<.001	.71	<.001

suggesting that temperatures in our sampling period could approximate mid-century conditions. Rainfall was also low in July/August 2022 and June 2023, which will have contributed to low fuel moisture.

Litter moisture was expected to be strongly related to rainfall, but interspecies differences in the canopy may modify the way that water, principally throughfall, reaches the forest floor. Differences in the structure of the litter layer (due principally

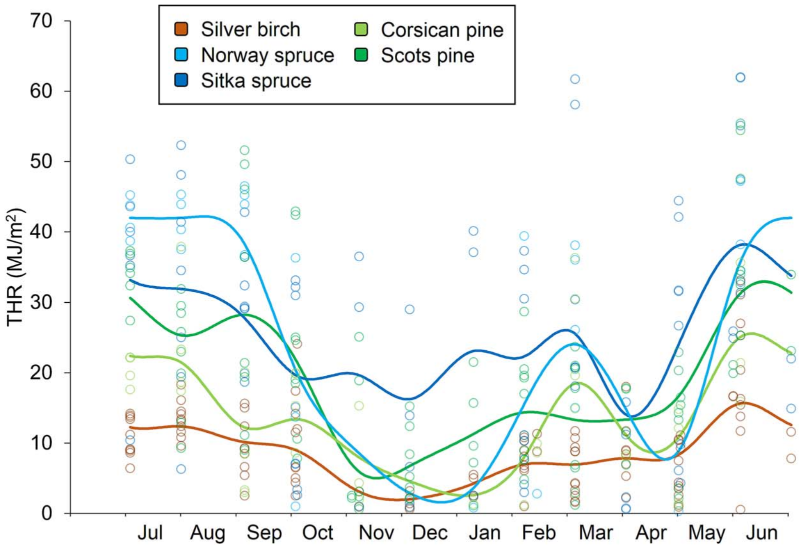

Figure 9. Seasonal variation in THR for litter of five tree species, showing each measured value and smoothed time series (left), and a boxplot of interspecies differences in THR when aggregated for all months and sites (right). Boxplots show minima, 1st, 2nd, and 3rd quartiles, and maxima.

to leaf morphology) will also affect rate of drainage and water retention, with contact time affecting the proportion of water absorbed into fuel components (Simard 1968). Water entering the litter layer by capillarity from duff or soil (Samran *et al.* 1995, Schaap *et al.* 1997) will have a greater time lag from its origin in rainfall. Evaporation depends on relative humidity, temperature, and wind speed (Matthews 2014), but the exposed surface area of the litter may also be important. This is also likely to vary between species, with short-needle species (including spruces), long-needle species (pines), and broadleaves resulting in different packing arrangements and different surface areas per unit mass of litter or unit area of forest floor. For litter of all five species, the strongest correlations with cumulative rainfall were for periods of 20–25 days prior to sampling (Table 2, Fig. 3). Although confidence intervals are broad, the consistency of the initial increase and subsequent decrease in correlation, across all five species, indicates that this observation does not arise from random error, though the timescale identified is not necessarily applicable to other species or environmental conditions. Knowing at what timescale such correlations are strongest may be useful in making longer-term forecasts of litter fuel moisture from meteorological data. No clear interspecies differences in these correlations were evident.

The higher moisture content in birch litter from November to January may be explained by accumulation and decomposition of abscised leaves, together with the effect of decreased canopy interception. Leaf fall for silver birch in Great Britain occurs between September and November (Atkinson 1992). As resistance to evaporation increases with the thickness of the litter layer above (Park *et al.* 1998), continued accumulation at the surface will reduce evaporation during leaf fall and while it remains on the ground. Leaf morphology will also contribute to restricting evaporation, with the flat leaves of birch being more subject to cohesion, decreasing aeration and maintaining wetter conditions within the litter layer. Pines in temperate regions also increase needle shedding in autumn; for Scots pine ~70% of annual needle fall occurs within ~1 month, occurring around October at the latitudes relevant to this study (Berg and Laskowski 2005). However, three factors may prevent this seasonality from resulting in substantial variation in litter depth: first, only a minority of the total foliage drops in any annual cycle (Berg and Laskowski 2005); second, decomposition is slower than for broadleaves (Krishna and Mohan 2017); and third, needles comprise only around 50%–80% of total litter, while other components such as twigs and cones lack annual periodicity (Berg and Laskowski 2005). No effect of seasonal litter fall was therefore evident for the pine species. Litter fall in spruces is typically not seasonal (Berg and Laskowski 2005).

