Dissertationes Forestales 319

Fire scars, ground vegetation fuels, and prescribed burning: towards better fire management in Fennoscandia

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Academic Dissertation

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ABSTRACT

Forest fires are an ambivalent issue in Fennoscandia. Although most long-term fire-history studies show a decrease in burned areas, the recent large fires have set challenges for the future given the increasing demand to develop more effective fire management methods. On the other hand, the low impact of fire has raised concerns regarding how to safeguard fire-induced biodiversity. Related to these subjects, in my thesis I have studied fire scar formation, the flammability of the most common ground layer fuels and the state of prescribed burning in Finland.

The main findings of my thesis were:

1. Low-intensity forest fires do not necessarily form fire scars in Scots pine stands. The scars found in the study were more common in younger stands as well as in smaller trees and were also formed in higher parts of tree trunks. The variability in shape, size and occurrence of scars suggest that the scar formation in young pine stands may be a stochastic phenomenon depending on fuel load, topography and weather conditions.
2. Prescribed burnings in Finland have declined during recent decades and their current ecological impact is low, despite scientific evidence and expert work having brought about the recommendation to increase burnings. This is primarily explained by the high costs and arduousness of burnings, which have led to decisions in state forest policies and forest certification modifications that have diminished burnings. Combined with low areas burned in wildfires, the current fire regime in Finland can poorly safeguard the fire-dependent habitats and species.
3. The most common ground vegetation fuels in Finnish forests differ in their moisture variation, ignition probability and mass loss during combustion. Amongst studied species reindeer lichen (*Cladonia* spp.) was clearly the most flammable with the fastest drying rates and the highest ignition probability, whereas fork moss (*Dicranum* spp.) was the least flammable, while feather moss (*Pleurozium schreberi*) and stairstep moss (*Hylocomium splendens*) were intermediate. Wind velocity clearly increased the ignition probability of the studied moss species, and increased wind speeds reduced the species-specific differences.

These major findings of my thesis could be of use in enhancing forest fire prevention and prescribed burnings as well as in interpreting past fire regimes.

Keywords: bottom layer, fire history, forest fires, flammability, fuel moisture content, ignition probability

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LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following articles, which are referred to in the text by their Roman numerals. Studies **I**, **II** and **III** are previously published articles and study **IV** is a manuscript.

I Piha A, Kuuluvainen T, Lindberg H, Vanha-Majamaa I (2013). Can scar-based fire history reconstructions be biased? An experimental study in boreal Scots pine. Canadian Journal of Forest Research. 43: 669–675. http://dx.doi.org/10.1139/cjfr-2012-0471

II Lindberg H, Punttila P, Vanha-Majamaa I (2020). The challenge of combining variable retention and prescribed burning in Finland. Ecological Processes 9**,** 4 https://doi.org/10.1186/s13717-019-0207-3

III Lindberg H, Aakala T, Vanha-Majamaa I (2021) Moisture content variation of ground vegetation fuels in boreal mesic and sub-xeric mineral soil forests in Finland. International Journal of Wildland Fire 30, 283-293. https://doi.org/10.1071/WF20085

IV Lindberg H, Aakala T, Vanha-Majamaa I (2021). Ignition probability and fuel consumption of boreal ground vegetation fuels – an experimental study in Finland. Manuscript.

Author contributions:

Study number	Original idea and study design	Data collection	Data processing	Data analysis	Preparing of the manuscript
I	HL, TK, I V-M	AP	AP	AP, TK	AP, TK, HL, I V-M
II	HL, PP, I V-M	-	-	-	HL, PP, I V-M
III	I V-M, HL	HL	HL	TA, HL	HL, TA, I V-M
IV	HL, I V-M	HL	HL	TA, HL	HL, TA, I V-M
Summary	-	-	-	-	HL

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ABBREVIATIONS

FWI	Canadian Fire Weather Index
FFI	Finnish Forest Fire Index
FMC	Fuel Moisture Content
ha	hectare(s)
VMC	Volumetric Moisture Content
MASL	Metres Above Sea Level
PEFC	Programme for the Endorsement of Forest Certification

1. INTRODUCTION

During recent decades, forest fires have raised growing global awareness as they represent a major threat to human property and society by destroying estates and infrastructure, damaging agricultural and forested areas and even causing numerous fatalities (Thomas et al. 2017; Robinne et al. 2018). Since there is a great variety of region-specific historical fire regimes, the understanding of past fire dynamics is essential when changes are analysed and future scenarios are compiled (Conedera et al. 2009).

Global warming is predicted to increase the threat of wildfires as fire seasons will be prolonged and fires will become more frequent and more intense (Flannigan et al. 2009a; Moritz et al. 2012; Robinne et al. 2018; Bowman et al. 2020). Climatic shift has especially spurred an increase of various extreme fire events, such as the catastrophic “megafires” (Tedim et al. 2018). These large fires with high intensity have raised growing concern, since they are difficult or even impossible to suppress and often result in high-severity and large-scale damage (Stephens et al. 2014). The increase of fires respectively produces a significant increase of greenhouse gases, thus accelerating climate change, although the estimations of the impact of wildfires do vary (Bowman et al. 2020).

The areas burned in wildfires have also increased in many parts of the boreal zone (Kirdyanov et al. 2020; Köster et al 2021) and are predicted to grow, according to future scenarios (Flannigan et al. 2009b). Within past decades in Fennoscandia, the wildfire hazard has been low compared to many other regions of the boreal zone, yet recently two exceptional wildfire events have occurred in Sweden: the Västmanland wildfire of 13,100 ha in 2014 (Gustafsson et al 2019), and the summer of 2018, when a total area of approximately 25,000 ha was burned (Skogsbränderna sommaren 2018, 2019).

Fuel management, defined as the “Act or practice of controlling flammability and reducing resistance to control of wildland fuels through mechanical, chemical, biological, or manual means, or by fire, in support of land management objectives.” (NWCG Glossary of Wildland Fire 2021), has been increasingly recognised as a pivotal wildfire mitigation method with growing importance. This is because along with the warming climate, forest fires with high fuel loads produce more energy and become increasingly difficult to extinguish (Agee and Skinner 2005; Fernandes 2013; Omi 2015) forcing the re-evaluation of forest fire prevention strategies, with a shift from suppression to prevention.

In fuel management, the fuel moisture content (FMC) is one of the most important characteristics directly affecting flammability and fire behaviour (Chuvieco et al. 2004; Keane 2015). The prediction of FMC is the main component of most fire weather indices, which in turn function as the basis of the fire danger rating systems (Dimitrakopoulos et al. 2011; Ziel et al. 2020). The FMC is also a key factor affecting performance and outcomes of prescribed burnings (Sandberg 1980; Hille and den Ouden 2005).

Although forest fires are primarily considered hazardous, they are also a natural disturbance factor that diversify forests in various scales (Wein and McLean 1983; Ryan 2002; McLauchlan et al 2020). Fires also shape biotopes, providing suitable habitats for numerous species. In Fennoscandia, the low amount of burned areas have raised concern about the decrease of fire-related biodiversity (Granström 2001). Prescribed burnings have been shown to be a useful habitat management tool (Koivula and Vanha-Majamaa 2020) and they are widely recommended for safeguarding fire-driven habitats and fire-dependent species in regions where fires have become rare.

2. BACKGROUND

2.1. Forest fires in Finland during past decades

The annual area burned in forest fires in Finland declined significantly in the latter half of the 20th century. A particularly steep decline occurred in the 1960s when the annual burned area dropped from ~ 5,800 ha during 1952-60 to ~ 700 ha during 1971-1980 (Aarne 1992). In recent decades, the annually burned area has mainly varied between 200 and 800 ha, occasionally exceeding 1,000 hectares (PRONTO-database: Statistical Data System of Finnish Rescue Services 2021). Consequently, the size of a single wildfire is currently only ~ 0.5 ha and large fires are rare. The last wildfire exceeding 1,000 ha occurred in the year 1970, and after that the only ones to spread across hundreds of hectares were in the years 1997, 2020 and 2021 (200-250 ha each)(Lindberg et al. 2021).

It is notable that although the climatic conditions, vegetation and primary tree species are generally similar in boreal forests of Fennoscandia the fire regimes differ in various regions. Compared to Norway, Sweden, and the Republic of Karelia, the annual burned areas in Finland are lower and the annual variation is less (Lindberg et al. 2021). Also, in comparison to Sweden, no similar increase of larger wildfires can be observed.

Since climatic forest fire risk in Finland does not explain the absence of large fires (Venäläinen et al. 2016) and has stayed rather stable during the last century (Mäkelä et al. 2012), the changes of fire regimes in Finland and the differences with neighbouring regions can be explained by other factors such as forest fire suppression actions, forest and landscape structure, and forest management (Päätalo 1998; Lindberg et al. 2021).

Currently, forest fires are not a major threat to property in Finland. Insurance compensation for burned forests are minor compared to windthrow and snow damages and during the years 2000-2013, they only made up ~ 2% of all compensation of abiotic damage (Peltola 2014). Nevertheless, there are several reasons why research and development on forest fire suppression can be justified.

First, the number of fires has stayed at the same level, or even increased during the last several decades (Lindberg et al. 2021). Thus, the firefighting duties burden local rescue services and produce significant costs to society, which have been estimated to range from > 1,000 euros up to even ~ 15,000 euros per suppressed forest fire (Kosenius et al. 2014).

Second, it has been estimated that the climatic risk for forest fires will increase in the future (Kilpeläinen et al. 2010; Lehtonen et al. 2014; Mäkelä et al. 2014), which means that forest fire suppression effort and the demand for preparedness will probably also increase.

Third, forest fire fighting in Finland relies primarily on voluntary fire brigades, which struggle with problems of recruiting new persons as populations in rural areas continue to age and decrease. These points emphasise the need to develop new methods of forest fire management in the future.

