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Ignition probability and fuel consumption of boreal ground vegetation fuels – an experimental study in Finland

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Highlights

- Ignition probability and mass loss rates clearly differed in experimental burnings among four common circumboreal moss and lichen species.
- *Cladonia rangiferina* was the most flammable, *Dicranum* spp. the least flammable and *Pleurozium schreberi* and *Hylocomium splendens* intermediate.

Abstract

In boreal forests fires often ignite and spread within the dominant moss and lichen cover of the ground layer vegetation, which thus greatly influences fire hazard. We used an experimental set-up in greenhouse conditions to study the differences in how (1) fuel moisture and (2) wind velocity influence the ignition probability and fuel consumption among four common circumboreal ground vegetation fuels, *Pleurozium schreberi* (Willd. ex Brid.) Mitt., *Hylocomium splendens* Schimp., *Dicranum* spp. and *Cladonia rangiferina* (L.) F. H. Wigg. Our results show that the reindeer lichen *C. rangiferina* was clearly the most flammable species, with high ignition probability even at high moisture contents and low wind velocities. Of the mosses, *Dicranum* was the least flammable, with low ignition probability and mass loss at low wind velocities regardless of moisture content. *P. schreberi* and *H. splendens* behaved somewhat similarly with wind velocities quickly increasing the initially low ignition probability and mass loss observed in the absence of wind. However, especially for mass loss, among-species differences tended to disappear with stronger winds. The observed differences can be explained by the different structures and growth forms of the studied species and open a potential avenue for improving forest fire risk predictions.

Keywords ground vegetation; flammability; forest fires; fuel moisture content; mass loss rate; prescribed burning
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1 Introduction

Until recent years, the forest fire hazard in Fennoscandia has been low compared to many other parts of the boreal zone, but recent large fires in Sweden (Gustafsson et al. 2019; Granström 2020) have forced a re-evaluation of the risk and significance of forest fires also in Fennoscandia. At the same time, the effective fire suppression has led to a decline of fire-associated biodiversity (Granström 2001), hence conservation of burned areas and increasing prescribed burning are considered necessary to safeguard fire-related habitats and species.

Both the potential risk of increasing impact of forest fires in the boreal zone and the need to maintain fire-related habitats require developing fire management methods. The flammability characteristics of fuels are key factors in predictions of fire ignition and spread (Ryan 2002). The fuel moisture content (FMC) is known to play a pivotal role in the ignition, fire behavior and fuel consumption during a fire, and can be considered as one of the most important inputs in forest fire prediction models (Keane 2015). Although somewhat less studied, wind velocity also affects the flammability of forest fuels by transporting oxygen and heat, as well as tilting the flame that further enhances heat transfer (Varner et al. 2015).

In many parts of the boreal zone, a continuous moss and lichen cover consisting mostly of a few circumboreal species forms the surface part of duff layer, where forest fires typically ignite and spread (Schimmel and Granström 1997; Tanskanen et al. 2005). The feather moss (*Pleurozium schreberi* (Willd. ex Brid.) Mitt.) is the most abundant in many areas of white (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) dominated forests of North America, Norway spruce (*Picea abies* (L.) H. Karst.), Scots pine (*Pinus sylvestris* L.), and larch (*Larix*) dominated forests in boreal Eurasia (Tesky 1992; Babintseva and Titova 1996; Mäkipää 2000; Ivanova et al. 2020). *Pleurozium schreberi* often shares dominance with the stairstep moss (*Hylocomium splendens* Schimp.), and fork mosses (*Dicranum*), that have in recent decades increased in abundance in Fennoscandia (Mäkipää and Heikkinen 2003). The reindeer lichens (*Cladonia*) are abundant in drier and xeric sites (Nousiainen 2000).

Although mosses and lichens are living organisms, they can be considered to behave similarly to fine, dead fuels, since they have no internal water holding or transporting organs, and thus dry rapidly (Tanskanen et al. 2006). Yet, these species can vary greatly in the amount of moisture they contain, because of their tissue material, stem structure and growth form (Tanskanen et al. 2006; Lindberg et al. 2021). Compared to mosses, reindeer lichens are known to have lower bulk density, lower surface-to-volume ratio, and lower heat content (Munger 2008). Of the moss species of our study *Dicranum* forms denser growth including thick tomentum (Peterson and Mayo 1975) which is shown in higher bulk density when compared with *H. splendens and P. schreberi* (Grau-Andrés et al. 2022).

