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– An Evaluation of Structural Outcomes from Restoration Oriented Prescribed Burns

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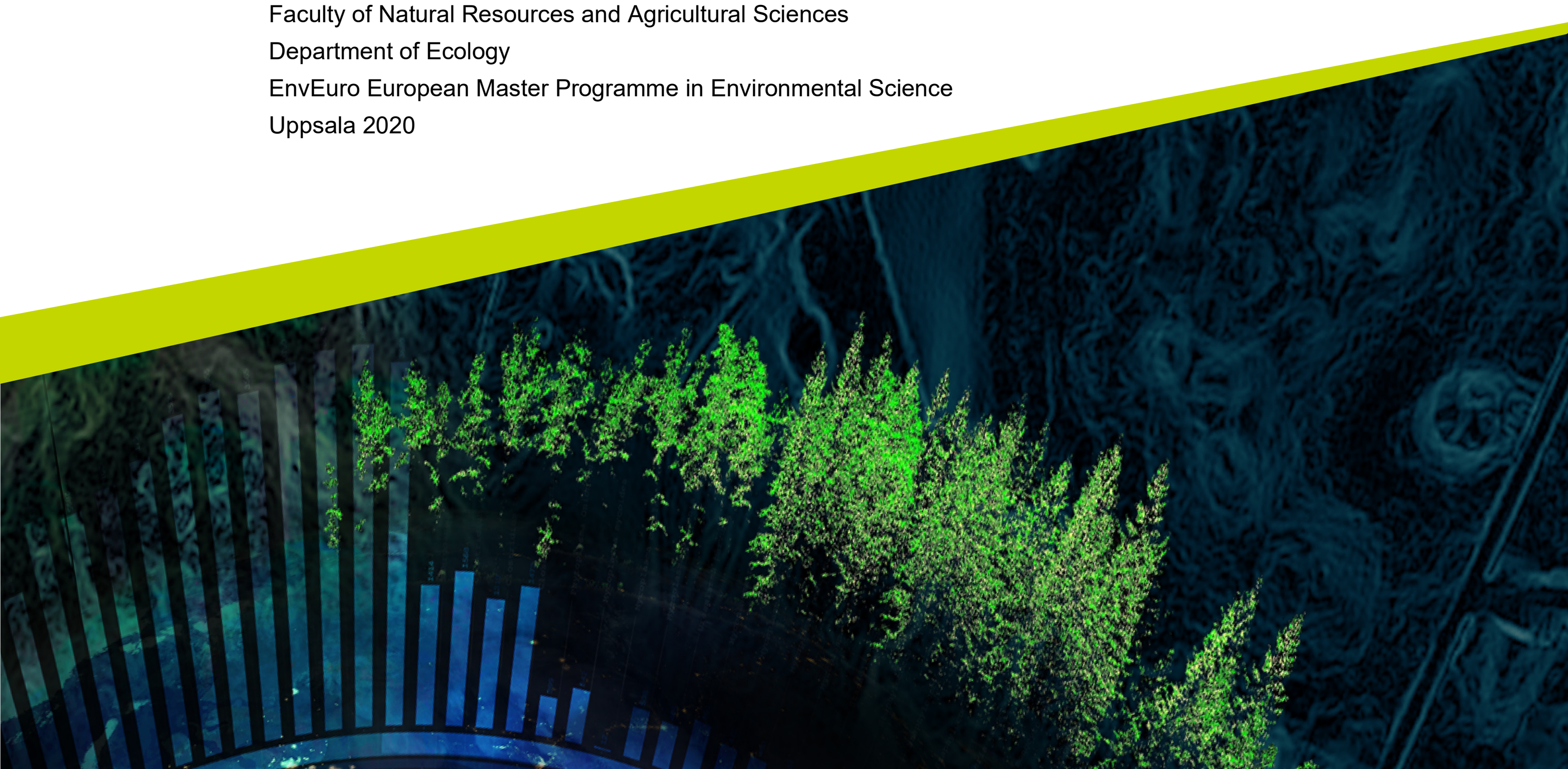

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Abstract

The application of prescribed burning as a conservation measure is a growing trend in Fennoscandia to restore forest landscapes that have been heavily impacted by humans. Both intensive management for forestry and wildfire suppression altered the disturbances shaping boreal forests over the past centuries, which seen today are more homogenous, lacking dead wood and deciduous trees, and are in the successional process towards darker *Picea abies* (Norway spruce) dominated stands. Prescribed burning in Sweden is intended to improve biodiversity by thinning *Pinus sylvestris* (Scots pine) stands and highly reducing the presence of spruce, creating high volumes of sun-exposed dead wood, fire scarred trees, and soil conditions benefitting deciduous trees.

The purpose of this project was to quantitatively evaluate the effectiveness of prescribed burning in producing these changes and features. Eleven prescribed burn sites were surveyed in fall 2019 for targeted structural values, and meteorological information was extracted from online national databases and from summary reports describing the burns. Field data was compared with meteorological conditions through correlation analysis to identify clear trends between burning conditions and the outcomes of the burns.

The results and field observations indicated that the burns were very low intensity, and in most cases, did not result in the targeted structural changes. Mortality rates were particularly low in older stands, especially in those without spruce, as the burns were most effective at killing spruce and small diameter pines. This highlights the importance of stand structure and choice of stand in achieving successful burn outcomes. Correlations between meteorological variables and outcome variables indicated that burning needs to take place when conditions are warmer and drier to achieve the desired structural values. Prescribed burning operations, however, may be limited to low intensity burning due to concerns around safety, values at risk, public opinion, as well as typical climate. Further research is needed to determine the characteristics of sites that this type of low intensity prescribed burning is appropriate for to achieve conservation targets, though this initial review indicated greater success in younger and more heterogeneous stands. Manual work done in preparation for prescribed burning could improve results. On-site weather and intensity data, as well as biodiversity surveys are needed to better understand the link between burning conditions and the outcomes in different types of stands, and what levels of targeted values need to be reached to provide habitat improvements and benefits to biodiversity.

Keywords: prescribed burning, restoration, boreal forest, biodiversity burning, dead wood.

Popular Science Summary

Before industrial activity dominated so much of the natural world, wildfires were important ecological events throughout Swedish forests. They typically occurred when weather was hot and dry and burnt over large areas, drastically changing the structures remaining and the ensuing regeneration that would occur. Fires added high volumes of dead wood to forests, which supported the many species who relied on dead wood as habitat or food. After deep burning fires, deciduous trees would abundantly establish, meaning that near exclusive patches of broad leaf trees were present throughout the landscape. Scots pine dominated much of the forest area with Norway spruce growing primarily in low-lying moist sites where fires were less frequent. Forests throughout Sweden were a mosaic of pine and spruce dominated stands of varying ages, patches of deciduous trees, and a complex of varying stages and sizes of decaying wood, which hosted highly biodiverse ecosystems, home to strong populations of species. Today however, there are many species that are threatened due to the extensive changes seen in forest structure compared to the rich and diverse landscape of the past.

A large part of the changes that have taken place over the past centuries has been the vast reduction in wildfires in Sweden. Suppression has become so efficient that less than 0.01% of forested areas burn each year. This has led to higher spruce abundance than used to be seen, and increasingly low deciduous tree abundance, as deciduous species rely on significant disturbances such as wildfire to regenerate. The intensive management of forests in Sweden has also contributed to the changes in forests, as most managed stands are a monoculture of one species and one age. Additionally, the historic emphasis placed on the "live tree" means that standing and fallen dead wood have become nearly absent in many forests.

When the species and biodiversity declines were recognized, there were efforts to set aside conservation areas where missing habitat elements could be recreated, such as high volumes of dead and decaying wood, deciduous trees, and a more mixed age structure of pine trees. Prescribed wildfires are one way that managers of conservation areas try to recreate these elements and have become increasingly common in the last ten years in Sweden. However, there has never been a study that investigates what structures these types of fires are creating on a larger scale, and whether the effects are comparable to those of the natural wildfires they are meant to replicate. This study assessed eleven prescribed burns that were completed in conservation areas in South Central Sweden over the past seven years and attempts to summarize the structures produced and how these related to the weather and climate conditions under which each burn took place.

Overall the results revealed that the prescribed burns were very low intensity compared to wildfires, and the changes within the stand were similarly minimal. The tree mortality rates were much lower than hoped by the burn managers, and in

most cases the targeted outcomes were not achieved. The burns primarily killed small diameter pine trees and in some sites effectively removed some spruce trees. This meant that in sites without smaller pine trees or spruce there was almost no dead wood produced. Disturbance to the organic soil layer was so minimal that regeneration of birch trees was low in all sites, and spruce seedlings continued to regenerate. These prescribed burns did not cause all of the desired effects; however, they provided some insight in the prescribed burning process. The data illustrated that the effects were greater when sites were burnt in drier and hotter periods (though burning under increasingly hotter and drier conditions raises some concerns around safety). Another trend was that sites that were more heterogeneous to begin with and were younger sites, tended to have better outcomes from the burns. This indicates that prescribed burning will not be effective in all forest types and perhaps other restoration measures are needed to support or replace prescribed burning in certain cases. Lastly, this study indicated how complex these processes are and how much is still to be learned. Further research is needed on this topic to understand the role that prescribed burning can play in restoring boreal forest habitats in Sweden.

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1. Introduction

1.1. The Importance of Fire in Sweden

It has been long accepted that natural boreal forests have been highly influenced by wildfire both as a natural disturbance factor and a driver of the regenerative processes which follow (Zackrisson 1977; Angelstam 1998). However, the development of highly effective fire suppression techniques aided by expansive forestry road networks has resulted in extreme reductions in the area burned each year to such an extent that important ecological effects of fire could be completely missing from vast areas of Fennoscandian boreal forest (Niklasson and Granström 2004; Majamaa *et al.* 2007; Lindberg *et al.* 2020). According to Ramberg *et al.* (2018) between 2011 to 2016 an average of 0.006% of Sweden's 23 million hectares of forest burnt annually, which differs drastically from the scale at which wildfires used to burn across Sweden. This change has significantly altered the disturbance regime of Swedish boreal forests and led to more homogeneous, and late successional stage forests (Esseen *et al.* 1997; Granström 2001). The intensification of forestry and the large-scale monopoly which industrial silviculture has on forested land in Sweden has further contributed to the homogenization of forests, with management choices rooted in forestry driving forest structure and comprising the main disturbances (Kouki *et al.* 2001; Gustafsson *et al.* 2010).

The result of this change in forest disturbance regime has been the decline of species that rely on the complex structures present in older more heterogeneous forests that are impacted by stochastic disturbances such as wildfire (Siitonen 2001; Granström 2001). In Fennoscandian boreal forests these components can include the presence of deciduous trees, variation in gap and successional dynamics, high elements of coarse dead wood at different decay stages, and longer temporal continuity of the forest stands themselves (Esseen *et al.* 1997). There have been some changes in forestry regulation, to try and promote such elements in managed forests through practices such as variable-retention, dead wood creation, selective logging, and in some cases prescribed burning of areas post-harvest (Jonsell *et al.* 1998; Rouvinen *et al.* 2002; Lindberg *et al.* 2020). However, these measures are not always completed to optimize ecological benefits, and instead can be driven by ulterior motives such as forestry industry certifications or applied without strong regard for the ecological links (Johnson and Miyanishi 1995; Lindberg *et al.* 2020).

In boreal forests there are relatively few species defined as pyrophilous or truly dependent on fire, but many species which are thought to benefit from the effects of fire (Wikars 1997; Jonsell 1998; Hjältén *et al.* 2018). This is considered to be especially true for saproxylic species which rely on dead wood. In Sweden, nearly 2000 invertebrates have been classified via the red-list as threatened species, and out of the forest dwelling invertebrates assessed by Jonsell *et al.* (1998), 69% percent were considered saproxylic. Their decline is consistently linked to reductions in the amount and size of dead wood found throughout forests and the replacement of forest management as the dominant factor shaping stand structure (Siitonen *et al.* 2001; Hjältén *et al.* 2018). Especially in beetle species, which can be used as a proxy for biodiversity, there have been marked declines of saproxylic types (Vanha-Majamaa *et al.* 2007).

Rouvinen *et al.* (2002) found volumes of dead wood as low as 6.6 m^3 ha^{-1} when surveying abundance of coarse woody debris in managed *Pinus sylvestris* (Scots pine) stands in Fennoscandia. This drastically differs from the averages of 67 and 92 m^3 ha^{-1} found in the natural sites included in the study (Rouvinen *et al.* 2002). While there are certainly ranges of dead wood abundance in both natural and managed forests, the pattern of highly reduced volumes in managed forests has been well established (Siitonen 2001; Rouvinen *et al.* 2002; Sandström *et al.* 2019). One suggested mediation for this is to increase fire across the landscape that should impose tree mortality and produce dead wood for saproxylic species of concern (Hjältén *et al.* 2018). If fire intensity is too low to impose mortality, fire scars or marks may form on trees and contribute to the desired structural and substrate heterogeneity within a burnt stand (Piha *et al.* 2013; Life Taiga n.d.).

Fire is also thought to support biodiversity through the effects of stand thinning, which creates more sun exposed areas (Kuuluvainen *et al.* 2002; Niklasson and Granström 2004). This could be particularly relevant in later successional Scots pine stands overgrown with *Picea abies* (Norway spruce) (Esseen *et al.* 1997). More than half of the red-listed species discussed in Jonsell *et al.* (1998) were assessed as being at least indifferent to or to favour sun exposure. Numerous species were found to particularly favour sun exposed dead wood, which should be a product of burning and as such, burning should particularly benefit that group of threatened species (Jonsell *et al.* 1998). Increased sun exposure should also benefit ground vegetation and tree seedlings which establish following burns, among other possible benefits to regenerating plants, such as increased nutrient availability, modifications to the soil and humus layer, and decreased vegetative competition (Pasanen *et al.* 2015). Though increases to nutrient availability, changes to soil pH, and organic layer consumption will be minimal from low intensity burns (Vanha-Majamaa *et al.* 2007).

In more extreme cases, high intensity fires can lead to significant increases in deciduous tree populations by near complete consumption of the humus layer, as many deciduous trees can only establish seedlings on mineral soil or where a very shallow organic layer remains (Gustafsson *et al.* 2019). In this way, many deciduous trees could be considered highly fire favoured, as could the insect and bird populations for whom deciduous tree species are ecologically important (Angelstam 1998). Pines can similarly benefit from consumption of the organic soil layer along with increased sunlight following fires and will make up a large part of the post-fire succession along with deciduous species (Zackrisson 1977). The establishment of young seedlings, particularly in areas where mortality was high after a fire, is thought to contribute to creating the gap dynamics and multi-stage stand structure that are reminiscent of Swedish boreal forests governed by fire regimes (Esseen *et al.* 1997; Kuuluvainen *et al.* 2002; Keeley 2008).