2.2. The Finnish Forest Fire Index and early warning systems for forest fires in Finland

Currently, the most widely used fire index system globally is the Canadian Forest Fire Weather Index System, 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).

Despite the wide use of the Canadian Forest Fire Weather Index System, national fire indices are still commonly used in many countries. In Finland, forest fire risk is estimated by the Finnish Forest Fire Index (FFI), which is based on empirical monitoring of a 6 cm surface layer in three clear-cut areas and one mature stand in Southern Finland (Heikinheimo et al. 1998). The monitored fuels were a mix containing mostly raw humus, moss and litter. It is notable that FFI is based on volumetric moisture content (VMC) where the volume of water is proportioned with the total volume of the sample, so the values are not directly comparable to more widely used gravimetric moisture content values, which themselves are calculated as a ratio of the mass of the water and the mass of the material. Drying and wetting curves were defined for estimating the VMC of monitored samples, and a model predicting the VMC of the top 6 cm of surface layer using precipitation and potential evaporation as explanatory variables was constructed by the Finnish Meteorological Institute. For operational use, the VMC is scaled to six wetness classes and respectively to FFI values ranging from 1-6. An FFI value of 4.0, which predicts a VMC under 20%, was chosen as the threshold value based on forest fire statistics (Heikinheimo et al. 1998; Vajda et al. 2014).

The potential evaporation is calculated based on net radiation, wind speed, air temperature and relative air humidity, which are obtained for operational use every three hours from meteorological field stations in Finland. The weather data is complemented by using data obtained from numeric weather prediction models and data from weather radars and rain gauges (Vajda et al. 2014) and is then spatially interpolated into 10 km x 10 km squares and to regional and county levels using the kriging method (Venäläinen and Heikinheimo 2003).

The regional FFI values are used to estimate the need to initiate aerial surveillance flights, which usually begin with values exceeding 4.0 (Soisalo 2021). When an FFI value in a certain region exceeds 4.0, a forest fire warning defined in the Finnish Rescue Act (2011) is announced in the media, e.g., prohibiting the use of open fire. FFI has also been modified to predict grass fire danger during spring. For this purpose, the model has been adjusted to predict the VMC of a layer with a thickness of 3 cm. As in FFI, if the VMC rises over a value of 4.0, a grass fire warning is announced in a similar way as in forest fire warnings. After green-up, grass fire risk is low and not estimated. In the recent update of the Finnish Rescue Act in 2019, the nature of grass fire warnings was changed to be more obliging, as it currently also forbids the use of open fires.

2.3. Fire history studies in Fennoscandia

Studies dealing with boreal Fennoscandian fire history have reported a high variation in fire cycles. At the shortest, cycles of just a few decades have been documented (e.g. Niklasson and Drakenberg 2001; Lehtonen et al. 1996; Lehtonen and Huttunen 1997), while at the longest, several centuries have been presented (e.g. Stejlen and Zackrisson 1987; Pitkänen et al. 2003; Wallenius et al. 2010). The shorter cycles have been typical in pine-dominated forests, especially in southern and middle boreal forests (Niklasson and Drakenberg 2001; Lehtonen et al. 1996; Lehtonen and Huttunen 1997; Groven and Niklasson 2005), which can be explained by the faster drying rate of the flammable ground vegetation layer (Tanskanen et al. 2005, 2006). Respectively, the more shady spruce forests dry slower and are less flammable yet more prone to crown-fires, thus leading to longer fire cycles (Stejlen and Zackrisson 1987; Wallenius 2004). It has been shown that the establishment of spruce forests in Fennoscandia changed the fire regime to longer fire cycles (Tryterud 2003; Ohlson et al. 2011), whereas increasing fire activity leads to low-density, pine-dominated forests (Pitkänen and Huttunen 1999). This development can be due to climatic (Drobyshev et al. 2014; Aakala et al. 2018) or human-induced (Niklasson and Granström 2000; Wallenius 2011) reasons, the latter probably being dominant during recent centuries (Niklasson and Granström 2001; Granström and Niklasson 2008; Storaunet et al 2013; Rolstad et al. 2017; Ryzhkova et al 2020). However, it is noteworthy that methodological differences also influence these large differences in the fire cycle estimates (Conedera et al. 2009; Kasin et al 2013).

Even in the same studies, the fire intervals vary depending on time period (e.g., Wallenius et al. 2007; Rolstad et al 2017; Ryzhkova et al. 2020), and also areas close to one another can differ greatly in their past fire regimes (Aakala 2018). It is good to notice that practically all studies using the most reliable method, dendrochronology, have taken place at a time when human influence has been significant. They have also often been targeted to areas where (pine) trees with fire scars can be found, thus possibly directing the studies to the sub-xeric and xeric part of the site-quality gradient. The fire history studies present a rather fragmented picture of the past so generalisations must be made with caution.

2.4. Prescribed burnings in Fennoscandia

In prescribed burnings (controlled burnings), fire is used intentionally to achieve the desired beneficial impacts on vegetation and soil. Globally, prescribed burnings most often aim to reduce fuel load and fire risk, manage habitats and safeguard biodiversity, and foster areas for grazing and wildlife (Burrows and McCaw 2013; Fernandes et al. 2013; Ryan et al. 2013). Yet in Fennoscandia during the last century, the main reasons for prescribed burning were silvicultural and were aimed to improve forest regeneration. These silvicultural burnings of clear-cut areas were widely practiced in Finland and Sweden, reaching their peak during the 1950s and early 1960s, when tens of thousands of hectares were burned annually (Cogos et al. 2020; Parvianen 1996). Although such burnings decreased drastically in the late 1960s and the 1970s, they are still practiced in Sweden and Finland with increasing biodiversity-related targets, yet the current annual areas are < 500 ha in Finland and > 500 ha in Sweden (Ramberg et al. 2018; Finnish Forest Statistics 2021). In Norway, the prescribed burnings of regeneration areas were also used from the 1930s to the 1950s, but to a much lesser and more local extent (Mysterud 1997), whereas in Russian Karelia, prescribed burnings were common in the 1920s and 1930s, but after that, gradually diminished and were finally forbidden in 1993 (Shorohova et al. 2019). During recent decades, the importance of fire for forest biodiversity has been acknowledged (Granström 2001) and prescribed burnings have also been introduced to nature conservation areas

(Similä and Junninen 2012) and prescribed burning has been driven increasingly by biodiversity, and less by silvicultural goals.

3. AIMS OF THE THESIS

The conjunctive theme of my thesis is the history, use and mitigation of fire in Fennoscandian boreal forests with a special focus on Finnish forests. The theme can be divided into three subjects (1) Fire history in Fennoscandia (2) The role, history and potential development of prescribed burnings in Finland and (3) Fire prevention in Finland.

Related to these subjects, the main questions of my thesis are: (1) How and to what extent are fire-scars formed in young pine stands by low-intensity surface fires (substudy **I**)? (2) What is the current impact of fire on forest biodiversity in Finland and how could it be enhanced by prescribed burnings (substudy **II**)? (3) How do Finnish forest ground vegetation fuels differ in their moisture behaviour and ignition characteristics and how could the possible differences be used to interpret past fire regimes and in the development of forest fire prevention and prescribed burnings (substudies **III** and **IV**)?

4. MATERIAL AND METHODS

4.1. Study area

The empirical studies (**I**, **III**, **IV**) were all done in Evo area, located in Hämeenlinna, Southern Finland (Figure 1), with the exception of three sample plots in study **III**, which were located in the Vesijako area ~ 20 km north of the Evo area. The study area belongs to the southern boreal vegetation zone (Ahti et al. 1968), the elevation of the study area varies between 120-190 MASL, the mean annual temperature in the region is +3.1°C, the average annual precipitation is 670 mm, and the growing season is 160 days (Juvakka et al. 1995). The bedrock is mostly orogenic granitoid covered by a thick, stony morainic layer, but glacier sedimented areas like deltas, sandur deltas and eskers with sand or gravel are also common (Okko 1972).

The forest types of the area are mostly the semi-xeric *Vaccinium*-type, the mesic *Myrtillus*-type or the herb-rich *Oxalis-Myrtillus*-type (Cajander 1949). The studied stands represented normal Finnish commercial forests, even-aged, intensively managed and primarily treated with clear-cutting and artificial regeneration, pre-commercial and commercial thinnings that favour conifers. The stands were Scots pine (*Pinus sylvestris* L.), dominated in studies **I** and **IV**, and either Scots pine or Norway spruce (*Picea abies* (L.) Karst.) dominated mature stands, or fresh clear-cuts, in study **III**.