These properties also influence air flow and can be expected to modify the influence of wind on the ignition and spread of fires. Forest floors with different moss and lichen community composition are thus known to have different drying rates (Ivanova et al. 2020; Lindberg et al. 2021), affecting their flammability. It is possible that the species also differ in their flammability even with similar FMC values and wind conditions because of their structural differences. In this experimental study we examined the impact of FMC and wind velocity on the ignition probability and fuel consumption of above-mentioned common moss and lichen species. Since the study was done in controlled greenhouse conditions our aim was to find out possible general patterns and relative differences between the studied materials. Thus, the focus of the study was not to define threshold values directly applicable in field conditions.

2 Materials and methods

2.1 Sampling and experimental set-up

Undisturbed samples of four common circumboreal moss and lichen species of mature mineral-soil forests were collected from a mature Scots pine-dominated semi-xeric *Vaccinium*-type forest stand of approximately one hectare in size in Evo state forest in Hämeenlinna, Southern Finland (61°12′N, 25°05′E). The stand was 55 years old, with a standing volume of 180 m^3 ha^{-1}, and average tree height of 19.5 m. Stand structure was typical to a Finnish managed stand with an evenly aged structure and practically absent understory, as a result of several pre-commercial and commercial thinnings. The stand had a characteristic raw humus layer of ~4 cm which is typical to semi-xeric sites in Finland and a continuous ground layer where moss and lichen species dominance varies in patches.

The four collected species were those that are in general the most abundant in mesic and semi-xeric forests in Finland: *Dicranum* spp., mainly *D. polysetum* Sw. ex anon, with possible marginal amounts of other *Dicranum* species, *P. schreberi*, *H. splendens* and *Cladonia rangiferina* (L.) F. H. Wigg. We randomly sampled monospecific patches of each target species from uniform moss-lichen carpet, so they represented similar substrates and micro-locations. The samples were separated from the raw humus layer carefully by hand and thus included only the loose living growth (height 5–10 cm) of species, retained their original growth structure and contained no raw humus nor litter.

Samples were placed in aluminum trays (110 mm × 84 mm × 41mm) and were oven-dried in 105 °C temperature for 18 hours to measure their dry mass. They were then fully moistened with 100 milliliters of water, which equals a rainfall of approximately 10 millimeters and wets the moss or lichen layer thoroughly. After this they were dried to target dry weight FMC values of 11% (tolerance ± 0.9%), 25% (± 0.9%), 43% (±1.1%), 67% (±2.0%) and 100% (±2.0%). The used FMC values were chosen so that they covered a wide range of moisture contents, to ensure that the shape of the response and differences among the species were captured.

Immediately after the targeted FMC were reached the samples were placed on a table in a greenhouse, where three different wind velocities (0, 1, 2 m s^{-1}) were created by a fan. Since this was an experimental study, we used rather low velocities to analyze the sensitivity of ignition to even small changes in wind velocity. For each combination of FMC value, wind velocity and species, at least five replicate samples were targeted (Table 1). However, as several samples were contaminated by mold, the targeted burning of five replicates could not be achieved in all cases (Table 1). Especially for *Dicranum*, experiments with 25% and 43% FMC values and 0 m s^{-1} wind velocity were reduced because of this. (Table 1). The air humidity and temperature could not be fully controlled but the ignition tests were timed on circumstances when air relative humidity was observed to be between 40% and 60% and temperature over 20 °C. The ignition potential of similar fuels has been previously studied by match ignition trials in field experiments in Canada (Lawson et al. 1993), Sweden (Granström and Schimmel 1998) and Finland (Tanskanen et al. 2005). In our study we adapted similar point-ignition source method, yet instead of matches the samples were ignited by keeping a long tube open-flame gas igniter for 30 seconds in the center of the lower quarter (relative to wind direction). After the potential burning was completed, the percentage of burned area was determined and samples were dried and weighed to calculate the mass loss.

Flammability is most often understood as the general ability of a fuel to ignite and combust in the absence of ignition source (Varner et al. 2015), so in our study all samples with successful ignitions were considered flammable. In this study no separation to smoldering and flaming combustions was made (see Larjavaara 2005).

Table 1. The number of ignition tests performed in the study by species, moisture content and wind velocity. Total number of tests: 293, location of the study: Evo state forest, Hämeenlinna, Finland.