1.2. Variation in Structural Outcomes of Fire

The potential conservation benefits of fires are well recognized; whether they manifest after different fire events, however, is highly dependent upon the fire intensity and behaviour, and structural features of the burnt stand (Angelstam 1998). Tree mortality for example, is dictated by both species and size, and the type and intensity of fire which moves through the stand (Zackrisson 1977; Reinhardt and Ryan 1988). Scots pine have heightened resistance to the effects of burning due to thick, thermally resistant bark, and a tap root which is not damaged by burning (Reinhardt and Ryan 1988). Comparatively, Norway spruce is shallow rooted with much thinner bark so is not protected from the effects of fire, and fire intensities which are non-lethal to pine can be lethal to spruce (Zackrisson 1977; Reinhardt and Ryan 1988). However, according to Tanskanen *et al.* (2004), wildfire ignition success was higher in pine dominated stands in Finland. This illustrates how species composition can have an impact on moisture in the ground fuels, and as such the experienced fire intensity. Although spruce is more vulnerable to fire, the ground fuels in a spruce dominated area could have higher moisture content due to the denser tree foliage and more closed canopy, thus resulting in lower intensity fire (Zackrisson 1977; Tanskanen *et al.* 2004; Tanskanen *et al.* 2006).

Fire intensity is governed by the fuel available to burn, the moisture conditions of the fuel, and the weather conditions on the day of burning. In high intensity wildfires, more extreme mortality will take place due to high rates of thermal energy coming from the flames, inflicting damage on the trees (Granström 2001). These types of fires are known as stand replacing due to the mass mortality imposed (Lindberg *et al.* 2020). An example of this type of fire could be the 2014 megawildfire in South Central Sweden which inflicted near total mortality throughout more than 13,000 hectares of production forest (Gustafsson *et al.* 2019). Comparatively, ground or surface fires are of much lower intensity and will generally not cause tree candling due to the flaming combustion. Mortality is instead inflicted through damage to the vascular cambium of a tree, the resilience of which differs greatly between tree sizes and species (Johnson and Miyanishi 1995; Dickinson and Johnson 2001). In two studies looking at the effects of low intensity ground fires, mortality of the lowest size class (less than 10 cm diameter at breast height, DBH) was as high as 90% and decreased to 20% or lower in trees just larger than 10 cm DBH (Linder *et al.* 1998; Sidoroff *et al.* 2007). However, in both intensities of fire, glowing combustion or smouldering will occur following the flame front to the degree dictated by moisture content in the humus and duff layer, and can impose further mortality on shallow rooted tree species such as Norway spruce (Reinhardt and Ryan 1988; Johnson and Miyanishi 1995; Schimmel and Granström 1996). This type of combustion is primarily responsible for consumption of the duff layer, which has implications for tree regeneration, particularly of deciduous trees (Johnson and Miyanishi 1995; Pasanen *et al.* 2015).

When only partial death of the tree cambium occurs due to a passing flame front, trees may form fire scars if they have sufficient thermal resistance to its effects (Gutsell and Johnson 1996). According to Dickinson and Johnson (2001) fire scars can form due to a phenomena called the "chimney effect" during a wind driven fire event, where the flames enter a vortex on the leeward side of a tree causing increased combustion, height of flame, and residence time, thus inflicting more damaged to one side of the tree. However, the chimney effect will not occur at low wind speeds or when the diameter of a tree is too small for these vortexes to form, and fire scars formation will be less predictable as a result (Dickinson and Johnson 2001; Piha *et al.* 2013). Additionally, when trees are small a passing fire could result in total cambium death instead of fire scar formation, as smaller trees tend to have less protective bark (Piha *et al.* 2013). Large pine trees are likely to recover from partial death in the cambial layer and form a fire scar, where under comparable circumstances a spruce tree might die (Zackrisson 1977).

The intensity of a flame front will dictate whether damage is inflicted on trees in the form of a mark, a scar or tree death, as determined through the structural components of each tree (Reinhardt and Ryan 1988; Gutsell and Johnson 1996). As such, this type of outcome within the stand is determined by both the conditions of the fire and the stand which it is moving through. The impact that a fire has on soil though, is more directly linked to moisture conditions (Linder *et al.* 1998; Jordan 2013; Pasanen *et al.* 2015). Only in conditions of extreme drought will there be near total consumption of the humus layer exposing mineral soil (Gustafsson *et al.* 2019). In more moist conditions such as the conditions prescribed burns are generally carried out under, glowing combustion will be minimal due to low flammability of the organic layer, and the passing flame front consuming fine fuels will be the primary cause of change within the stand (Johnson and Miyanishi 1995; Jordan 2013). Due to differential moisture holding capacities, finer surface fuels can become flammable during periods of warm and dry weather far faster than mosses and the organic layer in the soil (Van Wagner 1974; MSB n.d.), as such, surface fires can occur in a stand with minimal to no consumption of the organic layer. Vanha-Majamaa *et al.* (2007) also attribute minimal consumption of the organic layer to lack of wind during burning.

These relationships highlight the importance of weather conditions during a fire and in the weeks leading up to burns as being highly formative as to the type and intensity of fire, and if a fire will result from ignition. Some suggest that weather is the ultimate determinant of how fires manifest (Granström 2001). Moisture levels in fine fuels and their flammability thresholds determine whether fire will propagate through an area, though the amount and type of fine fuels determines the fuel load, which impacts fire behaviour and spread (Tangren 1976; Keeley 2008; Piha *et al.* 2013). According to Keeley (2008) the fire climate at any given time is the culmination of the previous weather conditions and events which contribute to the fuel conditions within a stand. Precipitation events will increase moisture content in fuels, and periods of cold or humid weather will not allow for fuel drying. However, after periods of drought with hot weather and high winds, substantial fuel drying will take place and flammability will increase. The weather conditions during burning are described as largely determining the fire behaviour or intensity and together are termed the fire weather (Keeley 2008). Wind has been put forward as the most important factor of fire weather, particularly in wildfires (Granström and Niklasson 2008; Keeley 2008). Wind is also an important factor in prescribed burns as it often dictates ignition patterns and has been found to be highly related to tree mortality (Sidoroff *et al.* 2007).

Weather and fuel conditions, and the structural composition of a forest stand are inextricably linked in regard to fire behaviour and outcomes. The Fire Weather Index was developed in Canada as a predictive tool for describing wildfire risk and fire weather on a daily basis and was created by incorporating these compounding factors (Van Wagner 1974). The outputs of the system include the primary sub-indices Fine Fuel Moisture Code (FFMC, ground litter and cured fine fuels), Duff Moisture Code (DMC, mosses and superficial soil layer), and Drought Code (DC, thick humus layer) which represent the moisture content of the corresponding fuel types within a forest (Van Wagner 1974; MSB n.d.). Two intermediate sub-indices are calculated: the Initial Spread Index (ISI, wind speed + FFMC) and the Build-Up Index (DMC + DC). These are then combined to deliver the final index, the Fire Weather Index (FWI) which represents the intensity of the modelled fire in a fuel type (Van Wagner 1974; MSB n.d.). All of the indices have different ranges of values with low values corresponding to low fire intensity (high moisture content in fuels) and high values corresponding to high fire intensity (low moisture content in fuels).

The system relies on past and predicted weather data to calculate the six indices. However, the system incorporates different assumptions of standardized fuel types which influence the model, and different values for each index are calculated based on the fuel type in which they are applied (Van Wagner 1974). The indices provide practitioners with better understandings of potential fire behaviour in particular areas based on forest type. The index has been adapted and applied in Sweden by the Civil Contingencies Agency (MSB) and is used to provide daily fire risk indices throughout the country which best represent mid-afternoon conditions. While it has been officially implemented in Sweden, its effectiveness as a predictive system in Fennoscandia is still not fully understood, particularly for different types of fires such as prescribed burns (Tanskanen and Venäläinen 2008; Jordan 2013).

1.3. Prescribed Burning in Sweden

Based on the aforementioned ecological benefits of fire and its historic presence, there has been pressure across Fennoscandia to reintroduce fire throughout forested land in the form of prescribed burning. One way this trend has manifested has been through the Life Taiga project in which 120 restoration oriented prescribed burns were completed in Natura2000 areas throughout Sweden (Life Taiga n.d.). The burns were intended to increase structural habitat diversity which is thought to lead to increases in species diversity and abundance, particularly for threatened pyrophilous or saproxylic species (Toivanen *et al.* 2007; Hjältén *et al.* 2018; Life Taiga n.d.). Ideally, the outcomes of burning would be some degree of tree mortality and thinning to increase incoming sunlight and create dead wood, fire damage, and scarring on live trees, consumption of the humus layer in large areas to favour deciduous tree regeneration, and mortality of spruce trees in some cases, which all contribute to restoring gap-phase dynamics in a stand (Granström 2001; Kuuluvainen *et al.* 2002; Vanha-Majamaa *et al.* 2007). However, according to Kuuluvainen *et al.* (2002) there needs to be further research and understanding as to the connections between fire behaviour and the outcomes of burns, especially as they relate to techniques for carrying out restoration oriented prescribed burns. There has yet to be a large-scale study on whether prescribed burns are achieving the targeted outcomes in Sweden, particularly given the inherent limitations of the process.

As has been highlighted, the effects of high intensity natural wildfires differ greatly to the effects of low intensity surface fires (Granström 2001; Granström and Niklasson 2008). Prescribed burns are typically limited to burning in low intensity conditions due to constraints dictated by safety, which while certainty a crucial consideration has large implications for the possible outcomes. Public opinion has long played a role in motivating fire suppression and continues to influence where and how prescribed burns take place (Niklasson and Granström 2004; Lindberg *et al.* 2020). For example, the need for burns to be planned in areas with explicit borders (such as lakes or roads) for supporting containment, and the further complications of private land-ownership in Sweden often dictate site selection, rather than where the largest ecological improvements could be seen (Esseen *et al.* 1997; Granström 2001). According to Granström (2001), there tends to be more of a focus by managers on the total area burnt, rather than what is accomplished by burning. However, prescribed burning cannot be treated as a uniform tool for restoring sites as based on historic forests (Granström 2001), nor should the ecological effects of high intensity wildfires be expected due to restrictions on fire intensity and potential burn sites, as dictated by public concern and burning logistics.

Many studies and sites have reported positive effects on ecological and biodiversity outcomes following prescribed burns, though this is not always the case, and clear patterns between outcomes and treatments have yet to be identified (Toivanen and Kotiaho 2007; Eales *et al.* 2018). A part of this issue is the lack of explicit metrics and quantitative targets which are applied when restoration burns are monitored, with a focus on structural monitoring rather than indicator species (Angelstam 1998; Vanha-Majamaa *et al.* 2007). In addition, there is still a lack of understanding in how to effectively complete prescribed burns according to ecological prescriptions in European boreal forests (Granström 2001; Niklasson and Granström 2004). Among many academics there are calls for research and monitoring on this link between the target structural and biological state of a forest area, and how this can be achieved and executed through prescribed burning (Johnson and Miyanishi 1995; Kuuluvainen *et al.* 2002; Vanha-Majamaa *et al.* 2007). A more systematic approach to monitoring burns is necessary in order for techniques for effective burning to be developed for Sweden's boreal forest type, and for fire to be applied as a successful tool for biodiversity restoration (Kuuluvainen *et al.* 2002).

1.4. Research Objectives

This project was motivated by the need to develop target-based prescribed burning techniques and practices for Sweden. It is the pilot-project for a larger study of prescribed burns that will take place over the coming years, and in later stages will include site surveys for species of interest and biodiversity metrics. In this study, prescribed burn sites were surveyed for the structural changes seen throughout stands as a result of burning. The objectives were to (a.) quantify the structures of restorative value produced by the burns, and (b.) to identify any clear links between burning conditions and the structures produced, using the following questions as a guide.

1. Which targeted values were achieved in the prescribed burns and to what degree?
    - What rate of tree mortality was achieved?
    - How much dead wood was produced?
    - How abundant were fire scars on live trees?
    - How many tree seedlings have established since burning?
    - What was the effect on the organic soil layer and ground cover?

2. How were the outcomes of the prescribed burns related to the conditions prior to and during the burns?
    - Were precipitation and temperature prior to burning related to the outcomes of the burns?
    - Were the temperature, relative humidity, and wind speed during burning related to the outcomes of the burns?
    - Could the same relationships be seen between the values of the Fire Weather Indices for each burn day and the outcomes of the burns?
    - What were the effects of stand structure on the outcomes of the burns?

3. How were outcomes of the prescribed burns related to one another?
    - Were there climatic or structural conditions that were similarly driving multiple outcomes?

Through answering these questions, key trends between burning conditions and outcomes could be identified and put forward as recommendations for forest managers in the planning and execution of prescribed burns. In addition, the results should inform future stages of the project as to how sites can be best surveyed for these types of outcomes following a prescribed burn.

2. Methods

Data was collected from numerous sources to capture the full picture of the conditions leading up to, during the prescribed burns, and the state of the forests some years following the burns. Field data collected in fall 2019 was used in conjunction with meteorological data from the Swedish Meteorological and Hydrological Institute (SMHI) and the Swedish Civil Contingencies Agency (MSB), and prescribed burn summaries acquired through the County Administrations responsible for carrying out the prescribed burns. Data from field work was organized and averaged to illustrate the presence and abundance of structures in the burn sites which are considered of restoration value, and as based on the targets of the burns. Data analysis was completed using RStudio to determine whether there were correlations between the data representing the structures that the burns produced, the weather conditions leading up to and during the burns, the Fire Weather Indices on burn days, and the rate of burn.

2.1. Prescribed Burn Sites

Eleven prescribed burn sites were surveyed in the fall of 2019 over the course of ten days. Sites selected for this project were chosen based on their common restoration oriented burning targets, though stand age and composition were allowed to differ. Location, size, and proximity to one another were also factors given that field work was completed in a constrained amount of time due to seasonal limitations. Recently burnt sites were not surveyed because some structural effects are not apparent until some years after burns take place. The burn sites surveyed in this project were located in South Central Sweden in the Dalarna, Örebro, Västmanland, and Värmland counties. The most South Westerly was the Brattforsheden burn and the most South Easterly site was the Lappland conservation area with includes the Lappland A and Lappland B burns. The most Northern site was the Skattlösberg H site. The burn site names, locations, and sizes are summarized in Table 1.

