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The role of fire in the boreal forests of Fennoscandia:
Past, present and future

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Abstract

The dichotomy of forest fires, on one side costly and destructive, and on the other side beneficial for nature conservation, is a complex issue. Understanding the interactions between the social and environmental factors that influence past and present fire regimes is necessary to make informed decisions pertaining to fire management and policy, both now and in the future. Historically, fire has been an integral element of the boreal forest ecosystems of Fennoscandia. Fire activity varied across the region, influenced by human activities, climate, vegetation and landscape structures. Today, due to industrialized forestry and efficient fire suppression, fire is a rare event in the forest landscape of Fennoscandia. Human activities are largely responsible for the few fires that do start. Prescribed fires are today the main source of burnt area annually. Fires increase structural heterogeneity within a landscape, which is recognized as pivotal for maintaining high biodiversity. Therefore, there is a need of reoccurring fires in the landscape, yet negative effects need to be considered. In the light of climate change, evaluating future wildfire risk is becoming increasingly important. In Fennoscandia, climate scenarios point to an increase in precipitation, but also an increase in extreme weather events such as droughts. What this may mean for future wildfire activity depends on the response and interaction of anthropogenic activities, vegetation and other disturbances to climate change. Prescribed fire can be used both as mitigation measure against wildfire, and to maintain ecological fire legacies. More research is needed to clarify how prescribed fire can be best utilized as a conservation tool, but it is clear that the need for prescribed fire in the forest landscape is unlikely to diminish.

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Introduction

In the summer of 2014 a single fire encompassed 13 100 hectares of forest land in the county of Västmanland, a fire of unprecedented size in modern-day Sweden (Gustafsson *et al.* 2019). Four years later, in 2018, summer drought resulted in several large fires in Sweden, with approximately 21 000 hectares of forest land being burnt (MSB 2019). The socio-economic impact in the wake of these fires has been high. For example for the Västmanland fire, the costs of firefighting, insurance, damaged infrastructure and timber stocks have been estimated to have reached a billion SEK (Länsstyrelsen Västmanland 2015). In Sweden, wildfires at the urban-wildland interface have generally been effectively prevented in modern-times, but with large fires, such as those in 2014 and 2018, ultimately the risk of the fire encroaching on settlements increases. This threat to private property and human lives adds to the generally negative public perception of fire. Furthermore, the consequences of climate change, and what it may mean for future wildfire risk, is getting increased attention.

During the same time period (2015-2019), the EU project LIFE taiga executed prescribed fires within forested Natura-2000 areas in Sweden, as a restoration measure to benefit biodiversity (Life Taiga 2019). Despite the two mentioned large fire years (years with unusually high number of wildfires) in the last decade, the current fire frequency is very low in a historic perspective (Niklasson & Granström 2000; Ramberg *et al.* 2018). Effective fire suppression, in combination with current forest management practices that lead to for example fragmentation, has fundamentally changed the structure and composition of Swedish forests, with subsequent negative impact on biodiversity (Wikars 2018; Angelstam & Andersson 2014). Several pyrophilous and specialist species, such as certain saproxylic beetles, are threatened due to lack of substrates and habitats that fire creates (e.g. Dahlberg & Stokland 2004). Prescribed fire is one mitigation strategy employed to benefit such species. However, as there is a succession that follows a disturbance event such as a fire, which benefits different groups of species at each stage, prescribed fires needs to be executed with not only the spatial scale in mind but also the temporal scale (Kuuluvainen 2002; Halme *et al.* 2013). This highlights the need of reoccurring fires in the boreal forest landscape across time i.e. there is no endpoint at which enough area has been burnt.

This dichotomy of forest fires, on one side costly and destructive, and on the other side beneficial for nature conservation, is a complex issue that requires careful examination. If robust fire and forest management plans are to be developed understanding the interactions between the social and environmental factors that influence past and present fire regimes is necessary (Gillson *et al.* 2019). In this essay, I review what role fires have in the boreal forests of Fennoscandia. I discuss the history of fire in the boreal forest landscape, the present day state, the ecological responses to fire, and finally I explore what role fire may have in future forests.

