ADVANCES IN FOREST FIRE RESEARCH

2022

Edited by

DOMINGOS XAVIER VIEGAS

LUÍS MÁRIO RIBEIRO

Influence of tree species on surface fuel structure in Swedish forests

Frida Vermina Plathner*[1]; Johan Sjöström[1]; Anders Granström[2]

[1] *Department of Fire Technology, RISE Research Institutes of Sweden, Box 857, 501 15 Borås, Sweden, {frida.vermina.plathner, johan.sjostrom}@ri.se*
[2] *Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, 901 83, Umeå, Sweden, {anders.granstrom@slu.se}*

**Corresponding author*

Keywords

Fuel depth; tree species; fuel bed; boreal; fuel load; BEHAVE

Abstract

The highly managed forests of Fennoscandia are dominated by coniferous (Scots pine and Norway spruce) stands with occasional inclusion of deciduous trees (Betula spp, Populus tremula, Quercus robur). Without active pre-commercial thinning, broadleaved deciduous trees would be more common and it is often assumed this would reduce flammability. Generally, there is little information on surface fuel structure in Fennoscandia and its relation to the dominant tree species. We therefore evaluated fuel characteristics in 153 plots from 82 mature, closed-canopy forest stands dominated by Pinus sylvestris (23), Picea abies (20), Quercus robur (20), Betula pendula (14), Populus tremula (5).

Stand properties (tree species and basal area) were measured on site and fuel bed composition was determined by destructive sampling of two 0.25 m2 plots per stand (species, fuel bed depth, weight, %-coverage). Dry weight per fuel category was measured in the laboratory. The measured parameters were used as input to the BEHAVE wildfire model, to assess relative fire behaviour for these different fuel assemblies.

The results show that the moss/litter layer (sometimes including lichens) was thicker and had a larger dry weight under pure pine stands compared to that under spruce stands. BEHAVE modelling suggested both fireline intensity and rate-of-spread to be substantially higher for pine stands. As for the broadleaved deciduous tree species, even a small inclusion in the coniferous stands severely affected the moss/litter layer. Leaf litter formed horizontal, multi-layered packs that replaced the porous structure and high surface-to-volume ratio of the moss/litter with a more compacted pure litter layer, resulting in reduced flammability.

The BEHAVE models presented here are available at https://www.ri.se/sites/default/files/2021-12/SwedishForestFuels_0.zip.

1. Introduction

Of the three main driving factors for wildfire spread and intensity – weather, terrain, and fuel – it is only the fuel that can be modified to reduce risk (Skowronski & Gallagher 2018). For tactical fire suppression it is also essential to characterize various biotopes from a fuel quality perspective, e.g. in the form of standardized fuel maps (Fernandes, 2009).

As for boreal regions it is often assumed that the fuel situation is relatively uniform, with a conifer canopy above moss/litter surface fuels. There are, however, surprisingly few quantitative analyses to illustrate this (but see Brown, 1974; McRae, 1979). The Fennoscandian boreal region, comprising Sweden, Finland and part of Norway is dominated by two conifer tree species, *Pinus sylvestris* and *Picea abies*, but there is also a high potential for broadleaved deciduous trees, primarily *Betula* spp and *Populus tremula*, which often outcompete the conifers unless culled by pre-commercial thinning (Andersson, 1993).

Experimental burns (Granström & Schimmel, 1998; Tanskanen, 2005) as well as empirical evidence from large fires (Nilsson et al., 2014; Granström, 2020) suggest that fires in Fennoscandia most often burn as surface fires, consuming mainly the moss/litter layer including lichens on the forest floor. Crown fires are rare and when they occur usually cover only minor parts of the burnt area.

Although the tree canopy seldom becomes involved in the fire directly (i.e. crowning), the stand type and structure will have an indirect effect through the litter composition and quantity, as well as by affecting both the vascular and non-vascular flora on the forest floor. For instance, leaf size affects both the litter characteristics and the extent of shadowing by the sub-canopy layer (Kauf et al., 2018; Dickinson et al., 2013). These stand-type to surface fuel relationships are not yet well established in Fennoscandia. Here we aim to relate stand properties to the surface fuel characteristics for five homogenous stand types and to provide indications of how deciduous tree inclusion in coniferous stands alter the surface fuel structure.