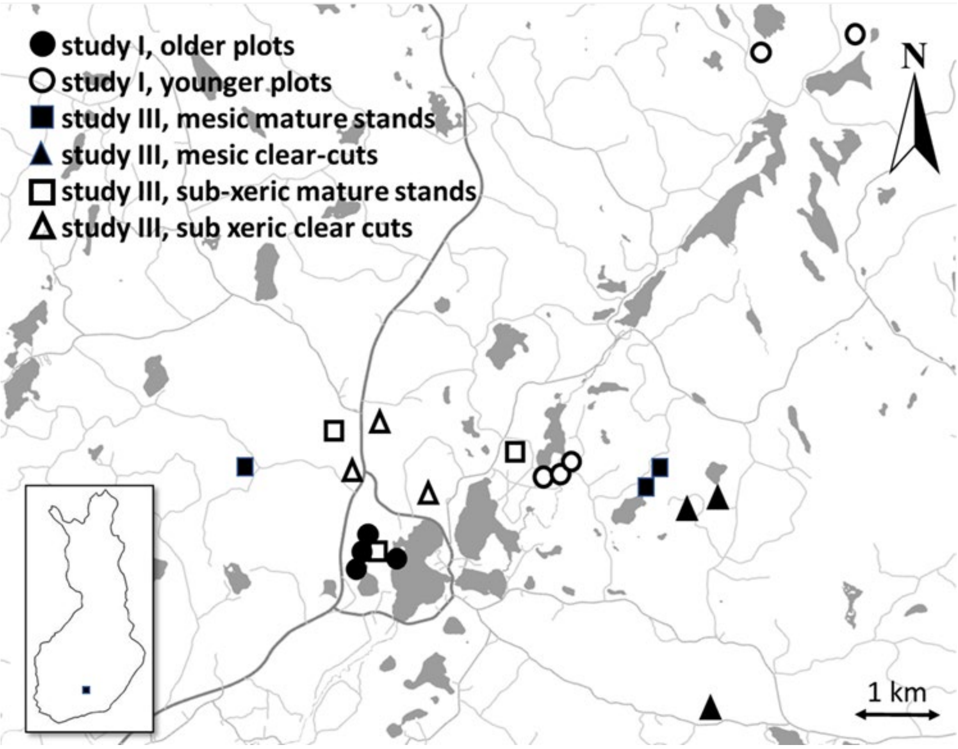

Figure 1. The sample plots in studies **I**, **III** and **IV**. Three plots in study **I** were located ~ 20 km north of other plots and are not shown on this map. The samples used in study **IV** were collected from the southernmost sub-xeric mature stand of study **III**.

4.2. The fire scar inventory (I)

The study was based on 12 Scots pine-dominated, 30 x 30 m sample plots which were burned in the summer of 2002 as a part of a larger set of experimental burnings (Figures 1 and 2, Tanskanen et al. 2007). Five stands were 30-35 years old at burning time and seven stands were 45 years old. The older stands had been thinned before burning. The stem density of plots varied between ~ 1,000 and ~ 2,200 stems per ha in younger stands and between ~ 600 and ~ 1,100 in older stands. The respective range of mean breast height diameter was ~ 13-18 cm in younger plots and ~ 18-24 cm in older plots. All stands were typical, homogenous, monocultural even-aged stands representing the semi-xeric *Vaccinium*-type.

Figure 2. Examples of sample plots in study **I**. Upper left: Older and thinner stand with low mortality. Lower left: Younger stand with higher mortality. Right: Younger stand with lower mortality. (From original article **I**, photos Aura Piha)

These 12 stands were inventoried during summer 2010 to estimate the mortality and detect the possible fire scars caused by the experimental fires. All trees were manually examined by looking at visible scars as well as tapping the bark to find hollow areas, indicating potential scars where bark had not yet fallen. In these cases, the scars were revealed by knife. The scars were visually classified by type and their width and height were determined.

4.3. Gathering data from prescribed burnings in Finland (II)

For the review article in study **II**, the background literature, research evidence, legislation, political steering, certification criteria and practical issues were examined to present an overview of the current situation of prescribed burnings in Finland. Also, data from forest statistics (Aarne 1992; Peltola 2014) and PRONTO-database: Statistical Data System of Finnish Rescue Services (2021) were used to construct a time series for prescribed burnings and wildfires in Finland. Since there have not been any data available dealing with burnings of retention tree groups, an inquiry was sent to the operators known to perform them, in order to form a perception of their current scope and significance.

4.4. Ground layer vegetation fuel studies (III, IV)

In study **III**, 12 forest stands from the study area were chosen with four different stand types and three replicates from each (Figure 1). The stand types were: Sub-xeric, mature, *Vaccinium*-type, Scots pine dominated stand; Sub-xeric, *Vaccinium*-type clear-cut area; Mesic, mature, *Myrtillus*-type, Norway spruce dominated stand; Mesic, *Myrtillus*-type clear-cut area. From each stand, samples of the most common ground layer species were collected on 17 sampling days. From all stands, feather moss (*Pleurozium schreberi* (Brid.) Mitt) and fork mosses (*Dicranum* spp) were collected, in addition to stair-step moss (*Hylocomium splendens* Hedw.) from *Myrtillus*-type stands and reindeer lichen (*Cladonia* spp) from *Vaccinium*-type stands (Figure 3)

The sampling was targeted on dry and drying periods but was not carried out during constant wet periods (which covered a major part of the sampling period). The sampling was done in the afternoons of the sampling days with humus auger. The auger samples were divided into two layers: surface and raw humus. Five subsamples of each layer were pooled into one joint sample representing the average from that stand. After sampling, fresh-weighing and drying was carried out, and after an 18 hour oven-drying in 105˚C, the dry-weight moisture content was determined. The Finnish Forest Fire Index and the Canadian Fire Weather Index values for the sampling days of the study area were received from the Finnish Meteorological Institute.

In study **IV**, undisturbed samples of the same four moss or lichen species in study **III** were collected from a mature Scots pine-dominated *Vaccinium*-type stand. Samples were then placed in aluminum trays and dried, weighed and rewetted into the contents of five target moistures with five replicates from each combination of species, wind speed and target moisture. The samples with the target FMCs were weighed and then test-ignited in a greenhouse with three different fan-created wind speeds (0, 1, 2 m/s). After the ignition test and potential combustion, samples were weighed, and the mass loss was calculated (Figure 3).

The data was analysed by logistic regression analysis in substudies **I** and **III** (ignition probabilities) and by generalised additive models in substudies **III** and **IV** (fuel consumption).

Figure 3. Center: Studied moss and lichen species in substudies **III** and **IV** (cover picture from original article **III**, photos Erkki Oksanen/LUKE), Upper left: semi-xeric mature pine-dominated stand as in substudy **III** (photo Henrik Lindberg), Lower left: mesic mature spruce-dominated stand as in substudy **III** (photo Antti Sipilä), Upper right: drying and weighing work in substudies **III** and **IV**, Lower right: The set-up of ignition tests in substudy **IV** (photos Henrik Lindberg).

Figure 4. Examples of different types of prescribed burning in Finland: a) silvicultural prescribed burning with retention trees, b) burning of a single retention-tree group, c) habitat management burning of sun-exposed esker slope, d) restoration burning of managed Scots pine stand in a conservation area. From original article **II**, photos: Henrik Lindberg (a), Juha-Matti Valonen (b), Timo Vesanto (c), Raimo Ikonen (d).

5. RESULTS AND DISCUSSION

5.1. Scars from low-intensity fires vary in presence, shape, size and location in young Scots pine tree stands (I)

Based on stem number, the average mortality of Scots pines eight years after the experimental fire was 18% with high variation, ranging from 0% to 63%. The experiment had no unburned control areas, but the burned stands showed a higher mortality when compared to the overall mortality of < 5 % reported by Ulvcrona et al (2011) from unburned *Pinus sylvestris*-dominated young and middle-aged stands in Sweden.

Altogether 217 fire scars were observed in 142 trees. Almost 70% of scarred trees had only one scar, but even trees with six separate scars from the same fire were detected. The proportion of scarred trees compared to existing living trees per plot was generally rather low, being in most cases under 20%. However, there were two plots with proportions over 60% and 80%.

The age class and diameter size had a significant impact on the scarring of the trees, since only 18 scarred trees were found in older age-class plots with larger-sized trees compared to 135 ones in younger stands. The proportion of fire-scarred trees out of all trees per plot was ~ 17% in young stands and ~ 3% in older stands. In four older plots no scarred trees were found. Also, fire intensity and tree size explained partly the occurrence of fire scars because the probability of scar formation was higher in smaller trees and in plots with higher flame heights.

The detected scars varied notably in their size and shape. The average width of scars was ~ 7 cm and the height ~ 117 cm. There were clearly two distinctive scar groups: the normal scars and large scars observed above two metres, which were found in only two younger stands and are probably explained by the higher flame heights observed during the burnings of these plots (Tanskanen et al. 2007). Excluding these larger scars, the mean width of scars was ~ 4 cm and the height was ~ 35 cm. However, there were also numerous scars in this group which were not located at the base of tree, since the mean height of the lower end was ~ 50 cm and 43% of scars were located lower than 20 cm.

These results can be grouped into four main findings: (1) The experimental, low-intensity fires left the majority of Scots pine trees unscarred and there were even four out of 12 plots with trees with no scars at all. (2) The scars were the most common in younger stands and smaller trees. (3) The scars were also formed in higher parts of the trunk than the base level. (4) Generally, the shape, size and occurrence of scars show a wide variability suggesting that the scar formation in young pine stands may be a stochastic and irregular phenomenon depending a lot on, e.g., fuel load, topography and weather conditions, thus leading to heterogenic scarring, which may be difficult to predict.

Because of their thick and insulative bark, especially older Scots pines are fairly fire-tolerant, yet often scarred (Fernandes et al 2008). According to our results, it is possible that the bark thickness affects the scarring vulnerability of younger trees, since smaller trees with apparently thinner bark were scarred more easily. It is also possible that this can be explained partly by the smaller diameter of trees with a weak formation of vortex, so the results somewhat differ from the traditional perception where scars are presented to form rather regularly by a leeward side vortex (Gutsell and Johnson 1996). The great variety in the occurrence of fire scars also suggests that fire scars in younger stands are formed in several different ways like with a direct result of surface fire or as a result of partial torching in denser and younger stands with stems not pruned yet, which can explain the formation of large upper scars. It is possible that stands with stems already partially pruned can survive low-intensity surface fires, yet not necessarily form fire scars.