Table 1. Burn site names, the municipality and county in which they are located, and the year that each site was burnt. Burn size is included in hectares, as is the corresponding number of sample points that were surveyed in each site.

Site Name	**Municipality & County**	**Year Burnt**	**Burn Size**	**Plots & Transects**
Brattforsheden	Karlstad, Värmland	2015	9.0	9
Lappland A	Skinnskatteberg, Västmanland	2014	16.4	16
Lappland B	Skinnskatteberg, Västmanland	2016	20.2	17
Nitten	Ljusnarsberg, Örebro	2013	2.65	4
Römyren	Ljusnarsberg, Örebro	2016	26.1	24
Skattlösberg H	Ludvika, Dalarna	2015	4.6	4
Ställbergsmossen A	Hällefors, Örebro	2015	12.2	12
Ställbergsmossen B	Hällefors, Örebro	2015	6.6	6
Västeråsmossen A1	Hällefors, Örebro	2015	21.5	16
Västeråsmossen A2	Hällefors, Örebro	2015	6.0	6
Västeråsmossen B	Hällefors, Örebro	2015	4.0	5

All but the Nitten site were burnt in conjunction with Life Taiga forest restoration project, so were unified in their general purpose. However, the burns were orchestrated by the County Administrations where the burns were located so procedures and personnel differed. Furthermore, within each county, the burns were in many cases executed by different contracting companies who operate independently so implementation of protocol, preparation, and methods were likely all varying.

The eleven burn sites were located in designated conservation areas, however, were generally lacking many structural features associated with areas of high biodiversity. Most sites were designated as such due to the presence of other features considered of conservation value. The stands were nearly all dominated by Scots pine (*Pinus sylvestris*), however differed greatly in their abundances of Norway Spruce (*Picea abies*) and Birch (*Betula spp*) throughout. In addition, there was variation between stands in terms of forest age and tree density. The forest ages listed in the burn summaries ranged from 20-140 years old, however were only provided as explicit ages for four of the sites (Table 2).

Most sites were surrounded by a wetland or mire feature and included evidence of forestry activity still remaining from past management, such as grown in roads, or machine cut logs or stumps. This was also evident by the relatively young forest ages of many of the sites. The forest floor was populated with dwarf shrubs typical of Fennoscandian boreal forests including bilberry (*Vaccinium myrtillus*), lingonberry (*Vaccinium vitis-idaea*), heather (*Calluna vulgaris*), and Labrador-tea (*Rhododendron tomentosum*). In many plots forest mosses, such as *Pleurozium* *schreberi*, *Hylocomium splendens* and *Cladonia sp.* (reindeer lichens) were also present.

Table 2. Descriptions of prescribed burn sites including the forest stand composition, the age of the dominant forest elements, and any distinguishing features that were noted. Information was gathered from burn summary reports acquired from the County Administrations responsible for the burns, as well as from field notes taken in fall 2019.

Site Name	Stand Composition	Age	Distinguishing Features
Brattforsheden	Open pine stand with some larger spruce and regenerating pine and birch	Unknown	Little to no dead wood
Lappland A	Old pine dominated coniferous forest with minor elements of spruce and birch	Unknown	Some old pine and birch (150-170 years) noted throughout the stand, as well as some standing dead wood
Lappland B	Old pine dominated coniferous forest with minor elements of spruce and birch	Unknown	Coarse pine and birch (150-170 years) noted throughout the stand
Nitten	Widely spaced pine dominated stand	Unknown	Few juvenile pines seen throughout the stand Generally large diameter pines
Römyren	Near homogeneous pine stand with small presence of spruce and birch	Tree age varies	Spruce and birch abundant in North Eastern burn area along marshland
Skattlösberg H	Pine dominated stand with some birch in the East of the burn area	35-40 year old stand	Some medium-large diameter spruce concentrated together, indications of insect infestation in older trees
Ställbergsmossen A	Pine dominated stand	120+ year old stand	----------
Ställbergsmossen B	Pine dominated with spruce throughout stand	Unknown	----------
Västeråsmossen A1	Near evenly mixed pine and spruce stand	Unknown	Signs of insect infestation in older trees throughout site, long elevated spine feature throughout burn site
Västeråsmossen A2	Pine dominated with spruce throughout	20 and 50 year old sections	Wet area with younger trees in North East of burn area
Västeråsmossen B	Open mature pine stand	140+ year old stand	Old drainage ditch along one site border, juvenile trees in this area

The Brattforsheden, Lappland A and B, and Skattlösberg H burn plans included explicit targets for the desired effects of the burns, however we do not have information about targets set at the other sites other than what we can infer from the Life Taiga project and restoration burns in general. When included, explicit burn targets differed between sites as they differed in their starting stand structures. Commonly listed targets were to create an open pine dominated forest with fire scars on live trees. Targeted spruce mortality was between 75-90%, with more conservative mortality goals for pine. Humus consumption was listed as a secondary target to stand thinning. Only in the Lappland A and B sites did they set producing high amounts of dead wood as a target. However, all sites listed targets of relatively high mortality and thinning of mature trees, which by nature produces dead wood.

2.2. Field Survey

The forest stands were surveyed with circular plots (radius 5 m) and transects (length 50 m), spaced approximately every hectare throughout the burn areas. In some cases fewer plots and transects were surveyed due to homogeneity of the site, a lack of evidence of burning having taken place in some areas and thus reductions in the burn size, or due to limitations of daylight hours.

Geographic coordinates for the centre of plots were determined using the ArcMac "Fishnet" and "Clip but not buffer" tools (completed by Ellinor Ramberg). In the field, circular plots with a five-metre radius (78.54 m^2 area) were surveyed for vegetative species presence and stand structural parameters. Plot perimeters were established in the field using a five-metre extendable rod, which was held stationary at the coordinate location, as determined using a handheld GPS. Transects began at the coordinates denoting the centre of the corresponding plots and extended 50 metres to the North, South, East, or West from the plot centre, marked using a 50 m retractable tape. North-South and East-West running transects were evenly distributed throughout the burn sites as much as possible.

Plots were surveyed to acquire information about multiple variables within the forest stand which could then be used to assess the effects of burning (Table 3). Within plots, live and dead trees (tree top greater than 1.3 m) were counted, including whether dead trees were standing or fallen, killed by the burn, their species, and diameter at breast height (DBH, 1.3 m) were noted. Previously dead trees were distinguished by more advanced stages of decay, the absence of bark and needles, or evidence of other causes of tree mortality such as insect infestation or heart rot. Basal diameter of both live and dead trees was determined using a relascope from the centre of each plot. All live trees within the plots were assessed for fire scars or dripping resin, which generally indicates the development of a fire scar. Area of bare ground and visible rock within each plot was estimated in square metres and totalled per plot. Seedlings within the plot area were counted by species.

Transects were surveyed to gather data on the presence and abundance of standing and fallen coarse (>10 cm diameter) dead wood (Table 3). Along the 50 metre transect all fallen dead wood with a diameter of more than 10 cm which intersected with the transect tape was recorded, including the diameter at point of crossing, the species of the tree, whether the tree was killed by the fire, and whether the tree fell as a result of the fire. For the purposes of notation and variable names, trees killed by the fire were considered "newly" dead. These factors were determined through the location of charring on the tree, the level of decay, and whether there was evidence of causes of death other than the fire.

Table 3. Descriptions of plots and transects sampled in field work, their dimensions, identification methods and the relevant variables measures in each sampling area.

	Dimensions	**Identification**	**Variables Recorded**
Plot	Circular plot with 5 m radius	GPS point	Live and dead tree counts DBH and species of dead trees Fire scar counts Basal area (live and dead) Seedling counts Ground cover estimates Area of bare ground and rock
Transect	Transect running North-South or East-West 5 m width along 50 m length	GPS point indicating transect start, centred on 50 m tape	DBH and species of fallen coarse dead wood (diameter >10 cm) intersecting the transect and standing coarse dead wood (DBH >10 cm) within 2.5 m of transect tape

To elaborate, if a fallen tree was minimally decayed, with charring only on the bottom 1 m of the trunk, we assumed that the tree was killed by the fire, standing at the time of the burn, and so was newly dead and had fallen as a result of the fire. If a fallen tree was highly decayed, but only had charring on the bottom 1 m of the trunk, we assumed that it was killed prior to the fire but was standing at the time of the fire, and so was not killed by but fell as a result of the fire. Standing dead trees of greater than 10 cm DBH within 2.5 m of the transect line were recorded, including their species, DBH, and whether they were killed due to the fire. The 5 m width of the transect was measured using the extendable rod held centred on the transect tape. Field data was used in analysis as "output variables" describing the effects of the burns and was summarized for comparison between the sites. Data was adjusted in many cases to create variables better representing the burning outcomes of interest and averaged to derive a per site value.

Percent mortality of all trees was determined by combining counts of newly dead trees and live trees from plots and calculating the proportion of newly dead trees. Basal area-based mortality was also calculated to represent mortality, but specifically mortality of large diameter trees, as the variable percent morality included all trees taller than 1.3 m regardless of their DBH. The live basal area measured in each plot, and the data on newly dead trees from the transects were used to calculate the basal area-based mortality. The diameters of standing and fallen newly dead wood were converted to values of per tree basal area, which were then summed to give the basal area of newly dead coarse wood per transect. A conversion of 40 was then used to increase the newly dead basal area to a per hectare scale. This value was combined with the live basal area per hectare determined in each plot to return a theoretical "pre-fire live basal area". From this value the basal area-based mortality could be determined and used as a second metric for mortality representing the changes seen in the large diameter trees within each stand.

Variables representing the quantity of fallen, standing, and total new coarse dead wood (CDW) were determined using the transect data. The volume of fallen coarse dead wood was calculated using the line intersect method from Van Wagner (1968). In this method, a transect of know length is laid out at random, and fuel on the ground which intersects with the transect is recorded. In our study this method was applied to fallen coarse dead wood of 10 cm diameter or greater that was killed due to the fire ("newly dead"). The data was converted to a measure of volume using the following equation (Van Wagner 1968):

$$V = \frac{\pi^2 \sum d^2}{8L}$$

Where:

V is the volume of wood per hectare
d is the diameter of each piece
L is the length of the transect

These measures of volume per hectare were then averaged by site. The metric used for standing dead wood was basal area, in which the diameter of each tree was converted to its basal area and then summed over the 250 m^2 area of the transect. The multiplier of 40 was applied to increase the basal area of newly dead standing coarse wood to a per hectare scale, and then averaged by site. Lastly, the total volume of newly dead coarse wood was calculated using the Van Wagner equation for volume per hectare. This was calculated as an approximation as the standing dead wood recorded per transect was not in accordance with the protocol of this method, and likely returned an overestimation. However, it was calculated as such to assess the per site averages, as total volume of dead wood is the metric discussed in studies related to the conservation value of dead wood (Rouvinen *et al.* 2002; Tikkanen *et al.* 2006).

Fire scars per plot were increased by a conversion of 127.4 (plots per hectare) to approximate fire scars per hectare, and then were averaged per site. However, since this variable is potentially impacted by the frequency of live trees remaining within each site, a second variable was calculated to represent the frequency of fire scars on live trees on a per tree scale. The percent of live trees with fire scars was calculated using counts of fire scars on live trees and counts of live trees per plot. Seedling counts and bare ground area per plot were multiplied by the plot conversion factor to give measures of seedlings per hectare and bare ground area per hectare.

In addition to representing the results of the burn, some of the field data was used to represent stand characteristics. Pre-fire live basal area was the strongest descriptor of the forest stand from this study's field data as it provided a metric describing the stand dominance. In addition, in some cases output variables were correlated with more simple variables representing post-fire forest structure including counts of live trees, and post-fire live basal area.

2.3. Prescribed Burn Summaries

Summary reports of the prescribed burns were acquired from the responsible County Administrations. Where provided, flame length, burn duration, and on-site weather data were extracted from the reports to be used as input variables representing conditions during burning. The quantity and quality of data varied greatly between reports and administrations, and in the most limited case only the date of the burn was provided. The content of the most detailed reports included descriptions of the burn sites, goals and intentions for the burns, plans regarding ignition, safety, and personnel, pre- and post-burn forest stand surveys, pre- and post-burn humus layer surveys, and data from the burn days including on site weather, ignition patterns, and flame length data. Pre-burn forest stand data was unfortunately lacking from many of the burn summaries, so was not able to be used for analysis. However, the information and site descriptions proved useful in explaining trends in results and gave insight into the conditions and factors contributing to burn outcomes.

In some cases, burn sizes were listed as rough approximations or were absent. When this was the case, the burn area was extracted from a GIS layer containing prescribed burn data compiled by Ellinor Ramberg. During sampling, indication of burnt or unburnt areas were recorded within and around plots and transects, and in some cases, it was decided that the burn area should be reduced based on discrepancies between theoretical areas burnt and what was burnt in reality. Ställbergsmossen A was reduced by 4 hectares due to there being large unburnt areas noted during field work. The size of the Lappland A burn was reduced by 0.3 hectares on account of there being one patchily burnt area, and two plots lying just outside of the actual burn perimeter.

2.4. Meteorological Data

Historical meteorological data was gathered from the Swedish Meteorological and Hydrological Institute (SMHI). Using the SMHI data portal the weather stations geographically closest to the prescribed burn sites were determined, and weather data was extracted accordingly. In most cases the closest weather stations were quite far from the burn sites so the weather data is likely representative of the regional conditions, and not necessarily the exact conditions at the burn sites. Daily precipitation totals were extracted for the three weeks leading up to each prescribed burn, and the number of days prior without rainfall was recorded. Using this data, the precipitation totals for three weeks, two weeks, and one week leading up to the burns were calculated. Similarly, the maximum daily temperature at the closest weather station was recorded for the three weeks leading up to each burn, and the average maximum temperature was determined for three weeks, two weeks, and one week leading up to the burns. Through this data, a picture of the regional weather leading up to the burns was captured and could be used for analysis.

The Swedish Civil Contingencies Agency (MSB) was contacted for access to wildfire risk data, which is a combination of meteorological data, and two fire weather indexes: the Canadian Fire Weather Index (FWI) model and the Swedish HBV Grassland Fire Model. In this case the prescribed burns were only carried out in forest environments, so the FWI was the relevant index (MSB n.d.). The MSB calculates FWI values using meteorological data from weather stations operated by SMHI and the Swedish Road Administration, in addition to forecasted information from satellite images and weather radar. It is then analysed using the statistical method MESAN to apply extrapolated values representing fire risk to each regional area in 11 km by 11 km grids (MSB n.d.). FWI values were extracted from the MSB data for the dates of the prescribed burns at each of their corresponding sites.