Wildfire modelling has several important uses, for instance as an operational tool during large incidents, and in preventive planning, to identify areas with an elevated hazard. In models such as BEHAVE, the fuel composition is accounted for using so called "fuel models". There are 53 predefined fuel models for the BEHAVE software, based on extensive field sampling of biotopes in the U.S. (Burgan & Rothemel, 1984; Scott & Burgan, 2005), which also form the basis for their national fuel map. None of these models apply *a priori* to boreal forests with moss/litter as the main fuel component. Thus, a secondary aim of this study was to build fuel models for wildfire modelling based on the quantitative fuel distributions we obtained.

2. Methods

2.1. Selected sites

Fuel characteristics were recorded for 153 sample plots under 82 mature stands of *Pinus sylvestris* (pine) (23), *Picea abies* (spruce) (20), *Betula pendula* (birch) (14), *Populus tremulus* (aspen) (5) and *Quercus robur* (oak) (20). Stands were sampled from the 55th to the 64th parallel for most species (Fig 1). Homogeneous oak stands, however, occur predominantly in the south-eastern Sweden and thus, geographically restricted the sampling.

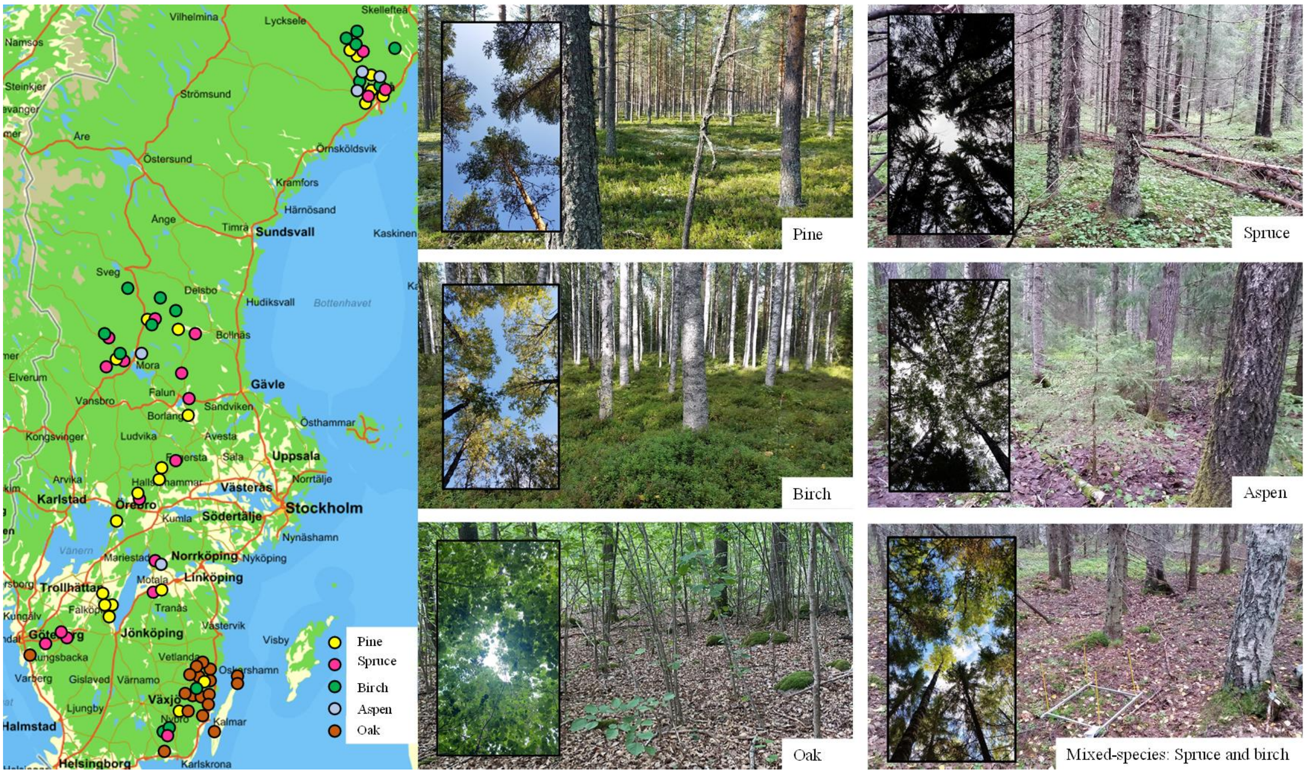

Figure 1. Geographical locations of stands and examples of selected stand types.

