Differences and similarities in stand characteristics after prescribed burning and wildfire:

Implications for conservation of forest biodiversity

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Differences and similarities in stand characteristics after prescribed burning and wildfire: Implications for conservation of forest biodiversity

Skillnader och likheter i beståndspåverkan efter naturvårdsbränning och naturlig brand: Betydelse för bevarande av biologisk mångfald i skogen

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Abstract

1. Wildfires are a natural disturbance in the boreal forests of Fennoscandia and have shaped and formed forests in the past, resulting in very heterogeneous forests containing large amounts of dead and living trees in various age classes. Over the past centuries, forest management simplified forests, so that they today are much less variable than historically. Further, the economic value of timber has incentivized more effective fire suppression methods. As a result, fire events have become rare and together with the effects of industrial forestry led to a decline of forest-dwelling species. Those species depend on the heterogeneity and structures which today sparsely occur. Today, prescribed burning is seen as an effective tool to restore forests that lost their historical values.
2. In this study, I describe and compare differences and similarities between natural fires and prescribed burnings in Sweden. Further, I identify if, and which goals of prescribed burnings can be reached. For goals that are difficult or not possible to achieve with prescribed burning, I present what changes that may improve the results of prescribed burning and what possible alternative measures can be undertaken to achieve such goals.
3. Data was collected in the summer of 2022 in ten areas within the wildfire area around Kårböle, Ljusdal, in central Sweden, as well as in ten prescribed burns in Gävleborg, Västernorrland, Dalarna, and Jämtland county.
4. Wildfires and prescribed burnings generate significantly different outcomes for most variables studied. Pine mortality was 93% greater in the wildfire sites. Sites that were exposed to wildfire had up to 276% higher volumes of coarse woody debris than sites exposed to prescribed burning. Regeneration of *Populus tremula*, *Salix caprea*, *Betula spp.,* and *Pinus sylvestris* was significantly higher in wildfire sites and was, depending on species, 202% to 875% greater in the latter. The proportion of fire-killed birches with fruit bodies of *Daldinia loculata* was more than 26 times as high in the wildfire sites compared to the prescribed burning sites. For signs of woodpeckers' feeding activity on dead trees, results showed that feeding activity on pines was greater in the wildfire sites, whilst feeding on spruce and birch was greater in the prescribed burning sites. Targets of prescribed burns were not always clearly stated in the County Administrative Board reports, and it was thus difficult to evaluate if they were met or not. Differences in tree mortality, volumes of deadwood, and regeneration between wildfires and prescribed burns are likely due to differences in the fire severity. General targets such as creating fire-shaped forests with prescribed burning, enhancing the regeneration of deciduous trees, and creating deadwood can be reached, tough not to the same level as by wildfires.
5. Practical implications: If prescribed burnings aim to mimic the effects of wildfire, they should be executed under drier and warmer periods, and burning strokes should be allowed to reach higher severity. Conifers could be girdled, or manually felled in advance to guarantee thinning and creation of deadwood, especially of trees with greater diameters. The humus layer could be manually removed after the burn to expose mineral soil and favor deciduous tree regeneration.

Keywords: coarse woody debris, conservation, biodiversity, boreal forest, *Daldinia loculata*, Fennoscandia, prescribed burning, regeneration, wildfire, woodpecker

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Abbreviations

CAB	County Administrative Board
CWD	Coarse woody debris (minimum DBH 10 cm)
DBH	Diameter in breast height
DF	Degrees of Freedom
SE	Standard Error

