# Moisture content variation of ground vegetation fuels in boreal mesic and sub-xeric mineral soil forests in Finland

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**Abstract:** Forest fire risk in Finland is estimated by the Finnish Forest Fire Index (FFI), which predicts the fuel moisture content (FMC) of the forest floor. We studied the FMC variation of four typical ground vegetation fuels, *Pleurozium schreberi, Hylocomium splendens, Dicranum* spp., and *Cladonia* spp., and raw humus in mature and recently clear-cut stands. Of these, six were sub-xeric *Pinus sylvestris* stands, and six mesic *Picea abies* stands. We analyzed FFI's ability to predict FMC and compared it with the widely applied Canadian Fire Weather Index (FWI).

We found that in addition to stand characteristics ground layer FMC was highly dependent on the species so that *Dicranum* was the moistest, and *Cladonia* the driest. In the humus layer, the differences among species were small. Overall, the FWI was a slightly better predictor of FMC than the FFI. While the FFI predicted ground layer FMC generally well, the shape of the relationship varied among the four species. The use of auxiliary variables thus has potential in improving predictions of ignitions and forest fire risk. Knowledge of FMC variation could also benefit planning and timing of prescribed burnings.

**Brief summary**: The studied four moss and lichen species were found to dry at different rates, thus having different ignition potential and fire risk. Stand type, and particularly developmental stage also affected the drying rates. The fire risk indices could be improved by using these variables, which could benefit fire prevention.

**Keywords:** fire risk, forest fire index, forest type, prescribed burning, Norway spruce, Scots pine, stand structure

**Running head:** Variation in moisture content of ground vegetation fuels

## Introduction

In Finland, forest fires declined during the last century. This decline was particularly steep during the latter half of the century. The average annual burned area in 1950s was about 5,700 ha and in the 1970s it had declined to approximately 700 ha (Yearbook of Forest Statistics 1990-1991 (1992). In recent decades, the average annual burned area has varied between 200 and 800 ha, only occasionally exceeding 1,000 ha. The average size of an individual fire is currently about 0.4 ha (Finnish Statistical Yearbook of Forestry 2014). The climatological fire risk in Finland was relatively stable during the last century (Mäkelä *et al.* 2012), so the decline in fire occurrence is explained by other factors, such as efficiency in fire detection and suppression, and changes in ignition sources, stand structure, forest fragmentation, and vegetation (Päätalo 1998; Wallenius 2011). This is also supported by the difference between the fire regimes of Finland and neighbouring Sweden, where the annual burned area has been higher and large fires frequent (Lindberg *et al.* 2020).

Although forest fires do not currently form a major risk to society or property in Finland, they still employ rescue services leading to a need to improve forest fire risk assessment methods. This is partially due to the fact, that although the burned area has been low, the annual number of fires has been about 1,300 in the 21st century (Finnish Statistical Yearbook of Forestry 2014). Thus, the small-sized but frequent forest fires burden regional rescue services and local fire brigades during the forest fire season. Several studies have also predicted that the general forest fire risk in Finland (Kilpeläinen *et al.* 2010; Lehtonen *et al.* 2014; Mäkelä *et al.* 2014) and the risk for large fires (Lehtonen *et al.* 2016) will increase in the 21st century. One way to improve the preparedness of rescue services is to improve the ability to predict potential fire hazard days.

The fuel moisture content (FMC) of different fuels is one of the key factors when estimating fire risk. FMC is used to predict flammability, and it is also a factor in models predicting fire intensity and fire spread rate. Most forest fire indices are meteorological and use various weather data to compute indices for assessing fire risk (San-Miguel-Ayanz *et al.* 2003).

Currently, the most widely used fire index system is the Canadian Forest Fire Weather Index System (CFFWIS), which was initially designed for the Canadian boreal forest. Since being published in 1970 (Van Wagner 1987), it has gradually been adopted in many parts of the world, including different vegetation zones and fuel types (Dimitrakopoulos *et al*. 2011). The FMC estimation in CFFWIS is divided into three moisture codes: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC) (Van Wagner 1987). These moisture codes are calculated daily based on air temperature, relative humidity (not in DC), wind speed (only FFMC), and rainfall.  Two spread indices are then estimated: initial spread index using wind and FFMC and build-up index combining DMC and DC. The spread indices are then combined to determine the Fire Weather Index (FWI) (Van Wagner 1987).

CFFWIS  has proven suitable in forests with a flammable duff  layer typically consisting of a humus layer and moss cover like, for instance, the black spruce (*Picea mariana* ) (Mill.) Britton, Sterns & Poggenburg) forests in boreal Northern America (e.g. Ziel *et al.* 2020). Fennoscandian coniferous forests have a similar type of duff structure, and CFFWIS has generally been found to work well there (Granström and Schimmel 1998; Tanskanen *et al.* 2005).

Despite the increasing use of CFFWIS, national fire indices are still commonly used in many countries.  In Finland, the forest fire risk is estimated and predicted by the Finnish Forest Fire Index (FFI). FFI was constructed in 1996 to replace the former fire index, which was based merely on statistical correlations between weather variables and the occurrence of fires (Heikinheimo *et al.* 1998). In 1996, Sweden started to use CFFWIS  as a national forest fire index system (Sjöström *et al.* 2019), but the Finnish Meteorological Institute (FMI) decided to develop its own index, partly because CFFWIS was considered unnecessarily complicated with its hierarchical structure, and because it was lacking solar radiation as an explaining variable (Heikinheimo *et al.* 1998).

FFI is based on empirical relationships between weather data and the volumetric moisture content of a 6-cm thick layer of forest floor. In short (see Supplement 1 and Vajda *et al.* (2014) for details), air temperature values are obtained from the ground weather station network and spatially interpolated to a 10 km ×10 km grid using the kriging method (Venäläinen and Heikinheimo 2003). Evaporation is estimated based on this interpolated data and weather prediction models, and the precipitation is received from weather radars (Venäläinen and Heikinheimo 2003; Vajda *et al.* 2014). The index is a continuous variable calibrated to vary from 1.0 to 6.0, 6.0 being the driest. The index has been assigned a threshold value of 4.0, at which point it predicts a volumetric moisture content under 20%. When the index exceeds this threshold, a forest fire warning is announced in public media, which forbids the lighting of open fires. It must be noted that the FFI uses volumetric moisture content values based on non-destructive monitoring of fuels and thus they are not directly comparable with gravimetric moisture content values.