	Wind velocity 0 m s^{-1}				
Moisture content Species	11%	25%	43%	67%	100%
Pleurozium schreberi	6	5	5	5	5
Dicranum spp.	5	-^	2	5	5
Hylocomium splendens	5	4	5	5	5
Cladonia rangiferina	5	5	5	5	5
	Wind velocity 1 m s^{-1}				
Pleurozium schreberi	5	4	5	5	4
Dicranum spp.	5	4	3	7	4
Hylocomium splendens	5	7	7	5	4
Cladonia rangiferina	3	5	6	6	6
	Wind velocity 2 m s^{-1}				
Pleurozium schreberi	6	5	4	6	5
Dicranum spp.	5	8	4	4	5
Hylocomium splendens	5	5	5	5	5
Cladonia rangiferina	6	5	5	4	4

^) All samples in this group were contaminated by mold and omitted from analysis

2.2 Data analysis

Ignition was considered successful when ≥ 90% of the surface area was burned by flaming combustion and unsuccessful when < 90% was burned. The 90% threshold was chosen because in some cases small, unburned patches were left in the corners of the test trays. Ignition probability was then modelled as a function of FMC and wind speed (as a factorial variable), using logistic regression modelling. Models were fit separately for each species.

Fuel consumption was similarly modelled as a function of FMC and wind, separately for each species. Exploratory analyses showed that different-shaped non-linear relationships between FMC and fuel consumption were common, and thus generalized additive models (GAMs) were used to allow for differences in the shape of the response. Fuel consumption was modelled as a smooth function of FMC, with wind as a factorial variable. For strictly positive data (fuel consumed), a Gaussian error distribution with a log-link was used. The spline smoothers were constrained to be monotonically decreasing to prevent the biologically unrealistic increase in fuel consumption with moisture content, which occurred in few cases. This was visually judged to originate from high variation in fuel consumed at low wind speeds. Statistical analyses were conducted in R (version 3.5), using the package *scam* for the GAM models (Pya 2018).

3 Results

We identified clear differences in both ignition probability (Fig. 1, Table 2) and fuel consumption (Fig. 2, Table 3) among the species. The lichen *C. rangiferina* was the most flammable fuel with 100% ignition probability up to second highest moisture content tested (67%). Even in the 100% FMC, ignition probability stayed clearly over 50% (Fig. 1). Opposite to the mosses, *C. rangiferina*'s ignition probability was also almost independent of wind velocity, as response was shown only with the highest FMC values (Fig. 1).

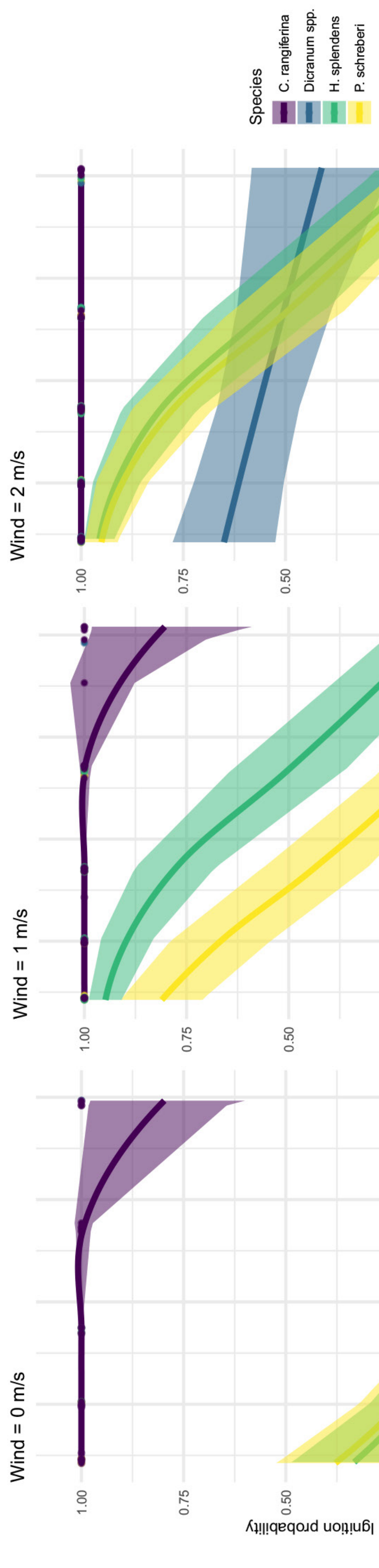

Fig. 1. Ignition probabilities of the studied species by wind velocity and fuel moisture content (%, dry weight basis) of used logistic regression models. Shaded areas show the standard errors of each fitted model and dots show the original measured observations.