However, the generalisations of results must be treated with caution since the plots were small-sized and flat, stands were managed, even-aged stands and the burnings were performed mostly at low windspeeds, so the conditions for, e.g., vortex-formation were not favorable. Nevertheless, the large number of unscarred trees and the general heterogeneity in scar formation suggest that the low-intensity surface fires do not necessarily leave detectable fire scars, which has also been presented in other studies (Kilgore and Taylor 1979; Swetnam et al. 1999; Baker and Ehle 2001). This can be explained by three reasons: (1) The fire scars simply do not always form because of low fire intensity and temperatures (Baker and Ehle 2001). (2) Young trees with thin bark are more vulnerable to fire than older trees and more often die as the result of fire (Linder et al. 1998; Wirth et al. 1999) and (3) since scars can also be formed in other parts of the trunk than the base, they can be overlooked as dendrochronological samples are usually taken from base. Thus, the results support the “recorder” tree concept where the absence of fire scars does not automatically indicate the absence of forest fire (Kilgore and Taylor 1979).

5.2. Prescribed burnings in Finland have declined during recent decades and their current ecological impact is low (II)

The literature reviewed in study **II** shows clear scientific evidence (Koivula and Vanha-Majamaa 2020) of beneficial impacts of prescribed burnings on studied species groups, such as polypores (Penttilä and Kotiranta 1996; Penttilä et al. 2013; Suominen et al. 2015), beetles (Hyvärinen et al. 2006; Toivanen and Kotiaho 2007a; 2007b; Heikkala et al 2016) and flat bugs (Heikkala et al. 2017). Thus, prescribed burnings can be considered an effective and recommended habitat management tool. To ensure the positive impact on biodiversity, a sufficient amount of retention trees should be left in burning areas, rather 10-20% of stand volume (Heikkala et al. 2014) or at least 10 m^3/ha (Hyvärinen 2006; Heikkala 2016).

These research results and the necessity of prescribed burns have been noticed widely in political decision-making and are consequently recommended in several national reports and guidelines, including the recent Red List of Finnish species (Hyvärinen et al. 2019) and even in the current Finnish Government Programme (Programme of …2019).

Because of the increasing biodiversity-related targets, the scope of prescribed burnings in Finland has widened in recent years to include different types of burnings with varying targets which can be divided into four groups (Figure 4):

(1) The traditional *silvicultural prescribed burnings* of clear-cut areas (Figure 4a), which aim to improve regeneration conditions by improving nutrient cycling and decreasing the competition of understory vegetation (Viro 1969; Parviainen 1996). The method was widely practiced in Finland and Sweden in the 1950s and 1960s when tens of thousands of hectares were burned annually (Parviainen 1996; Cogos et al. 2020). In recent decades, silvicultural burnings have been modified to also safeguard biodiversity by leaving and burning retention trees to create fire-affected wood and habitats for fire-dependent

species, and thus can be termed *nature-management prescribed burnings* or "*prescribed burnings to promote the biodiversity of forests*," as in the Temporary Act on the Financing of Sustainable Forestry (Kestävän metsätalouden rahoituslaki 2015).

(2) At the beginning of this millennium, a new practice of *burning single retention-tree groups* (Figure 4b), was introduced with the aim of maintaining biodiversity by creating small fire-affected habitat patches. This practice has been actively promoted in media, and several forest operators have declared that they favour these types of burnings. In re-evaluation processes of the most widely used PEFC forest certification system in Finland, the criterion concerning burnings has been modified to be number-based (having previously been area-based), which makes it easier to fulfill the criterion by burnings of retention tree groups.

(3) Barren and sun-exposed habitats are decreasing in Finland and many of these habitats and their species are considered endangered (Kontula and Raunio 2018; Hyvärinen et al. 2019). Burnings are recommended as natural and effective treatment to restore and safeguard the ecological characteristics and biodiversity of these habitats (Similä and Junninen 2012). The main goals of these burnings are to reduce biomass, thin the duff layer and expose the mineral soil, and in general, shape the biotope into a more extreme and barren direction. Such burnings are therefore termed *impoverishment burnings* or *management burnings of sun-exposed and xeric habitats* (Figure 4c).

(4) *Restoration burnings* are mostly performed in conservation areas with the aims of starting natural succession after fire, diversifying stand structure and tree-species composition, improving the continuity of decaying wood, and promoting suitable resources and habitats for fire-dependent species (Similä and Junninen 2012, Figure 4d).

It is notable that targets and desired fire impact are not similar in all burnings. Estimating suitable circumstances is thus important when burnings and planned and performed. Especially fuel moisture is crucial when, e.g., specified burning depths and fuel consumption rates are desired.

Despite the need to increase various types of prescribed burnings the combined annual areas of them have declined steadily during the first two decades of this millennium. The annual areas of silvicultural burnings have fallen to 200-300 ha, the average annual areas of restoration burnings have stabilised to ~ 100 ha and the burnings of sun-exposed and xeric habitats have been merely experimental.

It turned out that there was no available data to estimate the current scope of burnings of retention tree groups. Based on the results from the questionnaire to the forest operators performing burnings, it can be estimated that the annual number of burned retention groups has recently most likely varied between 30 and 50 annual burnings with sizes of 0.1-0.2 ha or even smaller, so altogether their annual pooled area has been maybe 5-10 hectares, which can be considered negligible.

It also turned out that there is practically no research done focusing on the burnings of single retention groups, so it is hard to estimate the possible impact of practice. Yet based on ecological reasoning it can be concluded that their benefits to biodiversity are probably rather low compared to larger burnings, since the most important resources they aim to form, the fire-affected wood and soil, are notably lower than in the traditional burnings (Lindblad et al. 2013; Suominen et al. 2018).

The recent development and guidelines regarding prescribed burnings show several important decisions which partially explain the decline of burnings, such as impairing PEFC-certification criteria in all re-evaluation processes, the cuttings of public subsidies for private landowners and the decision to terminate the silvicultural burnings in state owned commercial forests. The true reason behind these decisions and the cause for the decline of burnings is obviously their level of expense, arduousness and general difficulty, which does not encourage increasing them in modern, security-orientated society.

Several actions that could help in safeguarding fire-driven habitats and enhancing prescribed burns were presented, such as modifying the certification criteria, improving the subsidy system, re-introducing the burnings to the state commercial forests and targeting the burnings to the fire-continuum areas. Additionally, the possibility to conserve especially the larger wildfire areas as, e.g., in Sweden (Gustafsson et al. 2019) should be utilised more effectively and the problems hampering the process, such as the adequate pricing of timber, should be solved.

5.3. The common ground vegetation fuels in Finnish forest differ in their moisture variation and ignition probability (III, IV).

Substudies **III** and **IV** focused on the flammability characteristics of common boreal ground layer fuels. As hypothesised, the experimented materials that consisted of four common ground layer species differed notably in their moisture behaviour (**III**) and ignition probability (**IV**). The mosses *P. schreberi* and *H. splendens* behaved rather similarly in both moisture variation and ignition probability. The reindeer lichen *Cladonia* was clearly the fastest drying species with high ignition probability even with higher FMC values and the moss *Dicranum* was the moistest and least flammable. The gelatinous thallus, the loose stem structure and the high surface-volume ratio of *Cladonia,* result in extreme moisture behaviour and high flammability (Pech 1989; 1991), whereas *Dicranum*s mattress-type structure with dense tomentum has higher water holding capacity (Peterson and Mayo 1975). The differences in drying patterns were notable, as out of all *Dicranum* observations > 80 % stayed under the chosen flammability threshold value of 25 %, whereas the respective observations for the *Cladonia* were > 50 % (**III**). In the raw humus layer, no significant inter-species differences were found and the raw humus FMC values during all sample days stayed well above the threshold value, indicating the slow drying process which would require long drought periods, as was also reported by Granström and Schimmel (1998).

The wind velocity in substudy **IV** had a clear effect on ignition probability of all the studies moss species, and especially on *Dicranum*, whereas the impact was lesser on *Cladon*ia. Interestingly, the analyses showed that with increasing wind velocity, the species' ignition probabilities and fuel consumption rates start to resemble each other, suggesting that the increasing oxygen and heat transfer surpassed the structural differences of species. Though it must be noted that substudy IV included some uncertainty factors, so the results should be considered directional.

As was also previously reported by Granström and Schimmel (1998) and Tanskanen et al. 2005; 2006), the stand structure affected the FMC behaviour since the clear-cuts and the Scots pine-dominated stands dried faster. Yet compared to the results of Tanskanen et al. (2006), the developmental stage was a more important factor than the dominating tree species.

Concerning forest fire suppression, the results support the conclusions of Tanskanen et al. (2005; 2006) and Vajda et al. (2014) suggesting that the forest fire indices and the early warning systems in Fennoscandia could be developed by integrating stand variables into the used indices. Parameters as the developmental stage and the dominant tree species could likely improve the prediction ability of indices notably, which eventually could help the practical fire suppression activities by better anticipation and preparation. The need for this kind of development work was also adduced in recent report based on a questionnaire directed to the rescue and forest professionals (Kukkonen 2021).

The Canadian Fire Weather Index (FWI) predicted the potential flammable days slightly better than the Finnish Forest Fire Index (FFI), which is in accordance with Tanskanen et al. (2005). Based on ignition tests, they showed that the FWI was a better predictor of ignitions. Thus, the FWI could well be taken to use in Finland as it has been done in Sweden already in 1996 (Sjöström et al. 2019).

The results can also be applied in the timing and planning of prescribed burnings. The large FMC variation in the ground vegetation materials and in the different stands (**III**) and the different ignition probability of the studied materials (**IV**), combined together, indicate that the potential days for prescribed burnings also have a large variation depending on goals and desired impact. The practical guidelines for burnings in Finland have traditionally been based on silvicultural burnings and recommend that the burnings should be timed to rather dry periods, e.g., with FFI values higher than four as presented by Lemberg and Puttonen (2002). In study **III**, the days with the observed FMC values under the threshold FMC value of 25% occurred also in days with FFI values under four. Thus, e.g., often semi-open, Scots pine-dominated, sun-exposed habitats with the *Cladonia* dry clearly faster and ignite easier and thus offer more potential burning opportunities than most restoration burnings, which are done in slower drying, moss-dominated denser stands. Therefore, monitoring of areas where burnings are planned is recommended, so that all potential burning times can be fully utilised, and the desired impacts of burnings can be achieved.

