Minsavage-Davis C, Davies GM, Vatsø Haugum S, Thorvaldsen P, Velle LG, Vandvik V (2024).
Development and evaluation of generalized fuel models for predicting fire behaviour in northern European heathlands
iForest – Biogeosciences and Forestry – doi: 10.3832/ifor4394-017

Supplementary Material

Fig. S1 - Representation of Calluna-stand structure in response to management across the varying life-stages described by Watt (1955). This diagram represents a simplified depiction of realistic Calluna-stand structure; nearly all stands contain a heterogenous mixture of Calluna, generated when new seedlings fill in gaps as the degenerate individuals die and canopy space opens (Velle et al. 2021).

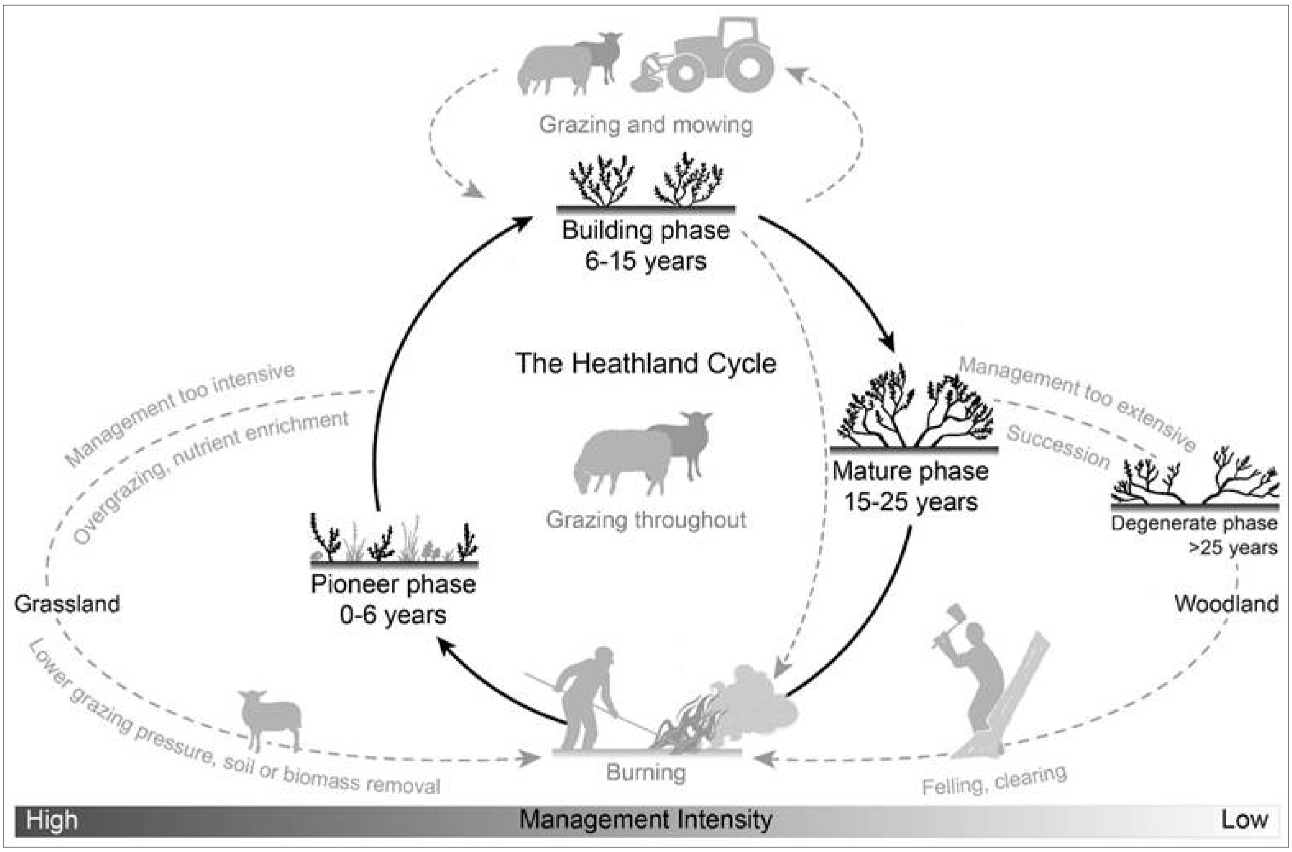


Fig. S2 - Diagram of fuel structure harmonization between Norwegian and UK fuel datasets. Colours relate to the restructured characteristics used for cluster analysis. Numbers relate to further aggregation of characteristics to produce Rothermel fuel models as described in Andrews (2018). Our Rothermel fuel models were created for the oceanic European dormant season (late-autumn-spring), a time in which most herbaceous fuels are dead and wildfire risk has generally been greatest. Thus, all herbaceous fuels were added into 1-hr dead fuels for rate of spread predictions.