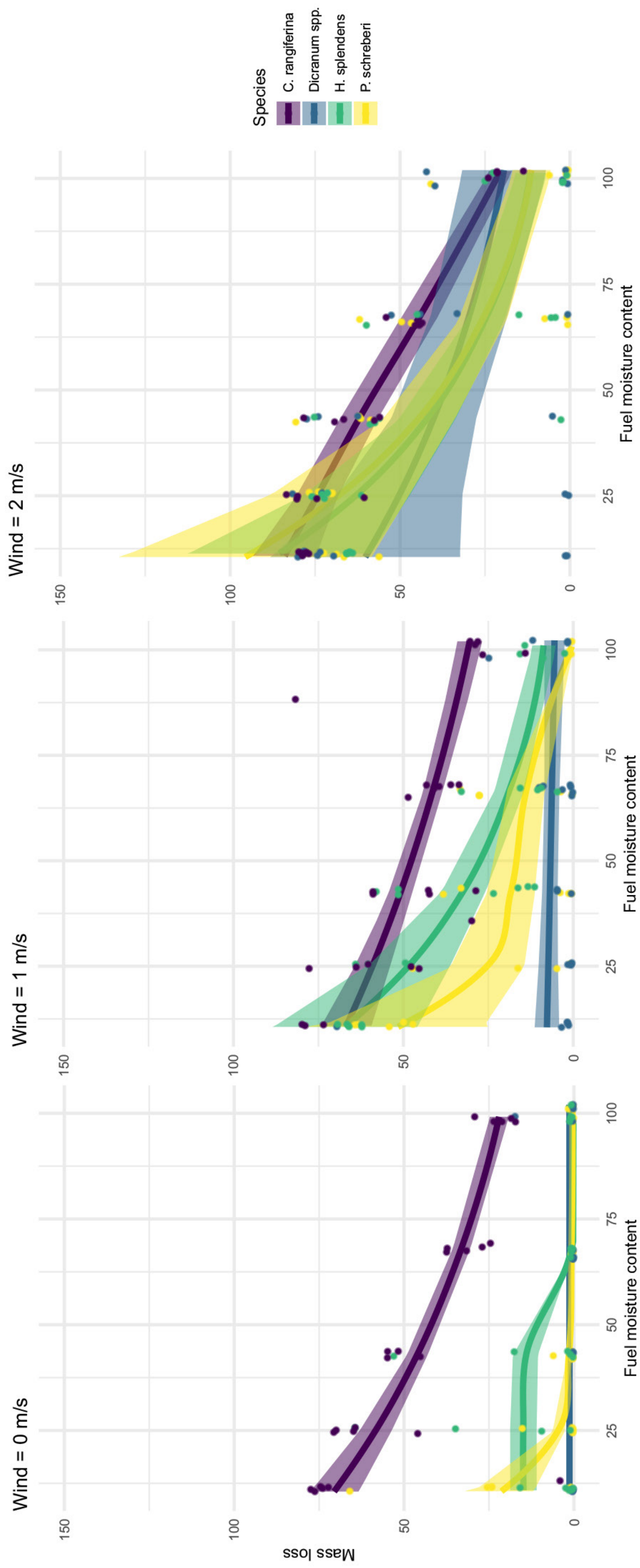

Fig. 2. Mass losses (%, dry weight) of the studied species by wind velocity and fuel moisture content (%, dry weight basis) of used generalized additive models. Shaded areas show the standard errors of each fitted model and dots show the original measured observations.

Table 2. Coefficients of the logistic regression model (ignition probability analysis).

Species	Variable	Estimate	Std. error	p
Cladonia rangiferina	Intercept	14.08	13.22	0.28
	Moisture%	–0.13	0.14	0.34
	Wind 1 m s^{-1}	0.35	1.59	0.83
	Wind 2 m s^{-1}	18.26	4715.29	1
Dicranum spp.	Intercept	2.22	1.14	0.05
	Moisture%	–0.01	0.01	0.30
	Wind 1 m s^{-1}	0.36	1.27	0.78
	Wind 2 m s^{-1}	2.95	1.11	0.01**
Hylocomium splendens	Intercept	–0.14	0.75	0.86
	Moisture%	–0.05	0.01	<0.001***
	Wind 1 m s^{-1}	3.60	0.96	<0.001***
	Wind 2 m s^{-1}	3.78	0.99	<0.001***
Pleurozium schreberi	Intercept	0.06	0.68	0.92
	Moisture%	–0.05	0.01	<0.001***
	Wind 1 m s^{-1}	1.95	0.81	0.016**
	Wind 2 m s^{-1}	3.45	0.92	<0.001***

Table 3. Parametric coefficients and significances of smoother terms of generalized additive model (mass loss analysis). Edf: efficient degrees of freedom.