The differences in flammability of the surface layer play an important role in the overall disturbance dynamics of the Fennoscandian boreal forests, since the surface layer is the most important fuel bed, where most fires are ignited and spread (Schimmel and Granström 1997; Tanskanen et al. 2005). The results (**III**, **IV**) indicate that the combined effect of the growing stock, the dominating tree-species and the ground floor vegetation affect the flammability in Fennoscandian boreal forests. This is explained partially by the different radiation conditions, and partially by the different drying behavior (**III**) and the ignition characteristics (**IV**) of surface fuels. During periods of high fire activity, the accumulation of slowly drying, thick moss-covered raw-humus layer is prevented since the abundance of more flammable *Cladonia* spp is known to increase after fires (e.g., Webb 2008). This leads to the Scots pine dominance partly due to fire-tolerance of pine and partly due to the ability of *Cladonia* to form a favorable seed bed for pine (Zackrisson et al. 1997; Hyppönen et al. 2013). Even if the Norway spruce saplings are established, they are swept out by the regular low-intensity surface fires. The Scots pine-dominance leads to drier and more flammable forests, increasing the incidence of fires (Pitkänen and Huttunen 1999; Wallenius 2004) eventually leading to an uneven-aged cohort structure (Pennanen 2002; Kuuluvainen and Aakala 2011). If the ignitions decrease because of climatic or human reasons, the forests develop gradually into a moss-dominated, mesic and Norway spruce-dominated direction, which prolongs the fire cycle (Siren 1955; Pitkänen and Huttunen 1999; Wallenius 2004) and eventually leads from cohort dynamics to gap dynamics (Aakala 2018).

The abundance of *Cladonia* has substantially decreased during recent decades in Finland (Nousiainen 2000; Mäkipää and Heikkinen 2003; Tonteri et al. 2016, This is often connected to fertilisation phenomenon caused by atmospheric deposition of nitrogen, where the lichen-rich xeric and barren types have developed to a more moss-dominated mesic direction (Raunio et al. 2008) as well as to the impact of forestry actions (Tonteri et al.

2016). Similarly, the decrease of forest fires and prescribed burnings have been unfavourable for the *Cladonia* (Nousiainen 2000). The decline has been especially steep in Northern Finland due to increased reindeer grazing which has reduced significantly the coverage of the *Cladonia* (Nousiainen 2000; Mäkipää and Heikkinen 2013; Akujärvi et al. 2014). At the same time, a notable increase in the abundance of the *Dicranum* has been documented especially in parts of Northern Finland (Mäkipää 2000; Mäkipää and Heikkinen 2003). The results suggest that it is possible that this shift from fast-drying and easily igniting *Cladonia* to slow-drying *Dicranum* has decreased the forest fire risk in Northern Finland as well as the general decline of flammable *Cladonia*.

6. CONCLUDING REMARKS

In the future, the occurrence of forest fires, their risks and impacts involve several open questions and uncertainties which challenge society to react. According to current predictions, the climatic forest fire risk in Finland will increase, yet it is possible that this will not definitely mean an increase in burned areas. For example, despite recent decades' exceptionally warm and dry summers, annual burned areas did not increase significantly. Therefore, if Finland wishes to maintain the current fire regime with low annual burned areas, proactive actions targeted at fire suppression operations are needed, since ignitions and firefighting work will probably increase.

If the burned forest areas will increase in the near future, these areas should be utilised effectively by forming nature conservation areas out of them with aim to safeguard fire-driven habitats and fire-dependent species. Even with this kind of development, prescribed burnings are needed since the sun-exposed and xeric habitats need frequent nature management, in order to maintain their special ecological characteristics and species diversity.

There is simultaneously a demand to safeguard property and society from harmful forest fires and to also safeguard fire-related biodiversity. Thus, there is a need for a wider fire strategy which should include, e.g., future fire prevention policies and guidelines, fire continuum areas where fire could be used frequently, and effective compensation systems ensuring the conservation of burned areas and the continuity of prescribed burnings.

In both fire prevention and prescribed burning, the knowledge of different fuels, their ignition characteristics and moisture variation play an essential role. Thus, fire indices and early warning system used in Finland could be developed by integrating auxiliary stand variables into them. The practical firefighting could benefit, e.g., from fuel-based maps, which could help in choosing the right suppression tactics. In prescribed burnings, different fuels and their moisture variation are crucial factors which often determine the fire impact and the suitable conditions for burning. In these potential future development tasks, I hope that my results presented in this thesis will provide useful information.

REFERENCES

Aakala T (2018) Forest fire histories and tree age structures in Värriö and Maltio Strict Nature Reserves, northern Finland. Boreal Environ Res 23, 209–219. http://www.borenv.net/BER/archive/pdfs/ber23/ber23-209-219.pdf

Aakala T, Pasanen L, Helama S, Vakkari V, Drobyshev I, Seppä H, Kuuluvainen T, Stivrins N, Wallenius T, Vasander H, Holmström L (2018) Multiscale variation in drought controlled historical forest fire activity in the boreal forests of eastern Fennoscandia. Ecol Monogr 88,74–91. https://doi.org/10.1002/ecm.1276

Aarne M (ed) (1992) Metsätilastollinen vuosikirja 1990-91 [Yearbook of forest statistics 1990-91]. SVT Maa- ja metsätalous [SVT Agriculture and forestry] 1992(3):1-281. Folia Forestalia 790:1-281. In Finnish with English summary. http://urn.fi/URN:ISBN:951-40-1205-4

Agee J, Skinner, C (2005). Basic principles of forest fuel reduction treatments. Forest Ecol Manag 211. 83-96. https://doi.org/10.1016/j.foreco.2005.01.034

Ahti T, Hamet-Ahti L, Jalas J (1968) Vegetation zones and their sections in northwestern Europe. Ann Bot Fenn 5, 169–211.

Akujärvi A, Hallikainen V, Hyppönen M, Mattila E, Mikkola K, Rautio P (2014) Effects of reindeer grazing and forestry on ground lichens in Finnish Lapland. Silva Fenn vol. 48 no. 3 article id 1153. https://doi.org/10.14214/sf.1153

Baker W, Ehle D (2001) Uncertainty in surface-fire history: The case of ponderosa pine forests in the western United States. Can J Forest Res. 31. 1205-1226. https://doi.org/10.1139/x01-046

Bowman D, Kolden C, Abatzoglou J, Johnston F, Werf G, Flannigan, M (2020). Vegetation fires in the Anthropocene. Nature Reviews Earth & Environment. 1. 500-515. https://doi.org/10.1038/s43017-020-0085-3

Burrows N, McCaw L (2013) Prescribed burning in southwestern Australian forests. Front Ecol Environ, 11: e25-e34. https://doi.org/10.1890/120356

Cajander AK (1949) Forest types and their significance. Acta Forestalia Fennica 56, 1-71. https://doi.org/10.14214/aff.7396

Chuvieco E, Aguado I, Dimitrakopoulos A (2004) Conversion of fuel moisture content values to ignition potential for integrated fire danger assessment. Can J Forest Res, 34, 2284-2293. https://doi.org/10.1139/x04-101

Cogos S, Roturier S, Östlund L (2020) The origins of prescribed burning in Scandinavian forestry: the seminal role of Joel Wretlind in the management of fire-dependent forests. Eur J Forest Res 139, 393–406. https://doi.org/10.1007/s10342-019-01247-6

Conedera M, Tinner W, Neff C (2009) Reconstructing past fire regimes: Methods, applications, and relevance to fire management and conservation. Quaternary Sci Rev 28: 555–576. https://doi.org/10.1016/j.quascirev.2008.11.005

Dimitrakopoulos A, Bemmerzouk AM, Mitsopoulos I (2011) Evaluation of the Canadian fire weather index system in an eastern Mediterranean environment. Meteorol Appl 18, 83–93. https://doi.org/10.1002/met.214

Drobyshev I, Granström A, Linderholm HW, Hellberg E, Bergeron Y, Niklasson M (2014) Multi-century reconstruction of fire activity in Northern European boreal forest suggests differences in regional fire regimes and their sensitivity to climate. J Ecol 102, 738–748. https://www.jstor.org/stable/24541428

Fernandes P (2013) Forest fuel management for fire mitigation under climate change. In book: Forest Management of Mediterranean Forest Under the New Context of Climate Change: Building Alternatives for the Coming Future (pp.31-41), Chapter: 3. Publisher: Nova Science Publishers, Inc. Editors: M.E.Lucas-Borja. https://www.researchgate.net/publication/237100300_Forest_fuel_management_for_fire_mitigation_under_climate_change/link/00b4951b8536e5ff75000000/download

Fernandes P, Vega J, Jiménez E, Rigolot E (2008) Fire resistance of European pines. Forest Ecol Manag 256. 246-255. https://doi.org/10.1016/j.foreco.2008.04.032

Fernandes P, Davies G, Ascoli D, Fernández C, Moreira F, Rigolot E, Stoof C, Vega J, Molina D (2013) Prescribed burning in southern Europe: developing fire management in a dynamic landscape. Front Ecol Environ 11 (Suppl. 1): e4-e14. https://doi.org/10.1890/120298

Finnish Forest Statistics (2021) Silvicultural and forest improvement work: prescribed burning. http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/. Accessed 22 April 2021.