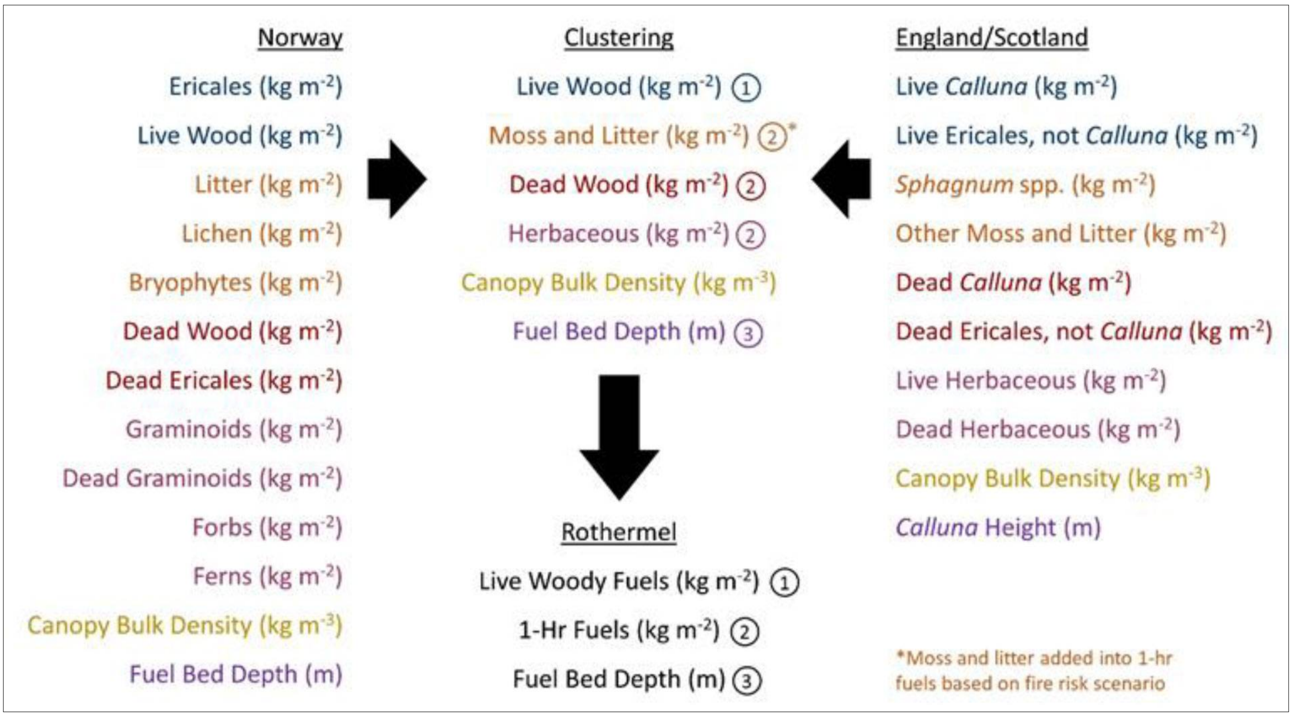


Fig. S3 - Scree plot of variance across the dataset explained by hierarchical fuel groups based on Bray-Curtis dissimilarity and Ward's minimum variance method. The final number of fuel groups was determined by a trade-off prioritizing numerous enough groups to explain fuels in oceanic heathlands, fewer groups to maintain parsimony and avoid strongly overlapping groups, and a declining amount of variation explained by adding a new group. After 6 fuel groups, additional variation explained by added groups increased at a much lower rate.