The historic influence of fire in the boreal forests of Fennoscandia

Historically, fire has been an integral element of boreal forest ecosystems (Zackrisson 1977; Lehtonen & Kolstrom 2000; Niklasson & Granström 2000; Bergeron *et al.* 2004; Rolstad *et al.* 2017). Across the circumboreal region this has been repeatedly illustrated by forest fire researchers, led by pioneers such as Lutz (1956) who studied the ecology of fires in Alaska. In Fennoscandia, forest ecologists have recognized the importance of fire since at least 1977, when Zackrisson published his seminal study on historic fire activity in northern Sweden. In the decades since, researchers have utilized dendrochronology, pollen analysis, and sedimentary charcoal to gain information on historic fire size, distribution, season, number of fires and fire intervals (Zackrisson 1977; Wallenius *et al.* 2004; Granström & Niklasson 2008; Ohlson *et al.* 2011). Additionally, patterns in fire activity across regions and time, historic records, and climate data have been used to reconstruct the fire regimes across Fennoscandia (Wallenius 2011; Drobyshev *et al.* 2014; Rolstad *et al.* 2017). These studies have provided a clearer picture of how fire activity varied across Fennoscandia, influenced by human activities, climate, vegetation and landscape structures.

A major challenge when reconstructing past fire activity is deciphering the ignition source of a fire. The natural source of fire is lightning strikes (Granström 1993). In Sweden, the frequency of lightning ignitions is, compared to other regions of the world, relatively low. For example, in the western pine forests of USA approximately four fires per 10 000 ha/year are due to lighting, whilst in Sweden 0.05-0.23 lightning ignitions occur per 10 000 ha/year (Granström 1993; Kay 2007). Lightning ignitions peak in early July, with a slightly longer season in the southern part of the country (Granström 1993). Additionally, they generally occur after a prolonged drought when the fuel bed is dry, and as a result, fires caused by lighting often burn deep and affect all forest types (Hörnberg *et al.* 1995; Granström 2001; Granström & Niklasson 2008). However, humans have long been utilizing fire in the forest landscape for their own purposes e.g. slash and burn cultivation and in contrast to lightning ignitions humans can initiate fires under conditions when natural fires are not probable (Wallenius *et al.* 2004; Granström & Niklasson 2008). For example, burning in spring and early summer when lightning is not likely to strike and having certain control over the range of the fires they light. These differences between naturally ignited fires and human ignited fires can have an effect on the ecological response after the fire. Knowing the source of historic fires can therefore give an indication of the impact the fire has had on the landscape. Untangling the anthropogenic impact from ‘natural’ dynamics also gives us an idea of the historic baseline of the influence fire has had on boreal forest ecosystems.

Reconstructions of past fire activity can use information on for example fire size and season to draw conclusions in patterns seen. Across Fennoscandia, there are two major shifts in fire activity that both can be attributed to anthropogenic activity. The first shift occurred from around 1600 in southern Norway and Sweden to late 1700 in northern Norway. It was characterized by a reduction in fire size, increased fire frequency, and increased frequency of early season fires, indicating a growing human impact on the fire regime (Zackrisson 1977; Niklasson & Granström 2000; Niklasson & Drakenberg 2001; Wallenius *et al.* 2004, 2010; Rolstad *et al.* 2017). Additionally, the number of fires from this period is much higher than average lightning ignition frequency, which supports the large influence that humans have had on increasing fire in the boreal forest landscape at this time in history (Granström & Niklasson 2008; Wallenius 2011). Furthermore, records of human population migrations and growth coincide with the difference in timing between regions in this shift of fire activity in Fennoscandia, starting with the south and expanding northwards (Granström & Niklasson 2008; Rolstad *et al.* 2017).