Flannigan M, Krawchuk M, de Groot W, Wotton M, Gowman L (2009a) Implications of changing climate for global wildland fire. Int J Wildland Fire 18, 483-507. https://doi.org/10.1071/WF08187

Flannigan M, Stocks B, Turetsky M, Wotton M (2009b) Impacts of climate change on fire activity and fire management in the circumboreal forest. Glob Change Biol, 15: 549-560. https://doi.org/10.1111/j.1365-2486.2008.01660.x

Granström A (2001) Fire management for biodiversity in the European boreal forest, Scand J Forest Res. Suppl. 3, 62–69. https://doi.org/10.1080/028275801300090627

Granström A, Schimmel J (1998) Utvärdering av det kanadensiska brandrisksystemet - testbränningar och uttorkningsanalyser: [Assessment of the Canadian forest fire danger rating system for Swedish fuel conditions.] P21–244/98. Räddningsverket Karlstad. 34 p [Rescue Service: Karlstad, Sweden. 34 p]. In Swedish with an English abstract.

Granström A, Niklasson M (2008) Potentials and limitations for human control over historic fire regimes in the boreal forest. Philos T R Soc B 363. 2353-8. https://doi.org/10.1098/rstb.2007.2205

Groven R, Niklasson M (2005). Anthropogenic impact on past and present fire regimes in a boreal forest landscape of southeastern Norway. Can J Forest Res. 35(11):2719-2726 https://cdnsciencepub.com/doi/10.1139/x05-186

Gustafsson L, Berglind M, Granström A, Grelle A, Isacsson G, Kjellander P, Larsson S, Lindh M, Pettersson LB, Strengbom J, Stridh B, Sävström T, Thor G, Wikars L-O, Mikusiński G (2019). Rapid ecological response and intensified knowledge accumulation following a north European mega-fire. Scand J Forest Res 34: 234-253. https://doi.org/10.1080/02827581.2019.1603323

Gutsell S, Johnson E (1996) How fire scars are formed: Coupling a disturbance process to its ecological effect. Can J Forest Res. 26. 166-174. https://doi.org/10.1139/x26-020

Heikinheimo M, Venäläinen A, Tourula T (1998) A soil moisture index for the assessment of forest fire potential in the boreal zone. In Proceedings of the International Symposium on Applied Agrometeorology and Agroclimatology (Volos, Greece), Office for Official Publication of the European Commission (Luxembourg), NR Dalezios (ed), EUR 18328-COST 77, 79, 711. 549– 555.

Heikkala O (2016) Emulation of natural disturbances and the maintenance of biodiversity in managed boreal forests: the effects of prescribed fire and retention forestry on insect assemblages. Dissertationes Forestales 222. https://doi.org/10.14214/df.222

Heikkala O, Suominen M, Junninen K, Hämäläinen A, Kouki J (2014) Effects of retention level and fire on retention tree dynamics in boreal forests. Forest Ecol Manag 328: 193-201. https://doi.org/10.1016/j.foreco.2014.05.022

Heikkala O, Seibold S, Koivula M, Martikainen P, Müller J, Thorn S, Kouki J (2016) Retention forestry and prescribed burning result in functionally different saproxylic beetle assemblages than clear-cutting. Forest Ecol Manag 359: 51-58. https://doi.org/10.1016/j.foreco.2015.09.043

Heikkala O, Martikainen P, Kouki J (2017) Prescribed burning is an effective and quick method to conserve rare pyrophilous forest-dwelling flat bugs. Insect Conserv Diver 10: 32-41. https://doi.org/10.1111/icad.12195

Hille MG, den Ouden J (2005) Fuel load, humus consumption and humus moisture dynamics in Central European Scots pine stands. Int J Wildland Fire 14, 153-159. https://doi.org/10.1071/WF04026

Hyppönen, M, Hallikainen V, Niemelä J, Rautio P (2013) The contradictory role of understory vegetation on the success of Scots pine regeneration. Silva Fenn 47(1) id 903. https://doi.org/10.14214/sf.903

Hyvärinen E (2006) Green-tree retention and controlled burning in restoration and conservation of beetle diversity in boreal forests. Dissertationes Forestales 21. https://www.dissertationesforestales.fi/article/1804

Hyvärinen E, Kouki J, Martikainen P (2006) Fire and green-tree retention in conservation of red-listed and rare deadwood-dependent beetles in Finnish boreal forests. Conserv Biol 20: 1711-1719. https://doi.org/10.1111/j.1523-1739.2006.00511.x

Hyvärinen E, Juslén A, Kemppainen E, Uddström A, Liukko U-M (eds) (2019) Suomen lajien uhanalaisuus - Punainen kirja 2019 / The 2019 Red List of Finnish Species. Ympäristöministeriö & Suomen ympäristökeskus/Ministry of the Environment & Finnish Environment Institute, Helsinki. 703 p. http://hdl.handle.net/10138/299501

Juvakka M, Viinikainen J, Puputti I, Kuupakko S (1995) Vesijaon tutkimusalue, hoito- ja käyttösuunnitelma 1994–2003. Metlan tutkimusmetsien julkaisusarja 5. Vantaa. 228 p. ISSN 1238-0830. [Plan for the management and use of forests in Vesijako research area 1994–2003.] In Finnish.

Kasin I, Blanck YL, Rolstad J, Storaunet KO, Ohlson M (2013). The charcoal record in peat and mineral soil across a boreal landscape and possible linkages to climate change and recent fire history. The Holocene 23, 1052–1065. https://doi.org/10.1177/0959683613479678

Keane R (2015) Wildland Fuel Fundamentals and Applications. Springer. 191 p. https://doi.org/10.1007/978-3-319-09015-3

Kestävän metsätalouden määräaikainen rahoituslaki (2015). Suomen laki 2015/34. [Temporary Act on the Financing of Sustainable Forestry. Finnish Act 2015/34.] In Finnish.

Kilgore BM and Taylor D (1979) Fire History of a Sequoia-Mixed Conifer Forest. Ecology, 60: 129-142. https://doi.org/10.2307/1936475

Kilpeläinen A, Kellomäki S, Strandman H, Venäläinen A (2010) Climate change impacts on forest fire potential in boreal conditions in Finland. Climatic Change 103, 383–398. https://doi.org/10.1007/s10584-009-9788-7

Kirdyanov, AV, Saurer M, Siegwolf R et al. (2020) Long-term ecological consequences of forest fires in the continuous permafrost zone of Siberia. Environ Res Lett, 15 (3). https://doi.org/10.1088/1748-9326/ab7469

Koivula M, Vanha-Majamaa I (2020) Experimental evidence on biodiversity impacts of variable retention forestry, prescribed burning, and deadwood manipulation in Fennoscandia. Ecol Process 9, 11. https://doi.org/10.1186/s13717-019-0209-1

Kontula T, Raunio A (eds) (2018) Suomen luontotyyppien uhanalaisuus 2018. Luontotyyppien punainen kirja. Osa 1 - tulokset ja arvioinnin perusteet. [Threatened habitat types in Finland 2018. Red List of habitats. Part I: Results and basis for assessment.] Suomen ympäristö [The Finnish Environment] 5/2018. 388 p. In Finnish with an English summary. http://urn.fi/URN:ISBN:978-952-11-4816-3

Kosenius, A-K, Tulla T, Horne P, Vanha-Majamaa I, Kerkelä L (2014) Metsäpalojen torjunnan talous ja ekosysteemipalvelut – Kustannusanalyysi Pohjois-Karjalasta, PTT työpapereita 165. Helsinki: Pellervon taloustutkimus PTT, s. 54. [The economics and ecosystem services of forest fire prevention - a cost analysis from Northern Carelia. PTT Working papers 165.] In Finnish. http://www.ptt.fi/media/liitteet/tp165.pdf

Köster K, Aaltonen H, Berninger F, Heinonsalo J, Köster E, Ribeiro-Kumara C, Sun H, Tedersoo L, Zhou X, Pumpanen J (2021) Impacts of wildfire on soil microbiome in Boreal environments. Current Opinion in Environmental Science & Health. 22. 100258. https://doi.org/10.1016/j.coesh.2021.100258

Kukkonen M (2021) Metsäsektorin ja pelastusalan käsityksiä metsäpaloista. Lapin ammattikorkeakoulun julkaisuja. Sarja B. Tutkimusraportit ja kokoomateokset 6/2021 [The opinions of forestry professionals and rescue authorities concerning forest fires. The publications of Lapland University of Applied Sciences. Series B: Research reports and Compilations 6/2021.] In Finnish. https://www.lapinamk.fi/loader.aspx?id=18c1bbbf-078e-4009-a4c8-99ddd6047a50

Kuuluvainen T, Aakala T (2011) Natural forest dynamics in boreal Fennoscandia: a review and classification. Silva Fenn 45(5), 823–841. https://doi.org/10.14214/sf.73

Lehtonen H, Huttunen P, Zetterberg P (1996) Influence of man on forest fire frequency in North Karelia, Finland, as evidenced by scars on Scots pines. Ann Bot Fenn 33: 257–263. http://www.sekj.org/PDF/anbf33/anbf33-257.pdf

Lehtonen H, Huttunen P (1997) History of forest fires in eastern Finland from the fifteenth century AD – the possible effects of slash-and-burn cultivation. Holocene 7: 223–228. https://doi.org/10.1177%2F095968369700700210

Lehtonen I, Ruosteenoja K, Venäläinen A, Gregow H (2014) The projected 21st century forest-fire risk in Finland under different greenhouse gas scenarios. Boreal Env. Res. 19: 127–139. https://www.researchgate.net/publication/285955800_The_projected_21st_century_forest-fire_risk_in_Finland_under_different_greenhouse_gas_scenarios

Lemberg T, Puttonen P (2002) Kulottajan käsikirja. Metsälehti kustannus. Vammalan kirjapaino. [Guide for prescribed burning. Textbook.] In Finnish.