1. Introduction

Forestry has been conducted on an industrial scale in Scandinavia since the late 19th century, which has imposed drastic changes on forest structure (Esseen et al. 1997). This has led to a suppression of fire in order to protect economic values, as timber prices increased since the late 1800s (Niklasson & Granström 2004). Industrial forestry implies short rotation cycles, large clear-cuts, and monocultures focusing on conifers, which has led to the impoverishment of forest stands complexity and structure. According to Felton et al. (2020), in 2014, Norway spruce and Scots pine constituted 80% of the standing volume in Sweden. Humans have impacted and controlled the fire regime in Sweden for a long time, since before forestry became important. Niklasson & Granström (2000) and Granström (2001) point out that already during the late 1600s, settlers in northern Sweden induced a trend of smaller-sized but higher numbers of fires. Between 2011 and 2015, 20442 ha of the total forest land burned, which averages to 4088 ha burned annually, or 0.013% of Sweden's forest land (Ramberg et al. 2018). However, the numbers are inflated due to one single mega-fire in Västmanland 2014, which encompassed 11070 ha. Without the Västmanland fire, only 9372 ha burned between 2011 and 2015, which gives an annual average of 1874 ha or 0.006% of Sweden's total forest area. Generally, most fires were below 20 ha between 2011 and 2015, and the mean prescribed burn sites were more than three times larger than the wildfire areas (Ramberg et al. 2018). Looking back in time, 150 years ago around 1% of the forest land burned yearly in Sweden (Jakobsson 2017).

1.1. Wildfires

Fires are a natural disturbance (Niklasson & Granström 2000), and they are important as they shape complexity and structure (Gillson et al. 2019) in boreal forest ecosystems, but have been almost excluded from the ecosystem due to the forest industry during the past centuries. According to Hekkala et al. (2014), the absence of fire over a long time period, as well as other changes in the natural disturbance regime, can alter species' dominance and productivity and thus impact the functioning of the forest ecosystem. Fire shapes forest stands in many ways, for example by facilitating the regeneration of trees (Hekkala et al. 2016), which leads to varying age class distribution (Gillson et al. 2019) and variation in tree species, as fire favors pioneer tree species (Niklasson & Granström 2004; Vanha-Majamaa et al. 2007; Kuuluvainen 2009; Hekkala et al. 2014). Niklasson & Granström (2004) especially point out that fire promotes the reproduction of aspen and goat willow. Aspen and goat willow regenerate poorly under the present forest management practices and are particularly important as they are considered to be keystone species and provide habitat for several red-listed species (Kuusinen 1994; Kouki et al. 2001; Tikkanen et al. 2006; Hekkala et al. 2014; Enescu et al. 2016). Fire creates dead wood (Hekkala et al. 2016), charred wood, and fire-damaged trees. Fires are also of great importance as they impact biogeochemical cycles and nutrients (Hekkala et al. 2016; Gustafsson et al. 2019; Granath et al. 2021).

Lindberg et al. (2020) accentuate that fire gives rise to a variation in forest structures on a stand- and landscape-level, as both fire severity and the area affected vary. Vanha-Majamaa et al. (2007) explain that light fires may impose no major changes on the ecosystem, while more severe fires may result in the loss of soil organic matter or nitrogen. Also, Hekkala et al. (2014) refer to that wildfire in the boreal zone is variable in both intensity and ecological effects. Further on, the varying ages of different post-fire successions and varying sizes of fire-affected patches "i.e., pyrodiversity, as well as the patch connectivity, maintain biodiversity and ecological integrity and function." (Gillson et al. 2019, p. 3).

Fire intensity and fire severity are two key components commonly used to describe a fire. Fire intensity is defined as the energy released during various phases of a fire event, which means the physical combustion process of energy that is released from organic matter (Keeley 2009). Granström (2001) states that fire intensity is more immediately important, as it directly controls tree mortality and thus affects species composition and stand structure. Fire severity, or burn severity, defines the loss of or change in the organic matter above- and belowground, and is broadly defined as a fire's ecosystem impact (Keeley 2009).