The second change in fire activity in Fennoscandia occurred from c.1800 in the south to early 1900s in the north and entailed a radical reduction of forest fires, essentially eliminating fires from Fennoscandian forest ecosystems (Wallenius 2011). Estimated fire interval gives us an idea of the reduction in fire activity. Before the fire suppression era, the fire interval in Fennoscandia is estimated to between 20 and 350 years (Niklasson & Drakenberg 2001; Wallenius *et al.* 2010), while it today is estimated to be 10^3-10^4 years (Drobyshev *et al.* 2012). Estimating the area that burnt annually in the region before records of fires were consistently kept is a challenging, if not an impossible, task. Studies reconstructing fire history often report annual burnt area of 1% or higher (Zackrisson 1977; Niklasson & Granström 2000; Wallenius 2011). However, as the study areas that these estimates are built on are limited in size, (for perspective: 1% in Niklasson & Granström (2000) = 600 ha, compared to 1% of the forest landscape in Sweden = 283 000 ha), extrapolating this percentage to the landscape or national level involves a large amount of uncertainty. Nevertheless, we can be certain that the fire activity drastically reduced during the 19th century, and today is only a fraction of what it was historically. The main cause of this decline in forest fires is attributed to the modernization and industrialization of forestry and agriculture, with the subsequent abandonment of traditional uses of fire (Wallenius 2011). Moreover, as timber and timber products increased in value, fire suppression was prioritized (Wallenius 2011). The anthropogenic signature can also be seen in other fire regimes across the boreal zone. Both in North America and in Russia similar patterns in fire activity can be linked to human practices and migration, though the extent and timing varies (Lehtonen & Kolstrom 2000; Bergeron *et al.* 2004; Kay 2007; Wallenius 2011; Ryan *et al.* 2013).

Though human activities have clearly influenced fire activity in the past, and continue to do so, other variables have also shaped past fire regimes, such as climate. The climate-fire relationship is evident in reconstructions of past fire activity with large fire years correlating with climatic variables such as precipitation, temperature and oceanic pressure patterns. In North America, for example, studies have shown a link between long term climate patterns and the spatial synchrony of fires (Bergeron *et al.* 2001; Kitzberger *et al.* 2007). In Fennoscandia climatic variability has also had influenced fire activity, both on a temporal and spatial scale (Drobyshev *et al.* 2014, 2016; Aakala *et al.* 2018). A large scale study over eastern Fennoscandia pinpointed precipitation as the strongest driver of historic large fire years, with temperature coming second (Aakala *et al.* 2018). This pattern is seen across time, regardless of anthropogenic impact (Aakala *et al.* 2018). Large scale climate and Atlantic Ocean dynamics have a significant effect on the climate across Fennoscandia, with the western region largely impacted by Atlantic Ocean dynamics and the eastern region instead affected by continental climate dynamics (Drobyshev *et al.* 2016; Aakala *et al.* 2018). The difference in when large fire years in Finland have occurred (Aakala *et al.* 2018), compared to Sweden (Drobyshev *et al.* 2014) gives an indication of this climatic divergence. These larger scale climatic dynamics also seem to influence the climate-fire relationship on the regional scale. In the northern part of Sweden (above 60 degrees), the number of large fire years were fewer, but stronger correlated to temperature and precipitation than in the south during the period 1400 to 1800 (Drobyshev *et al.* 2014, 2016). Atlantic Ocean weather patterns could be one reason for the difference with shift leaving the northern region cooler and drier and the south warmer and wetter (Drobyshev *et al.* 2016). Precipitation and temperature affect the moisture content of fuel-loads in forests, thereby controlling their probability of burning.

Small-scale variability in historic fire activity in Fennoscandia has largely been attributed to variation in landscape and vegetation characteristics (Hörnberg *et al.* 1995; Hellberg *et al.* 2004; Wallenius *et al.* 2004; Ohlson *et al.* 2011). The northern boreal forests are heterogeneous landscapes, with north and south facing slopes, depressions with water bodies and mires and a number of different forest types. Natural fire breaks such as waterbodies, mires and moist northern slopes result in patchy fire occurrence (Hellberg *et al.* 2004; Wallenius *et al.* 2004). Hellberg *et al.* (2004) comparing a landscape with high areal coverage of mires to a relatively mire-free landscape found that fire activity differed significantly between the sites, with fires being larger and more common in mire-free landscapes. However, in years of severe drought mires also dry out, and their role as fire breaks diminishes (Hellberg *et al.* 2004; Wallenius *et al.* 2004). The role of forest types has also been widely studied and debated, specifically the difference between Scots pine (*Pinus sylvestris*) dominated and Norway spruce (*Picea abies*) dominated stands (Zackrisson 1977; Hörnberg *et al.* 1995; Wallenius *et al.* 2004; Ohlson *et al.* 2011). Spruce forests are generally mesic compared to drier pine forests. However, pine are also more adapted to fire with thick, scaly bark, and high crowns, whilst spruce with their low branches are more sensitive to fire. Several historical studies have found that though spruce stands were less prone to fire they were by no means true fire-refugia; during dry years these forests also burnt (Hörnberg *et al.* 1995; Wallenius *et al.* 2004; Ohlson *et al.* 2011). On the landscape scale topographic features and different forest types have led to a patchy fire occurrence both spatial and temporally, with some areas burning frequently and others more seldom. Additionally, the stochastic nature of lightning fire ignitions enhanced the variability of fire occurrence in the forest landscape. In contrast to Fennoscandia the dominating traditional view in other parts of the boreal zone has been that stand-replacing, large fires were the norm (e.g. Heinselman 1981). However, this picture has become more nuanced over time as fire research has increased into the vast heterogeneous tracts of Canada and Russia, and it is today widely recognized that fire behavior is diversified by variation in topography and vegetation (Cyr *et al.* 2007).