In addition to its role in wildfire, FMC plays an important role in prescribed burnings, used in Finland as a silvicultural tool and nowadays also for ecological restoration and management for biodiversity. Because of this, the scope of prescribed burnings in Finland has widened in recent years to a more diverse set of burnings with different ecological aims such as burnings of retention trees, restoration burnings in nature conservation areas and management burnings of sun-exposed and xeric habitats (for details see Lindberg *et al* 2020). The various aims also set diverse targets for fire impact and depth. However, despite the recognized importance of fire for restoration, the overall area of prescribed burns has declined in recent decades (Lindberg *et al.* 2020).

FMC is one of the most significant factors determining the potential days of prescribed burnings and intended burning depth (Sandberg 1980; Ferguson *et al.* 2002; Hille and den Ouden 2005; Hille and Stephens 2005). Because of different ecological aims, understanding how FMC develops in various fuels and their effect on fire impact and burning result is necessary. As an example, in silvicultural burnings and burnings on barren habitats, the aim is to decrease the organic layer, which requires a sufficiently low FMC. If the moisture of the ground layer and in some cases raw humus is too high, the burning effects are not fully achieved. In restoration burnings, more various moisture conditions are possible, since more diverse burning results are accepted (Lindberg *et al.* 2020).

Boreal ground layer species differ in their structure and growth form which affects their water-holding capacity (Peterson and Mayo 1975; Busby and Whitfield 1978; Pech 1989). The aim of this study was to determine the FMC variation of dominant forest floor mosses and lichens and raw humus in different stands of the two most common forest types in Southern Finland. We analyzed how the moisture content of selected species varied as a function of FFI, and we compared the ability of FFI and FWI to predict the FMC of selected fuel materials.

We hypothesize that as clear-cut areas and pine-dominated sub-xeric stands receive more radiation and are more exposed to the drying effect of wind: i) ground vegetation fuels dry faster in clear-cut areas as compared to closed-canopy forests, ii) fuels in pine-dominated forests dry faster than in spruce-dominated forests, iii) varying water holding capacity of studied materials explains the possible differences in their FMC behavior and potential days of ignition.

## Materials and methods

### *Study area*

The study area is located in Southern Finland in the Evo State Forest (Fig. 1) belonging to the southern boreal vegetation zone (Ahti *et al.* 1968). The elevation of the study area varies between 100-190 meters a.s.l., mean annual temperature in the region is +3.1°C, the average annual precipitation is 670 mm, and the growing season 160 days (Juvakka *et al.* 1995). The bedrock is mostly orogenic granitoid covered by a thick, stony morainic layer, but glacier sedimented areas such as deltas, sandur deltas and eskers with sand or gravel are also common (Okko 1972). Of the sampled stands, the sub-xeric stands were mostly located in sedimented, sandy soils and mesic stands on sandy or fine sandy moraines (Fig. 1).

**Figure** 1

### *Experimental design and sampling*

Nearly 90% of Finnish forests are managed commercially (Finnish Statistical Yearbook of Forestry 2014). The management is typically done relatively uniformly, including artificial regeneration, 2-4 low thinnings, and clear-cutting with less than 3% retention of tree volume (Finnish Forestry, Practice and Management 2011, Kuuluvainen *et al.* 2019). The stands are thus evenly aged, relatively sparsely stocked and most often dominated by Norway spruce (*Picea abies* L.) H. Karst and Scots pine (*Pinus sylvestris* L.)

The most common forest site types on mineral soils in Finland are mesic forests (*Myrtillus*-type), which cover 52% and sub-xeric forests (*Vaccinium*-type), which cover 26% of forests (Finnish Statistical Yearbook of Forestry 2014).

Both forest types in their later successional stages are characterized by dwarf shrubs bilberry (*Vaccinium myrtillus L.*), lingonberry (*Vaccinium vitis-idaea L.*) and common heather (*Calluna vulgaris* L. (Hull)). In sub-xeric forests *V. vitis-idaea* and *Calluna* are dominant, and in mesic forests *V. myrtillus* is dominant and *Calluna* practically absent.

Managed conifer-dominated mesic and sub-xeric forests on mineral soils typically have an easily distinguishable raw humus layer with a typical thickness of 3-5 cm in Southern Finland (Tamminen 1991). In these forests, moss and lichen dominated ground vegetation is the most common and the most important flammable fuel bed, where the majority of forest fires ignite and spread (Schimmel and Granström 1997; Tanskanen *et al.* 2005). A continuous moss carpet is typical in later successional stages of coniferous forests whereas in young successional stages it is less abundant, thus decreasing fire risk (Schimmel and Granström 1997). Yet, recent clear-cuts where the moss carpet still exists and herbs and graminoids have not yet colonized the areas are flammable similar to the mature forests. A recent study showed that a significant number of forest fires in Sweden are started in clear-cuts as the sparks produced by forest machines are an important source of ignitions (Sjöström *et al.* 2019). The raw humus layer is also potentially flammable, and the targets and success of prescribed burnings are often estimated by burning depth, which indicates the decrease of moss and raw humus layer.

The feather moss (*Pleurozium schreberi*) (Brid) Mitt. is the most abundant moss species with a coverage of approximately 30% in mesic and 35% in sub-xeric forests. (Mäkipää 2000a). Fork mosses (*Dicranum* spp., *D.polysetum Sw.* and *D.scoparium* Hedw. being the most dominant) cover about 10% in both mesic and sub-xeric types (Mäkipää 2000b), whereas stairstep moss (*Hylocomium splendens*) (Hedw.) is clearly more abundant in mesic types with a share over 10% but in sub-xeric types only 3% (Mäkipää 2000c). Reindeer lichens (*Cladonia* spp) are practically absent in mesic forests but patchy with an average share of 5% in sub-xeric forests (Nousiainen 2000). *Cladonias* abundance increases significantly in xeric and barren forests, which are less common (pooled share 4%) and are concentrated in Northern Finland (Finnish Statistical Yearbook of Forestry 2014).

Twelve forest stands from the study area were chosen, consisting of four different stand types and three replicates from each. The stand types were: 1. Sub-xeric, mature, *Pinus* dominated stand. 2. Sub-xeric, clear-cut area. 3. Mesic, mature, *Picea* dominated stand. 4. Mesic, open, clear-cut area (Fig. 1, Table 1). The age and standing stock of a stand is referred to as the developmental stage (either clear-cut or mature) and the combination of forest type and dominant tree species as stand type (either sub-xeric/*Pinus* or mesic/*Picea*) (Table 1).