The study was delimited by selecting stands that were on dry or mesic soils according to the SLU site index estimation (Hägglund & Lundmark 1977), lacked large stone blocks, had a closed canopy with homogenous stand properties (except mixed stands) and were not in the first cycle of forest on abandoned farmland. Most Swedish forests are production forests where occasional thinning takes place. Thinning will add branch litter and impact surface fuels. We therefore omitted any stand with thinning operations less than 10 year before sampling.

2.2. Field data collection

Stand height and basal area of all tree species in each stand was determined using a relascope and hypsometer. Surface fuel was destructively sampled on two representative 0.25 m^2 plots in each stand (Fig 2). Cover of field layer species (mostly ericaceous shrubs e.g. *Vaccinium* spp or *Calluna vulgaris*) was visually assessed and their respective height measured. They were then cut at the top of the moss layer and brought to lab for obtaining dry weight after drying at 95°C. Similarly, the surface cover of moss/litter layer was assessed per species and litter type (leaves, needles etc.).

Figure 2. Progressive steps for quantifying the fuel structure: (a) Estimating surface cover of different shrub species; (b) Photographing stand characteristics and performing relascope measurements; (c) Defining shrub height and harvesting for dry weight determination; (d) Estimating surface cover of litter and moss species; (e) Defining depth of moss litter layer by several pressure probe measurements; (f) Harvesting moss/litter layer for dry weight specification and determining humus depth.

Surface fuel depth was determined using the penetration depth of a 2 cm sided L-shaped aluminium probe with a 15 N downward force. This is related to previous observations of what is typically consumed by flaming fire and defines the depth of the moss/litter-layer, a very loosely packed fuelbed of moss/lichen intermixed with tree litter (leaves, needles and other small litter) (Fig 2). The moss/litter layer was thereafter collected to the depth defined by the probe and brought to lab where easily defined litter (dead tree-branches, bark flakes and cones) were separated from the litter/moss-layer, sorted in different size classes (1-h, 10-h and 100-h) (Fosberg, 1971) and dry weight determined. The remaining *Vaccinium/Calluna* stems penetrating the moss layer were also collected separately. Finally, the humus layer was cut through with a knife and its thickness measured with a ruler, down to the underlying mineral soil.

2.3. Modelling

Results from the field work were used to create five 'custom fuel models' for each fuel type in BEHAVE. BEHAVE divides fuels into different size classes, as well as into a 'live' or 'dead' class. Three modelling parameters; the dead fuel moisture of extinction (25%), the surface area to volume ratio (SA/V) of moss, and other 1-, 10- and 100-h fuels as well as their heat content were extracted from literature (Schimmel & Granström, 1997), Table 1. Finally, all input parameters were weighted based on their average fraction of the dry weight of the fuel package within each size class, Table 2.

Table 1. Fuel parameters taken from Schimmel and Granström (1997)

Modelling parameter	**SA/V** (cm^{-1})	**Heat content** (kJ/kg)
1-h (moss)	115	18700
1-h (needles, bark, dwarf shrub litter etc)	45	18700
10-h	3	18700
Ericaceous shrub	80	21000
Grass and herbs	115	18700

Table 2. Modelling parameters based on the field work

Modelling parameter	**Pine**	**Spruce**	**Birch**	**Aspen**	**Oak**
1-h fuel load (g/m^2)	963	643	396	342	406
10-h fuel load (g/m^2)	40	11	47	47	124
100-h fuel load (g/m^2)	0	3.3	1.3	0	15
Live herbaceous fuel load (g/m^2)	6	6	28	6	8
Live woody fuel load (g/m^2)	192	39	101	63	3
1-h fuel SA/V (cm^{-1})	108.2	107.4	93.8	97.8	97.4
Fuel bed depth (cm)	9.1	5.6	5.5	4.5	2.8
Live fuel heat content (kJ/kg)	20929	20693	20501	19327	19327

These fuel models were run in two different weather situations, (1) a "mild" weather/fuel moisture scenario: 11% m.c. of the dead fine fuel, 170% m.c. of live herbaceous fuel and 100% m.c. of the live woody fuel, and (2) a "severe" weather/fuel moisture scenario (8%, 120% and 90% m.c. respectively). For both scenarios we employed midflame wind speeds ranging between 0-3 m/s and no slope.