Forest fire activity in present day Fennoscandia

In present day Fennoscandia, fire is essentially eradicated from the forest landscape. In Sweden, it is estimated that 0.006% of forests burn annually (2011-2015 without the Västmanland fire), which is less than 2000 ha per year (Ramberg *et al.* 2018). The marginalization of fire as a disturbance agent in Fennoscandia can be attributed to efficient modern fire suppression techniques, utilizing extensive road networks, regulations and fire prognosis systems (Skogstyrelsen 2019). Human activities are, however, still responsible for the majority of fires started, with only a few percent of ignitions linked to lighting strikes (MSB 2019). Further evidence of the human signature is the clustering of fires around cities and towns (Ramberg *et al.* 2018). Prescribed burning is the major contributor of burnt forest area in Sweden in recent times, with 65% of the total burnt forest area (2011-2015) attributed to prescribed fires (Ramberg *et al.* 2018). About half of the area that prescribed burning covers annually is due to burning on clear-cut forests sites (Ramberg *et al.* 2018)[1]. Wildfire area tends to increase in years of drought. For example, during the two large fire years of 2014 and 2018, weather conditions were the underlying reason for the extensive area burnt. However, the ignitions source during these years is still dominated by human activities. For example, the large wildfire in Västmanland 2014 started due to sparks from a forestry machine involved in soil scarification (Länstyrelsen Västmanland 2014). Present day fires therefore seem to largely mirror the fire activity between 1600 and 1800 in Fennoscandia (if at a much smaller scale), with anthropogenic activities largely steering fire, but with climate influencing at larger temporal and spatial scale. This similarity between past and present fire activity, integrating both anthropogenic influence and climate, can be useful when discussing future fire activity and management.

[1] For further details on current forest fire activity in Sweden pleases see Ramberg *et al.* 2018.

The effect of fire on boreal forest structure and species

Structural heterogeneity within a landscape is generally recognized as being pivotal for supporting biodiversity, and is maintained through disturbance events and successional processes (Kuuluvainen 2002). In boreal forests, fire is recognized as one of the most important disturbance agents. The effect that fire has on a forest landscape depends on several factors such as topography, weather conditions and fuel-load build-up, which consequently affect the fires depth, intensity and size (Granström 2001). These variables in turn lay the foundation for the succession that follows.

Burn depth and fire intensity both largely affect vegetation structure and dynamics. Deep burns expose mineral soil which allows for the colonization of seed dispersing plants, resulting in recruitment of deciduous trees, which alters the vegetation structure in the long term (Schimmel & Granström 1996; Gustafsson *et al.* 2019). Seed bank plant species are also favored by deeper burns, especially fire adapted species such as *Geranium bohemicum* that generally need high temperatures for the seeds to germinate (Schimmel & Granström 1996; Risberg & Granström 2012). In contrast, shallow burns seldom have any long-term effects on plant succession. Rhizomatous dwarf shrub species (eg *Vaccinium sp.*) that are abundant in boreal forests, often survive surface fires and commonly recover after only a few years (Schimmel & Granström 1996). Moreover, as the organic soil layer is still largely intact after a shallow burn, recruitment of deciduous seedlings is limited (Gustafsson *et al.* 2019). Tree mortality can be a result of both burn depth and fire intensity. Deep burns may cause tree mortality if roots are damaged, often killing the trees relatively slowly. In contrast, high-energy fires result in extreme heat and crown fires, killing trees more directly. The result of both burn depth and intensity is an increase in standing and fallen dead burnt wood. Tree mortality also alters the shade, moisture and nutrient conditions on the forest floor, benefiting seedling growth. In contrast, less intense fires often damage trees, creating for example fire scars. On a larger spatial and temporal scale, fires of different intensity and depth result in mixed-species multi-layered forests containing substantial amounts of dead wood.