Lastly, the regional weather was acquired for each burn day by extracting weather data from the SMHI portal to be tested for correlations between regional weather conditions during burning and the resulting structures of the burns. Average daily temperature and maximum daily temperature were acquired from the regional weather data. Relative humidity and wind speed values were extracted for the hours in which the burns took place and averaged. Together these values represent the regional weather on the days prescribed burning took place. This data was only extracted for the seven sites for which on-site weather data was provided in the burn summaries, so that the results of these groups of correlations could be compared.

2.5. Data Transformations and Analysis

Data analysis consisted of running correlations between the input and output variables, as well as between potentially related output variables. Input variables consisted of meteorological data leading up to and during the burns, conditions during the burns, and some stand descriptive variables. Output variables were those representing the effects of the burns in terms of structures created, regeneration, and change in the forest stands. These included: percent mortality of all trees, basal area-based mortality, volume of fallen and total new coarse dead wood, basal area of standing new coarse dead wood, fire scars per hectare, percent of live trees with fire scars, total seedlings per hectare, pine seedlings per hectare, spruce seedlings per hectare, birch seedlings per hectare, and bare ground area per hectare. Rate of burn was calculated as a proxy for the intensity of burning, so was used in correlations as an input variable. It was also tested in correlations with meteorological data and Fire Weather Indices to test for relationships between the weather and moisture conditions with rate of burn as the output variable. Similarly, pre-fire live basal area and post-fire live basal area were tested as input variables in correlations as forest structure can have strong effects on the results of burning.

Two methods of correlation were used in RStudio from the *stats* package. The methods differ in both their strength and in their assumptions. Pearson's product-moment correlation is by far the stronger of the two tests, however, calls for normality of data. As the field data was biological count data it generally did not conform to a normal distribution. In order to fit the assumptions of the Pearson method, much of the field data needed to be transformed to improve its fit to a normal distribution. According to Zar (1974) this type of statistical test will still produce reliable results when there are slight deviations from normality. For this reason, transformations were accepted even where there were still slight deviations to normality. Where transformations were not sufficient to improve the normality of the data, correlations were run using Spearman's rank correlation which tests the correlation of the data as ranked values, and as such acts as a form of data transformation and does not call for normality. The transformations made to the output variables, and the corresponding method used to test correlations with each variable accordingly are summarized in Table 4. The meteorological and FWI input variables were considered sufficiently normal that transformations were not applied before running correlations.

Table 4. Accepted transformations for output variables and their corresponding equations (from Zar 1974), in addition to the correlation method employed based on whether a transformation sufficiently improved the data's fit to normality.

Variable	Accepted Transformation	Equation	Correlation Method
Percent Mortality	Square Root	$X' = \sqrt{X}$	Pearson
Basal Area-Based Mortality	Square Root	$X' = \sqrt{X}$	Pearson
Volume of Fallen Coarse New Dead Wood	Logarithmic	$X' = \log(X + 1)$	Pearson
Basal Area of Standing Coarse New Dead Wood	None	n/a	Spearman
Total Volume of New Coarse Dead Wood	None	n/a	Spearman
Fire Scars per Hectare	Square Root	$X' = \sqrt{X + \frac{3}{8}}$	Pearson
Proportion of Live Trees with Fire Scars	Square Root	$X' = \sqrt{X + \frac{3}{8}}$	Pearson
Total Seedlings	Logarithmic	$X' = \log(X + 1)$	Pearson
Pine Seedlings	Logarithmic	$X' = \log(X + 1)$	Pearson
Spruce Seedlings	None	n/a	Spearman
Birch Seedlings	None	n/a	Spearman
Bare Ground Area	Logarithmic	$X' = \log(X + 1)$	Pearson
Rate of Burn	Logarithmic	$X' = \log(X + 1)$	Pearson
Burn Size	Logarithmic	$X' = \log(X + 1)$	Pearson
Pre-fire Live Basal Area	None	n/a	Spearman
Post-fire Live Basal Area	None	n/a	Spearman

3. Results

3.1. Tree Mortality

Basal area-based mortality ranged from 0% in the Nitten site, to 47% in the Västeråsmossen A2 site (Table 5). Basal area-based mortality was negatively correlated with the cumulative precipitation two weeks prior to burning (Figure 1). Otherwise, basal area-based mortality was not correlated with other pre-burn meteorological conditions, with FWI values, or on-site weather conditions from burn days. However, was found to be positively correlated with the volume of new fallen coarse dead wood ($r(9) = 0.64$, $p = 0.017$), the basal area of standing new coarse dead wood ($r_s = 0.95$, $p < 0.001$), and the volume of total new coarse dead wood ($r_s = 0.92$, $p < 0.001$).

Table 5. Basal area-based mortality and percent mortality of all trees summarized by site. These variables differ in the data used to calculate them, as percent mortality includes counts of all trees (taller than 1.3 m) including small diameter trees, whereas basal area is a metric which describes the cross-sectional area of only coarse trees in the stand (in this case 10 cm diameter or greater).

Site	Basal Area-Based Mortality (%)	Mortality (%)
Brattforsheden	22	41
Lappland A	2	30
Lappland B	9	55
Nitten	0	25
Römyren	2	19
Skattlösberg H	32	48
Ställbergsmossen A	11	27
Ställbergsmossen B	2	32
Västeråsmossen A1	11	38
Västeråsmossen A2	47	85
Västeråsmossen B	1	34

The highest percent mortality imposed by the burns was seen at the Västeråsmossen A2 site (85%), and the lowest was 19% as seen at the Römyren site (Table 5). Percent mortality was not correlated to any pre-burn meteorological conditions, or weather-related variables. It was, however, negatively correlated with the post-fire basal area of live trees (Figure 2). Stand conditions and burn conditions including pre- and post-burn live basal areas, and the FWI values for all sites are summarized in Table 6.

Table 6. Summaries of calculated pre-burn live basal area, post-burn live basal area, and the burn-day Fire Weather Index values. The Fire Weather Index values are the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Build-Up Index (BUI), and the final Fire Weather Index (FWI). Higher index values indicate higher predicted fire intensity and lower moisture conditions.

	Live Basal Area							
Site	Pre-burn (m^2ha^{-1})	Post-burn (m^2ha^{-1})	FFMC	DMC	DC	ISI	BUI	FWI
Brattforsheden	24.2	18.6	88.5	35.6	197.9	5	49.1	13.1
Lappland A	15.7	15.4	81.7	51.2	192.4	3	61.5	9.8
Lappland B	17.9	16.1	91.2	47.2	78.8	10.4	47	22.2
Nitten	11	11	88.8	33.9	220.4	7.6	49	18
Römyren	29.1	28.7	91.1	45.6	131.5	9.5	48.8	21.2
Skattlösberg H	11.3	7.8	88.5	34.6	188.1	5.5	47.4	13.8
Ställbergsmossen A	32.2	28.3	88.9	36.9	207.7	5.9	51.1	15.2
Ställbergsmossen B	23.8	23.3	90.3	27	165.8	9.8	38.3	19.2
Västeråsmossen A1	31.7	28.3	88.1	39.5	204.6	6.2	53.2	16.3
Västeråsmossen A2	9.8	5.3	88.6	34.8	190.8	4.5	47.8	11.9
Västeråsmossen B	24.7	24.6	89	37.5	197.8	5.8	50.9	15.1

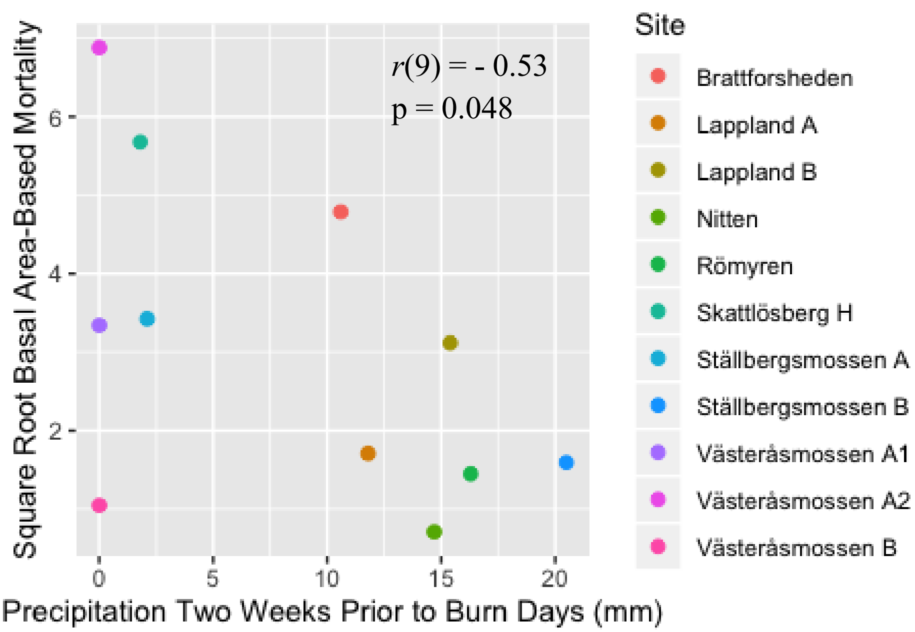


Figure 1. Scatter plot of cumulative precipitation during the two weeks leading up to burn days and the square root transformed basal area-based mortality (X' = sqrt(X+0.5)).

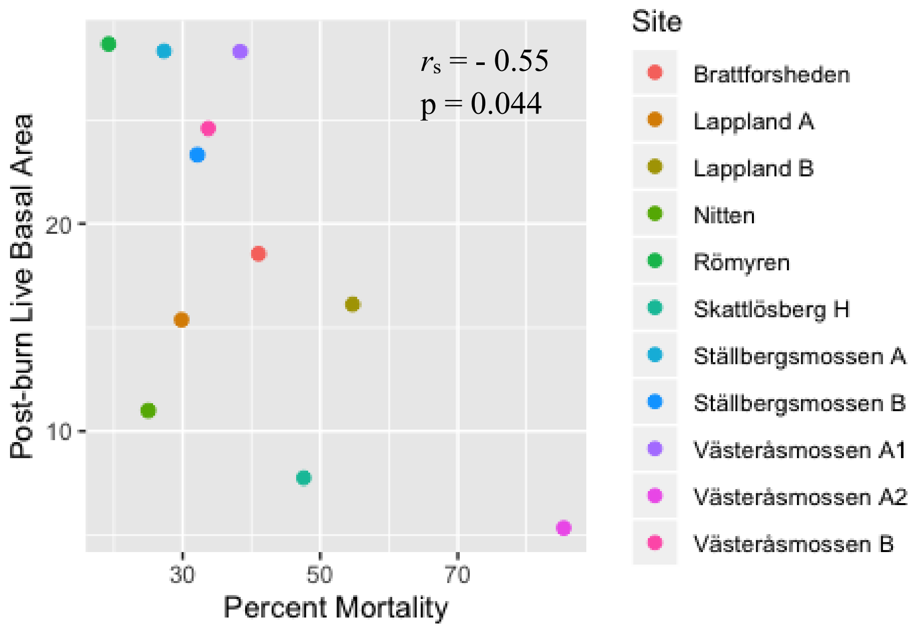


Figure 2. Scatter plot of percent mortality overall and the post-burn live tree basal area (square meters per hectare).

3.2. Coarse Dead Wood Creation

The total volume of coarse dead wood (CDW) produced by the burns ranged from 0 m^3 ha^{-1} at the Nitten site, to 45 m^3 ha^{-1} at the Brattforsheden site (Table 7). The mean total volume of CDW was 18 m^3 ha^{-1}, and upwards of 30 cubic metres per hectare of CDW was added at five of the sites. Additions in the form of standing dead wood were higher in most cases (Table 7).

A positive correlation was found between the volume of fallen CDW and the basal area of standing CDW (r_s = 0.86, $p < 0.001$). Basal area of standing CDW was positively correlated with percent mortality (r_s = 0.62, p = 0.024) and basal area-based mortality (r_s = 0.95, $p < 0.001$). However, none of the measures of added coarse dead wood were correlated with meteorological variables describing conditions leading up to or during the burns.

Table 7. Per site averages and the corresponding standard deviations for the volume of fallen coarse dead wood and the basal area of standing coarse dead wood which were produced by the burns. Also included is the calculated volume of standing CDW, and the corresponding volume of total new CDW per hectare.

Site	Volume of Fallen CDW (m^3 ha^{-1})	Basal Area of Standing CDW (m^2 ha^{-1})	Volume of Standing CDW (m^3 ha^{-1})	Volume of Total New CDW (m^3 ha^{-1})
Brattforsheden	8.0 ±8.5	5.0 ±4.0	37	45
Lappland A	1.0 ±2.5	0.2 ±0.7	2	3
Lappland B	1.0 ±2.7	1.6 ±2.0	13	14
Nitten	0.0 ±0.0	0.0 ±0.0	0	0
Römyren	0.3 ±0.7	0.2 ±0.4	2	2
Skattlösberg H	2.0 ±3.5	3.5 ±3.5	28	30
Ställbergsmossen A	1.0 ±3.3	3.8 ±4.4	30	31
Ställbergsmossen B	3.0 ±3.6	0.3 ±0.6	3	6
Västeråsmossen A1	5.0 ±7.6	3.3 ±3.6	26	31
Västeråsmossen A2	3.0 ±4.0	4.0 ±1.8	31	34
Västeråsmossen B	0.1 ±0.3	0.1 ±0.3	1	1

3.3. Fire Scar Creation

Fire scar abundance ranged from 0 fire scars per hectare at the Nitten site, to 318 fire scars per hectare at the Römyren site (Table 8). The Lappland B site had the highest percentage of live trees with fire scars (34%) and the Nitten site had the lowest, as no fire scars were found throughout the site (Table 8). Excluding Nitten, the site with the lowest counts of fire scars and lowest percentage of live trees with fire scars was Lappland A (8 fire scars per hectare, 2%, Table 8).

Fire scars per hectare was negatively correlated with the on-site relative humidity during burning (Figure 3). Using the regional relative humidity, the correlation was non-significant ($r(5) = -0.42$, $p = 0.17$). Fire scars per hectare was positively correlated with the Fire Weather Index (Figure 4) and the Initial Spread Index for burn-days ($r(9) = 0.52$, $p = 0.049$). Percent of live trees with fire scars was positively correlated with the Fine Fuels Moisture Code (Figure 5).