Rate of spread (RoS) (m/min), flame length (m) and fireline intensity (kW/m) were obtained for the different type of tree stands as an indication of relative fire hazard.

3. Results and discussion

3.1. Fuel characteristics

The conifer stands, together with birch, had the most developed field-layer (Fig 3). Lingonberry was far more common under pine stands compared to other tree-species. The forest floor in coniferous stands was almost completely covered with moss/lichen while under the deciduous trees the mosses were much reduced, apparently smothered by the leaf-litter. Live herbaceous plants on the other hand, were more abundant under the deciduous stands (Fig 3).

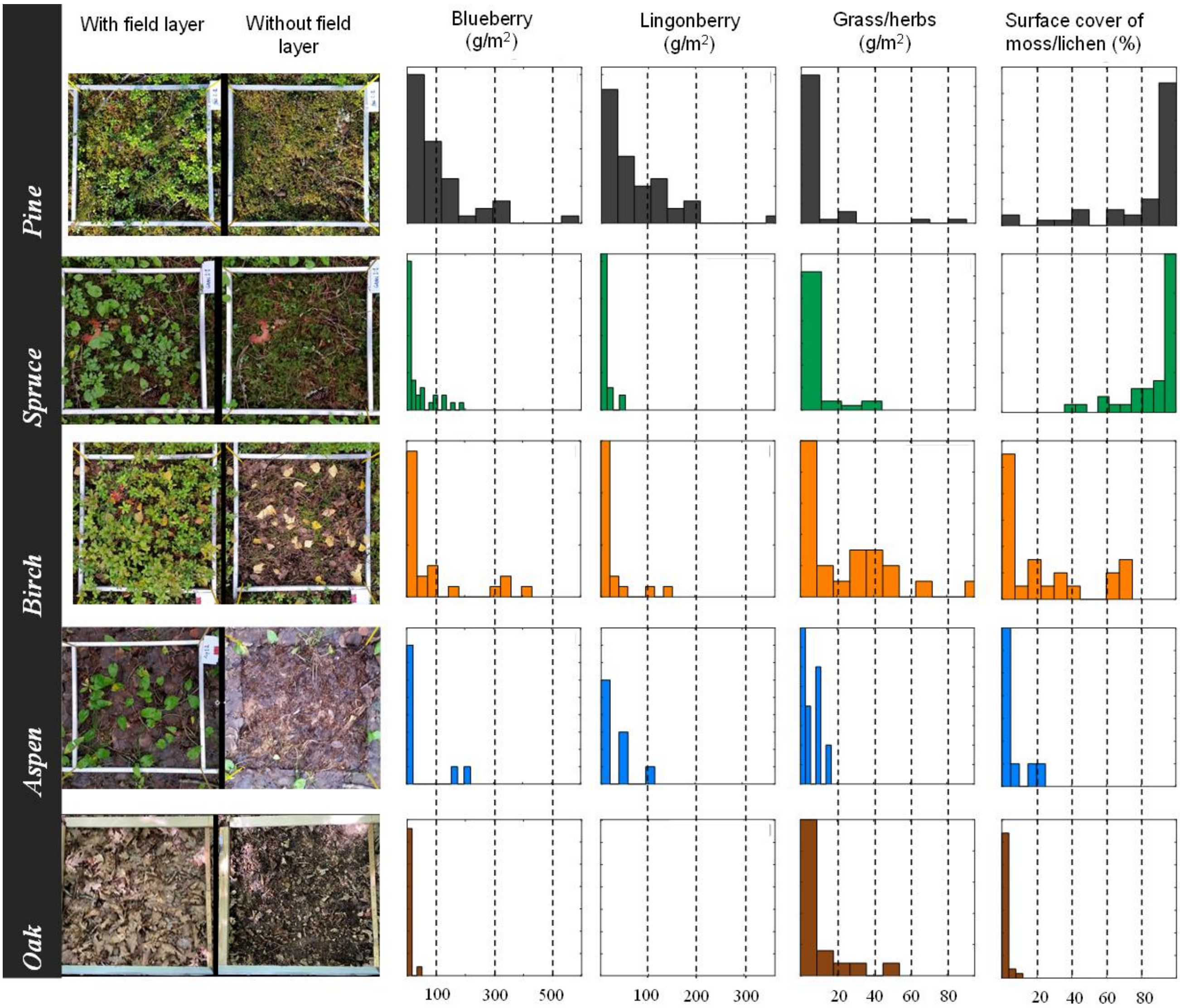

Figure 3. Distributions of measured field-layer fuel parameters and the estimated moss/litter layer surface cover for the five stand types. Photos exemplify the field layer for each stand type before and after removal of the field layer (pine, spruce, birch) and before and after removal of herbaceous species and the litter layer (aspen, oak).

Histograms for the moss/litter layer fuel bed depth and dry-weight show that most coniferous stands had deeper and more massive litter/moss-layers (mean values of 7.6 and 5.2 cm for pine and spruce stands respectively, as opposed to 2-3 cm for deciduous species) (Fig 4). The occurrence of other 1-h fuels and larger-sized litter varied less between stand types except that 10-h fuels were less common in spruce stands and more common in oak stands (Fig 4).