Lindberg H, Granström A, Gromtsev A, Levina M, Shorohova E, Vanha-Majamaa I (2021) The annually burnt forest area is relatively low in Fennoscandia. In: Aalto J and Venäläinen A (eds): Climate change and forest management affect forest fire risk in Fennoscandia. Reports 2021:3. Finnish Meteorological Institute. https://helda.helsinki.fi/handle/10138/330898

Lindblad J, Jahkonen M, Laitila J, Kilpeläinen H, Sirkiä S (2013) Energiapuun määrä ja laatu sekä niiden arviointi [The volume, quality and estimation of energy wood.] Metlan työraportteja [Working Papers of the Finnish Forest Research Institute] 259: 1-53. In Finnish. http://www.metla.fi/julkaisut/workingpapers/2013/mwp259.pdf

Linder P, Jonsson P, Niklasson M (1998). Tree mortality after prescribed burning in an old-growth Scots pine forest in northern Sweden. Silva Fenn vol. 32 no. 4 article id 675. https://doi.org/10.14214/sf.675

Mäkelä H, Laapas M, Venäläinen, A (2012) Long-term temporal changes in the occurrence of a high forest fire danger in Finland. Nat Hazard Earth Sys 12, 2591-2601. https://doi.org/10.5194/nhess-12-2591-2012, 2012.

Mäkelä H, Venäläinen A, Jylhä K, Lehtonen I, Gregow H (2014). Probabilistic projections of climatological forest fire danger in Finland. Climate Res 60. 73-85. https://doi.org/10.3354/cr01223

Mäkipää R (2000) Dicranum. In: Reinikainen A, Mäkipää R, Vanha-Majamaa I, Hotanen J-P. (eds.) Kasvit muuttuvassa metsäluonnossa. [Changes in the frequency and abundance of forest and mire plants in Finland since 1950]. Tammi, Jyväskylä. 384 p. In Finnish with an English summary.

Mäkipää R, Heikkinen J (2003) Large-scale changes in abundance of terricolous bryophytes and macrolichens in Finland. J Veg Sci 14, 497–508. https://doi.org/10.1111/j.1654-1103.2003.tb02176.x

McLauchlan KK, Higuer PE, Miesel J, et al. (2020) Fire as a fundamental ecological process: Research advances and frontiers. J Ecol. 108: 2047– 2069. https://doi.org/10.1111/1365-2745.13403

Moritz MA, Parisien, M-A, Batllori E, Krawchuk MA, Dorn J, Ganz DJ, Hayhoe K (2012). Climate change and disruptions to global fire activity. Ecosphere, 3, 1-22. https://doi.org/10.1890/ES11-00345.1

Mysterud I (1997) Anthropogenic burning and impact. In: Bleken E, Mysterud I, Mysterud I (Eds.). Forest fire and environmental management: A technical report on forest fire as an ecological factor. Contracted Report. Directorate for Fire & Explosion Prevention and Department of Biology, University of Oslo, pp. 49-80. https://gfmc.online/globalnetworks/balticregion/Norway-Fire-Environment-Mysterud-2003.pdf

Niklasson M, Granström A (2000) Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81, 1484–1499. https://doi.org/10.2307/177301

Niklasson M, Drakenberg B (2001) A 600-year tree-ring fire history from Kvill National Park, southern Sweden - implications for conservation strategies in the hemiboreal. Biol Conserv 101, 63-71. https://doi.org/10.1016/S0006-3207(01)00050-7

Nousiainen H (2000) Cladina. In: Reinikainen A, Mäkipää R, Vanha-Majamaa I, Hotanen, J-P. (eds.) Kasvit muuttuvassa metsäluonnossa. [Changes in the frequency and abundance of forest and mire plants in Finland since 1950]. Tammi, Jyväskylä. 384 p. In Finnish with an English summary.

NWCG Glossary of Wildland Fire, PMS 205 (2021) https://www.nwcg.gov/glossary/a-z. Accessed 21 September 2021.

Ohlson M, Brown KJ, Birks HJB, Grytnes JA, Hornberg G, Niklasson M, Seppä H, Bradshaw RHW (2011) Invasion of Norway spruce diversifies the fire regime in boreal European forests. J Ecol 99(2), 395-403. https://doi.org/10.1111/j.1365-2745.2010.01780.x

Okko M (1972) Jäätikön häviämistapa Toisen Salpausselän vyöhykkeessä Lammilla. [Deglaciation in the Second Salpausselka ice-marginal belt at Lammi, South Finland.] Terra 84(3), 115-123. In Finnish with an English summary.

Omi PN (2015) Theory and Practice of Wildland Fuels Management. Curr Forestry Rep 1, 100–117. https://doi.org/10.1007/s40725-015-0013-9

Päätalo M-L (1998) Factors influencing occurrence and impacts of fires in Northern European forests. Silva Fenn 32(2), 185-202. https://doi.org/10.14214/sf.695

Parviainen J (1996) Impact of fire on Finnish forests in the past and today. Silva Fenn 30: 353-359. https://doi.org/10.14214/sf.a9246

Péch G (1989) A model to predict the moisture content of reindeer lichen. Forest Sci 35, 1014-1028. https://doi.org/10.1093/forestscience/35.4.1137

Péch G (1991) Dew on reindeer lichen. Can J Forest Res 21, 1415–1418. https://doi.org/10.1139/x91-198

Peltola A (ed) (2014) Metsätilastollinen vuosikirja 2014 [Finnish Statistical Yearbook of Forestry]. SVT Maa-, metsä- ja kalatalous 2014 [Official Statistics of Finland: Agriculture, forestry and fishery]. Metsäntutkimuslaitos [Finnish Forest Research Institute]. 428 p. In Finnish with an English summary. http://urn.fi/URN:ISBN:978-951-40-2506-8

Pennanen J (2002) Forest age distribution under mixed-severity fire regimes – a simulation-based analysis for middle boreal Fennoscandia. Silva Fenn vol. 36 no. 1 article id 559. https://doi.org/10.14214/sf.559

Penttilä R, Kotiranta H (1996) Short-term effects of prescribed burning on wood-rotting fungi. Silva Fenn 30: 399-419. https://doi.org/10.14214/sf.a8501

Penttilä R, Junninen K, Punttila P, Siitonen J (2013) Effects of forest restoration by fire on polypores depend strongly on time since disturbance – a case study from Finland based on a 23-year monitoring period. Forest Ecol Manag 310: 508-516. http://dx.doi.org/10.1016/j.foreco.2013.08.061.

Peterson W, Mayo J (1975) Moisture stress and its effect on photosynthesis in Dicranum polysetum. Can J Botany 53, 2897–2900 https://cdnsciencepub.com/toc/cjb/53/24

Pitkänen A, Huttunen P (1999) A 1300-year forest-fire history at a site in eastern Finland based on charcoal and pollen records in laminated lake sediment. Holocene 9, 311-320. https://doi.org/10.1191/095968399667329540

Pitkänen A, Huttunen P, Tolonen K, Jugner H (2003) Long-term fire frequency in the spruce dominated forests of Ulvinsalo strict nature reserve, Finland. Forest Ecol Manag 176, 305-319. https://doi.org/10.1016/S0378- 1127(02)00291-8

Programme of Prime Minister Sanna Marin's Government (2019) Inclusive and competent Finland - a socially, economically and ecologically sustainable society. Publications of the Finnish Government 2019:33. 228 p. http://urn.fi/URN:ISBN:978-952-287-811-3

PRONTO-database (2021) Statistical Data System of Finnish Rescue Services. Emergency Services Academy Finland. Data inquiry 18 March 2021

Ramberg E, Strengbom J, Granath G (2018) Coordination through databases can improve prescribed burning as a conservation tool to promote forest biodiversity. Ambio 47: 298-306. https://doi.org/10.1007/s13280-017-0987-6

Raunio A, Schulman A, Kontula T (eds) (2008) Suomen luontotyyppien uhanalaisuus - Osa 1: Tulokset ja arvioinnin perusteet [Assessment of threatened habitat types in Finland – Part 1: Results and basis for assessment]. Suomen ympäristö [The Finnish Environment] 8/2008. 264 p. In Finnish with an English summary. http://hdl.handle.net/10138/37930

Rescue Act (2011) Finnish Act 379/2011. https://www.finlex.fi/en/laki/kaannokset/2011/en20110379

Robinne F-N, Burns J, Kant P, de Groot B, Flannigan MD, Kleine M, Wotton DM (eds) (2018) Global fire challenges in a warming world. Summary note of a global expert workshop on fire and climate change. International Union of Forest Research Organizations, IUFRO Occasional Paper No. 32. 58 p. http://pure.iiasa.ac.at/id/eprint/15707/1/op32.pdf

Rolstad J, Blanck Y, Storaunet KO (2017) Fire history in a western Fennoscandian boreal forest as influenced by human land use and climate. Ecol Monogr 87(2), 219–245. https://doi.org/10.1002/ecm.1244

Ryan, KC (2002) Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fenn 36(1): 13–39. https://doi.org/10.14214/sf.548

Ryan KC, Knapp EE, Varner JM (2013) Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Front Ecol Environ 11 (Suppl. 1): E15-E24. https://doi.org/10.1890/120329

Ryzhkova N, Pinto G, Kryshen A, Bergeron Y, Ols C, Drobyshev I (2020) Multi-century reconstruction suggests complex interactions of climate and human controls of forest fire activity in a Karelian boreal landscape, North-West Russia. For Ecol Manag 459:117770. https://doi.org/10.1016/j.foreco.2019.117770.