The lower moisture content of the coniferous species' litter throughout the year may result partly from leaf morphology. Needle leaves typically retain less water than broadleaves after rainfall (Sato *et al.* 2004, Zhao *et al.* 2022), and allow greater vertical drainage, and lesser lateral drainage (Sato *et al.* 2004). Litter moisture may also be influenced by the underlying duff, which is typically deeper and less dense for conifers (Morison *et al.* 2012). If the lower density of conifer duff is associated with higher permeability, this will also allow faster drainage from the litter layer. The lower moisture content of pine and spruce litter may therefore result from differences in litter and duff properties that are shared with conifers generally.

Duff moisture

A widely accepted generalisation is that duff can sustain fire in the absence of other fuels at moisture contents <30%, will burn under heating from combustion of surface fuels at between 30%–120%, and will not burn at moisture contents >120% (Sandberg 1980, Brown *et al.* 1985, Little *et al.* 1986, Hille and Stephens 2005). As duff moisture content for all five species spanned all three moisture classes, this suggests that across the year, the duff experienced periods of negligible ground fire risk, as well as periods when burning could have been sustained even in absence of surface litter. The seasonal cycle in duff moisture was less pronounced than for litter moisture (for which values <30% moisture were recorded in all months except January and April). As noted for litter moisture, the values recorded here represent a year that was warm by historical standards but may be average by 2060.

Duff moisture was notably lower for Norway spruce, with only 3 of 21 samples at >120% (Fig. 2), suggesting potentially higher ground fire risk for this species. While differences in site conditions will affect all genera equally (each genus being represented at every site), at species level fuel moisture may be affected by differences in rainfall, and Norway spruce is usually selected over Sitka spruce for planting in areas of lower rainfall. However, while the mean annual rainfall for Norway spruce sites was 760 mm, and for Sitka spruce sites was 870 mm, the difference in mean duff moisture was far greater, at 69% for Norway spruce, and 155% for Sitka spruce. Apparent interspecies differences may result from hydrological properties of the duff itself, or those of underlying or overlying strata. The high porosity of duff results in high hydraulic conductivity (Fosberg 1977) and unimpeded drainage, so the permeability of underlying soils is an important factor in the water content of the duff (Fosberg 1977). Variability in canopy structure, due to both species and tree density, also affects duff moisture (Raaflaub and Valeo 2008). Therefore the notably lower duff moisture for Norway spruce does not necessarily represent properties of the duff itself or of the species, but could be linked to soil type or stand density.

Ignitability

The positive relationship between moisture content and TTI results from the heating required to evaporate excess moisture prior to ignition. Ignitability tracked moisture content for all species (Fig. 6), with the litter being less ignitable in winter, evident to differing degrees in TTI and non-ignitions. Apparent secondary peaks in TTI and non-ignition in spring are associated with a return to higher moisture levels following the unusually low rainfall in February 2023, and are presumed atypical. The most distinct annual cycle was seen in silver birch, with both measures raised substantially around the maximum litter moisture from November to January (Fig. 6). This suggests that new litterfall altered the ignitability of the litter layer, with increased moisture content requiring greater heat input prior to ignition. Fuel moisture has been shown to account for the majority of variation in TTI for other fine fuels (Dimitrakopoulos and Papaioannou 2001, Pellizzaro *et al.* 2007).

Ewald *et al.* (2025) suggest that their broadleaf litter was more ignitable than needle leaves due to differences in specific leaf area (SLA), since the ratio of surface area to mass strongly predicts ignition time for individual leaves (Murray *et al.* 2013, Grootemaat *et al.* 2015). However in our data birch litter was not more ignitable than needle-leaf litters according to either TTI or % non-ignition. Across the year, birch had a mean TTI of 56.6 s and 25% non-ignitions, while conifers had a mean TTI of 44.6 s and 19% non-ignitions. Excluding the effect of increased winter litter depth, values for February–August were similar for birch (mean TTI 34.2 s; 8.5% non-ignitions) and conifers (mean TTI 33.5 s; 9.3% non-ignitions), and GLM results indicate that species was not a useful predictor of TTI. Since the samples used by Ewald *et al.* (2025) were acclimatised to hot and dry conditions, the SLA of the leaves translates fairly directly to the exposed surface area of the litter (which also contained no other fuel components), while in the natural moisture conditions of our study the water in the litter will have caused adhesion between leaves, other fuel particles, and fine sediment, creating 'clumped' fuel particles with specific surface areas much lower than those of the component leaves. Under such conditions, the SLA of individual leaves ceases to be a meaningful property of the fuel bed, and differential ignition properties dependent on SLA will not be observed. The relation between leaf SLA and ignitability of the litter bed suggested by Ewald *et al.* (2025) may only exist at the very low moisture conditions they replicated. Even in such conditions, we suggest that the effects of prior wetness on the content and structure of the litter bed should be considered.