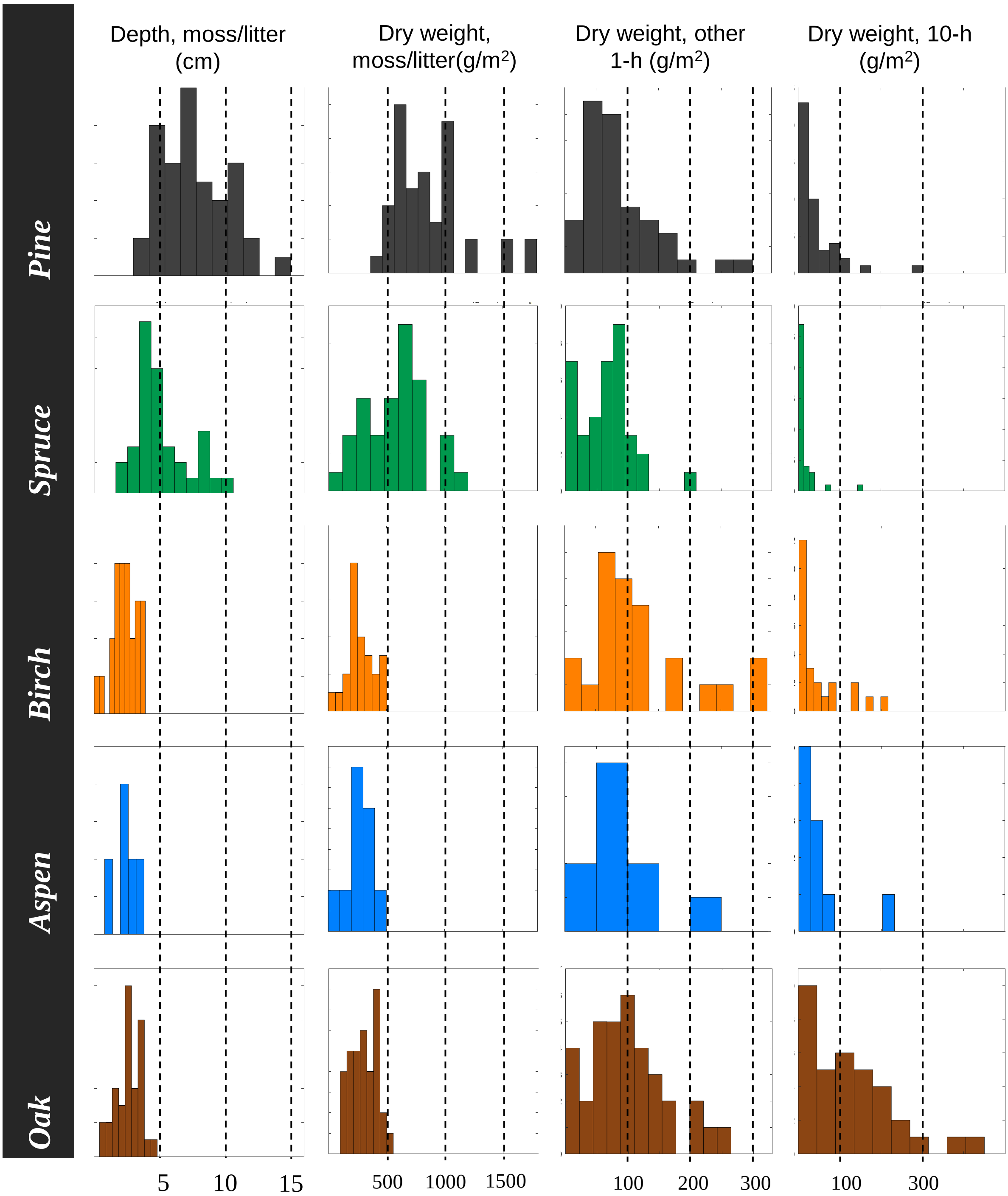

Figure 4. Distributions of measured moss/litter layer fuel parameters for the five stand types. Other 1-h fuels include e.g. easily separated dead tree-branches, twigs and bark flakes.

3.2. Mixed species stands

Sampling of mixed-species stands indicate that even a minor inclusion of broad-leaved trees affected the fuel bed substantially (Fig 5a). The surface cover of moss/lichens was also reduced monotonically with increasing deciduous component (Fig 5b). Moreover, the dry weight of the moss/litter layer decreased with the inclusion of just a few deciduous trees, from 750(±140) g/m^2 for pure conifer stands to an average of around 200 g/m^2 for stands with basal area of birch/aspen trees ≥4 m^2/ha (Fig 5c). No clear effect on the amount of Ericaceous shrubs was found (Fig 5d).