**Table** 1

We selected individual stands from the forest planning databases of the study area, according to the following criteria: mature stands had to be over 70 years of age and be either *Pinus*- or *Picea*-dominated, with at least 70% dominance (Table 1). The clear-cut stands had to be harvested during the previous winter with no mechanical scarification. All stands had a distinctive raw-humus layer and a characteristic continuous moss layer with patches of *Cladonia* in sub-xeric stands. The growing stock and structure of the mature stands represented typical Finnish managed forest stands with an evenly aged structure and minor understory.

From each stand, samples of three dominant moss and/or lichen species were collected on 17 days during summer 2003. The days were chosen using FFI values received from the Finnish Meteorological Institute, so that they would cover different weather and drying conditions (Fig. 2). Sampling was focused especially on dry and drying periods whereas, during constant wet periods (which covered the most part of the sampling period), it was not carried out.

We sampled each stand in the afternoons of the sampling days. On each occasion, five randomly chosen samples consisting of moss or lichen and raw humus were taken with humus auger with a diameter of 5.8 cm, height of 10 cm and volume of 264 $cm^{3.}$ The samples were taken from a 300 $m^2$ circular sample plot and were located at least 30 m from the stand edge.  In mesic stands, the sampled species were: *Pleurozium.schreberi*, *Dicranum spp (D. polysetum* being the most abundant) and *Hylocomium splendens.,* and on sub-xeric stands *Pleurozium*, *Dicranum* and *Cladonia.* (C. *rangiferina* (L.) Weber ex F.H. Wigg. being the most abundant). The third replication of mesic clear-cut area had an insufficient cover of *Hylocomium,* so only *Pleurozium* and *Dicranum* were sampled.

Each sample was then divided into two layers: surface and raw humus. Five subsamples of each layer were pooled into one sample representing the average from that stand. Thus, each sampled stand had six combined samples: a combined sample of each of the three surface species, and three combined samples from raw humus under each species. The collective samples were preserved during transportation in air-tight plastic bags. The fresh-weighing and drying was done directly after transportation with a minimum of 18 hours of oven-drying at 105 °C. Sufficient drying time was ensured by experimental dryings before actual sampling. After drying, the samples were weighed and the dry-weight FMC was determined.

*Data analysis*

The noon values of FFI and FWI were used in analysis. The FWI values were received from FMI and calculated according to Van Wagner and Pickett (1985) using weather data from the nearest meteorological station located approximately 4 km south-west of the center of the study area. The wind values came from the nearest available station, about 25 km north-east of the study area. We modeled FMC separately for each species, and the surface and raw humus layers, as a function of FFI, stand type, and the development class. Preliminary analyses showed that the shape of the relationship between FMC and FFI varied among the species and was often non-linear. We thus used generalized additive modeling (e.g. Zuur et al. 2009), in which FMC was predicted as a smooth function of FFI. For the strictly positive data (FMC), we used a Gaussian error distribution and log-link function, and the smoothers were allowed to vary as a function of developmental stage. To avoid problems with overfitting and to ensure biologically realistic model behavior, we used monotonically decreasing P-splines as smoothers and limited their flexibility (number of knots in the splines $k = 4$). To compare the performance of FFI to the more widely used FWI, we then repeated the analyses, using FWI as the continuous predictor in place of FFI. The models were compared using pseudo-$R^2$ values for both (models with FFI and FWI). For model validation (*sensu* Zuur et al. 2009), we visually inspected the residuals as a function of FMC and each predictor, as well as day of year to ensure there were no temporal patterns in the residuals (Supplement 2). All models were fitted using R (R Core Team 2019) and the package scam (Pya 2018).

The observed and predicted days of ignition of surface fuels in different stands were analyzed by calculating a probability using FMC frequencies. In Fennoscandia, the FMC values for moisture content of extinction have been estimated to range from 25 to 35 % (Granström and Schimmel 1998; Tanskanen *et al.* 2005). We used the lower limit since it was considered a more suitable estimate for the timing of prescribed burnings, which was justified because in prescribed burnings one aim is to decrease organic material and ensure a sufficient ecological impact (Lindberg *et al.* 2020). The frequencies over threshold value were compared to all the values of the examined variables or their combinations. Thus, if for instance *Pleurozium* in sub-xeric clear-cuts had 21 observations under a 25% threshold value of FMC, these 21 were compared to all 51 observations in sub-xeric clear-cuts resulting in a probability ratio of 41% (21/51) X 100=41%).

## Results

During the measurement period, the FMC of surface layer varied between 3% and 300% (Fig. 2). The overall patterns in how the moisture conditions changed during the summer were similar among the species, sites and site types, but the levels differed greatly among species and sites (Fig. 2). It should be noted that the weather conditions during summer 2003 were relatively variable with no long dry periods. This is visible in the distribution of the FFI values, where the highest values (4-6) are missing, which means that the driest circumstances did not occur during sampling (Fig. 2).

**Figure 2**

Of the species, *Dicranum* was generally the moistest and *Cladonia* the driest, whereas *Pleurozium* and *Hylocomium* were between the two. When modeling the FMC as a function of FFI, stand type and developmental stage, several patterns were visible in the surface layer. First, there were clear differences between species in the shape of the relationship between FMC and FFI. *Pleurozium*, *Hylocomium* and *Cladonia* had a tendency for a steadier decline compared to *Dicranum,* which retained moisture up to a higher FFI before declining more rapidly in moisture content (Fig. 3). It is noteworthy that, despite the quick decline at higher FFI values for *Dicranum*, the predicted moisture content in mature stands stayed above the 25-35% level, considered a threshold of ignition (Fig. 3). Stand type was not a significant predictor for any of the species in the surface layer (Table 2). The effect of the developmental stage was significant in the smoother terms only (Table 3, Fig. 4). Plot-level random effects were significant only for *Pleurozium.*

For the raw humus layer, the relationship between FFI and fuel moisture content were close to linear in most cases, and the differences in the smoothers were clearly smaller compared to the surface layer (Table 2). Similarly, the effect of stand type was different from the surface layer so that, for both *Pleurozium* and *Dicranum,* the sub-xeric sites were drier than the mesic sites (Table 3). Plot-level random effects were significant only for *Cladonia*. The raw humus variation among the stand types was lower but clear among the developmental stages and, in all stands, well above the 25-35% level.

**Table 2**

**Table 3**

**Figure 3**

**Figure 4**

FWI predicted the FMC of surface layers slightly better than FFI (Table 4). Both models predicted the FMCs of *Pleurozium* and *Hylocomium* better than *Dicranum* and *Cladonia.* In raw humus, the prediction ability was clearly lower, and FWI and FFI performed practically equally (Table 4). The predicted moisture variation curves as a function of FWI are shown in Supplement 3.