In addition to correlations with meteorological data, the fire scar variables were found to be correlated with numerous other output variables, and variables representing stand structure of the burn sites. Fire scars per hectare was positively correlated with area of bare ground ($r(9) = 0.65$, $p = 0.015$), in addition it was positively correlated with three variables representing stand characteristics: live trees per plot ($r(9) = 0.67$, $p = 0.011$), pre-burn live basal area ($r(9) = 0.60$, $p = 0.025$), and post-burn live basal area ($r(9) = 0.62$, $p = 0.022$). Percent of live trees with fire scars was positively correlated with percent mortality overall ($r(9) = 0.56$, $p = 0.037$).

Table 8. Fire scar abundance summarized by site as fire scars per hectare and percent of live trees with fire scars. Sites with the highest and lowest of each variable are noted.

Site	Fire Scars per Hectare	Live Trees with Fire Scars (%)
Brattforsheden	42	12
Lappland A	8	2
Lappland B	97	(highest) 34
Nitten	(lowest) 0	(lowest) 0
Römyren	(highest) 318	23
Skattlösberg H	64	17
Ställbergsmossen A	64	9
Ställbergsmossen B	170	26
Västeråsmossen A1	135	15
Västeråsmossen A2	64	30
Västeråsmossen B	153	17

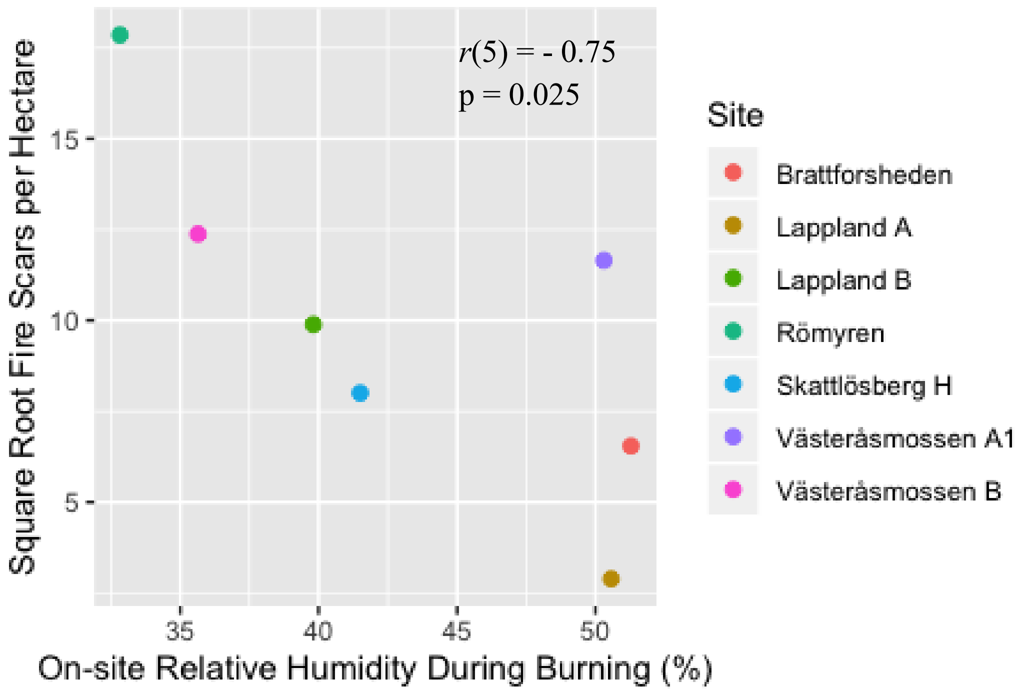


Figure 3. Scatter plot illustrating negative correlation between on-site relative humidity during burning (%) and square root transformed (X' = sqrt(X+(3/8))) counts of fire scars per hectare.

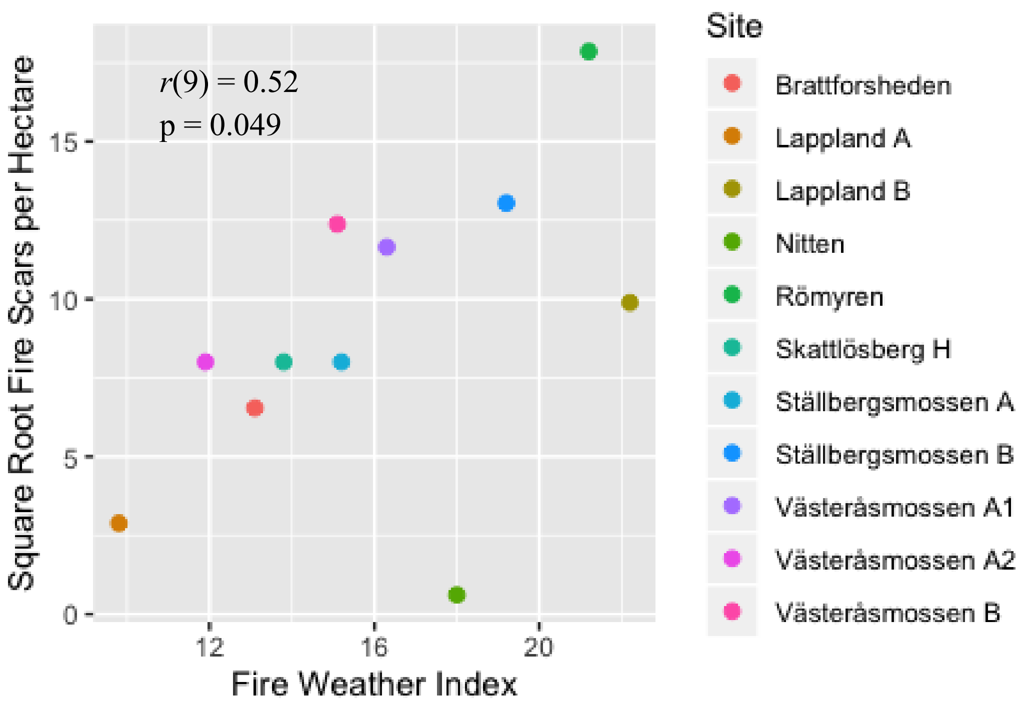


Figure 4. Scatter plot illustrating positive correlation between the Fire Weather Index (FWI) values and the square root transformed (X' = sqrt(X+(3/8))) fire scars per hectare.

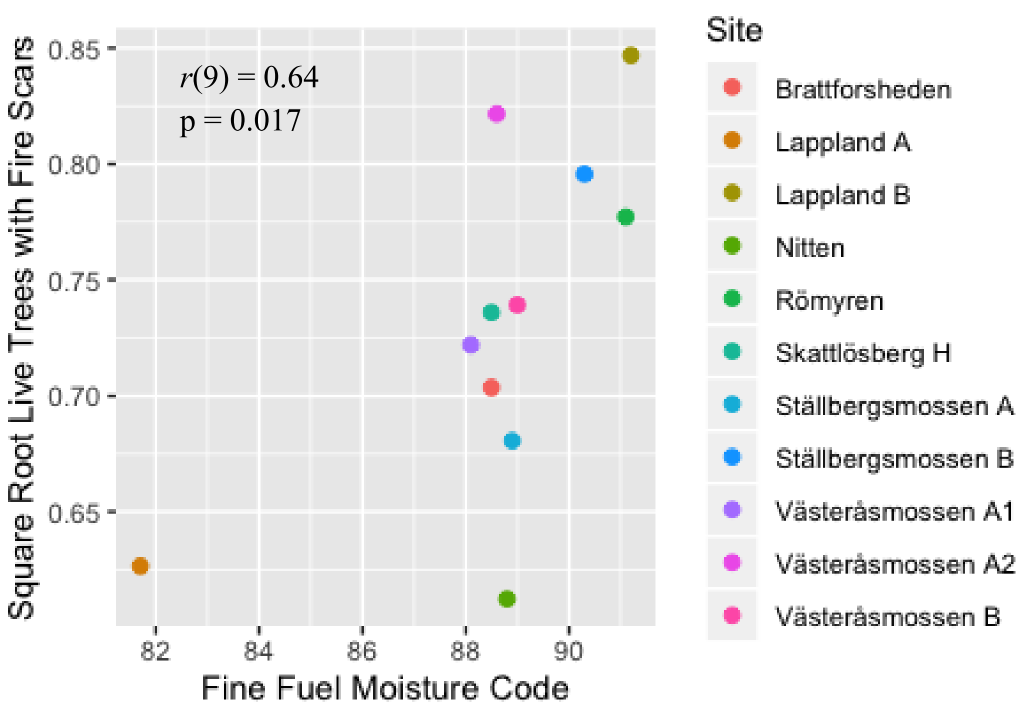


Figure 5. Scatter plot illustrating positive correlation between burn-day Fine Fuel Moisture Code (FFMC) values and the square root transformed (X' = sqrt(X+(3/8))) proportion of live trees with fire scars.

3.4. Seedling Regeneration

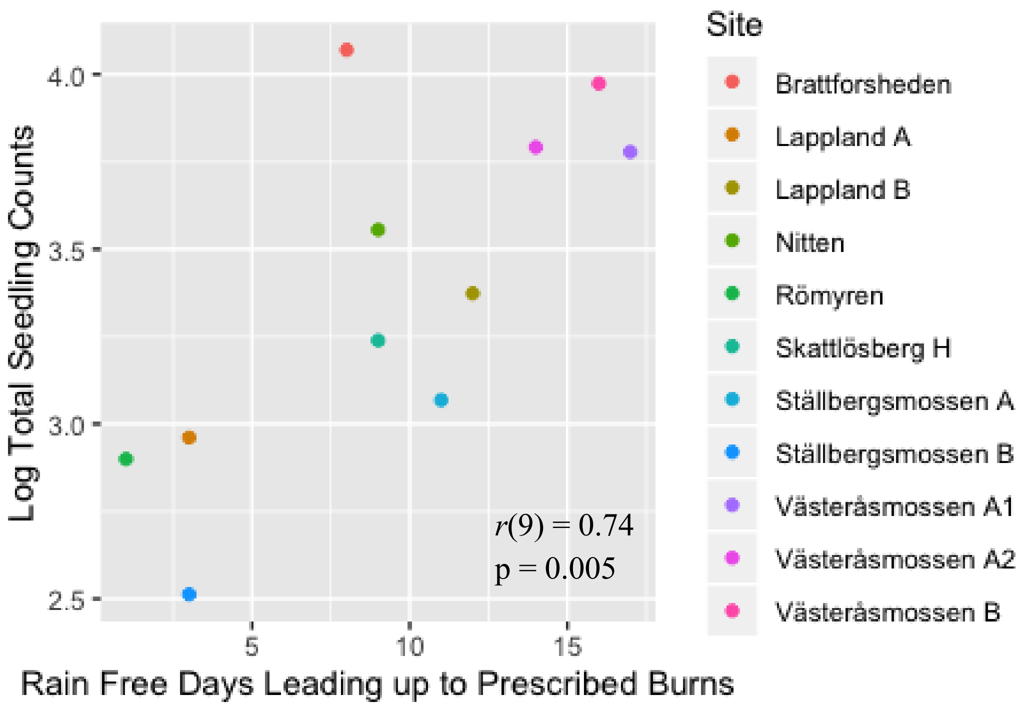
Abundance of total seedlings ranged from 1444 seedlings per hectare in the Ställbergsmossen B site, to 7332 in the Brattforsheden site (Table 9). Ställbergsmossen B had the lowest abundance of pine seedlings (1168 per hectare), and the Västeråsmossen B site had the highest (6166 per hectare). In most sites considerably fewer spruce seedlings were found, with the highest amount found in Vasterasmosesen A1 (3846 per hectare), and the lowest in Nitten where no spruce seedlings were found. Birch seedlings were even fewer, with none found in the Ställbergsmossen A and B sites, and the most found in the Lappland A site (1107 birch seedlings per hectare).

Table 9. Per hectare seedling counts summarized by species, and as total seedlings based on counts in plots.

Site	Total Seedlings (ha^{-1})	Pine Seedlings (ha^{-1})	Spruce Seedlings (ha^{-1})	Birch Seedlings (ha^{-1})
Brattforsheden	7332	5916	1373	42
Lappland A	2333	1186	40	1107
Lappland B	3589	2892	60	637
Nitten	4331	4299	0	32
Römyren	2187	2086	42	53
Skattlösberg H	3121	2580	382	96
Ställbergsmossen A	2611	1953	658	0
Ställbergsmossen B	1444	1168	276	0
Västeråsmossen A1	5446	1457	3846	72
Västeråsmossen A2	5520	3227	2102	191
Västeråsmossen B	6650	6166	306	178

Total seedling data was positively correlated with maximum daily temperature one week prior to burning, number of rain free days prior to burning, on-site mid-burn temperature, and on-site average temperature during burning (Table 10a). It was negatively correlated with the two-week cumulative precipitation prior to burning (Table 10a). Regional average temperature on the days of the burns was also tested for correlation with total seedlings, but the result was not significant. However, total seedling data was positively correlated with regional maximum temperature for burn days (Table 10a); the corresponding variable of on-site maximum temperature returned a non-significant result. Two of the strongest correlations with total seedlings were with rain free days leading up to the prescribed burns and average on-site temperature during burning (Figure 6a, b).

a.



b.

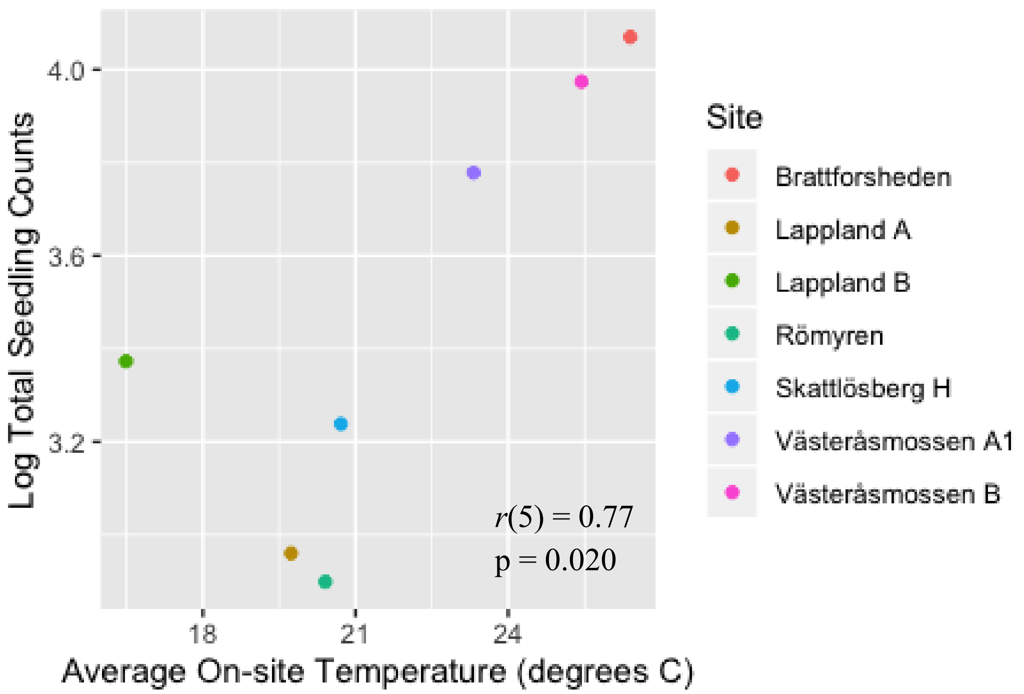


Figure 6. Scatter plots illustrating correlations between log transformed total seedling counts (X’ = log(X+1)) with (a.) rain free days leading up to prescribed burns, and (b.) average on-site temperature during burning.