The fire-shaped structures and variation are important for biological diversity. Nappi & Drapeau (2011, p. 994) underline that "burned forests typically represent high-quality habitats for many plant and animal species.". Moreover, fire creates habitats for pyrophilous species (Granström 2001). Siitonen (2001, p. 24) defines pyrophilous species as species that are "strongly associated with, and probably dependent on newly burned areas.". The change in fire frequency has resulted in the rarefication and sometimes extinction of several hundred fire-adapted and fire-requiring species, that had previously been common (Niklasson & Granström 2004). Some of these species are strictly dependent on fire itself, while the majority are dependent on both forest structures and processes that are created and induced by fire events (Niklasson & Granström 2004; Kuuluvainen 2009; Wikars 2018). The fungi *Daldinia loculata* lives inside birch trees and develops fruit bodies only if the tree is killed by a fire event (Johannesson & Dahlberg 2001). A number of fire-specialized insects are linked to this fungi's fruiting bodies (Wikars 2004). Examples of such species are *Apomyelois bistriatella* and *Platyrrhinus resinosus* (Johannesson & Dahlberg 2001), as well as *Biphyllus lunatus*, which is believed to be completely dependent on *Daldinia loculata* (Wikars 2006). Tikkanen et al. (2006) mention the importance of severe fires, as these create forest patches with large amounts of deadwood, which are a prerequisite for saproxylic species. According to Kouki et al. (2001), up to one-fourth of all forest species are dependent on deadwood. Saproxylic species are an important food source to many bird species, especially to woodpeckers. Abundance of woodpeckers' signs of feeding activity can indicate the abundance of wood-boring insects (Nappi et al. 2003). Furthermore, woodpeckers are an indicator species for biodiversity (Versluijs et al. 2020), especially for forest bird diversity (Nappi et al. 2015), and are a keystone species as they provide cavities (Bütler et al. 2004; Nappi et al. 2015; Versluijs et al. 2020).

Another structure that is shaped by fires is fire scars. Piha et al. (2013, p. 669) conclude that fire scars can form "if lethal temperature linger at the surface of the stem for a sufficient amount of time and cause cell death in the bark, cambium and xylem.". *Pinus spp*. tree's primary defense to wounding is to close wounds with resin in order to protect itself from entering water, insects or pathogens (Lombardero et al. 2006; Arbellay et al. 2014; Bär et al. 2019), thus resin flow can indicate the formation of a fire scar.

1.2. Prescribed burning

Prescribed burning is a planned fire, which is applied to meet management objectives (US Forest Service 2016). Passive conservation efforts, such as the protection of forest stands are no longer sufficient, as the majority of forest land is managed and only a few natural forest systems remain (Hjältén et al. 2017). Thus, active restoration is needed for both managed and protected forests (Halme et al. 2013; Komonen et al. 2014; Hjältén et al. 2017). The Swedish Environmental Protection Agency informs that 2.4 million ha of forest land is formally protected, which equals 8.8% of Sweden's forest land. 1.3 million ha of the 2.4 million ha are classified as productive forest land, which corresponds to 6% of the country's productive forest area (Naturvårdsverket 2023). The majority of the formally protected forest is situated near the mountainous region of Sweden, close to the Norwegian border.

Fires are often perceived as negative, as they are seen as a threat to ecosystems (Lindberg et al. 2020), economic values, and health (Gillson et al. 2019). However, Gillson et al. (2019, p.2) state that "recognizing the importance of fire as an ecological process has increased acceptance for the use of prescribed burns. The practice maintains more manageable fuel loads that dampen wildfire risks, and economic costs while conserving or restoring ecosystem processes, heterogeneity, and native biota.". Prescribed burning is a relatively new tool to reach biodiversity targets (Lindberg et al. 2020). According to Lindberg et al. (2020), burning has proven to be a highly effective tool when aiming to increase the abundance and diversity of polypores and also other species that are rare or threatened. Hekkala et al. (2016) conclude that prescribed burning may be the most effective tool for restoration. Furthermore, North et al. (2012, p. 397) raise that prescribed burnings can produce similar effects on vegetation as low-intensity wildfires and that "efforts to increase forest restoration and resilience need to incorporate fire.". This demonstrates that prescribed burning can be a very effective tool for nature conservation, as different studies have pointed toward positive outcomes, especially in regard to polypores. On a larger scale, prescribed burning could also help to prevent mega-fires if they were incorporated into the management of production forests.

Prescribed burnings are conducted in both conservation areas to favor and maintain high natural values (Naturvårdsverket 2008) and also in managed production forests to decrease woody debris and benefit regeneration after harvesting (Lindberg et al. 2020). According to Nilsson (2005), the main targets of prescribed burns in protected areas are to reach a favorable conservation status for both fire-dependent and fire disturbance-dependent species and ecosystems by 2030. The favorable conservation status is maintained by the continuous use of prescribed burnings, and prescribed burnings are carried out in all protected areas in which this is included in their management plans. Prescribed burnings' central goals are also to restore and maintain pine-dominated multi-storied forests (Lindberg et al. 2020). According to Hekkala et al. (2016), prescribed burnings create heterogeneous habitats, for example by the creation of diverse deadwood, the death of a variety of tree species, and trees in different diameter classes. Vanha-Majamaa et al. (1996) further observed that prescribed burnings create structural elements, for example in the form of charred wood, and also enhance regeneration.