The substrates that a fire creates and the vegetation succession that follows diversifies the habitat structure in the forest. This has repercussions for several species groups, both in the short term and in the long term. According to Dahlberg and Stokland (2004) approximately 400 species of fungi, lichen, mosses and insects are associated with burnt wood. Fire associated species can be group into two categories: pyrophilous (fire-loving) and fire-favoured (Hjältén *et al.* 2018). Pyrophilious species mainly occur in brunt areas, have evolved traits in response to fire and rely on fire for their long-term survival (Wikars 1997). Though few species are truly pyrophilious (approximately 100 species in Sweden) many exhibit one or two traits associated with fire, these are known as fire-favoured species (Wikars 1997, 2018; Hjältén *et al.* 2018). Beetles are one group of species that benefit from habitat changes that fire creates (Hjältén *et al.* 2018). Pyrophilous beetles are found on burn sites soon after a fire. Several are able to detect fire from a considerable distance and often are symbiotic with pyrophlious fungi (Hjältén *et al.* 2018; Wikars 2018).

Many of the saproxylic beetles that are favored by fire, benefit from the large quantities of dead wood created by the fire (Wikars 2018). As damaged trees slowly die and dead wood decays, it promotes high biodiversity as different saproxylic species benefit from different decay stages. The gaps in the canopy created by dead trees also increases the amount of sun-exposed wood which has shown to be an important habitat for many saproxylic insects (Dahlberg & Stokland 2004; Hjältén *et al.* 2018). Increases in insect populations in turn attract predators such as birds. One bird group that benefits are woodpeckers. They thrive a few years post-fire in response to large influxes of saproxylic beetle (Versluijs *et al.* 2017; Gustafsson *et al.* 2019). Dead trees are also important habitats for many birds. These are only some examples of species responses to fire and the succession that follows. Other affected groups include rodents, butterflies, ungulates, fungi, and lichen (e.g. see Gustafsson *et al.* 2019). The large number of species in Fennoscandian boreal forests that depend on, and are adapted to fire, gives an indication of the role fire has had as a principal disturbance agent in the region historically. Knowledge of these ecological responses to fire gives us an idea of what conservations measures are necessary to preserve biodiversity.

The lack of fire in present day Fennoscandia is a threat to boreal forest biodiversity. Several organisms that in some way rely on or are favored by fire are endangered (Dahlberg & Stokland 2004; Wikars 2006, 2018) and prescribed fire is one mitigation measure used to benefit these species. As prescribed burning is a major contributor to the burnt area, which these species benefit from, the need for effective planning and execution of fires is essential. It is also vital, however, to take a wider perspective and see the forest landscape as a whole. Silvicultural practices have largely reduced boreal forests to homogenous stands and increased fragmentation of protected forests and old-growth forests (Angelstam & Andersson 2014; Wikars 2018; Felton *et al.* 2019). Additionally, due to current forest management practices the volume of high quality dead-wood in production forests is substantially less than in natural forests (Jonsson *et al.* 2016). These factors negatively affect biodiversity, for example by limiting the dispersal of, and substrate for, saproxylic beetles. The condition of the forest matrix is therefore also increasingly recognized as important for fire-favored organisms (Saint-Germain *et al.* 2008; Wikars 2018).

Future perspectives

Wildfire

Evaluating future wildfire risk is becoming increasingly important in the light of climate change. Predictions on future wildfire activity are largely based on climate models (Yang *et al.* 2015; Khabarov *et al.* 2016; Lehtonen *et al.* 2016) which result in different climate scenarios based on the geographical location and the concentration of greenhouse gases used. Currently, four climate scenarios are utilized globally, RCP2.6, RCP4.5, RCP6 and RCP8.5, of which the first is the least extreme and the latter scenario the most extreme (for details and definitions on scenarios see: IPCC 2014 & Persson *et al.* 2015). Based on current trends of greenhouse gas emissions scenarios RCP6 and RCP8.5 are the most likely, resulting in a global temperature increase of 2°C- 4°C by 2100 (IPCC 2014).