Pine seedling data was positively correlated with regional maximum temperature for burn days, as well as total seedling counts (Table 10b). The correlation with on-site maximum temperature during burning, however, did not return a significant result. Spruce seedlings were positively correlated with cumulative precipitation two weeks prior to burning, rain free days prior to burning, on-site average temperature during burning, and regional average temperature on burn days (Table 10c). In addition, spruce seedling data was positively correlated with both mortality measures, and all variables describing additions of coarse dead wood (Table 10c). Lastly, birch seedlings were found to be positively correlated with the Duff Moisture Code values, as well as with regional wind speed on burn days (Table 10d). The on-site average wind speed during burning was not significantly correlated with birch seedling counts.

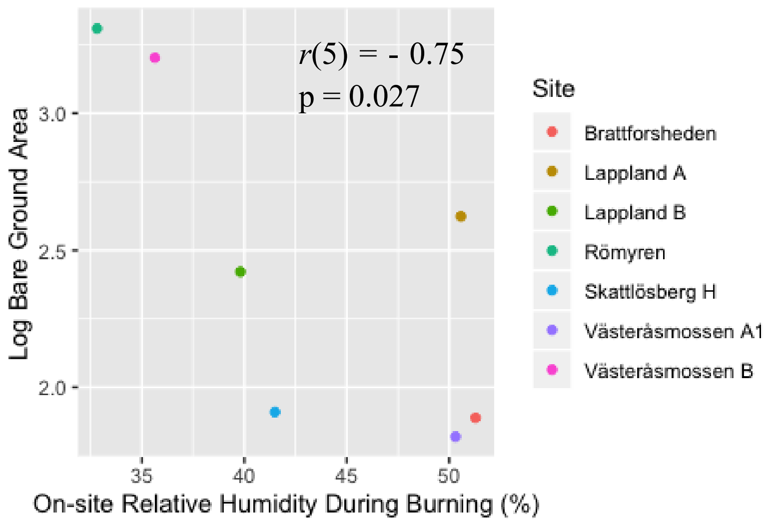
Table 10. Results from correlations between variables representing seedling abundance and therefore stand regeneration. Correlations with log transformed total seedlings and log transformed pine seedling counts were ran using the Pearson product-moment correlation method. Correlations with spruce and birch seedling counts were ran using the Spearman rank correlation method.

Variable	**Correlation Coefficient**	**P-value**
(a.) Correlations with Total Seedlings:		
Cumulative precipitation 2 weeks prior to burning	$r(9) = -0.57$	p = 0.034
Maximum daily temperature 1 week prior to burning	$r(9) = 0.65$	p = 0.015
Rain free days prior to burning	$r(9) = 0.74$	p = 0.005
On-site average temperature during burning	$r(5) = 0.77$	p = 0.020
On-site mid-burn temperature	$r(5) = 0.76$	p = 0.025
Regional maximum temperature on burn days	$r(5) = 0.71$	p = 0.036
(b.) Correlations with Pine Seedlings:		
Regional maximum temperature on burn days	$r(5) = 0.70$	p = 0.040
Total Seedling Counts	$r(9) = 0.77$	p = 0.003
(c.) Correlations with Spruce Seedlings:		
Cumulative precipitation 2 weeks prior to burning	$r_s = -0.71$	p = 0.008
Rain free days prior to burning	$r_s = 0.58$	p = 0.031
On-site average temperature during burning	$r_s = 0.71$	p = 0.044
Regional average temperature on burn days	$r_s = 0.79$	p = 0.024
Regional maximum temperature on burn days	$r_s = 0.71$	p = 0.044
Percent mortality	$r_s = 0.58$	p = 0.033
Basal area-based mortality	$r_s = 0.75$	p = 0.006
Volume of fallen new coarse dead wood	$r_s = 0.82$	p = 0.002
Basal area of standing new coarse dead wood	$r_s = 0.79$	p = 0.003
Volume of total new coarse dead wood	$r_s = 0.83$	p = 0.002
(d.) Correlations with Birch Seedlings:		
Duff Moisture Code	$r_s = 0.62$	p = 0.022
Regional wind speed on burn days	$r_s = 0.71$	p = 0.044

3.5. Bare Ground Area

The area of bare ground ranged from 137 m^2 ha^{-1} at the Nitten site to 3360 m^2 ha^{-1} at the Römyren site, with a mean value of 1357 m^2 ha^{-1}. Area of bare ground was negatively correlated to the on-site relative humidity during burning (Figure 7a); the correlation with regional relative humidity was not significant. In addition, bare ground area was positively correlated with fire scars per hectare (Figure 7b).

a.



b.

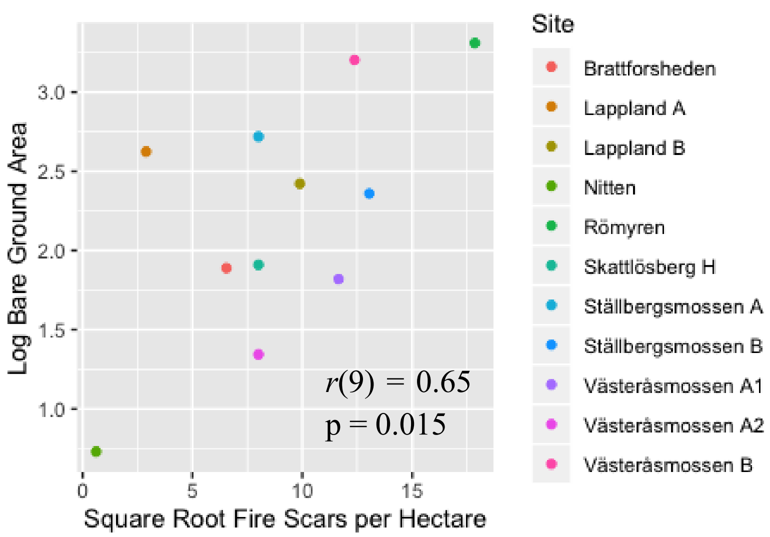


Figure 7. Scatter plots illustrating correlations between log transformed bare ground area (X' = log(X+1)) and (a.) on-site relative humidity during burning and (b.) square root transformed fire scars per hectare.

3.6. Rate of Burn

Rate of burn ranged from 0.7 hectares per hour at the Västeråsmossen B site to 4.5 hectares per hour at the Römyren site (Table 11). The rate of burn was calculated for all sites except for Nitten, for which the time taken to complete the burn was unknown. Though it was calculated to be tested as an input variable, rate of burn was not significantly correlated with any output variables. Rate of burn was found to be positively correlated with the Duff Moisture Code values (Figure 8).

Table 11. Burn sizes and calculated rates of burns for the ten sites that burn durations were acquired for. Rate of burn is listed as hectares burnt per hour.

Site	**Burn Size (ha)**	**Rate of Burn (ha hr^{-1})**
Brattforsheden	9.0	1.8
Lappland A	16.4	2.2
Lappland B	20.2	2.8
Römyren	26.1	4.5
Skattlösberg H	4.6	1.2
Ställbergsmossen A	12.2	2.4
Ställbergsmossen B	6.6	1.1
Västeråsmossen A1	21.5	3.6
Västeråsmossen A2	6.0	1.0
Västeråsmossen B	4.0	0.7

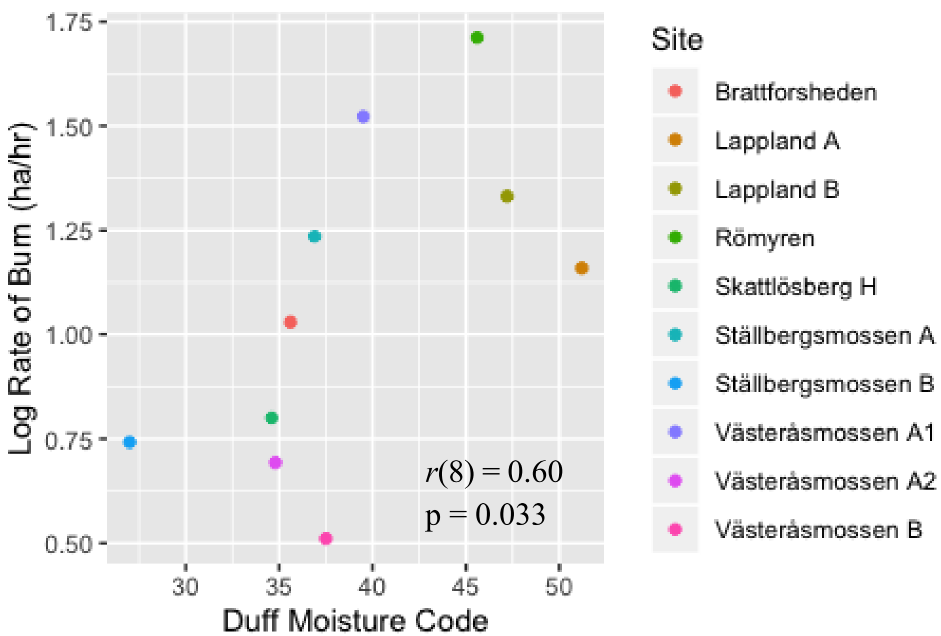


Figure 8. Scatter plot illustrating the relationship between the log transformed rate of burn (X' = log(X+1) and the Duff Moisture Code (DMC) values for each site.

4. Discussion

4.1. Tree Mortality

Tree mortality was inherent in the goals of the prescribed burns as they were intended to produce more open, thinned pine stands. Mortality rates varied greatly between the eleven burn sites surveyed and clear trends between stand characteristics and the results can be seen, particularly through the variable basal area-based mortality. The sites with the highest basal area-based mortality were Västeråsmossen A2 (47%) and Skattlösberg H (32%) which were the youngest sites, with the smallest and therefore most vulnerable pine trees. Comparatively, two of the presumed oldest sites, with the most widely-spaced, coarse pine trees were Västeråsmossen B and Nitten, which had the lowest basal area-based mortality of 1% and 0% respectively. According to studies of comparable burns in the literature, such low intensity prescribed burns are only effective at killing Scots pine trees of small diameters, and correspondingly thin bark, with decreasing mortality rates as trees became older and coarser (Linder *et al.* 1998; Sidoroff *et al.* 2007). Linder *et al.* (1998) reported over 80% mortality of both pine and spruce trees under 10 cm DBH, but only 20% mortality in trees between 10-12 cm DBH. Mortality of pines between 20-29 cm DBH was less than 10% (Linder *et al.* 1998). Although our data did not include size-class specific mortality rates, this same trend can be seen through variation in site composition and highlights the importance of stand structure as a factor in dictating possible outcomes from burning. Namely, that mortality from prescribed burning will be higher in sites with smaller pines, and more vulnerable trees throughout.

In spite of the strong influence of stand structure, the variable representing basal area-based mortality was negatively correlated with the variable representing the precipitation two weeks prior to each burn. This correlation represents the important role that weather plays in driving burning conditions, as areas that experienced more precipitation leading up to burning in general had lower mortality rates throughout the sites. As can be seen in Figure 1, the Västeråsmossen B site does not follow the otherwise strong trend of the correlation and although this site experienced no precipitation for the two weeks leading up to the burn, it had the second lowest change in basal area. As this site is potentially the oldest site in this study (Table 2), and due to the increased resilience of pine to fire with age (Sidoroff *et al.* 2007), this stand should have experienced substantially higher fire intensity to cause mortality of the dominant trees within the stand. Additionally, spruce trees which contributed significantly to mortality in many other sites due to their vulnerability to the effects of fire (Zackrisson 1977), were nearly absent from this site. The two sites with similarly little precipitation prior to burning were Västeråsmossen A1 and A2 which had more complex stand structures and composition including many younger and more vulnerable pine trees, and comparatively numerous spruce trees throughout. These stand elements contributed to the much higher changes in basal area under the same pre-burn precipitation regimes. This finding suggests that prescribed burns may produce more targeted values in sites with higher initial heterogeneity, compared to sites which are more homogenous, particularly older sites.

Basal area-based mortality was not found to be correlated with on-site weather conditions or the Fire Weather Indices, which is likely due to the high variability in stand structure between sites, compared with the relatively similar conditions under which all studied burns took place. The same can be said for percent mortality overall which was not significantly correlated with any weather-related variables. However, percent mortality was negatively correlated with the post-fire live basal area. An initial interpretation of this relationship might be that the sites with lower mortality rates had higher post-burn live basal areas, simply because of the lower mortality throughout. However as has been outlined, the mortality counts contributing to the percent mortality overall were inclusive of juvenile trees which are not included in the basal area measure. Instead, perhaps the relationship indicates that sites with low basal area were generally younger sites with more juvenile trees, which had higher rates of mortality from the low intensity prescribed burns. The exception of course is the Nitten site which had a low basal area due to the wide spacing of the stand and not because it was a young stand. Percent mortality would likely have been negatively correlated with stand age due to higher numbers of small and juvenile trees in younger stands which were generally killed by the burns, and the comparatively low rates of mortality and minimal presence of juvenile trees in some of the older sites.