Sandberg DV (1980) Duff reduction by prescribed burning in Douglas-fir. USDA Forest Service Research Paper PNW-272, 18 p. https://doi.org/10.2737/PNW-RP-272

Schimmel J, Granström A (1997) Fuel succession and fire behavior in the Swedish boreal forest. Can J Forest Res 27, 1207–1216. https://doi.org/10.1139/x97-072

Shorohova E, Sinkevich S, Kryshen A, Vanha-Majamaa I (2019) Variable retention forestry in European boreal forests in Russia. Ecol Process 8:34 https://doi.org/10.1186/s13717-019-0183-7

Similä M, Junninen K (eds) (2012) Ecological restoration and management in boreal forests - best practices from Finland. Metsähallitus Natural Heritage Services, Vantaa. 50 p. https://julkaisut.metsa.fi/assets/pdf/lp/Muut/ecological-restoration.pdf

Sirén G (1955) The development of spruce forest on raw humus sites in northern Finland and its ecology Acta Forestalia Fennica 62(4), 408 p. https://doi.org/10.14214/aff.7453

Sjöström J, Plathner FV, Granström A (2019) Wildfire ignition from forestry machines in boreal Sweden. Int J Wildland Fire 28(9), 666-677. https://doi.org/10.1071/WF18229

Skogsbränderna sommaren 2018. Betänkande av 2018 års skogsbrandsutredning (2019) [Forest fires in summer 2018]. In Swedish. Statens offentliga utredningar (SOU) 2019:7, Stockholm. 334 p. https://www.regeringen.se/4906d2/contentassets/8a43cbc3286c4eb39be8b347ce78da16/skogsbranderna-sommaren-2018-sou-2019-7.pdf

Soisalo J (2021) Metsäpalojen tähystystoiminnan arviointi ja kehittäminen. Oulun yliopisto, tuotantotalouden tutkinto-ohjelma, diplomityö. 93 s. [Evaluation and Development of Forest Fire Detection. University of Oulu, Degree Programme of Mechanical Engineering, Master's thesis, 93 p]. In Finnish with an English abstract.

Steijlen I, Zackrisson O (1987) Long-term regeneration dynamics and successional trends in a northern Swedish coniferous forest stand. Can J Botany 65, 839–848. https://doi.org/10.1139/b87-114

Stephens SL, Burrows N, Buyantuyev A, Gray RW, Keane RE, Kubian R, Liu S, Seijo F, Shu L, Tolhurst KG, van Wagtendonk JW (2014) Temperate and boreal forest mega-fires: characteristics and challenges. Front Ecol Environ 12: 115-122. https://doi.org/10.1890/120332

Storaunet KO, Rolstad J, Toeneiet, M, Blanck Y (2013) Strong anthropogenic signal in historic forest fire regime: A detailed spatio-temporal case study from south-central Norway. Can J Forest Res 43, 836-845. https://doi.org/10.1139/cjfr-2012-0462

Suominen M, Junninen K, Heikkala O, Kouki J (2015) Combined effects of retention forestry and prescribed burning on polypore fungi. J Appl Ecol 52: 1001-1008. https://doi.org/10.1111/1365-2664.12447

Suominen M, Junninen K, Heikkala O, Kouki J (2018) Burning harvested sites enhances polypore diversity on stumps and slash. Forest Ecol Manag 414: 47-53. https://doi.org/10.1016/j.foreco.2018.02.007

Swetnam TW, Allen CD, Betancourt JL (1999) Applied historical ecology: Using the past to manage for the future. Ecol Appl, 9: 1189-1206. https://doi.org/10.1890/1051-0761(1999)009[1189:AHEUTP]2.0.CO;2

Tanskanen H, Venäläinen A, Puttonen P, Granström A (2005) Impact of stand structure on surface fire ignition potential in Picea abies and Pinus sylvestris forests in southern Finland. Can J Forest Res 35, 410-420. https://doi.org/10.1139/X04-188

Tanskanen H, Granström A, Venäläinen A, Puttonen P (2006) Moisture dynamics of moss dominated surface fuel in relation to the structure of Picea abies and Pinus sylvestris stands. Forest Ecol Manag 226, 189-198. https://doi.org/10.1016/j.foreco.2006.01.048

Tanskanen H, Granström A, Larjavaara M, Puttonen P (2007) Experimental fire behaviour in managed *Pinus sylvestris* and *Picea abies* stands of Finland. Int J Wildland Fire 16, 414-425. https://doi.org/10.1071/WF05087

Tedim F, Leone V, Amraoui M, Bouillon C, Coughlan M, Delogu G, Fernandes P, Ferreira C, McCaffrey S, McGee T, Parente J, Paton D, Pereira M, Ribeiro L, Viegas D, Xanthopoulos G (2018) Defining extreme wildfire events: difficulties, challenges, and impacts. Fire 1, 9 https://doi.org/10.3390/fire1010009

Thomas D, Butry D, Gilbert S, Webb D, Fung J (2017) The Costs and Losses of Wildfires: A Literature Review. National Institute of Standards and Technology Special Publication 1215. 72 p. https://doi.org/10.6028/NIST.SP.1215

Toivanen T, Kotiaho JS (2007a) Burning of logged sites to protect beetles in managed boreal forests. Conserv Biol 21: 1562-1572. https://doi.org/10.1111/j.1523-1739.2007.00808.x

Toivanen T, Kotiaho JS (2007b) Mimicking natural disturbances of boreal forests: the effects of controlled burning and creating dead wood on beetle diversity. Biodivers Conserv 16: 3193-3211. https://doi.org/10.1007/s10531-007-9172-8

Tonteri T, Salemaa M, Rautio P, Hallikainen V, Korpela L, and Merilä P (2016) Forest management regulates temporal change in the cover of boreal plant species. Forest Ecol Manag 381, 115-124. https://doi.org/10.1016/j.foreco.2016.09.015

Tryterud E (2003) Forest fire history in Norway: from fire-disturbed pine forests to fire-free spruce forests. Ecography 26(2), 161–170 https://onlinelibrary.wiley.com/doi/epdf/10.1034/j.1600-0587.2003.02942.x

Ulvcrona K, Kiljunen N, Nilsson U, Ulvcrona T (2011) Tree mortality in *Pinus sylvestris* stands in Sweden after pre-commercial thinning at different densities and thinning heights. Scand J Forest Res. 26, 319-328. https://doi.org/10.1080/02827581.2011.564205

Vajda A, Venäläinen A, Suomi I, Junila P, Mäkelä H (2014) Assessment of forest fire danger in a boreal forest environment: description and evaluation of the operational system applied in Finland. Meteorol Appl 21, 879-887. https://doi.org/10.1002/met.1425

Van Wagner CE (1987) Development and Structure of the Canadian Forest Fire Weather Index System; Forestry Technical Report 35; Canadian Forestry Service: Ottawa, ON, Canada, Volume 1, 48 p. https://cfs.nrcan.gc.ca/publications?id=19927

Venäläinen A, Heikinheimo M (2003) The Finnish forest fire index calculation system. In: Zschau, J. & Kuppers, A. (ed.). Early Warning Systems for Natural Disaster Reduction. Springer, 467 p. https://doi.org/10.1007/978-3-642-55903-7_88

Venäläinen A, Lehtonen I, Mäkelä A (2016) Laaja-alaisia metsäpaloja mahdollistavat säätilanteet Suomen ilmastossa. [The occurrence of weather conditions favouring widespread forest fires in Finland.] The reports of Finnish Meteorological Institute 2016:3. In Finnish with an English summary. https://www.researchgate.net/publication/303228907_Laaja-alaisia_metsapaloja_mahdollistavat_saatilanteet_Suomen_ilmastossa/link/57398a9b08ae9f741b2c5a22/download

Viro PJ (1969) Prescribed burning in forestry. Communicationes Instituti Forestalis Fenniae 67(7), 1-49. http://urn.fi/URN:NBN:fi-metla-201207171099

Wallenius T (2004) Fire histories and tree ages in unmanaged boreal forests in Eastern Fennoscandia and Onega peninsula. Academic Dissertation, June 2004.University of Helsinki, Faculty of Biosciences, Department of Biological and Environmental Sciences and Faculty of Agriculture and Forestry, Department of Forest Ecology. http://urn.fi/URN:ISBN:952-10-1893-3

Wallenius T (2011) Major decline in fires in coniferous forests - reconstructing the phenomenon and seeking for the cause. Silva Fenn 45, 139-155. https://doi.org/10.14214/sf.36

Wallenius T, Lilja S, Kuuluvainen T (2007) Fire history and tree species composition in managed Picea abies stands in southern Finland: Implications for restoration. Forest Ecol Manag 250 (1-2), 89-95. https://doi.org/10.1016/j.foreco.2007.03.016.

Wallenius T, Kauhanen H, Herva H, Pennanen J (2010) Long fire cycle in northern boreal Pinus forests in Finnish Lapland. Can J Forest Res 40, 2027-2035. https://doi.org/10.1139/X10-144

Webb E (2008) The effects of clearcut logging and forest fire on reindeer lichens in reindeer lichen-rich forest stands in northwestern Ontario. Clark university. 122 p.

Wein RW, MacLean DA (eds) (1983) The Role of Fire in Northern Circumpolar Ecosystems 322 p. Wiley.

Wirth C, Schulze ED, Schulze W, von Stünzner-Karbe D, Ziegler W, Miljukova IM, Sogatchev A, Varlagin AB, Panvyorov M, Grigoriev S, Kusnetzova W, Siry M, Hardes G, Zimmermann R, Vygodskaya NN (1999) Above-ground biomass and structure of pristine Siberian Scots pine forests as controlled by competition and fire. Oecologia. 121(1):66-80. https://doi.org/10.1007/s004420050908

Zackrisson O, Nilsson MC, Dahlberg A, Jäderlund A (1997) Interference mechanisms in conifer-Ericaceae-feather moss communities. Oikos 78, 209–220. https://doi.org/10.1139/x97-185

Ziel RH, Bieniek PA, Bhatt US, Strader H, Rupp TS, York AA (2020) Comparison of Fire Weather Indices with MODIS Fire Days for the Natural Regions of Alaska. Forests. 11(5):516. https://doi.org/10.3390/f11050516