Prescribed burnings have been found to promote biodiversity in several ways. For example, Toivanen & Kotiaho (2007) found that species richness and abundance of non-saproxylic and saproxylic beetles increased after a controlled burning in southern Finland. They also observed that the burned sites were preferred by rare species and especially rare saproxylic species as well as by red-listed and pyrophilous species. Also, Vanha-Majamaa et al. (2007) found that boreal forest diversity could be reinstalled through prescribed burning, as natural structures, processes and species composition can be restored, and found positive long-term effects on many species groups. Despite that wildfires nowadays are rare events and the above described positive effects of prescribed burning on biodiversity, surprisingly few studies have compared how the effects of prescribed burning differ from those generated by wildfires. One of the few exceptions to this is the study by Fredriksson (2021) in northern Sweden, who conclude that the effects of wildfire and prescribed burning are different. For example, Fredriksson (2021) detected differences in regard to tree mortality (greater in wildfire), the canopy cover (lower in wildfire), the amount of deadwood input (greater in wildfire), and impacts on the field layer vegetation, as well as numbers of red-listed and pyrophilous species (fewer in the prescribed burning). The prescribed burnings studied by Fredriksson (2021) were found to be more similar to the unburned control stands than to the studied wildfire areas. Fredriksson (2021) suggests that these differences arose from differences in fire severity and that the studied wildfire sites had a higher burn severity than the prescribed burns.

1.3. Motivation & Aim

Motivating this study was the lack of research comparing wildfires and prescribed burnings in Fennoscandia, as well as the lack of research on forest variables after large wildfires in Fennoscandia. Wildfires are likely to increase due to climate change in the near future (Gillson et al. 2019), and are thus important to take into consideration and study their effects. Prescribed burning is seen as an effective management action to restore and recreate fire-shaped landscapes (Gillson et al. 2019; Lindberg et al. 2020), but how effective are they compared to wildfires?

The aim of this study is to describe and compare differences and similarities between natural fires and prescribed burnings in Sweden. This study further aims to identify which of the targeted effects set by the County Administrative Board (CAB) and stated in their prescribed burning reports can be reached by prescribed burnings. For goals that are difficult or not possible to achieve with prescribed burning, what changes may improve the results, and what possible alternative measures can be undertaken to achieve such goals? Or is it possible to change the procedure of prescribed burnings to reach the objective of these actions?

I expected that both the wildfire and prescribed burnings led to tree mortality, mostly among Norway spruce trees, and that both fire types benefit the regeneration of Scots pine as well as deciduous trees. Further, I expected that the fire event would have led or will lead to multi-storied forest structures over time, e.g., forest stands with trees in a variety of different age-classes and thus heights, as new cohorts of tree seedlings would be recruited by the increased regeneration after the fire event. Prescribed burnings may have more variable effects on the forest stand than the wildfire, as weather conditions are often different at the time of prescribed burnings execution compared to wildfires.

2. Material & methods

To compare the effects of wildfires and prescribed burnings, as well as to answer which targets can be reached by prescribed burnings, I analyzed tree mortality, the change of living trees' basal area, the volume of deadwood, and the regeneration of birch (*Betula pendula* and *Betula pubescens*), aspen (*Populus tremula*), goat willow (*Salix caprea*), and pine (*Pinus sylvestris*), as well as the creation of fire scars by noting if living pines showed signs of resin flow, as resin flow preceeds the formation of fire scars. Proper examination of species responses was beyond the scope of this thesis, but to get some idea about the potential benefits that fire can generate I recorded the presences of fruiting bodies of *Daldinia loculata* on fire-killed birches and the proportion of dead trees with signs of woodpeckers' feeding activity. In the following section, the materials used in this study and the methods of data collection and analysis are presented.