In four of the prescribed burn summaries, practitioners included explicit targets for tree mortality, which according to this data were not achieved in all but one case. The exception being the Skattlösberg H site, where the low end of the 30-60% pine mortality target was likely met. This in itself is an important finding because it highlights the disconnect between the targets of these projects as restoration measures, and the capacity for low intensity prescribed burning to create the desired changes within stands. According to Dickinson and Johnson (2001), surface fires primarily affect mortality in stands through damage inflicted on tree's vascular cambium rather than through damage to the tree crown. However, even in the

Skattlösberg H site which was described as a 35 to 40 year old pine stand, the oldest trees making up the stands canopy layer should have been considered coarse enough to withstand the thermal conditions of a ground fire as exemplified in Sidoroff *et al.* (2007). In their study, which included mortality reports for Scots pine, low intensity prescribed burns were found to inflict 19% mortality on a 30 to 35 year old stand, and only 1% mortality in a stand ten years older (Sidoroff *et al.* 2007). With this in mind, the majority of the mortality targets for the burns in this study were set too high based on the known effects of prescribed burns, as they tend to manifest and be executed as low intensity ground fires (Sidoroff *et al.* 2007; Linder *et al.* 1998). As such, this type of burn will lead to negligible impacts if carried out in sites with larger more fire-resistant trees.

This type of result was seen at the Nitten site, which was of unknown age, but was generally a widely spaced flat stand with coarse trees. Very few juvenile or mid-aged trees were noted throughout the site, and based on the mortality trends in the literature, much higher intensity burning and weather conditions were needed for the prescribed burn to influence the stand. In fact, prescribed burns may have been planned at many of these sites with unrealistic expectations of the possible mortality outcomes. The Västeråsmossen A2 site had the highest rates of mortality, however had a large section which was only 20 years old and as such high mortality in at least this part of the site could be expected by the managers. Using the stand ages provided, our data showed this type of prescribed burn to be effective at thinning and causing mortality in young stands such as the Västeråsmossen A2 and Skattlösberg H sites, a notion which was supported by numerous studies (Reinhardt and Ryan 1988; Dickinson and Johnson 2001; Sidoroff *et al.* 2007; Piha *et al.* 2013). In this way, stand structure is highly impactful on the potential outcomes of prescribed burns. It should be a strong consideration as to which sites can be effectively altered through prescribed burning, and if burning should be supplemented with other measures to alter a stand.

4.2. Coarse Dead Wood Creation

While explicit targets related to dead wood were not included in the prescribed burn plans, the mortality targets imply the creation of dead wood, as do the overall goals of prescribed burning in Sweden and the Life Taiga project (Siitonen 2001; Sandstrom *et al*. 2019; Life Taiga n.d.). The mean volume of coarse dead wood produced by the burns was 18 m^3 ha^{-1} and ranged from 0 to 45 m^3 ha^{-1}. As such, the burns did not create as much dead wood as can be found in natural sites; up to 92 m^3 ha^{-1} according to Rouvinen *et al.* (2002). However, the results are comparable to those presented in two studies which assessed the effects of low intensity prescribed burns in boreal forest stands in Fennoscandia. Sidoroff *et al.* (2007) report that prescribed burns in young managed Scots pine forests increased dead wood volumes by 10 cubic metres per hectare. Although this is far from the volumes seen in natural stands, Sidoroff *et al.* (2007) suggest that it could still be an important enrichment for biodiversity. Using the 10 m^3 ha^{-1} measure as a benchmark, six of the sites surveyed could be said to have been enriched by the dead wood additions due to burning. Linder *et al.* (1998) reported additions of 21 m^3 ha^{-1} of dead wood, however, more than one third of this input was from extremely coarse fire killed pine trees (>50 cm DBH) that were vulnerable due to fire scars from past fire damage. In the sites we surveyed this size of truly large diameter pine was absent.

In five of the sites surveyed – Brattforsheden, Skattlösberg H, Ställbergsmossen A, Västeråsmossen A1 and A2 - the additions of dead wood were 30 m^3 ha^{-1} or greater which should be noted as a positive outcome in terms of the success of these particular burns. The dead wood additions at these sites were higher than the results described from the literature, and is likely due to structural and species differences between the stands in question. For example, in Sidoroff *et al.* (2007) the burns were carried out in young homogenous Scots pine stands, which differs from the five surveyed stands in question which all had some components of mature spruce. In Linder *et al.* (1998), the burn was completed in an unmanaged old growth stand with much coarser trees comprising a portion of the stand volume, and spruce (0-20cm DBH) comprising only 2% of the stand volume. In the sites surveyed for this project, the stands were comparatively younger than the stand surveyed in Linder *et al.* (1998), and as such, there could have been more trees of a size class that could have been killed by a ground fire and thus contributed to dead wood volumes. Additionally, in four of the sites in question – less Skattlösberg H - larger fire-killed spruce than described in Linder *et al.* (1998) were noted in the stand surveys which further contributed to high dead wood volumes added from the burns.

The sites with especially low contributions of dead wood (< 2 m^3 ha^{-1}) tended to be older sites, such as Nitten and Västeråsmossen B. Perhaps this was due to the lack of intermediate age and thus smaller trees at these sites (Linder *et al.* 1998; Sidoroff *et al.* 2007). These stands may have been planted as monocultures following clear-cut harvests of the areas, whereas some of the other sites may have been replanted after selective logging, leaving comparatively more size diversity. One such site was Römyren, which was described as a mixed age pine stand – not unlike those described by Sidoroff *et al.* (2007) – despite this, the burn produced very low additions of coarse dead wood. In this case, the low additions can only be attributed to low burning intensity, illustrated well by the low average flame length during burning (0.44m). Compared to the flame length reported in Sidoroff *et al.* (2007) which was at minimum 0.5 m and reached up to 4.1 m, it is not surprising that dead wood inputs were far less at the Römyren site. The low volume in the Lappland A site could similarly be explained by lower intensity burning conditions, when compared specifically to Lappland B, as their stand structure was the same, but the Lappland A burn produced far less dead wood. Lappland B had a much higher average flame length (2.67 m) than Lappland A (0.95 m) which could explain this result, as flame length is seen as a proxy for intensity (Keeley 2008).

The Brattforsheden and Nitten sites which had the highest and lowest coarse dead wood additions from the fires had FWI values of 13.1 and 18 respectively. The FWI values ranged over all sites from 9.8 to 22.2, corresponding to normal, to very high fire risk from the Swedish interpretation of the FWI (MSB n.d.). As the FWI is usually indicative of intensity which influences dead wood creation, we expected there to be more of a trend in this effect with the range of FWI values seen. This lack of correlation could be indicating that the FWI is not an effective measure to forecast fire outcomes for low intensity prescribed burning. However, when comparing the Lappland sites, Lappland B which had a significantly higher FWI value for its burn day, had significantly higher outcomes throughout the stand, though this trend was not clear for all sites. As such, the lack of correlation between the FWI and coarse dead wood volumes is more likely representative of the important influence that stand structure has on possible outcomes from a fire, as was the case with mortality in the stands.

Further to this point, as indicated by the high standard deviations (Table 7), the addition of dead wood was highly variable within sites. Many transects surveyed included no fire-killed dead wood, whereas some sites had pockets with quite high volumes found. This again points to structural factors throughout the sites impacting the burns effects. In order to best understand the causes of dead wood creation - and so also mortality due to prescribed burns - it would be optimal to have more detailed pre and post burn stand surveys with weather and fire behaviour data corresponding to the stand survey points. And additionally, for sufficient stand structure specific data to be compiled so that analysis could include a generalized linear model and interacting effects could be better understood. The dataset which we were able to compile is on the scale of each site and burn day, which we know to both have heterogeneity throughout. Given the amount of interacting causes and effects it is not surprising that there were no correlations between the volume of coarse dead wood created and the pre-burn meteorological conditions, nor with the on-site weather conditions during the burn which was a dataset of only seven of the burn sites.

4.3. Fire Scar Creation

All of the burns included in this study were carried out with a target of creating fire damaged and scarred trees throughout the sites. Abundance of fire scars per hectare ranged from 0 to 318, and the corresponding percentages of live trees that developed fire scars ranged from 0 to 34%. In this case it was difficult to define “success”, as there were no quantitative targets set for fire scars, nor quantitative data in the literature regarding fire scar abundance after burning. However, it is made clear in the literature that the mechanism of formation is highly related to a fire's intensity, which will affect mortality or partial cambium damage and the development of a fire scar, as dependant on tree species and size (Reinhardt and Ryan 1988; Piha *et al.* 2013). The highest counts of fire scars per hectare (318) was at the Römyren site, which is interesting because this site had close to the lowest basal area-based mortality. This suggests that the fire intensity was too low to cause mortality in the dominant tree class within the stand but was high enough to inflict some damage to the cambium of many trees.

Counts of fire scars per hectare were negatively correlated with on-site relative humidity during burning as can be seen in Figure 3. Higher humidity generally leads to lower intensity burning conditions due to less drying of fine fuels which impacts the fire intensity, and therefore the damage caused to trees (Flannigan and Van Wagner 1991). The Västeråsmossen A1 datapoint indicates though, that fire scar formation can occur even when average relative humidity is comparatively high (50.3%). This is possibly because there was variation in humidity within the site, due to variation in stand structure and topography, as Västeråsmossen A1 had the most extreme topography out of the sites surveyed. The sloped areas could have led to increased burn intensity, in spite of high humidity (Angelstam 1998), and contributed to pre-drying of fuels closer to the flame front where humidity and temperature surely differed from where the on-site weather station was located. In addition, a large factor contributing to the intensity of burning was the amount and distribution of fine fuels throughout the stand, which was not accounted for in pre-burn stand surveys. According to Schimmel and Granström (1996), more combustible fine fuels in an area leads to higher duration of burning, which could influence intensity felt by the encompassed trees. This could be particularly related to fire scars if there were high densities of fine fuels concentrated around the bases of trees, which could contribute to high burning intensity directly adjacent to tree stems.

The variable fire scars per hectare was positively correlated with both the Fire Weather Index (FWI) and the Initial Spread Index (ISI). However, the Nitten site appears as an outlier in these correlations, which are otherwise quite strong. The Nitten site had the most uniform stand structure which was almost exclusively large pines. In this case, the burn intensity was likely not high enough to damage the size of pines at the site enough to produce scarring, in spite of the relatively high indices. Regardless, the correlations suggest that under higher intensity conditions, burning should lead to the production of more fire scars. The strength of especially the FWI as an indicator of fire scar formation can be exemplified by comparing the results from the Lappland A and B sites, which were completed adjacent to one another within the same forest area and had generally the same stand structure and age. However, they were burnt under different conditions as indicated by the FWI values, for which Lappland B had the highest value out of all sites (22.2), and Lappland A the lowest (9.8). The Lappland B site had the highest percent of live trees with fire scars (34%) whereas the Lappland A site had the second lowest (2%). Based on these results, without the influence of stand structure, the FWI could be a very good indicator of the damaged inflicted to stands by fire, particularly in the form of fire scars.

The Fine Fuels Moisture Code was also positively correlated with the percent of live trees with fire scars, however the distribution of these two variables looks quite different due to a much narrower spread of the FFMC values (Figure 5). Other than the Lappland A site which had a value of 81.7, the other sites had values between 88.1 and 91.2. The scale of this parameter in Sweden is from 0-101, and according to MSB, values above 75 should indicate flammability of fine fuels (MSB n.d.). While all the sites have FFMC values higher than the threshold for flammability, the correlation suggests a connection between higher values of this index and higher fire scar abundance, which could be attributed to higher intensity burning of fine fuels.

Based on correlations from the data, fire scar formation is maximized when burning is completed under drier fuel conditions as indicated through higher FFMC values, and in the air as indicated through lower relative humidity. Further, correlations suggest that fire scar formation should be maximized when the FWI and ISI are higher. The ISI is of note because it is calculated in part through wind speed. From this correlation, and what I have put forward from the literature, fire scar formation should be high following burning under windy conditions. However, burns are unlikely to be carried out under such conditions due to the safety and public image related precautions taken in prescribed burning. There is also a fine line between conditions which create high mortality within the stand, and which create high fire scar occurrence, particularly in homogenous stands. For this reason when mortality and fire scar formation are targets, burns are likely to be more successful in heterogeneous stands, so that conditions can be optimized for mortality of thinner trees and partial damage of coarser trees causing fire scar formation. Further studies of restoration focused prescribed burns with full data documentation are required to understand what exactly defines these “ideal conditions” for different stand ages and species compositions.

4.4. Seedling Regeneration

While seedling regeneration, especially of deciduous species, is considered to be bolstered following major fire events, these prescribed burns prioritized completing the burns, over waiting and optimizing burn conditions to promote seedling regeneration. Regeneration of birch seedlings was particularly low as a result, with abundances of less than 200 seedlings per hectare at nine of the sites. Only in the

Lappland sites was birch regeneration relatively high, with 637 seedlings per hectare in Lappland B, and 1107 seedlings per hectare in Lappland A. However, in follow-up studies of the 2014 mega-fire in South Central Sweden, tree regeneration was monitored and birch seedling abundance was as high as 7000 per hectare in areas of higher intensity burn through a mature stand, 5700 in an area of relatively lower burn intensity, and were found along with high densities of other regenerating deciduous species (Åby Hedenius 2016; Jakobsson 2017). In other monitored areas, there were deciduous seedling abundances of nearly 17,000 per hectare, but according to one of the surveys, were rarely found in sites with more than 2 cm of humus layer remaining (Jakobsson 2017; Gustafsson *et al.* 2019). This puts into perspective the incredibly low birch regeneration seen in the prescribed burn sites surveyed for this project. In some cases, birch seedlings seemed to be vegetative off-shoots of slightly larger juvenile birch which had died in the burns. This fits with the lack of humus layer consumption reported in the burn summaries, and the documented importance of bare mineral soil for independent deciduous seedling establishment (Jakobsson 2017; Tikkanen *et al.* 2006).

Birch seedling data was positively correlated with the Duff Moisture Code (DMC) values for burns days. In Sweden the DMC only surpasses 100 after long periods of drought, when the topsoil and moss layer have fully dried, while a DMC value of 50 still indicates moisture present in this layer (MSB n.d.). The Lappland sites had the two highest DMC values of 51.2 (Lappland A) and 47.2 (Lappland B). While these do not suggest intense burning of the duff layer, there were perhaps some spots where the level of fuel moisture content was sufficiently low to allow for consumption of the humus layer to take place and facilitate birch regeneration. Neither spruce nor pine seedlings were correlated to this variable which exemplifies how the conditions needed for deciduous seedling establishment are different to, and more specific, than what the coniferous species require.