**Table 4**

The potential fire hazard days (i.e., days during which the FMC values were under 25%) were highest in *Cladonia* and lowest in *Dicranum* (Table 5). Clear-cut areas and sub-xeric pine stands had more fire hazard days than mature stands and mesic spruce-stands. The predicted fire hazard days by FFI formed 6% of sampled days, whereas the observed FMCs of > 25% during the same sampled days was 28%.

**Table 5**

## Discussion

Our results showed that the composition of ground floor vegetation has an effect on the flammability of the surface layer in Fennoscandian boreal forests, and how it varies during the fire season. This flammability was further modulated by the effect of stand growing stock along the lines shown in earlier studies (Granström and Schimmel 1998; Tanskanen *et al.* 2005; Tanskanen *et al.* 2006). The differences among species and developmental stages in how the surface layer moisture varied were prominent. As an example, *Dicranum* in mature stands retained a moisture content well above the 25-35% threshold of the FFI value of 4 (the threshold for public warning), whereas *Cladonia* was close to the flammability threshold throughout the range of FFI values included in the sample here.

The development of moisture content between the surface layer and raw humus was clear. Rain usually affects the surface layer saturating it rapidly. The raw humus layer receives some moisture, especially in heavier rains, but dries slowly. However, during longer dry periods, the surface layer and raw humus dry more thoroughly. Long drought periods did not occur during the sampling period so the FMCs in such circumstances could not be compared.

The FMC variation of surface and raw humus layers was great, especially in higher FMCs, which can be due to several reasons. The same FFI values estimated for a 10 km × 10 km square were used for all stands, so differences in rainfall between stands may have occurred due to local showers. The FMCs were determined layer by layer, which overlooks moisture variation within layers. It is known that the moisture gradient within layers is steep (Vasander and Lindholm 1985), so the upper parts of the surface layer could be clearly drier than the FMCs observed in this study.

When considering differences among the species in the surface layer, *Dicranum* was consistently the moistest, and *Cladonia* the driest. *Pleurozium* and *Hylocomium* were between these two and showed a relatively similar moisture behavior as presented by Busby and Whitefield (1978). The higher FMCs and slower drying curve of *Dicranum* is probably due to its dense tomentum-covered structure (Peterson and Mayo 1975), which leads to a higher moisture retaining capacity. As reported previously (Mutch and Gastineau 1970; Granström and Schimmel 1998), *Cladonia* was the driest surface fuel. This is explained by its gelatinous thallus, loose structure and high surface-to-volume ratio resulting in extreme moisture behavior (Heatwole 1966; Pech 1989, 1991).

FMC varied among stand types. The results of the FMC variation of the surface layer are in accordance with previous studies in which the differences between stands correlate with their ground vegetation flammability (Tanskanen *et al.* 2006). Using 30% threshold values for the FMC of moss layer, Tanskanen *et al.* (2006) reported two times more potential days of ignition in open than in mature areas, and in *Pinus*-dominated stands two to three times higher than in *Picea*-dominated stands. In our study, the differences between clear-cut and mature developmental stages were clear, but the impact of site type and the associated dominant tree species was smaller.

Comparison between the Finnish FFI and Canadian FWI showed that FWI was consistently a better predictor for the moisture content of the surface layer fuels, irrespective of the species. For the raw humus layer, the two indices performed almost identically. The better performance of FWI for surface fuels was similar to what Tanskanen *et al.* (2005) reported. Thus the CFFWIS could well be used in Finland.

Our results support the conclusions of Tanskanen *et al.* (2005) and Vajda *et al.* (2014) suggesting that FFI could be improved by using forest stand variables. Such parameters as developmental stage and dominant tree species could likely improve the FFIs prediction ability significantly, which could eventually help practical fire suppression activities by better anticipation and preparation.

Fire history studies in Fennoscandia have reported great variation in fire cycles. The shorter cycles have been typical in *Pinus*-dominated forests, especially in south- and middle boreal forests (e.g., Lehtonen and Kolström 2000), whereas in more northern and *Picea*-dominated forests, the cycle has been longer (e.g. Wallenius 2004). The differences have been explained by meteorological factors, dominant tree species, vegetation, fire suppression and general human influence (Wallenius 2004, 2011). According to our results, the differences in reported fire cycles could be partially explained by dominant tree species and changes in ground floor vegetation, especially in lichen-bryophyte ratio. For example, the abundance of *Cladonia* has substantially decreased in recent decades in Finland (Nousiainen 2000; Mäkipää and Heikkinen 2003; Tonteri *et al.* 2013).  At the same time, a notable increase in the abundance of *Dicranum* has been documented especially in Northern Finland (Mäkipää 2000b). It is possible that reduction in the cover of fast-drying *Cladonia* and increase in the cover of slowly-drying *Dicranum* has partially reduced forest fire risk particularly in Northern Finland.

In our study, the large variation of FMC in different stands and ground floor fuel materials show that potential days for prescribed burnings also have a large variation, especially when the variable ecological targets of burnings are taken into account. An often presented rule of thumb in guidelines for prescribed burnings is that the forest fire warning in Finland (FFI value 4) could be considered as a general threshold for successful burnings (Lemberg and Puttonen 2002). According to our results, this assumption is too simplistic, since suitable days for prescribed burning also seem to occur with lower FFI values. Yet it should be noted that the selected level of FMC 25% should be interpreted as a level where burning of studied surface layer fuels is possible. Thus, the various goals of prescribed burnings should be taken into account when suitable burning conditions are determined. For instance, in most restoration burnings no special burning depth is targeted as it is in silvicultural burnings. On the other hand, denser stands where restoration burnings are performed dry slower than regeneration areas. Also, if the aim is also to burn the humus layer, long drought periods are needed since the FMC values of raw humus did not reach the ignition threshold limits within the range of the FFI values we analyzed. Thus, a stand-specific monitoring of surface fuel and raw humus layer is recommended so that all potential burning days – whose small number often functions as a limiting factor – could be utilized more effectively, and the targeted impacts of burnings could be ensured.

*Conclusions*

Our results show that the different ground vegetation fuels differ in their moisture variation and ignition potential. Developmental stage and stand type of the forest affect the moisture variation of the studied fuels. Canadian FWI predicted the FMC of surface layer better than Finnish FFI, so it could be used in Finland. We conclude that, by using additional predictor variables, the ability of forest fire indices to predict fuel moisture could be improved. This could benefit forest fire prevention by enhancing early warning systems and by developing a GIS-based system providing online stand-wise

FMC estimates of surface fuels, which could be utilized in practical firefighting as well as in prescribed burning.