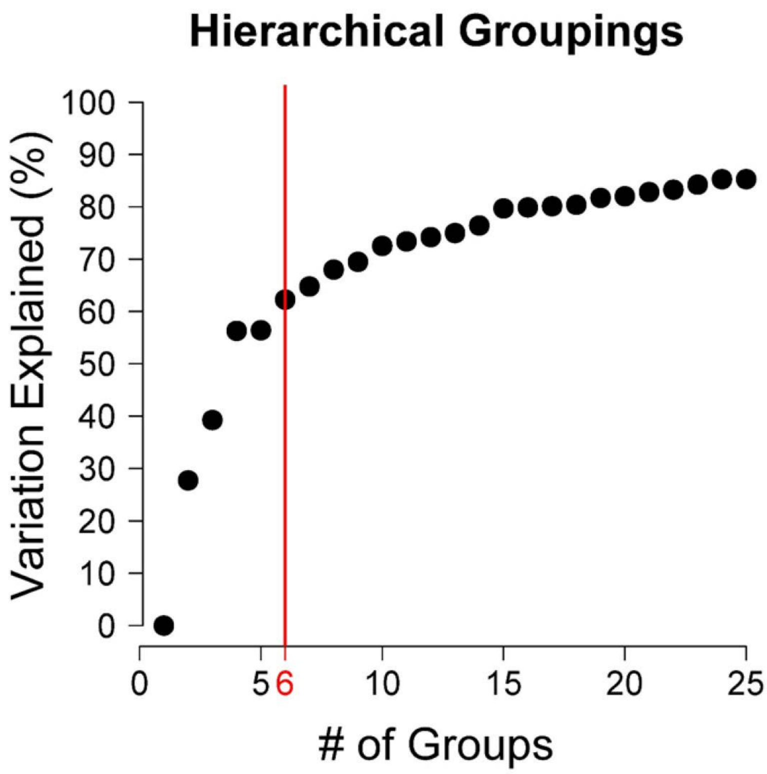


Fig. S4 - Dendrogram detailing hierarchical groups and their fuel type descriptor codes. The number of groupings selected was determined using the scree plot in Figure S3. Tips are individual fuel entries.