Energy release rate and fire intensity

Heat release rate (HRR), as power per unit area, is equivalent to a strict definition of fire intensity (Keeley 2009). Peak HRR (PHRR) is therefore a measure of the maximum fire intensity attainable by the fuel, which is determined by both material and structural properties. The material properties include water content and chemical composition, especially volatile content, which is positively correlated with fire intensity (Ormenõ *et al.* 2009, Dewhirst *et al.* 2020). The structural properties include the size and shape of individual fuel components, which determine the packing ratio of the fuel array; hence leaf morphology is important in determining oxygenation of the fuel bed, and thus the combustion rate (Varner *et al.* 2015).

We found the annual cycle in PHRR (Fig. 7) to be driven by fuel moisture (Fig. 5). Evaporation of fuel moisture delays ignition, and then slows the combustion reaction by diverting energy into latent heat (Nelson Jr 2001); the flux of water vapour also decreases oxygen supply to the combustion zone, reducing the flame temperature (Nelson Jr 2001, Keane 2015). Moisture content accounted for the majority of variation in PHRR ($R^2 = 0.71$), which tracked the annual cycle in fuel moisture (Fig. 4b) for all five species.

The generally higher PHRR for conifer litter than for birch may be attributed to a higher resin and volatile content (Ciccioli *et al.* 2014), while the generally higher PHRR of pine litter over spruce litter may be attributed to the higher packing ratio of short-needle litter, which restricts oxygen supply. Ewald *et al.* (2025) also found greatly increased PHRR from pine litter, compared to broadleaved and short-needled species, though in that case the difference was very clear, with Scots pine having roughly twice the PHRR of all six other species. That result, obtained using sorted litter samples composed only of identifiable leaves and leaf fragments (to better identify interspecies differences), is in contrast to ours, in which the interspecies differences varied considerably (Fig. 7b).

Total energy release and fire severity

The EHC is the energy released per unit mass. For all species, the annual cycle (Fig. 8a) was driven by litter moisture ($R^2 = 0.74$), with the unusually dry February of 2023 evident as an interruption to the cycle of autumn decrease and spring increase. Previous studies show EHC of vegetation to be strongly dependent on fuel moisture (Babrauskas 2006, Madrigal *et al.* 2011). There was no consistent difference in EHC values between the five species over the year, and species was not a significant predictor of EHC (Table 5). This contrasts with Ewald *et al.* (2025), who found that broadleaves had higher EHC than short-needle litter, but Scots pine (their sole long-needle species) had the highest EHC overall.

EHC is determined by the specific heat of combustion (HoC), i.e. energy content per unit mass released by total combustion, and the completeness of the combustion. EHC in a wildfire will always be lower than HoC, with the difference being principally due to the energy content of the remaining char. HoC is determined by the chemical composition of the fuel, with the energy content increasing with volatile content (Burgan and Rothermel 1984). The completeness of the combustion may be affected by the morphology of the fuel elements: leaf shape should influence the packing ratio, and packing ratio influences the completeness of combustion (Burton *et al.* 2021) through its effect on the aeration of the fuel bed. Short-needle litter should have the densest packing, potentially reducing aeration and inhibiting combustion. However, Grootemaat *et al.* (2017) and Burton *et al.* (2021) reported no relationship between leaf morphology and fuel consumption.

While Ewald *et al.* (2025) found the lowest EHC for short-needle litter, resulting from its high unburned fraction, our data do not indicate any influence of leaf shape on EHC (with the highest values being for spruce species, but no significant interspecies effect). The influence of leaf shape on packing ratio may be less in our study due to our use of unsorted litter samples, variously containing twigs, cones, mosses, organic and mineral particulate matter, and other material. Chemical composition is likely to be the dominant factor in EHC in our dataset, with the lowest EHC being for the nonconiferous species (silver birch) with low volatile content.

THR is the energy released per unit area, and is related to EHC by the areal density of the fuel mass. THR is closely related to the concept of fire severity. Fire severity metrics essentially aim to quantify fuel consumption or biomass loss per unit area (Keeley 2009), and the relative constancy of energy released per unit dry mass means that the total energy release per unit area is closely related to fuel consumption per unit area (Conard and Solomon 2009, Davies 2013). THR can therefore be taken as an approximation of the fire severity associated with a litter fuel. Higher THR tends to mean that the ground has been exposed to heating for a longer period. Measures of fire severity are important for immediate postfire assessment of subsequent ecosystem responses (Keeley 2009, Davies 2013, Davies *et al.* 2016), and are more relevant than fire intensity to impacts on the land surface (Doerr and Shakesby 2013).