## Abbreviations

| | |
|---|---|
| CFFWIS | Canadian Forest Fire Weather Index System |
| DC | Drought Code |
| DMC | Duff Moisture Code |
| FFI | Finnish Forest Fire Index |
| FFMC | Fine Fuel Moisture Code |
| FMC | Fuel moisture content |
| FMI | Finnish Meteorological Institute |
| FWI | Canadian Fire Weather Index |

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## Tables and figure captions

Table 1. The sampled stands. In clear-cut areas the dominant tree species refers to species of the pre-cut stand. Pine: *Pinus sylvestris*, spruce: *Picea abies*, birch: *Betula* spp.

| Stand | Developmental stage | Stand type | Age, years | Average height, meters | Standing stem volume: cubic meters/hectare | Standing tree species percentages by volume (pine/spruce/birch) |
|---|---|---|---|---|---|---|
| **SXC1** | clear-cut | sub-xeric/pine | 0 | 0 | 0 | - |
| **SXC2** | clear-cut | sub-xeric/pine | 0 | 0 | 0 | - |
| **SXC3** | clear-cut | sub-xeric/pine | 0 | 0 | 0 | - |
| **SXM1** | mature | sub-xeric/pine | 90 | 24 | 210 | 90/10/0 |
| **SXM2** | mature | sub-xeric/pine | 120 | 26 | 250 | 100 |
| **SXM3** | mature | sub-xeric/pine | 120 | 25 | 240 | 100 |
| **MC1** | clear-cut | mesic/spruce | 0 | 0 | 0 | - |
| **MC2** | clear-cut | mesic/spruce | 0 | 0 | 0 | - |
| **MC3** | clear-cut | mesic/spruce | 0 | 0 | 0 | - |
| **MM1** | mature | mesic/spruce | 75 | 26 | 260 | 10/80/10 |
| **MM2** | mature | mesic/spruce | 90 | 28 | 310 | 10/90/0 |
| **MM3** | mature | mesic/spruce | 90 | 27 | 290 | 10/90/10 |

Table 2. Parametric coefficients for factor variables in the models. Estimates for the developmental stage (Dev. Stage) are relative to clear-cut area, and site type relative to mesic site type. *Hylocomium* and *Cladonia* occurred only on a single type.

| Layer | Species | Variable | Estimate | Std. Error | t | p | |
|---|---|---|---|---|---|---|---|
| Surface | *Pleurozium* | **Intercept** | **4.75** | **1.72** | **2.76** | **0.006** | ** |
| | | Dev. stage mature forest | 2.24 | 2.42 | 0.92 | 0.356 | |
| | | Site type sub-xeric | -0.23 | 0.16 | -1.47 | 0.144 | |
| Surface | *Dicranum* | **Intercept** | **5.00** | **0.90** | **5.56** | **< 0.001** | *** |
| | | Dev. stage mature forest | 0.58 | 0.91 | 0.64 | 0.523 | |
| | | Site type sub-xeric | -0.10 | 0.10 | -0.98 | 0.327 | |
| Surface | *Hylocomium* | **Intercept** | **3.98** | **0.23** | **17.36** | **< 0.001** | *** |
| | | Dev. stage mature forest | 2.85 | 2.54 | 1.12 | 0.266 | |
| Surface | *Cladonia* | **Intercept** | **3.63** | **0.17** | **21.11** | **< 0.001** | *** |
| | | Dev. stage mature forest | 2.13 | 2.58 | 0.82 | 0.412 | |
| Raw humus | *Pleurozium* | **Intercept** | **5.39** | **0.21** | **26.01** | **< 0.001** | *** |
| | | Dev. stage mature forest | 0.13 | 0.35 | 0.36 | 0.719 | |
| | | **Site type sub-xeric** | **-0.20** | **0.05** | **-4.24** | **< 0.001** | *** |
| Raw humus | *Dicranum* | **Intercept** | **4.96** | **0.41** | **12.16** | **< 0.001** | *** |
| | | Dev. stage mature forest | 0.73 | 0.51 | 1.43 | 0.156 | |
| | | **Site type sub-xeric** | **-0.16** | **0.06** | **-2.44** | **0.016** | * |
| Raw humus | *Hylocomium* | **Intercept** | **5.30** | **0.37** | **14.50** | **< 0.001** | *** |
| | | Dev. stage mature forest | 0.43 | 0.47 | 0.92 | 0.363 | |
| Raw humus | *Cladonia* | **Intercept** | **4.76** | **0.09** | **54.53** | **< 0.001** | *** |
| | | Dev. stage mature forest | 0.62 | 0.28 | 2.24 | 0.027 | * |

Significant variables ($p < 0.05$) are in bold

Table 3. Significance of smoother terms and plot-level random effects

| Layer | Species | Smoother term | F | p | |
|---|---|---|---|---|---|
| Surface | *Pleurozium* | **s(FFI) x Dev. stage clearcut** | **32.18** | **< 0.001** | *** |
| | | **s(FFI) x Dev. stage mature forest** | **27.33** | **< 0.001** | *** |
| | | **plot (random effect)** | **3.09** | **< 0.001** | *** |
| | *Dicranum* | **s(FFI) x Dev. stage clearcut** | **27.37** | **< 0.001** | *** |
| | | **s(FFI) x Dev. stage mature forest** | **29.96** | **< 0.001** | *** |
| | | plot (random effect) | 0.04 | 0.393 | |
| | *Hylocomium* | **s(FFI) x Dev. stage clearcut** | **15.18** | **< 0.001** | *** |
| | | **s(FFI) x Dev. stage mature forest** | **12.75** | **< 0.001** | *** |
| | | plot (random effect) | 0.31 | 0.326 | |
| | *Cladonia* | **s(FFI) x Dev. stage clearcut** | **28.54** | **< 0.001** | *** |
| | | **s(FFI) x Dev. stage mature forest** | **11.76** | **< 0.001** | *** |
| | | plot (random effect) | 0.00 | 0.841 | |
| Raw humus | *Pleurozium* | **s(FFI) x Dev. stage clearcut** | **11.07** | **< 0.001** | ** |
| | | s(FFI) x Dev. stage mature forest | 2.49 | 0.111 | |
| | | plot (random effect) | 0.19 | 0.366 | |
| | *Dicranum* | **s(FFI) x Dev. stage clearcut** | **5.93** | **0.004** | ** |
| | | s(FFI) x Dev. stage mature forest | 2.36 | 0.118 | |
| | | **plot (random effect)** | **1.73** | **0.023** | * |
| | *Hylocomium* | s(FFI) x Dev. stage clearcut | 3.66 | 0.060 | |
| | | **s(FFI) x Dev. stage mature forest** | **6.77** | **0.011** | * |
| | | plot (random effect) | 0.00 | 0.815 | |
| | *Cladonia* | **s(FFI) x Dev. stage clearcut** | **30.09** | **< 0.001** | *** |
| | | **s(FFI) x Dev. stage mature forest** | **5.18** | **0.026** | * |
| | | **plot (random effect)** | **2.84** | **0.017** | * |