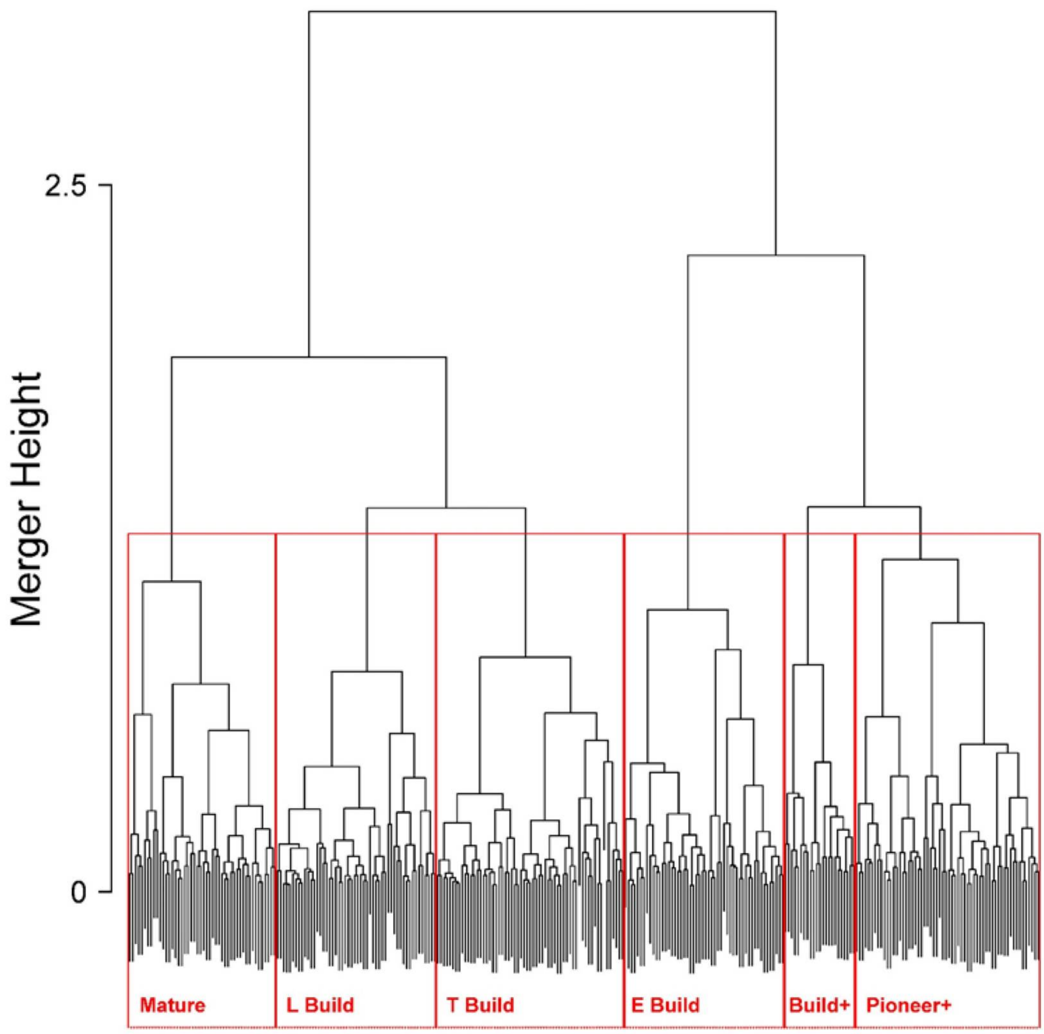


Fig. S5 - NMDS analysis examining variation in heathland fuel structure for the medium fire risk scenario. Shapes represent country of sampling. Fuels are visualized with regards to: A - Calluna stage (Gimingham 1981); B - EUNIS (and NVC) community code (Davies et al. 2004; Elkington et al. 2001); C - the fuel clusters identified via hierarchical clustering; and D - predicted rates of spread. In panes B and C ellipses respectively enclose the centroid ± 1 standard deviation for the EUNIS communities and fuel clusters. Centroids for key fuel components are also shown in pane C including explicit dead fuels (DEAD: 10% moss, litter, and dead wood), live woody fuels (LW), all herbaceous fuels (HERB), fuel bed depth (FBD) and Calluna canopy bulk density (CBD).