Our finding of highest THR for spruces and lowest for birch is in agreement with Ewald *et al.* (2025), who found that broadleaf litter had the lowest THR, Scots pine had intermediate values, and short-needle litter had the highest THR. The substantially different methodology in the present study shows that the influence of leaf shape on THR demonstrated by Belcher (2016) and Ewald *et al.* (2025) was not an artefact of experimental procedures. The high packing ratio of short needles results in greater heat production per unit area compared to broadleaves, with long pine needles being intermediate. Our data indicate that spruce litter has the potential to support more severe fires where litter depth is equal, and supports the idea that this is true of short-needle litter generally. However, the THR measured by cone calorimetry depends on the chosen sample depth, while in a natural setting litter depth will be determined by input, decomposition, and dispersion (of which the latter two may themselves be influenced by leaf morphology).

Fire risk prediction for UK forest environments

Although MOFSI has been effective in predicting some episodes of high potential wildfire severity in the UK (Glaves *et al.* 2020), recent years have seen increased frequency of very high FWIs, and this heightened fire risk implies the need for a more advanced fire danger rating system (Arnell *et al.* 2021, Belcher *et al.* 2021). A fire danger rating system or a fire behaviour prediction system tailored to the UK environment, with its particular climatic factors and fuel complexes, would provide improved risk forecasting, and if linked to a suitable public communication apparatus could counteract current deficiencies in public understanding of wildfire risk (Belcher *et al.* 2021).

This study contributes to fuel model development for UK forest litters, providing data on dead fuel moisture and energy content for typical plantation species through an annual cycle. This may assist the adaptation of systems such as BehavePlus (Heinsch and Andrews 2010) for the UK environment. Litter moisture data from this study, representing primarily 1-h fuels, but with a minority of 10-h fuel components in the form of cones or larger diameter twigs, may be taken as representative of fine dead fuel moisture, which BehavePlus uses to calculate ignition probability, spread rate, and fire intensity (Andrews 2014). Heat content data from this study may be used to replace the default value (18.62 MJ kg^{-1} net HoC by dry weight) that is incorporated into all 53 BehavePlus fuel models. That single value is a legacy of earlier models (Albini 1976), but heat content varies between fuels (Rivera *et al.* 2012) and phenologically (Belcher *et al.*, in review). Our data can provide more accurate estimates of HoC for UK forest litters. While the determination of appropriate values is beyond the scope of the present study, functions for converting EHC to HoC have been proposed by Madrigal *et al.* (2011) and Belcher *et al.* (in review).

Conclusions

This study provides the first extensive litter and duff moisture and associated flammability dataset for key forest litter types in the UK. We quantify the extent to which litter moisture drives key flammability metrics, and identify a timespan of ∼20–25 days as that for which prior rainfall most strongly influenced litter moisture at our sites. Silver birch had higher litter moisture than pines or spruces throughout the year, and mechanisms related to leaf properties and phenology indicate that this may apply to broadleaves vs. needle leaves generally, although more data on different species are needed to confirm this. Litter moisture accounted for much of the variation in TTI ($R^2 = 0.46$), THR ($R^2 = 0.48$), and PHRR ($R^2 = 0.71$). For all five species, minimum values of both litter and duff moisture of <30% indicate that both fuel types would have been capable of sustaining fire at some times during the year.

Our data do not show the greater ignitability of broadleaf litter that has been evidenced in other research, and we hypothesise that the previously identified relationship between morphology and ignitability does not necessarily translate from individual leaves to the litter bed. Differences in PHRR can be related to both structural properties and volatile content of the leaves. Interspecies differences in heat release, which have been associated with leaf shape, were evident on an areal basis (THR), but not on a mass basis (EHC), suggesting that such differences found in previous studies could be methodological artefacts. This study highlights how real forest litter compositions as sampled *in situ* can produce more complex data than the constructed samples often used in laboratory studies of flammability, while still showing distinct interspecies differences. The data and findings obtained here provide important insights that can be utilised to improve forecasting of fire risk in the UK.

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Supplementary data

Supplementary data are available at *Forestry* online.

The following supplementary material is available at *Forestry* online: monthly rainfall totals; Fisher's z for interspecies differences, and for differences between litter and duff, in correlation between fuel moisture and antecedent rainfall; AIC values for GLMs.

Conflict of interest

None declared.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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