Significant variables ($p < 0.05$) are in bold

Table 4. Performance of the Finnish Forest Fire Index (FFI) compared to the Canadian Fire Weather Index (FWI) as a predictor of FMC in different layers, measured as pseudo-R2.

| Surface layer | FFI | FWI |
|---|---|---|
| | $R^2$ | $R^2$ |
| *Pleurozium* | 0.55 | 0.64 |
| *Dicranum* | 0.46 | 0.54 |
| *Hylocomium* | 0.6 | 0.69 |
| *Cladonia* | 0.45 | 0.52 |

| Raw humus | FFI | FWI |
|---|---|---|
| | $R^2$ | $R^2$ |
| *Pleurozium* | 0.26 | 0.25 |
| *Dicranum* | 0.36 | 0.34 |
| *Hylocomium* | 0.35 | 0.36 |
| *Cladonia* | 0.42 | 0.34 |

Table 5. The potential fire hazard days (defined as fuel moisture content values under 25%) of studied surface layer materials, stand types and developmental stages. (MT= mesic stand, SX= sub-xeric stand, C=clear-cut area, M=mature stand, FFI pred = the potential days of ignition predicted by Finnish Forest Fire Index (FFI), index values> 4)

| | MTC | MTM | SXC | SXM | MT | SX | C | M | FFFI pred | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| *Pleurozium* | 54 % | 8 % | 41 % | 31 % | 28 % | 36 % | 47 % | 20 % | 6 % | 32 % |
| *Dicranum* | 32 % | 0 % | 27 % | 8 % | 14 % | 18 % | 29 % | 4 % | 6 % | 16 % |
| *Hylocomium* | 54 % | 4 % | | | 22 % | | 54 % | 4 % | 6 % | 22 % |
| *Cladonia* | | | 71 % | 20 % | | 45 % | 71 % | 20 % | 6 % | 45 % |
| | | | | | | | | | | |
| Total | 45 % | 4 % | 46 % | 20 % | 21 % | 33 % | 46 % | 12 % | 6 % | 28 % |
| | | | | | | | | | | |
| FFI > 4 | | | | | | | | | 6 % | |
| FFI < 4 | | | | | | | | | 94 % | |

Figure 1. Location of sampled stands

Figure 2. The observed fuel moisture contents (FMC) and Finnish Forest Fire Index (FFI) values on sampling days. Note the different y-axes.

Figure 3. The predicted fuel moisture content (%) of each studied species, by stand type and developmental stage, as a function of Finnish Forest Fire Index (FFI). Dotted lines show the 25-35% moisture content.

Figure 4. The predicted fuel moisture content (%) by studied species, as a function of Finnish Forest Fire Index (FFI) on different stand types and developmental stages. Dotted lines show the 25-35% moisture content.

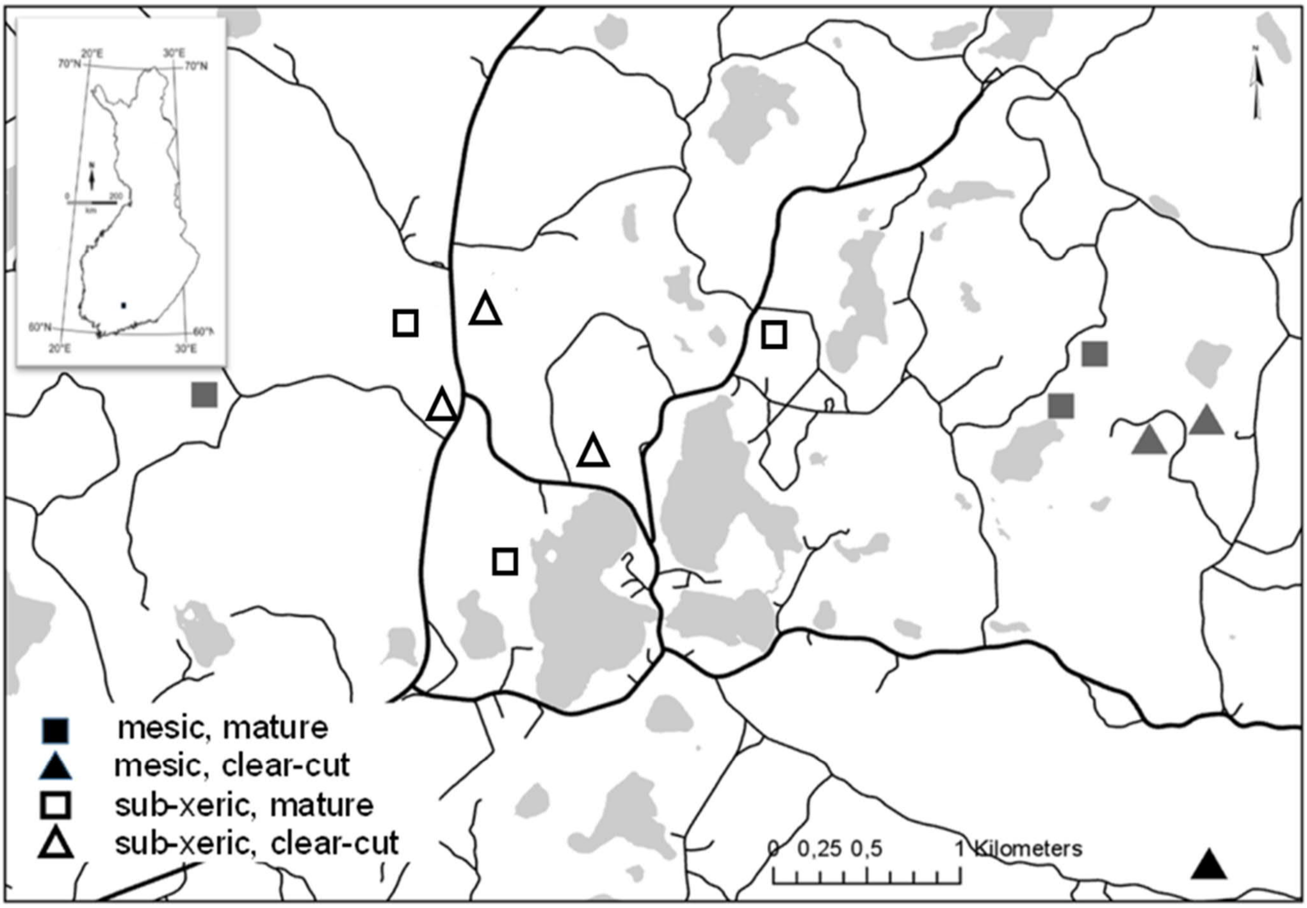
20°E
30°E
70°N
70°N
N
0
200
km
60°N
60°N
20°E
30°E
N
■ mesic, mature
▲ mesic, clear-cut
□ sub-xeric, mature
△ sub-xeric, clear-cut
0 0,25 0,5 1 Kilometers