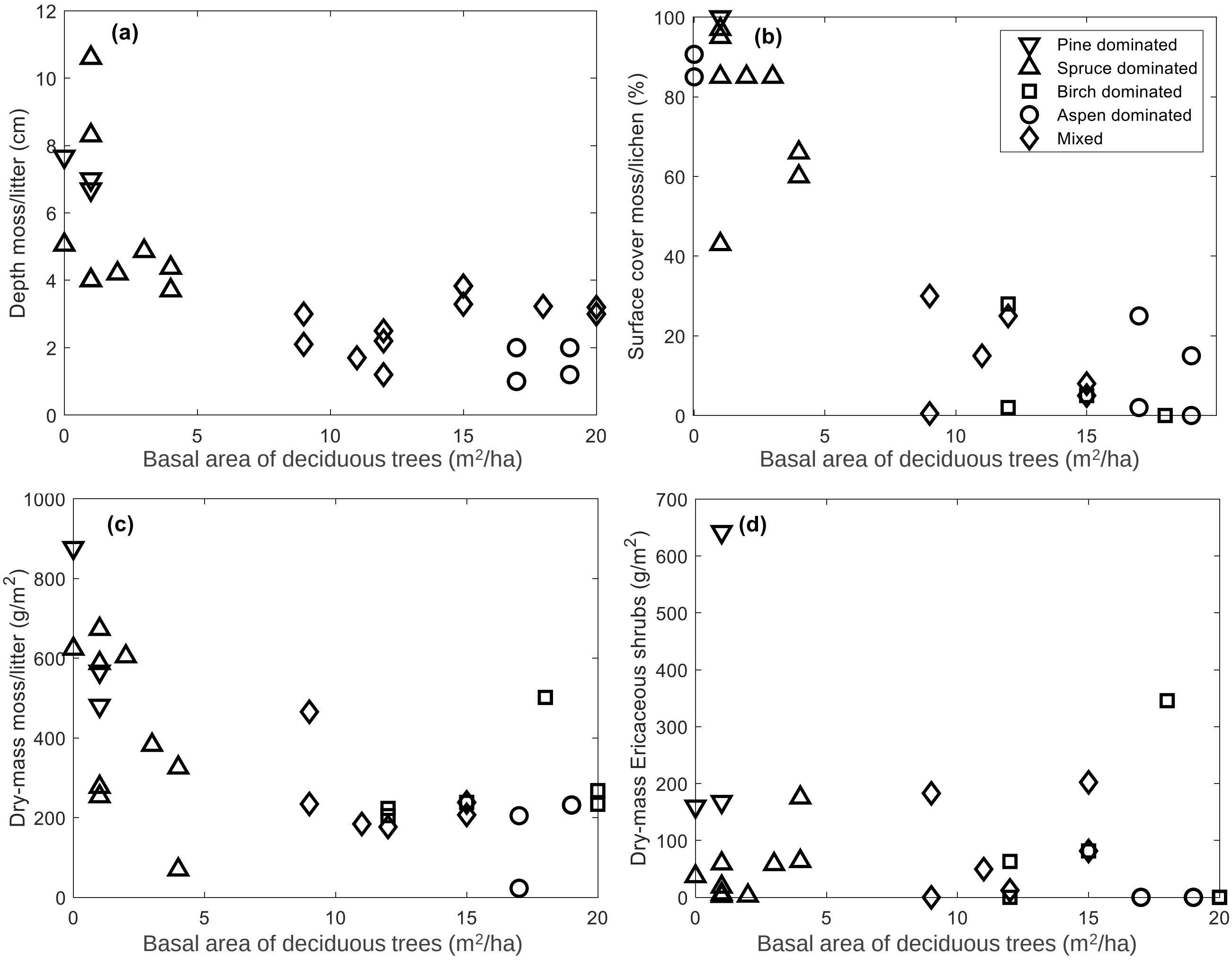

Figure 5. Effect of basal area of deciduous trees (i.e. number of trees in the relascope measurement) on (a) moss/litter depth; moss/lichen surface cover (b); moss/litter weight (c); Ericaceous shrubs weight (d).

3.3. Relative fire behaviour in BEHAVE

For both weather scenarios, pine generated the most severe fire behaviour, followed by spruce, birch, aspen and oak (Fig 6). This relationship holds regardless of wind speed and moisture content and can therefore be normalized to obtain relative behaviour (Fig 7). One can expect the RoS to increase by 50% and 200% when a surface fire enters a pine stand from a spruce or deciduous stand, respectively.