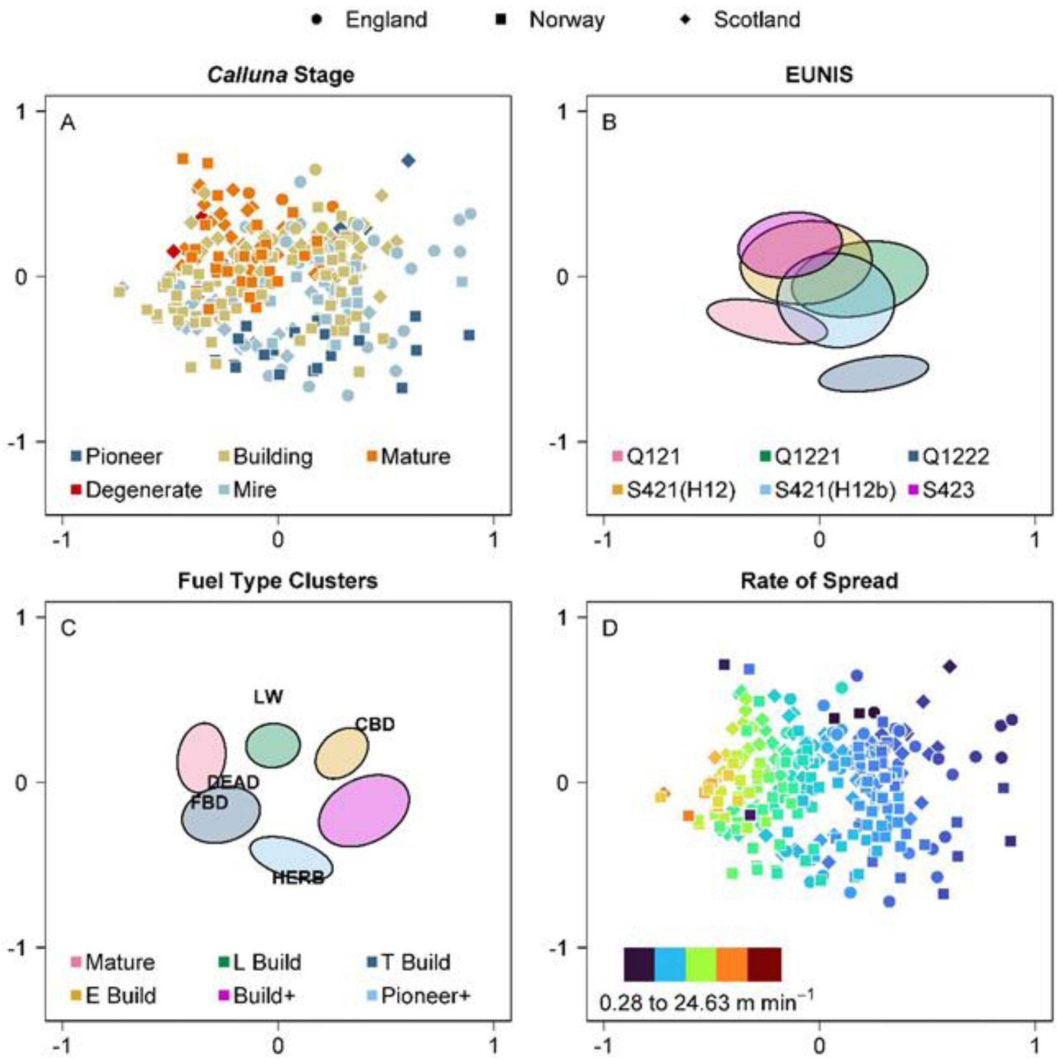
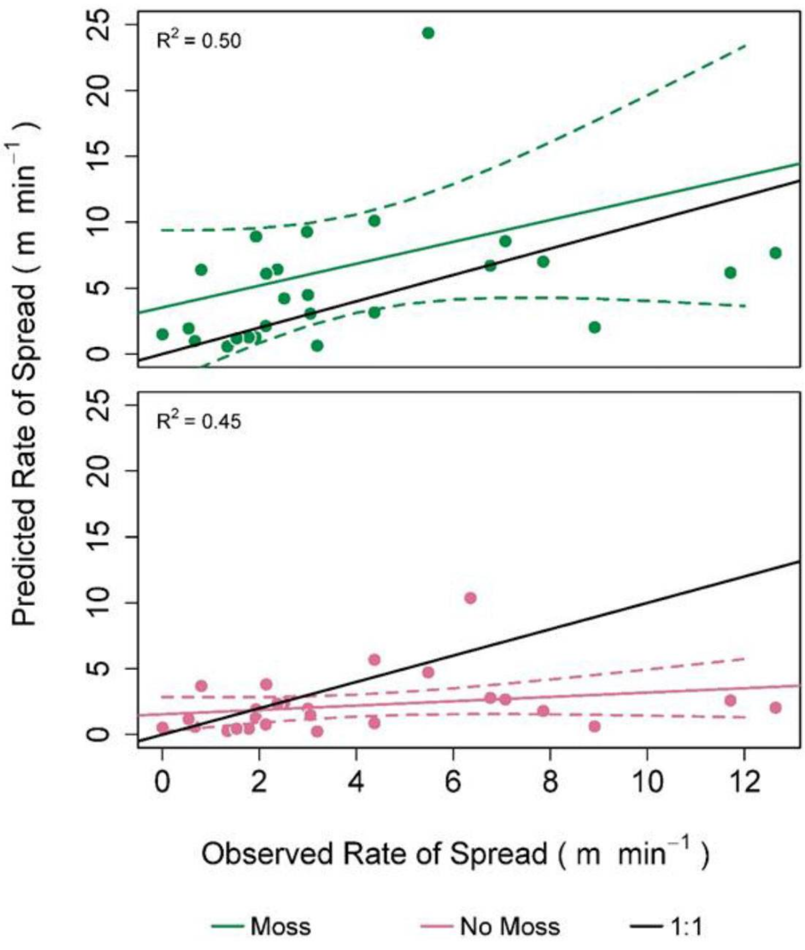


Fig. S6 - Results of linear regression analyses comparing predicted rates of spread from the Rothermel model to observations of rates of spread from prescribed burns. Each point represents an individual burn and data were available for fire-specific fuel, weather and fire behaviour characteristics (see Davies et al. 2009 for further details). Rates of spread were predicted using an appropriate final fuel model assigned to each fire using the classification tree developed in this paper (Fig. 6) and fire weather recorded during the day of burn. The black line on each plot represents the 1:1 LPA, where overlaps with linear model confidence intervals indicate a lack of difference between predictions and observations. Moss indicates rates of spread predicted with moss and litter active in fire propagation (i.e. an estimated appropriate amount added to the 1-hour fuel load) while no moss indicates such fuel was not added.