2.1. Material

The present study is based on a field inventory. Data were collected over four weeks in the summer of 2022. The study was conducted in central Sweden (Figure 1.) in the middle boreal zone (Ahti et al. 1968). Ten sites in the wildfire area of Kårböle (61.9871° N, 15.2994° E), Ljusdal municipality, Gävleborgs county, which comprises a total of 8995 ha (MSB 2020), were inventoried. Also a total of ten prescribed burning sites in nature reserves that had been conducted between 2017 and 2019, each with a total area of between 8 and 50 ha, in Dalarna, Gävleborg, Västernorrland, and Jämtland county, were surveyed.

Figure 1. Map over parts of northern Europe, star indicating the location of the studied areas in the middle of Sweden (Lantmäteriet 2022c).

The sites in the wildfire area were chosen as most of them have been proposed to be protected as nature reserves. One area has already been protected as a nature reserve since before the wildfire and one area has been voluntarily set aside (non-formal reserve) by the forest company Sveaskog. Shapefiles over the burned area and the proposed nature conservation areas were received from Andreas Wedman (CAB Gävelborg), John Granbo (CAB Västernorrland), and Anders Heurlin (CAB Dalarna) and loaded into QGIS 3.22.6. Inside these areas, polygons of an area of approximately 25 ha were arranged if the areas were larger than that, and so that the polygons were close to a road if possible and without mires or lakes within them. The size and position of a polygon was determined inside the QGIS application without prior information about the area. In each polygon, random points were sampled using the function Vector – research tools – random points inside polygons. The number of sample points varied depending on each polygon's area. Polygons with an area of 25 hectares received seven sample points, with a minimum distance of 50 meters between points. In each area, at least four random sample points with a minimum distance of 50 meters from each other were arranged (Table 1.).

The wildfire area Kårbölebrännan can be divided into three distinct wildfire areas, Enskogen, Nötberget, and Ängra (Figure 2.). Inside the northernmost wildfire area called Enskogen, with a total area of 4326 ha (MSB 2020), the future reserve Björkvallsberget can be found. Inside Björkvallsberget, I have placed two sample areas, here named Norra Björkvallsberget and Södra Björkvallsberget. The westernmost wildfire area is titled Nötberget and amounts to 872 ha in total (MSB 2020). Inside this wildfire area, the future reserve Södra Nötberget is situated, and the sampled area is named the same here. The southernmost distinct wildfire site, Ängra, sums up to a total of 3797 ha (MSB 2020). Inside this area, the sample sites Sveaskog hänsyn and the nature reserve Gommorsberget can be found. Further on, the site Ängraån inside the future reserve with the same name, Västra and Östra Ängrabrännan within the future reserve Ängrabrännan, and Västra and Östra Körbruksberget inside the future reserve Körbruksberget are placed in the Ängra wildfire area.

Table 1. Name of the inventoried wildfire sites, date of ignition, size of the sampled polygon in ha, as well as the number of circular sample plots.

Name	Dates of ignition	Polygons area	Number of circular sample plots
Östra Ängrabrännan	16/07	24 ha	7
Västra Ängrabrännan	16/07	25 ha	7
Ängraån	16-17/07 and 24/07	24 ha	7
Gommorsberget	24/07	23 ha	7
Sveaskog hänsyn	25 - 28/07	8 ha	4
Västra Körbruksberget	20/07	24 ha	7
Östra Körbruksberget	25-28/07	24 ha	7
Södra Nötberget	14-15, 19/07	23 ha	7
Södra Björkvallsberget	17/07	25 ha	7
Norra Björkvallsberget	17/07	23 ha	7