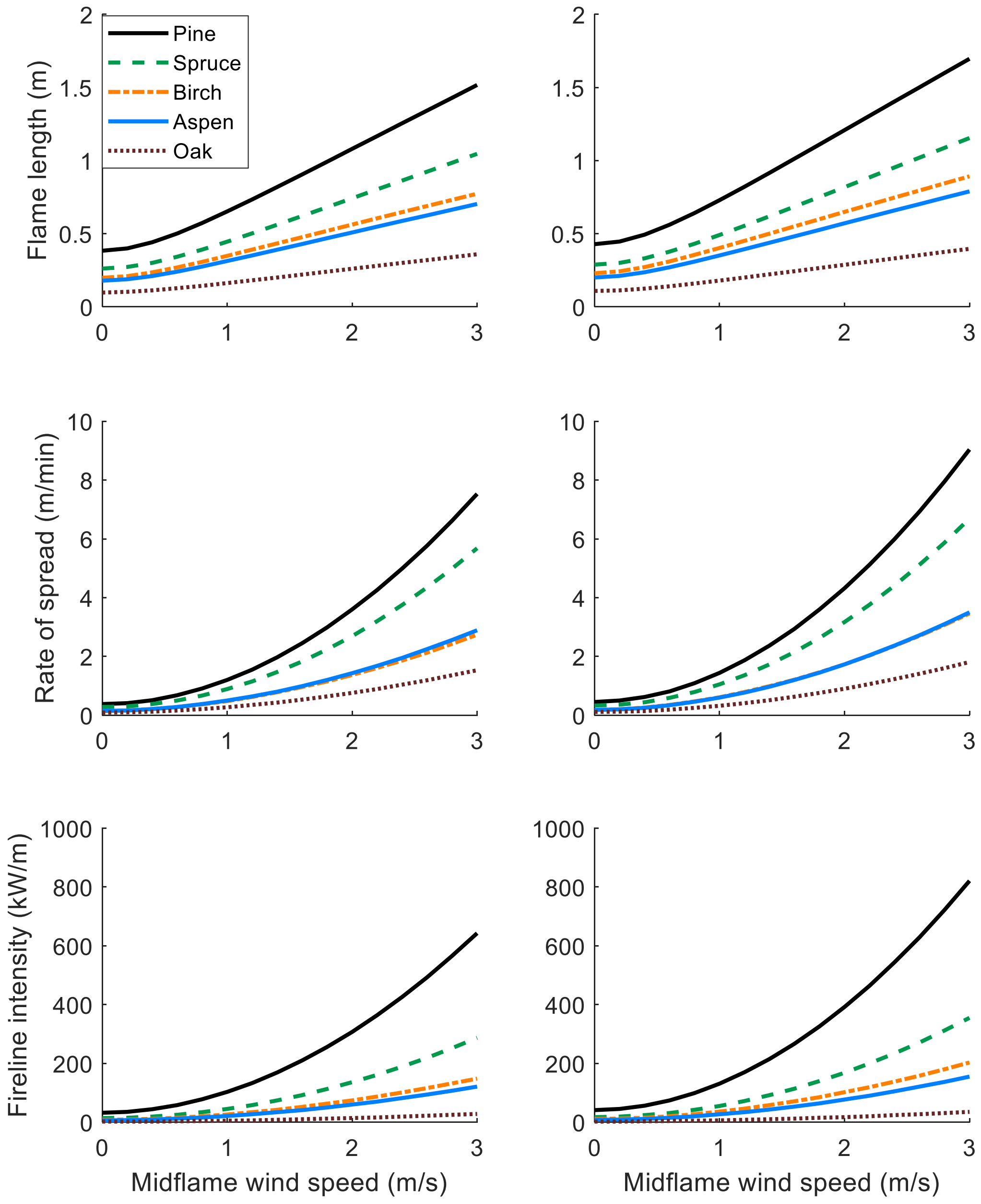

Figure 6. Modelling results for the two weather scenarios: Flame length, rate of spread and fireline intensity

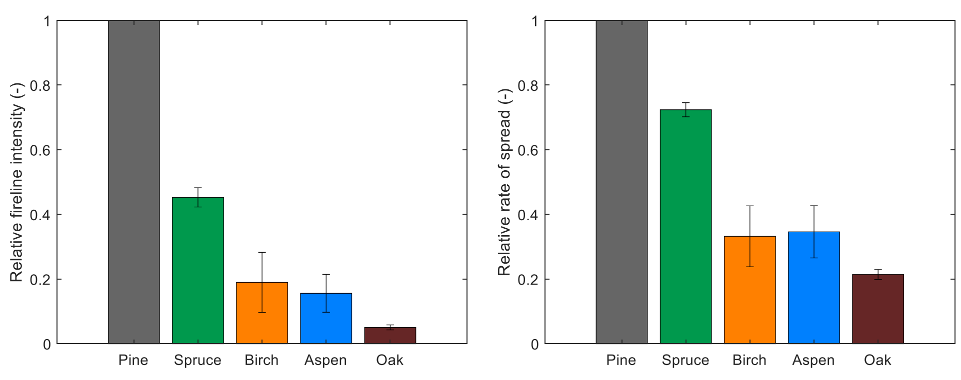

Figure 7. Relative fire behaviour between the different stand types

4. Discussion and conclusions

This study describes the surface fuel characteristics under typical north European closed-canopy stands of five different tree species. It shows that the flat leaves from birch and aspen can smother moss growth and thereby decrease the surface-layer depth and dry weight by more 50%. The porous structure and high surface-to-volume ratio of the moss/lichen under coniferous stands are transformed to a more compact layer of horizontally arranged leaf litter, which likely has a negative effect for both fire rate-of-spread and intensity.

Even a small portion of deciduous trees in a conifer stand has a significant effect on the forest floor fuel structure and as little as 20 % of deciduous trees in a coniferous stand makes the surface fuel structure essentially "leaf-dominated".

In the BEHAVE simulations we found a significant difference in intensity and rate-of-spread between pure pine and spruce stands, mainly due to differences in the depth of the moss/litter-layer. This is possibly related to the higher light availability in pine stands, but also due to structural differences in needles between the two conifers, pine having paired longer needles that add to the loose structure of the moss. According to the BEHAVE modelling this effect results in a 50% and 25% reduction of the fireline intensity and rate-of-spread, respectively, for both normal and extreme summer drought conditions. Relative to pine, broadleaved stands have the potential to reduce both fireline intensity and RoS in a progressing fire front by a factor of 1/5 and 1/3, respectively.

Models are available at https://www.ri.se/sites/default/files/2021-12/SwedishForestFuels_0.zip

5. Acknowledgements

This work was funded by the Swedish Civil Contingency Agency (MSB), under grant numbers 2337461 and 2021-14648.

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