Tab. S1 - Data descriptions for all fuel entries. UK mean annual temperature (MAT) and total annual precipitation (TAP) data from the Met office nearest weather stations 1991-2020 (Met Office 2022). UK fuels from Davies et al. (2008, 2009, 2016); Norwegian fuels and weather from Haugnum et al. 2021.

Country (number of entries)	Site (Lat, Long)	Elevation (m)	MAT (°C)	TAP (mm)	Sampling Method	Est. time since fire (yrs)	Vegetation	Management
Scotland (110)	Abernethy (57.2132, -3.6275)	360-380	9.22	865	0.25 m^2 quadrat	Unknown	Degenerate *Calluna* in Scot's pine forest understory	Some grazing
	Am Bauchaille (57.0258, -4.0739)	400-480	7.91	1186	0.25 m^2 quadrat	< 5 - > 30	Mixed-age *Calluna* heath	Managed burning
	Birse (57.0086, -2.7333)	220	8.00	800	0.25 m^2 quadrat	Unknown	Degenerate *Calluna* in Scot's pine forest understory	Unknown
	Black Hill (55.8545, -3.3003)	450	8.77	1057	0.25 m^2 quadrat	< 15	Building *Calluna* heath, some degenerate	Managed burning, grazing
	Crubenmore (56.9836, -4.2019)	270-510	6.87	1282	0.25 m^2 quadrat	< 5 - > 30	Mixed-age *Calluna* heath	Managed burning, grazing
	Drumochter (56.8847, -4.2408)	850	6.87	1282	0.25 m^2 quadrat	< 15	Building mixed-species heath	Managed burning, some grazing
	Finzean (57.0217, -2.7047)	350	8.00	800	1 m^2 quadrat, gas flux chamber	Unknown	Mixed-age *Calluna* heath	Managed burning, cutting
	Kirkconnel Flow (55.0133, -3.6086)	15	9.58	1181	1 m^2 quadrat	Unknown	Lowland raised bog	Historic peat cutting
	Lochan Odair (57.0492, -4.0867)	270	7.68	985	0.25 m^2 quadrat	> 30	Degenerate *Calluna* heath	Some grazing
	Loch Cuaich (56.9575, -4.1450)	345	6.87	1282	0.25 m^2 quadrat	> 15	Mature *Calluna* heath	Some grazing
	Meall Chuaich (56.9625, -4.1133)	620	6.87	1282	0.25 m^2 quadrat	> 15	Mature *Calluna* heath	Unknown
	Meall Dubh (57.0283, -4.1089)	290-300	8.73	1359	0.25 m^2 quadrat	< 5 - > 30	Mixed-age *Calluna* heath	Managed burning, some grazing
	Milton of Nuide (57.0550, -4.0903)	270	6.87	1282	0.25 m^2 quadrat	< 5 - > 30	Mixed-age *Calluna* heath	Managed burning, some grazing
	Nuide Moss (57.0383, -4.1183)	270-280	6.87	1282	0.25 m^2 quadrat	< 5 - > 30	Mixed-age *Calluna* heath	Managed burning, grazing
	Ralia (57.0456, -4.1275)	280	6.87	1282	0.25 m^2 quadrat	> 10	Late building, mature *Calluna* heath	Managed burning
	South Drumochter (56.8882, -4.2766)	410-800	6.87	1282	0.25 m^2 quadrat	> 10	Late building, mature *Calluna* heath	Managed burning, some grazing
	Starr (55.2035, -4.3861)	210	9.19	2697	1 m^2 quadrat, gas flux chamber	Unknown	Blanket mire	Possible drainage
England (59)	Anglezarke (53.6558, -2.5308)	310	9.65	1315	1 m^2 quadrat, gas flux chamber	Not recently burned	*Calluna* heath and blanket mire	Possible drainage, grazing
	Black Down (50.6875, -2.5498)	240	10.71	877	1 m^2 quadrat	Unknown	Mixed-species lowland dry heath	None known
	Marsden (53.6033, -1.9934)	425	8.77	1057	1 m^2 quadrat, gas flux chamber	Not recently burned	*Calluna* heath and blanket mire	Possible drainage, grazing
	Wainstalls (53.7827, -1.9258)	430	8.77	1057	1 m^2 quadrat, gas flux chamber	Not recently burned	*Calluna* heath and blanket mire	Possible drainage, grazing