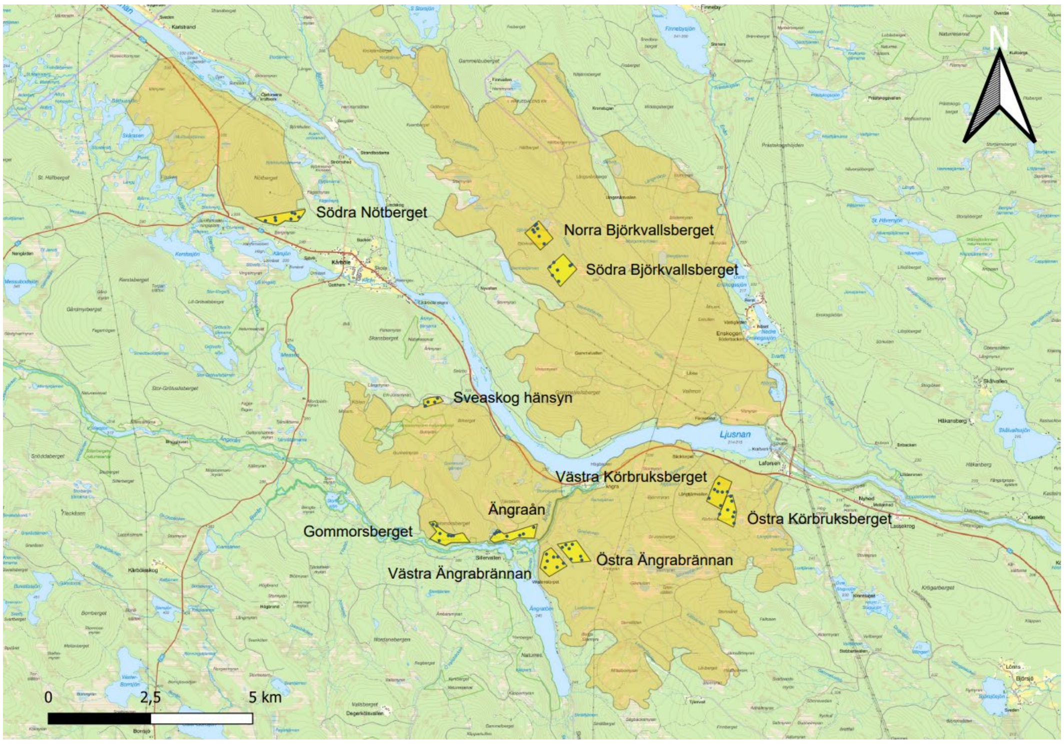

Figure 2. Map over the sampled areas within the wildfire (indicated in orange). The yellow areas indicate the ten surveyed sites (most within proposed nature reserves), and the blue dots indicate the location of sample points. The southernmost wildfire area is titled Ängra, the northernmost Enskogen, and the westernmost Nötberget (Lantmäteriet 2022b).

The prescribed burnings were chosen with the criteria that they had to be close to Kårböle geographically, conducted between 2017 and 2019 and planned by the respective County Administrative Board in protected forest stands for conservation purposes (Figure 3.). Ten areas were identified (Table 2.) in Gävleborgs, Västernorrlands, Dalarnas, and Jämtlands counties. All areas were burned as part of the Life Taiga project (2015-2020) (LifeTaiga 2023) and are protected in form of Natura 2000 areas. Natura 2000 is a network of protected areas and can be found in all 27 European Union countries (European Commission 2023). “The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive.” (European Commission 2023). In the prescribed burnings, sample points were chosen in the same manner as for the wildfire areas. Here, 0.3 sample points/hectare, with a minimum distance of 50 meters to each other, though a minimum of four points per object, were admitted. Basic information about the prescribed burning sites and the targets of the burn was found in reports from the respective County Administrative Board.