In Fennoscandia, simulations based on the RCP8.5 scenario indicates that summer temperatures will be 3°C- 4°C warmer than the baseline (1961-1990) by 2100, and that precipitation will increase, particularly in the northern parts of the region both in spring and summer (SMHI 2019). Additionally, due to warmer winters the vegetation period will increase by 40 days or more by 2100 (SMHI 2019). The other RCP scenarios result in similar, but less dramatic, changes by 2100 (SMHI 2019). For extreme weather events there are some trends, for example, droughts and heat waves are expected to increase, and cold snaps in winter will be less common. In general, regional models are associated with large uncertainties, and the following quote "Across many extreme variables, the available information is not sufficient to identify clear trends in recent decades" by Belusic *et al.* (2019) highlights the need of further research. The uncertainty carries over to future scenarios. However, based on current knowledge applied in climate models, most extreme weather conditions such as floods and droughts are expected to increase (Belusic *et al.* 2019). How these extremes will play out on a regional scale is uncertain. For example, the projected warmer temperatures in the southern parts of Scandinavia will result in increased evaporation and increased plant water uptake, exacerbated by little or no increase in precipitation, with subsequent increased risk of drought and wildfires. In contrast, in the northern parts the expected increase in precipitation is higher and therefore bouts of droughts are not deemed to increase in the future (Belusic *et al.* 2019). These types of climate scenarios together with the fire weather index (FWI) system are often used to predict future wildfire activity. FWI is a commonly used index to estimate the wildfire risk, taking into account fuel moisture levels and weather. Though the majority of research on future wildfire risk has been done in North America (Flannigan *et al.* 2009; Coogan *et al.* 2019), a limited number of studies have focused on Fennoscandia.

In Fennoscandia, the occurrence of large fire years are positively correlated with longer periods of dry weather (Drobyshev *et al.* 2014). We can therefore expect a higher wildfire risk, and a longer fire risk season in regions where climate scenarios predict an increased length of the growing season combined with extended periods of drought. Yang *et al.* (2015) and MSB (2013) both found that the south-eastern parts of Sweden are most likely to have increased fire risk in the future due to the warmer climate and moderate precipitation predicted for this region. The south-eastern part of Sweden is already today the region with highest fire risk (MSB 2013). In northern Sweden the fire risk is instead expected to be similar to present day risk, or even lower due to the increase in precipitation (MSB 2013; Yang *et al.* 2015). In Finland, Lehtonen *et al.* (2016) concluded that fire risk, number of large fires (>10 ha), and area burnt will increase across Finland in the future. Similar to Sweden the largest increase is in the southern parts of the country. However, it is important to note that present burnt area in Finland and Sweden is very small (Lehtonen *et al.* 2016; Ramberg *et al.* 2018), and thus a single large fire would have a large impact on statistics. The Västmanland fire of 2014 for example was 100 time larger than any other fire during 2011-2014 in Sweden, and was twice the total area burnt in Finland between 1996-2014 (Lehtonen *et al.* 2016; Ramberg *et al.* 2018). Additionally, results of studies based on modelling of future climate scenarios and fire risk contain large uncertainties, and vary to a large extent depending on which scenario and climate models is used. Furthermore, interactions and feedback mechanisms with other natural disturbances, changes in vegetation composition, precipitation and evaporation, and oceanic and continental climate dynamics are extremely challenging to model, which further increases the uncertainty. In a review, Seidl *et al.* (2017) concluded that several disturbances, including fire, will increase with global warming, and that interactions between disturbance agents is likely to amplify this effect. They also concluded that more research is needed to understand these complex mechanisms, and that many current models do not integrate interactions and indirect effects needed to accurately predict the responses (Seidl *et al.* 2017).

An equally important factor to consider in relation to climate change and wildfire risk is anthropogenic activities. Both past and present fire regimes have largely been influenced and managed by humans, and there is no evidence to suggest that this will change in the future (Granström & Niklasson 2008; Flannigan *et al.* 2009; Ramberg *et al.* 2018; Coogan *et al.* 2019). Lehtonen *et al.* (2016) found that there was little correlation between the FWI index and fire activity in spring and autumn, when human activities, such as clearing, hunting and prescribed burning take place. Thus, models only using fire indices and climate models to forecast future fire activity, ignores an important variable, human activity. Human ignitions is the main cause of fire, and often occur close to urban areas, increasing both threat but also allowing for faster detection and suppression (Flannigan *et al.* 2009; Lehtonen *et al.* 2016; Ramberg *et al.* 2018).