**Figure 1**.

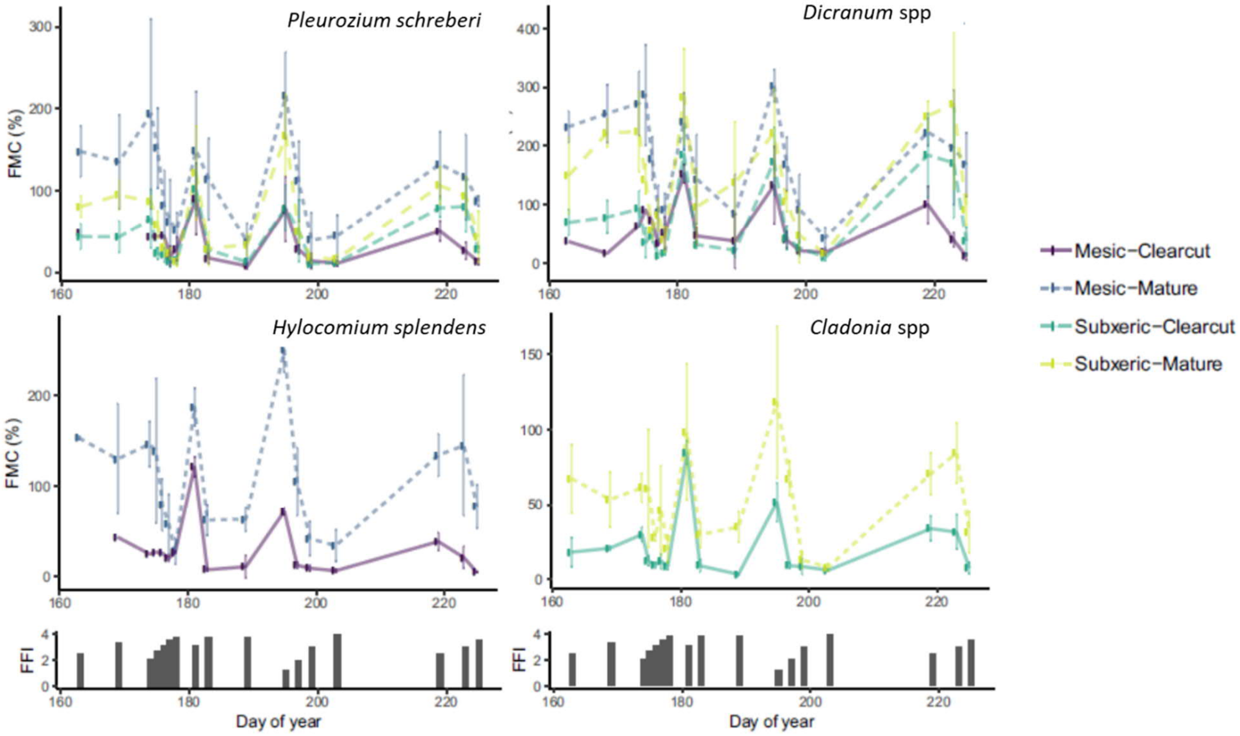
Pleurozium schreberi
Dicranum spp
Hylocomium splendens
Cladonia spp
FMC (%)
FFI
Day of year
Mesic−Clearcut
Mesic−Mature
Subxeric−Clearcut
Subxeric−Mature
0
100
200
300
400
50
150
2
4
160
180
200
220