While pine regeneration is described in the literature as benefiting from reduction of the humus layer after fire events, the results from this study show that pine regeneration can occur even when the humus layer stays relatively intact after burning. Pine was the most abundantly regenerating tree species in all sites, ranging from 1444 to 7332 seedlings per hectare. In the surveys following the 2014 wildfire, the regeneration was dominated by deciduous trees, but abundances of up to 8000 pine seedlings per hectare were seen where high intensity burning took place and consumed much of the humus layer (Jakobsson 2017; Gustafsson *et al.* 2019). In the prescribed burn sites surveyed, the pine seedling abundances were generally lower, but in Brattforsheden and Västeråsmossen B, were comparable to what was reported by Jakobsson (2017). This could perhaps be due to the high input of seeds from the many mature pines that survived the prescribed burns, as regeneration is also influenced by tree survivorship within a stand and their corresponding ranges of dispersal (Vanha-Majamaa *et al.* 1996). Additionally, regeneration could have been bolstered by some of the other positive effects of burning, such as reduced vegetation cover and increased incoming radiation (Pasanen *et al.* 2015), however, these benefits should not be exclusively beneficial to pine regeneration so likely the input of seeds was a key factor. This is further supported by the high regeneration of spruce seedlings in sites that had the highest abundances of mature spruce, including Västeråsmossen A1 and A2.

Counts of total seedlings were correlated to numerous variables describing the moisture and temperature of the sites on the days burning took place and prior to. Of particular note is the positive correlation between total seedling regeneration and the number of rain free days prior to burning (Figure 6a). Pre-burn meteorological data such as rain free days leading up to burning, describe the weather conditions (fire climate), which dictate fuel conditions, particularly dryness (Keeley 2008). Sites with less precipitation, longer drought periods, and warmer days leading up to the burns should have had drier fine fuels, which would lead to greater consumption of ground fuels, including dwarf-shrubs, and as suggested by the data, may have led to greater regeneration. Additionally, total seedlings showed correlation with numerous variables representing temperature conditions during the burn which are part of what makes up the conditions contributing to fire behaviour, or the fire weather, as defined by Keeley (2008). These correlations could have been improved by having on-site weather data for all sites, as the correlations were stronger between the on-site conditions and total seedling regeneration, than with the regional conditions.

Interestingly, the abundance of pine seedlings was only found to be correlated with one variable representing regional temperature on burn days, whereas abundance of spruce seedlings was found to be highly correlated with numerous variables representing fire climate, fire weather, and other effects of the burns (Table 10c). It should be noted that the correlations for spruce seedlings were completed with the Spearman rank correlation method, which is a weaker test than Pearson, so the results could indicate stronger patterns than really exist within that data. However, there were observations of note to make regarding the correlations. Spruce seedlings were positively correlated to the variables describing mortality and the creation of dead wood, which could be attributed to the corresponding changes in stand openness, reduced competition in the understory, and increased sunlight following a fire (Nilsson and Wardle 2005; Den Herder *et al.* 2009). However, in all but one site pine regeneration was considerably higher than spruce regeneration and it was not found to be positively correlated with these variables as would have been expected. Alternatively, perhaps both morality rates and spruce regeneration were similarly impacted by the presence of spruce within stands.

In some cases, burns were not intense enough to bring about mortality in the pine components of the stand, but intense enough to kill some coarse spruce, which contributed to the mortality and dead wood outcomes. In those same stands, we could expect there to be some surviving spruce due to relatively low mortality overall, which would influence regeneration compared to sites where there were fewer spruce to begin with or none at all. The Västeråsmossen A1 site illustrates this well, as the stand composition included high amounts of spruce throughout. This site had a relatively high volume of coarse fire-killed trees, which were almost exclusively spruce, and was the site with the highest spruce regeneration overall. Västeråsmossen A2 also had considerable counts of coarse fire-killed spruce and had the second highest spruce regeneration. It is also possible that mature spruce close to the perimeter of Västeråsmossen A1 were dispersing seeds into the A2 site as they are directly connected, and according to Vanha-Majamaa *et al.* (1996) can disperse as far as 200 metres.

It is, however, problematic that in nearly all sites there was spruce regeneration, which indicates that the single prescribed burn events were no sufficient to stop spruce encroachment. The single exception was the Nitten site, which was surveyed to be a homogenous pine stand. The Lappland sites had the next lowest spruce regeneration, and although the spruce mortality targets were likely not reached, the low spruce regeneration indicates that the burns brought the sites closer to the targeted conditions. Although seedling regeneration targets were not prioritized in the burn plans, one overarching target was to reinstate pine as the dominant tree species, which cannot be achieved if spruce continue to regenerate throughout the sites. While the abundances of spruce seedlings were generally low compared to pine, they are well suited to outcompete the pine seedlings in areas where spruce mortality was low, and such areas may continue to be shady and moist (Esseen *et al.* 1997; Nilsson and Wardle 2005).

4.5. Bare Ground Area

Bare ground area was estimated during field work to represent the variation in burn intensity. Initially, the planned survey variable was the area of exposed mineral soil per plot, however, due to the relatively low burn intensities and relatively high moisture in the duff layers during burning, exposed mineral soil was very rare. When the sites were surveyed, the bare ground area ranged from 137 m^2 ha^{-1} to 3360 m^2 ha^{-1}. While this was maximized by allowing burn sites to smolder for multiple days following ignitions, in many burn summaries practitioners reported less than complete consumption of ground fuels, and very minimal duff layer consumption. Surviving ground vegetation and the ease of plant regrowth from rhizomes protected in the unburnt humus layer, likely led to rapid re-establishment of the understory, particularly of dwarf shrubs (Schimmel and Granström 1996; Nilsson and Wardle 2005; Gustafsson *et al.* 2019). As such, the bare ground area has surely decreased since the burn years, and this measure is likely skewed by the different number of growing seasons which have passed since the burns took place.

Area of bare ground was found to be negatively correlated with the on-site relative humidity during the burns (Figure 7a). As was previously highlighted, the humidity during burning has strong effects on burning intensity and fuel consumption (Van Wagner 1974; Flannigan and Van Wager 1991), and according to this correlation burning under lower humidity conditions should result in more exposed bare ground. A significant result was returned for the correlation between bare ground area and fire scars (Figure 7b); however the result was not significant when correlated to the percent of live trees with fire scars. The first metric is perhaps a better comparison because it inherently includes elements of the forest structure in the metric such as tree density, which in turn influence the climatic conditions leading to differential consumption of ground fuels. One would also expect there to be correlations between bare ground area and the fire climate variables, as they influence fuel conditions, as well as with the FFMC, which represents the moisture conditions of the ground fuel (Van Wagner 1974; Keeley 2008). The lack of significant correlations with these variables is perhaps due to the fuel conditions overall being too moist, and with too little variation between sites to represent the differential influence that climatic conditions can have on the effects of burning.

4.6. Rate of Burn

Based on the link described in literature, we calculated a theoretical rate of burn as a proxy for burn intensity (Johnson and Miyanishi 1995; Keeley 2008). According to this metric, the intensity varied greatly between sites, as rate of burn ranged from 0.7 to 4.5 hectares per hour. Unfortunately, it cannot be decisively claimed as a good representation of burn intensity due to its lack of correlation with any output variables, nor with the ISI which should be representative of expected rates of fire spread (MSB n.d.). Rate of burn was found to be positively correlated with the DMC, which could be due to the strong effect of fuel moisture conditions on the rates of fuel consumption. If this were the case though, it would have made more sense for the rate of burn to be correlated with the FFMC, as this is the measure denoting fine fuel conditions, which drive flaming combustion (Dickinson and Johnson 2001). The connection between DMC and rate of burn could have been due to the way that the burn execution was impacted by moisture levels. For example, in sites with lower DMC values - corresponding to higher moisture levels in the moss and upper soil layers - it could have been harder to achieve ignition of the ground fuels, and an advancement of the flame front. This could have contributed to longer lengths of time spent lighting and burning out strips, or lighting using narrower strips, which would require more passes to burn a defined area. Unfortunately this type of account of ignition during the prescribed burns was minimal in the acquired burn summaries.

In a wildfire context the rate of burn is often highly related to intensity, due to its determination through fuel dryness, wind speed and fuel continuity (Johnson and Miyanishi 1995; Granström and Niklasson 2008; Keeley 2008). However, in a prescribed burn, the rate of burn is strongly influenced by the methods and decisions of the burn managers including the aggressiveness of ignition, and the speed at which they try to complete the burn. Both of which are influenced by the size of the burn, the size of the team executing the burn, fuel conditions during burning, and the comfort level of the individual(s) managing the burn. With this in mind, the outputs of prescribed burns are likely less related to the rate of spread than they would be in the context of a wildfire, and perhaps other measures of intensity would show correlation with prescribed burn outcomes. One such option could be to record fire front intensity or the speed of the advancing fire line, for each strip that is lit and burns out (Linder *et al.* 1998; Keeley 2008). More studies of conservation oriented prescribed burns with full and more intentional data collection could lead to a strengthened understanding of these relationships.

5. Conclusions and Recommendations for Future Prescribed Burning

One of the main complications in completing a prescribed burn is that the conditions under which burning should take place according to targeted values within the stands, often differ greatly from the conditions under which burn managers are comfortable executing burns. This can be due to values at risk nearby, limited resources at their disposal, lack of experience or advice, and concerns from the public about prescribed burning processes (Niklasson and Granström 2004). In addition, the summer climate in Fennoscandia does not always provide ample weather windows in which high intensity burning conditions can be achieved, so prescribed burning may be further limited to low intensities. This juxtaposition was seen consistently between the burn targets and the conditions under which the studied prescribed burns were completed, which in most cases resulted in the effects being far less than the targeted values.

An element of this disconnect is the site selection and the corresponding targets. In some of the older sites that we surveyed, including Nitten and Västeråsmossen B, the dominant tree size was quite coarse and widely spaced and would thus have needed high fire intensities to substantially impact the stand structure. Based on the site surveys, the conditions under which the burns were executed were not appropriate, as the effects of the burns were near negligible. In order to have produced the targeted changes, the sites would have had to be burnt in much drier and hotter periods. This adds additional risk and difficulty to the process of burning a site and perhaps is even limited due to ignition or fire restrictions when wildfire risk is high. In such cases, perhaps prescribed burns should not have been planned for these sites, and allocated funds could have been put towards implementing alternate measures. Furthermore, it is generally difficult to build high intensity prescribed burns at all, especially when they are carried out using the repeated strip burn method, as a flame front is not able to develop and the resulting intensity is relatively lower (Linder *et al.* 1998). This perhaps contributed to the few correlations found between the various FWI indices and the outputs of the burn, as the intensity is highly impacted by the width of strips and the fine fuels contained within that stretch, and not necessarily as related to the index, as it would likely be for a wildfire where the consumption of fuel is continuous (Tangren 1976).

In prescribed burn planning in British Columbia, Canada, the FWI system is highly relied on to dictate the weather conditions under which burning should take place. However, such prescribed burns tend to be larger in size and are executed using different ignition techniques (personal experience). While the FWI system is utilized in Sweden to forecast wildfire risk, and its application to boreal forests in Fennoscandia has been studied and determined to generally be appropriate during the fire season (Tanskanen *et al.* 2004; Tanskanen and Venäläinen 2008), its application has not been studied in the context of prescribed burning. This index was used by some of the burn managers, as a part of documenting the conditions under which burning took place (Lappland A and B) and as a method of outlining the targeted environmental conditions under which burning should take place (Skattlösberg H). While the system likely remains relevant in this context, a knowledge gap exists as to the relationship between the values of the index and the intensities that can be achieved through prescribed burns of this method.

The correlations between meteorological variables and the outputs variables led us to few clear recommendations centred around burning conditions. Fire scar abundance seemed to be maximized when sites were burnt under drier fuel and weather conditions. This relationship can be generalized in that it suggests that damage to trees increases with increasing dryness of fuels, likely due to its impacts on intensity of flaming combustion (Linder *et al.* 1998; Keeley 2008). The rate of mortality, as such, depends on how tolerant the trees within the stand are to the damage inflicted by the fire. Younger stands in this study were in general more impacted by the burns, whereas outcomes in homogenous, older stands, were minimal. In some cases, targeted outcomes were best achieved when there was heterogeneity in the pre-burn stand structure. These results illustrate the importance of considering site selection at the start of the planning process, as potential outcomes are inherently limited by the structures present.

The results from this study, although of lower magnitude than in related literature, showed that drier conditions in the humus layer led to higher establishment of birch seedlings. In fact, seedlings of all species, when considered together, were found to regenerate more after burns which took place in drier and hotter conditions. Managers should be advised that these trends were inclusive to spruce seedlings. Pasanen *et al.* (2015) suggested an alternative approach to increasing deciduous tree densities in sites, which involved manual felling of patches within a stand and burning the patches, exclusive of the rest of the site, when moisture levels in the humus layer are very low. In this way, more extreme smouldering combustion can occur in prescribed areas to expose mineral soil, without having to complete an entire stand burn under extreme weather conditions (Pasanen *et al.* 2015).

In numerous cases, the on-site weather data showed correlation or stronger correlation to output variables when compared with regional data, which illustrates the importance of having on-site weather and intensity conditions reported. Further study of the effects of burning are needed to inform prescribed burn practices in Sweden, and on-site data used in conjunction with more detailed pre- and post-burn stand surveys will be crucial to understanding the relationships between burning conditions and what targets are possible in different types of stands. Unfortunately, all the insights described above, from the data and from the literature, lead to recommendations of burning under warmer and drier conditions, which again brings forth the issue of safety and potential losses which limit the prescribed burning process. In some of the prescribed burn summaries there was discussion of pre-burn preparatory work which could have been completed to increase the intensity of burning, such as thinning trees and letting them cure throughout the site to increase ground fuels. This could be an alternative to burning under more extreme drought conditions and could be focused in areas where higher mortality is targeted, such as where spruce encroachment is high.

Alternatively, as was done in the Lappland sites, manual work can be done following prescribed burns to increase mortality and contributions to coarse dead wood. However, according to Koivula and Vanha-Majamaa (2020), trees that die artificially, such as through manual felling, host lower species richness of saproxylic species, when compared with trees that die naturally such as through the effects of fire. According to their results it could be more beneficial in regard to conservation to affect mortality through fire. This notion is supported by discussion in Sandström *et al.* (2019), though they suggest that higher amounts of dead wood can be produced through artificial means (felling and import) compared to prescribed fire. Perhaps prescribed burning could be carried out along with pre-burn girdling, or hand felling of large diameter trees to provide diversity in dead wood size classes (Linder *et al*. 1998), while also providing naturally produced dead wood and the otherwise beneficial effects of fire on the landscape. The effects of such alternative and additive measures to prescribed burning need to be studied along with the actual biodiversity effects to inform burn planners and optimize prescribed burning. Further research will reveal more explicit parameters indicating site types where prescribed burning is not an effective restoration tool, and in such cases, which other measures are more appropriate. Prescribed burns should be completed with explicit data-based targets, and not relied on as an all-encompassing restoration treatment for Swedish boreal forests.

6. References

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