The large number of recorded fires with small area (Cumming 2005; Lehtonen *et al.* 2016; Ramberg *et al.* 2018), indicate that most fires are swiftly controlled and that fire suppression is today, in general, effective. The challenge, both presently and in the future, is when many fires ignite within a short time frame, which is a common situation following extended periods drought. Since Fennoscandia has had few large fires in the past century, human activities have adjusted to this status quo. To meet changes that may occur under global warming fire prevention, preparedness and suppression techniques will need to be made more efficient. Some adaption strategies are for example avoiding certain forest operations and recreation activities during high fire risk periods (Flannigan *et al.* 2009; Coogan *et al.* 2019). In Sweden today, we have already seen both forestry activities and firefighting techniques revised to account for large fire years, largely due to the lessons learnt during the Västmanland fire of 2014 (MSB 2015; The Swedish Forest Agency 2019).

Prescribed fire

As previously mentioned, the importance of fire for boreal forest ecosystems is widely acknowledged and currently prescribed fires are used to maintain fire legacies (Granström 2001; Ryan *et al.* 2013; Eales *et al.* 2018; Ramberg *et al.* 2018). Two main arguments can be made for the continued use of prescribed fire. Firstly, prescribed burning is increasingly recognized as an efficient mitigation tool both to control wildfires and a pro-active measure to mitigate effects of wildfires (North *et al.* 2012; Khabarov *et al.* 2016; Flanagan *et al.* 2019). Secondly, as wildfire suppression is generally effective and pressures on forests are predicted to increase the need for prescribed burning as a conservation tool is likely to persist (Lindahl *et al.* 2017; Felton *et al.* 2019; Gillson *et al.* 2019).

In Fennoscandia, prescribed fire is not commonly used as tool in wildfire management, but in other parts of the world it is relatively common (North *et al.* 2012; Flanagan *et al.* 2019). However, if wildfires do increase in Fennoscandia in the future, prescribed burning may be a useful tool to reduce fuel loads, for example in sensitive areas such as the urban-wildland interface. Khabarov *et al.* (2016) suggest that increased use of prescribed fire is an effective tool to counter increased problems with wildfires under global warming, and according to their estimate prescribed fire would reduce the anticipated increase in wildfire by 150%. In addition, prescribed fire is cost efficient in comparison to alternative methods for reducing fuel loads, as well as being cheaper than suppressing wildfires (North *et al.* 2012).

Wildfires are a source of high carbon emissions and other airborne pollutants (Flannigan *et al.* 2009; Gustafsson *et al.* 2019; Rebane *et al.* 2019). Research comparing prescribed burning to wildfires show that carbon emissions and pollutants are lower from prescribed fires, as they are usually less intense (Liu *et al.* 2017; Flanagan *et al.* 2019). Thereby, using prescribed fire to control wildfire may reduce carbon emissions. In terms of carbon emissions, the alternative of not burning is, however, the best option. To date emissions from prescribed burning is seldom discussed in Fennoscandia. However, carbon emissions and sequestration with associated trade-offs within forestry is a subject that already today is debated (Lindner *et al.* 2010; Lindahl *et al.* 2017; Eyvindson *et al.* 2018), and as global warming becomes more pressing this discussion may well grow to include prescribed burning. To decide on the best course of action the carbon emissions that prescribed burning entail need to be balanced against both prescribed fires usefulness as a wildfire management tool and its importance for maintaining forest biodiversity.

In relation to the potential increase of wildfires in the future, it is essential that we keep in mind both past and present fire activity. Fire suppression today is effective, and we know that the forest area burnt annually in Fennoscandia is considerably lower than what has burnt historically (Niklasson & Granström 2000; Wallenius 2011; Lehtonen *et al.* 2016; Ramberg *et al.* 2018). Thus, it is fairly safe to assume that even if the frequency of wildfires increase with a change in climate, fire suppression will likely be efficient enough to keep the total burned area well below historic levels. Thereby, the need for prescribed fires as a conservation measure in boreal forests is likely to endure even with increased wildfire activity. In addition, choice of future forest management will also be of consequence for biodiversity, and thereby influence our need for conservation measures.