**Figure 2.**

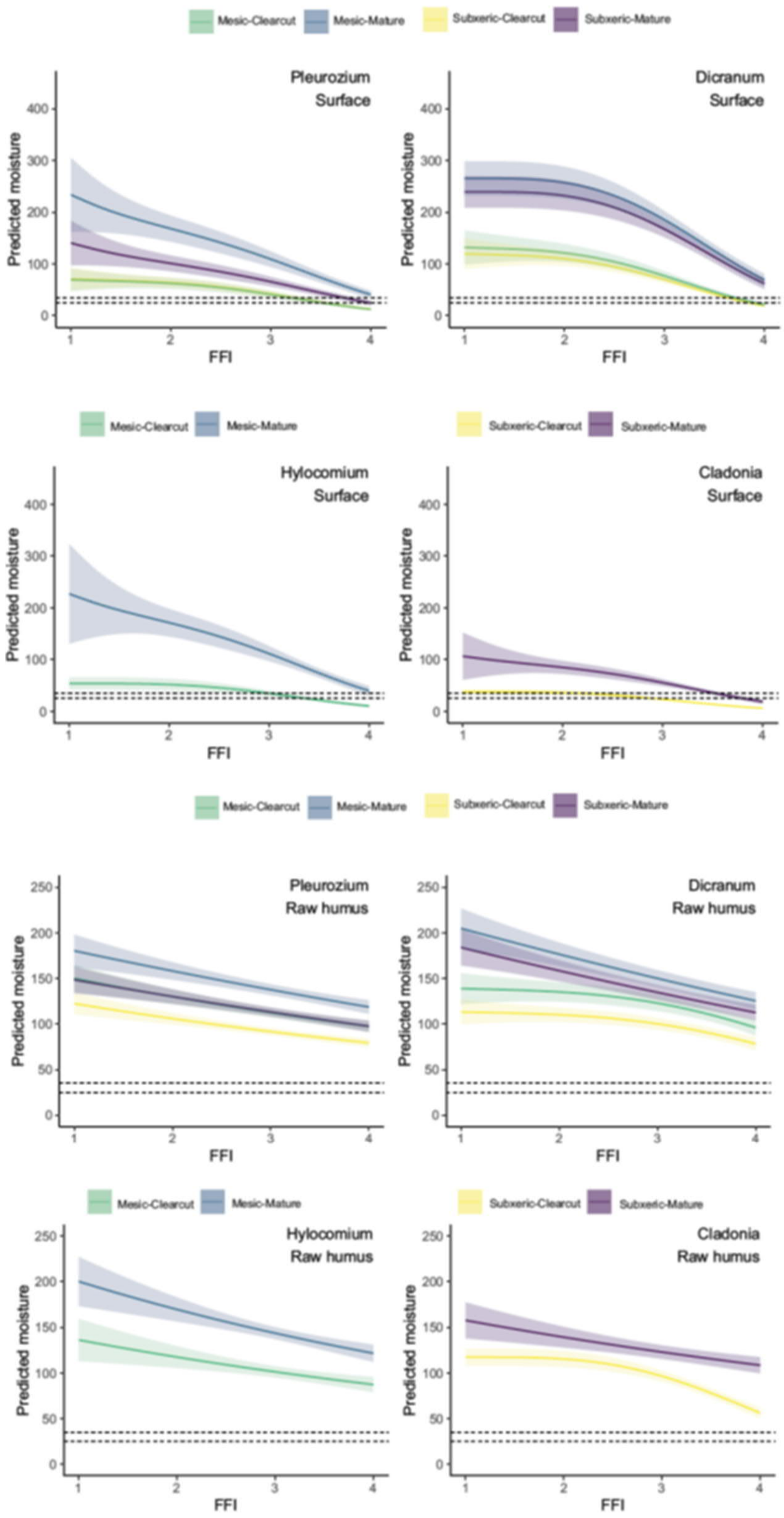
Mesic-Clearcut
Mesic-Mature
Subxeric-Clearcut
Subxeric-Mature
Pleurozium
Surface
Dicranum
Surface
Hylocomium
Surface
Cladonia
Surface
Pleurozium
Raw humus
Dicranum
Raw humus
Hylocomium
Raw humus
Cladonia
Raw humus
Predicted moisture
FFI
0
100
200
300
400
50
150
250
1
2
3
4

**Figure 3.**

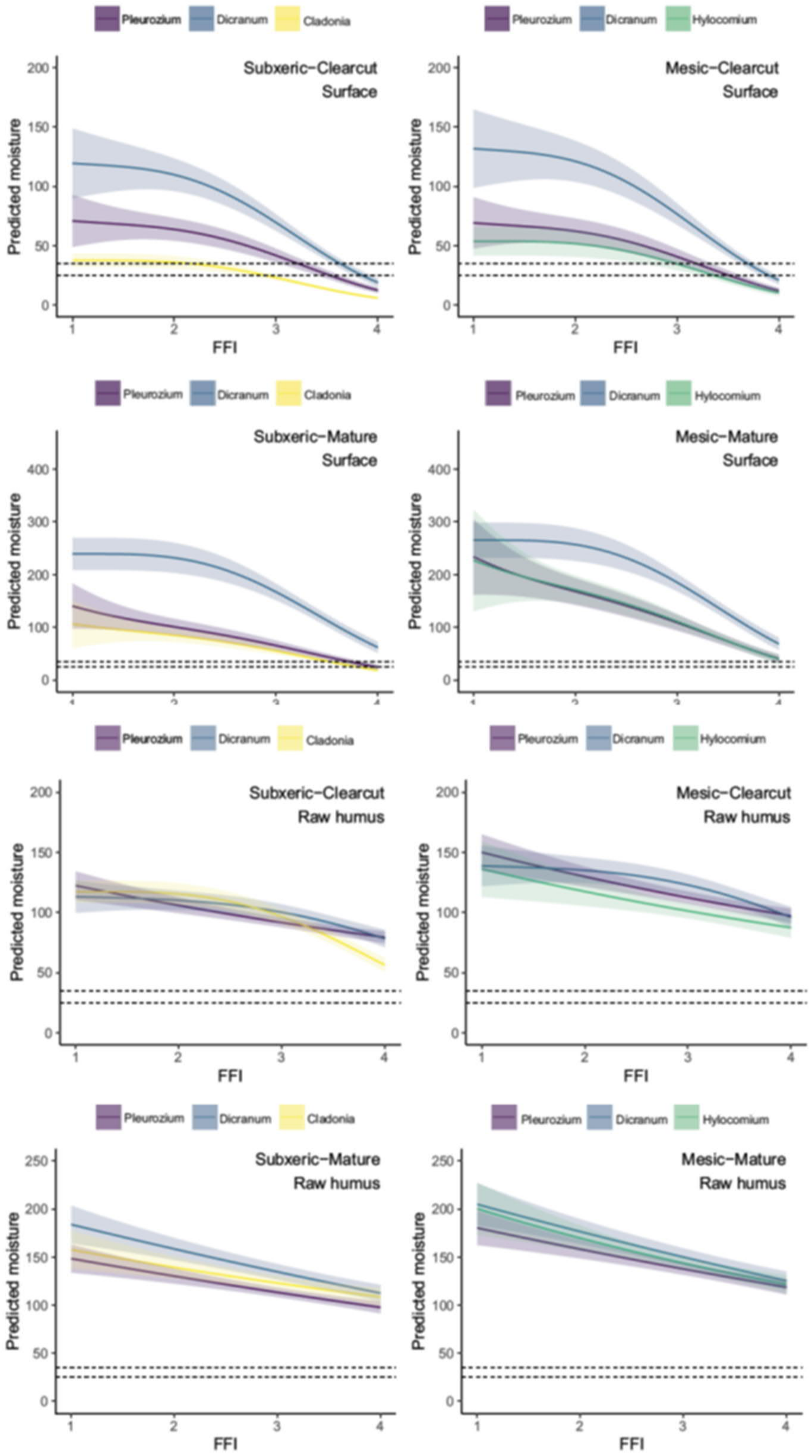
Pleurozium
Dicranum
Cladonia
Hylocomium
Subxeric−Clearcut
Surface
Mesic−Clearcut
Surface
Subxeric−Mature
Surface
Mesic−Mature
Surface
Subxeric−Clearcut
Raw humus
Mesic−Clearcut
Raw humus
Subxeric−Mature
Raw humus
Mesic−Mature
Raw humus
Predicted moisture
FFI
0
50
100
150
200
250
300
400
1
2
3
4

**Figure 4.**