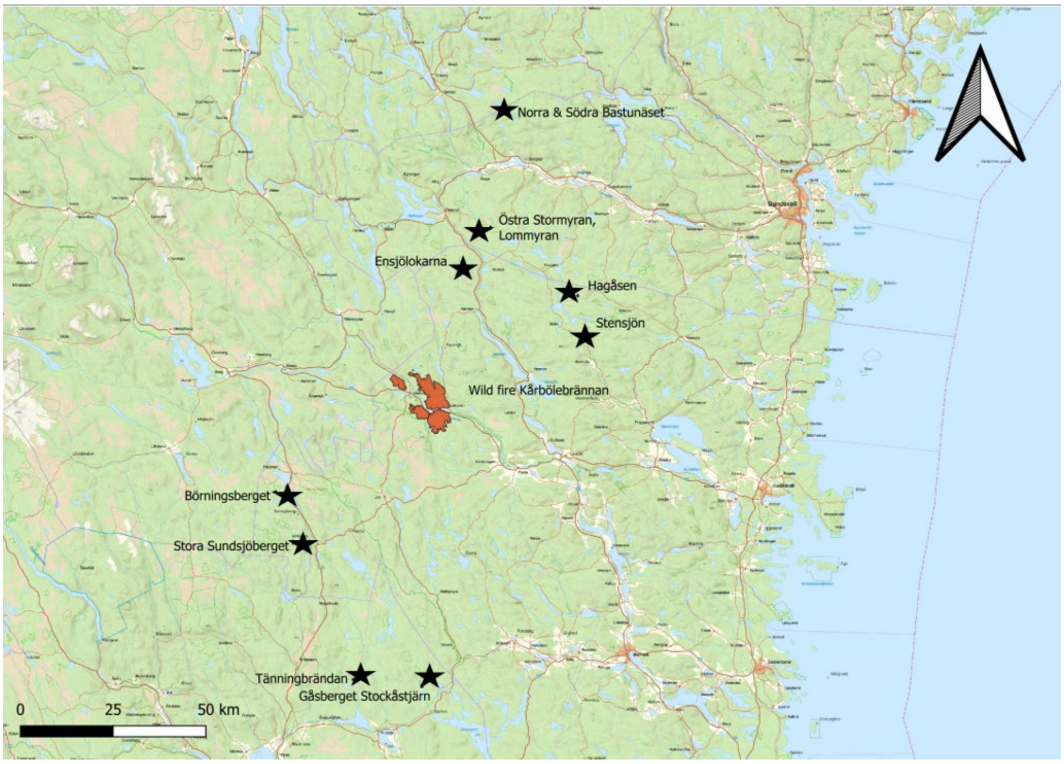

Figure 3. Map indicating the locations of the ten prescribed burns as well as the wildfire area (Lantmäteriet 2022a).

Table 2. Names, locations, dates, and sizes of the prescribed burn sites surveyed in this study.

Site Name	Municipality & County	Date Burnt	Burn Size
Börningsberget	Härjedalen, Jämtland	27/06/2018	20 ha
Tenningbrändan	Mora, Dalarna	07/07/2017	10 ha
Gåsberget Stocksåstjärn	Rättvik, Dalarna	18/05/2019	8 ha
Stora Sundsjöberget	Ljusdal, Gävleborg	25/05 and 06/07/2018	50 ha
Stensjön	Ljusdal, Gävleborg	23/05/ 2017	10 ha
Ensjölokarna	Ljusdal, Gävleborg	02/07/2018	12 ha
Hagåsen	Nordanstig, Gävleborg	04/07/2018	20 ha
Östra Stormyran, Lommyran	Ånge, Västernorrland	21/05/2018	28 ha
Södra Bastunäset, Jämtgaveln	Ånge, Västernorrland	08/06/2018	22 ha
Norra Bastunäset, Jämtgaveln	Ånge, Västernorrland	30/05/2018	9 ha

2.2. Field inventory

The sample points were located in the field using the application Avenza maps. Tif files of the prepared digital maps with the randomly sampled points were loaded into the app beforehand. If the center of the sample point was in a small mire zone or in a clearcut area, the sample plots midpoint was adjusted to fulfill the criteria that all sites should be located on upland and forested conditions. In each object, several different variables were surveyed in circular sample points and transects between sample points. For the measurements within the circular sample plot, a 5 m extendable fishing rod was used, and for regeneration, frames with three axes of each 50 cm and one open side were utilized. The diameters of trees, snags, and logs were measured with a 40 cm caliper. For transects, a 50-meter measuring tape was wielded. Tree heights were measured by a Haglöfs Vertex 5 hypsometer (calibrated every three days).

At each circular sample plot, the boundaries were determined using a handheld 5 m extendable rod (thus, each circular sample plot had a radius of 5 m and an area of 78.54 m^2). Inside the circular sample plot, tree saplings below 1.3 m height were sampled using frames of 0.25 m^2 area, which were thrown eight times randomly inside the circular sample plot (Figure 4.). The number of Scots pine, birch, aspen, and goat willow tree seedlings were counted.

Figure 4. Sampling of tree regeneration inside 0.25 m^2 frames within each circular sample plot.