Today's forests face multiple pressures and goals ranging from providing ecosystem services to increased wood production. Though in theory biodiversity and production goals should be equally prioritized, production is in practice usually prioritized (Lindahl *et al.* 2017). As a result a large percentage of forests in Sweden are highly managed homogenous production forests which has had negative effects on biodiversity (Kuuluvainen 2009; Halme *et al.* 2013; Wikars 2018; Felton *et al.* 2019). Efforts to move away from fossil-fuel based economies towards bio-based economies will put additional pressures on forest ecosystems in the future. Increased production is put forward as solution to many problems, for example as a method to increase carbon sequestration to mitigate climate change, which likely will result in even further pressure on biodiversity (Lindahl *et al.* 2017; Eyvindson *et al.* 2018; Normark & Fries 2019). Prescribed fire may be one conservation method that can alleviate the negative effects on biodiversity. Fire creates and maintains structural and species diversity. In parts of the boreal forest, e.g. in Canada, wildfires are allowed to burn unchecked if they are no major threat to people or property (Coogan *et al.* 2019). This is probably not possible in Fennoscandia, since a majority of the forested area has an economic value. Instead, prescribed fire may be a practical surrogate. The value of prescribed fires for biodiversity is generally acknowledged, many species that are favoured by wildfires are also favoured by prescribed fires (Eales *et al.* 2018). Furthermore, wildfires location is somewhat random in contrast to prescribed fires which can be planned within protected areas allowing the values that fire creates to endure (Ramberg *et al.* 2018). For example, the prescribed fires within the Life Taiga project are all within Natura-2000 areas (Life Taiga 2019). An additional motivation for continued use of prescribed burns is that diversity is advocated to increase resilience of forest ecosystems in regard to changing disturbance regimes due to climate change (Seidl *et al.* 2016). Thereby, not only is prescribed fire potentially a useful conservation measure it may also be a method to increase the ability of production forests to withstand disturbances.

There are, however, some gaps in knowledge in regard to prescribed fires tied to methods of execution, site choice and when to burn to be most beneficial for biodiversity. As prescribed fires are both costly, and limited in the extent they can be applied in the landscape due to economic and social factors, it is important that the prescribed fires that are executed are effective and that conservation goals are met. For example we know little of what type of forest is most favourable to burn, forest with innately high conservation value (e.g. old growth forests) or forest with low conservation value (e.g. homogenous pine forests). The first option would enhance values already present whilst the latter is a restoration measure. In addition how the surrounding landscape affects the result of a prescribed burn, both in terms of distance to other fires and landscape characteristics is still debated (Hjältén *et al.* 2018). An additional issue is the timing of the burn. A common criticism is that prescribed fires are often executed when the ground fuels are relatively moist (Granström 2001; Ryan *et al.* 2013). This is due to safety issues, which is understandable, but the value of the burn as a conservation measure under such conditions is unclear. More research is needed to clarify how prescribed fire can be best utilized as a conservation tool but it is evident that the need for prescribed fire in the forest landscape, now and in the future, is unlikely to diminish.

Conclusions

Fire regimes are formed by complex interactions and feedbacks between climate, landscape, ecology and human activities and policy. Historic and present fire activity is vital for understanding the range of variability of these systems. This is turn is necessary for shaping realistic fire management policy and resilient forest ecosystems, now and in the future. In Fennoscandia, fire has historically been a major disturbance agent, but is today a rare event, which in itself is a threat to biodiversity. Therefore, maintaining fire in forest landscapes is vital, yet the negative aspects of fire need to be considered. Though future fire activity is uncertain, there are indications that wildfires will become more common in certain regions of Fennoscandia due to global warming. The need for prescribed fire as a conservation measure is, however, likely to remain high, as it is improbable that future fire activity will reach historic levels as fire suppression is efficient. Thereby, for fire legacies to endure prescribe fires will need to be executed. Additionally, increased pressure on forest ecosystems goods and services in the future is deemed to have negative effects on biodiversity, highlighting the need for effective conservation measures. Although the value of prescribed fire for preserving biodiversity is generally acknowledged, more research is needed to increase the efficiency of prescribed fires.

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