Country (number of entries)	Site (Lat, Long)	Elevation (m)	MAT (°C)	TAP (mm)	Sampling Method	Est. time since fire (yrs)	Vegetation	Management
Norway (126)[2]	Lygra (60.70084, 5.09257)	10	8.5	2020	0.1875 m^2 quadrat	4, 13, 21	Pioneer, building, mature mixed-species heath	Sheep grazing until spring same year
	Haverøya (64.77900, 11.21930)	15	6.4	1720	0.1875 m^2 quadrat	7	Building mixed-species heath	None known
	Store Buøya (65.83677, 12.22451)	15	6.5	1254	0.1875 m^2 quadrat	3	Pioneer mixed-species heath	Sheep grazing until spring same year
	Skotsvær (65.79602, 12.22450)	15	6.5	1254	0.1875 m^2 quadrat	> 30	Mature mixed-species heath	Sheep grazing until spring same year

[1]Times since fire based on conversations with managers, field observations and *Calluna* stage. For Norwegian samples exact times since fire are known

[2]Note that one year of collection for Norwegian fuels (2018) was a relatively dry year.

Tab. S2 - Summary of input constants for R and Farsite. Modified from Legg et al. (2007). Live herbaceous fuels were combined, based on relative sizes, with 10 and 100-hour fuels due to a lack of representation.

Input Description	Value	Data Source
1-hour Surface Area-to-Volume Ratio (m^{-1})*	9560	EUFirelab (2002)
Live Woody Surface Area-to-Volume Ratio (m^{-1})	1000	EUFirelab (2002)
Calluna Heat of Combustion (kJ kg^{-1})	20810	Hobbs (1981)
Moisture of Extinction (%)	30	Legg et al. (2007)

*There were no 10-hour, 100-hour or live herbaceous fuels in the fuel type clusters.

Tab. S3 - Pairwise PERMANOVAS comparing fuel characteristics between individual factor levels. Values are for significance of each comparison set against α = 0.05.

		Mature	L Build	T Build	E Build	Build+
Cluster Comparisons	**L Build**	0.001	-	-	-	-
	T Build	0.001	0.001	-	-	-
	E Build	0.001	0.001	0.001	-	-
	Build+	0.001	0.001	0.001	0.001	-
	Pioneer+	0.001	0.001	0.001	0.001	0.001
EUNIS Habitat Comparisons		**Q121**	**Q1221**	**Q1222**	**S421 (H12)**	**S421 (H12b)**
	Q1221	0.001	-	-	-	-
	Q1222	0.003	0.001	-	-	-
	S421 (H12)	0.001	0.001	0.001	-	-
	S421 (H12b)	0.001	0.003	0.001	0.001	-
	S423	0.001	0.004	0.001	0.658	0.001
Calluna Stage Comparisons		**Building**	**Degenerate**	**Mature**	**Mire**	**-**
	Degenerate	0.083	-	-	-	-
	Mature	0.002	0.352	-	-	-
	Mire	0.002	0.009	0.002	-	-
	Pioneer	0.002	0.005	0.002	0.010	-

Tab. S4 - Pairwise PERMANOVAS comparing fuel characteristics between individual factor levels. Values are for test statistics of each comparison.

		Mature	L Build	T Build	E Build	Build+
Cluster Comparisons	**L Build**	51.627	-	-	-	-
	T Build	40.472	75.648	-	-	-
	E Build	127.889	43.754	129.859	-	-
	Build+	106.342	73.161	61.129	37.890	-
	Pioneer+	87.909	107.990	23.969	94.457	31.744
		Q121	**Q1221**	**Q1222**	**S421 (H12)**	**S421 (H12b)**
EUNIS Habitat Comparisons	**Q1221**	17.276	-	-	-	-
	Q1222	6.469	8.303	-	-	-
	S421 (H12)	17.696	13.886	14.104	-	-
	S421 (H12b)	11.069	6.427	7.650	12.021	-
	S423	11.032	4.696	14.124	0.571	5.718
		Building	**Degenerate**	**Mature**	**Mire**	**-**
Calluna Stage Comparisons	**Degenerate**	2.380	-	-	-	-
	Mature	14.210	1.128	-	-	-
	Mire	9.587	4.184	35.737	-	-
	Pioneer	12.224	5.106	37.186	4.587	-

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