Species	Variable/Smooth term	Estimate	Std.error	p	edf
Cladonia rangiferina	Parametric coefficients				
	Intercept	4.43	0.12	<0.001***	
	Wind 1 m s^{-1}	–0.11	0.18	0.54	
	Wind 2 m s^{-1}	0.11	0.21	0.60	
	Smooth terms				
	s(moisture): wind 0 m s^{-1}			<0.001***	1.03
	s(moisture): wind 1 m s^{-1}			<0.001***	0.98
	s(moisture): wind 2 m s^{-1}			<0.001***	1.80
Dicranum spp.	Parametric coefficients				
	Intercept	0.27	0.38	0.48	
	Wind 1 m s^{-1}	1.83	0.67	0.008**	
	Wind 2 m s^{-1}	3.99	0.68	<0.001***	
	Smooth terms				
	s(moisture): wind 0 m s^{-1}			–	0
	s(moisture): wind 1 m s^{-1}			0.66	0.65
	s(moisture): wind 2 m s^{-1}			0.21	1.11
Hylocomium splendens	Parametric coefficients				
	Intercept	2.70	0.26	<0.001***	
	Wind 1 m s^{-1}	1.80	0.47	<0.001***	
	Wind 2 m s^{-1}	2.06	0.47	<0.001***	
	Smooth terms				
	s(moisture): wind 0 m s^{-1}			<0.001***	1.00
	s(moisture): wind 1 m s^{-1}			<0.001***	0.93
	s(moisture): wind 2 m s^{-1}			0.001**	1.11
Pleurozium schreberi	Parametric coefficients				
	Intercept	4.81	1.44	0.001**	
	Wind 1 m s^{-1}	0.04	2.44	0.99	
	Wind 2 m s^{-1}	0.05	1.52	0.97	
	Smooth terms				
	s(moisture): wind 0 m s^{-1}			<0.001***	2.38
	s(moisture): wind 1 m s^{-1}			<0.001***	3.20
	s(moisture): wind 2 m s^{-1}			0.05*	1.24

For all three moss species, the absence of wind led to low ignition probability. Even with the driest treatment, the ignition probability remained below 50%. Among moss species, *Dicranum* was clearly the least flammable (Fig. 1).

Increasing wind had a significant effect on the ignition probability of all studied mosses. *P. schreberi* and *H. splendens* showed higher ignition probability already with the 1 m s^{-1} wind velocity, since over 50% of ignitions were predicted for FMC values under ~40% for *P. schreberi,* and under ~65% for *H. splendens,* whereas *Dicranum* stayed well below the 50% probability even with lowest FMC values. In the highest wind velocity (2 m s^{-1}), all moss species ignited with 50% probability in FMC values lower than ~70%, but *P. schreberi* and *H. splendens* showed similarly higher probabilities than *Dicranum,* especially with lower FMC values (Fig. 1). Compared to *C. rangiferina* the moss species showed clearly more stochastic ignition behaviour.

In mass loss curves (Fig. 2), homologous behavior among species was apparent. Mass loss curves for *C. rangiferina* were almost linear, with a minor impact of wind velocity showing that fuel consumption was mainly dependent on FMC. Wind affected the mass loss of moss species clearly and in similar pattern as with ignition probabilities: *H. splendens* and *P. schreberi* reached higher mass losses already with 1 m s^{-1} velocity. *Dicranum*`s mass loss increased only at the highest wind velocity (2 m s^{-1}, Fig. 2). It is notable that with 2 m s^{-1} velocity the shapes and values of mass loss curves among species were starting to resemble each other, yet among the moss species the mass loss values were slightly lower and deviation higher than for *C. rangiferina* (Fig. 2).

4 Discussion

Our results are consistent with previous studies characterizing *Cladonia* as one of the most flammable forest fuels due to its high surface-to-volume ratio, gelatinous thallus, lack of rhizoids and loose growth form (Pech 1991; Munger 2008; Ivanova et al. 2020). This also possibly explains why the wind velocity had a minor impact on the ignition probability of *C. rangiferina*, since compared to mosses, the airy stem structure transfers heat and oxygen more rapidly after ignition.

The studied mosses showed different ignition probabilities and clear responses to wind velocity. *Dicranum* was the least flammable with practically no ignitions with wind velocities of 0 and 1 m s^{-1} but showed a notable increase in ignition probability with 2 m s^{-1} wind velocity. This is probably explained by the compact, mattress-like growth form and dense tomentum of *D. polysetum,* which hinders the transfer of oxygen and heat more efficiently than the looser *P. schreberi* and *H. splendens,* which showed increasing ignition probabilities already with 1 m s^{-1} wind velocity. Although comparable experiments with these species are lacking, studies with other fine surface fuels support the impact of wind on flaming ignition (Dimitrakopoulos et al. 2010; Marino et al. 2010; Masinda et al. 2020). In our study increasing wind velocity increased the ignition probability in general and lowered the differences in flammability. Thus, with increasing wind speeds, species identity becomes irrelevant. It must be noted that since we examined the studied materials by their entire living growth the moisture gradient within the growth was not taken into account. The surface layer of mosses is known to dry more rapidly than the denser lower parts, thus possibly enabling ignitions of the surface layer even if the FMC of the entire growth would be too high for ignition.

The correlation with FMC and mass loss of mosses and lichens in fires has been reported in several studies (Hille and den Ouden 2005; Hille and Stephens 2005; Ivanova et al. 2020). Earlier studies have considered FMC values below 30% to result in complete consumption and values of 30–120% in partial reduction (Hille and Stephens 2005). In their laboratory experiment Blauw et al. (2015) reported mass loss rates of >80% and ~60% with respective FMCs of 10% and 30%. In our study, mass loss of *C. rangiferina* was in line with these principles, as the reduction was

~75% with the lowest FMC (11%) and decreased almost linearly to ~25% with the highest FMC value (100%).

Our results showed low ignition probabilities in the absence of wind for all moss species, regardless of moisture conditions. Even when considering differences in how ignitions are defined, the ignition probabilities were clearly lower than the near 30% moisture content considered as ignition threshold for dead fuels (Keane 2015). In laboratory tests Blauw et al (2015) found both 10% and 30% FMC samples of *P. schreberi* ignitable. In different field tests, earlier studies have reported clearly higher (e.g., 25–35%; Granström and Schimmel 1998; Tanskanen et al. 2005) FMC values below which ignitions increase, whereas Ivanova et al. (2020) present a range of 10–40% for mosses and 25–40% for lichens based on studies in Russia. The low ignition probabilities in our experiment are likely partially explained by the rather high relative humidity conditions on which the test burnings were performed as FMC of lichens and mosses are influenced rapidly by the atmospheric relative humidity (Norum 1982; Pech 1989). In our experiment the relative humidity varied between 40% and 60%, whereas in their laboratory study Blauw et al. (2015) maintained a clearly lower air humidity of 20–40%. In our experiment we studied flaming combustion with open-flame ignition tests, so the results cannot be adapted to smouldering combustion, which can occur in clearly higher FMC values (Frandsen 1997).

5 Conclusions

The studied species differed notably in their ignition probability and mass loss rates, in a manner that was consistent with differences in their morphology and compactness. Also, wind velocity had a clear impact on the ignition probabilities of mosses and on mass loss of all studied species. Importantly, increasing wind speed seems to even out among-species differences relative to ignition or mass loss at a given moisture content. The results indicate potential for improving fire weather indices by providing more species-specific information as well as helping to predict the burn depth e.g. in prescribed burnings to better achieve the targeted goals.

Major changes in fire regimes in the European boreal region are often explained by transitions from spruce-dominated to pine-dominated forests (and vice versa) (Tryterud 2003; Ohlson et al. 2011), which can be partially due to the lichen/moss ratio. Our results support this hypothesis since there were major differences in the ignition probabilities of *C. rangiferina* and mosses which, combined to their different moisture behavior result in notable differences in their flammability. Finally, it must be emphasized that the results of this experimental study are not directly applicable to field conditions but form a basis for further developing models for ignitions and fuel consumption, based on moisture content, wind, and species characteristics.

Abbreviations

FMC: Fuel moisture content.
GAM: Generalized additive model.

Data availability statement

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

Authors' contribution

HL and I V-M presented the original idea and designed the experiment. HL coordinated the data collecting and data processing. TA performed the statistical analysis. HL prepared the first version of manuscript and all authors participated in finalizing the manuscript.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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