Then, trees over 1.3 m top height inside the circular sample plot were measured. For living, standing dead trees, as well as downed dead trees that were rooted inside the sample point, species, diameter at breast height (1.3 m), cause of death (if it was obvious that the tree died prior to the fire event, caused by insects for example), as well as the presence of resin flow on living pines were noted (Figure 5.). Death previous to the fire event was determined if the trees were more decayed than the majority of trees nearby, e.g., if an individual tree had no leaves or needles left, if the bark was absent from large parts of the trunk, or if parts of the crown or branches were missing. Leaning trees were considered downed.

Figure 5. Pine with resin flow in the wildfire site Västra Ängrabrännan. Resin flow indicates the creation of a fire scar.

In between sampling points, three transects with a length of 50 meter each were inventoried in each site. Five-meter-wide transects were placed so that they stretched in different directions (north to south and east to west) and spread over each site. In 2.5 meters on each side of the measuring tape, I measured all dead standing trees of at least 10 cm in diameter at breast height (DBH). For each tree, species, diameter at breast height, height, cause of death, presence of *Daldinia loculata* on newly killed birches (Figure 6.), and signs of woodpeckers' search for food (Figure 7.) were noted. Dead downed wood was measured where the measuring tape crossed the stem (if they were at least 10 cm in diameter) (Figure 8.).

Figure 6. Daldinia loculata on a fire killed birch in the wildfire site Östra Körbruksberget.

Figure 7. Signs of woodpeckers' feeding activity at the base of a pine in one of the transects in the wildfire site Norra Björkvallsberget.

Figure 8. Diameter measuring of a downed pine in one of the transects in the wildfire site Gommorsberget. The consistent charring of the log indicates that this pine was downed and dead before the fire event.

Downed before or after the fire was assessed whilst looking at the charring of the stems. If the downed tree was only charred within 2 m of the stem base, it was assumed that the tree was standing during the fire and fell shortly after. If the charring extended over the whole stem, the assumption was made that the stem had already been downed by the time of the fire.

2.3. Calculations

The inventoried data was saved in a Microsoft Excel version 2303 file. The data was analyzed and visualized in the application R Studio 2022.12.0 Build 353.

Differences for wildfire and prescribed burnings variable values were pooled across and averaged over whole sites and, in most cases, scaled to per-hectare values. Proportions were just calculated and not scaled. Visualisations were done using the "ggplot2" package in R studio.

Table 3. Overview of the response and respective surveyed variables, if they were inventoried in cicular sample plots or transects in the field, as well as their formula.

Response variable	Surveyed variables	Inventory	Formula
Tree mortality	Trees > 1.3 m height, alive, standing dead and downed trees, species, DBH, cause of death	Circular sample plots	
Change in living trees' basal area	Trees > 1.3 m height, alive, newly dead standing, newly downed	Circular sample plots	1
Regeneration	Tree spalings < 1.3 m height, pine, birch, aspen, goat willow counts	Circular sample plots	
Resin flow	Alive pines, resin flow	Circular sample plots	
Standing deadwood	Trees > 1.3 m height, species, DBH > 10 cm, height, cause of death	Transects	2, 3, 4, 5
Downed deadwood	Logs > 10 cm diameter, species, diameter, downed before or after fire	Transects	6
Total deadwood	Downed and standing deadwood	Transects	
Fire created deadwood min 10 cm diameter	Newly downed and standing deadwood	Transects	
Fire created deadwood min 20 cm diamater	Newly downed and standing deadwood	Transects	

The proportion of mortality was calculated for each tree species with data from the circular sample plots. Tree mortality means the proportion of pines killed by the fire event or in the 3-5 years after the fire event. First, dead-standing trees of tree species x and logs of tree species x were added to receive a value for "X_dead".

Then, the number of x that was noted to have been dead before the fire event was subtracted from "X_dead", to receive the number of trees of species x killed by the fire event ("X_killed"). Living trees of species x and "X_killed" were added to calculate the number of trees that were alive before the fire event ("X_alive_before"). Lastly, "X_alive_before" was divided by "X_killed" to receive the proportion of species x that died during the fire event.

Proportional change in basal area was calculated using formula 1:

(1) $BA = \pi * ((\frac{DBH}{200})^2)$,

where BA is the basal area in m^2, and
DBH is the diameter in breast height in cm.

With this formula, the basal area was calculated using the measured diameters of alive trees in plots, newly dead standing, and newly dead downed trees. The values for newly dead standing and newly dead downed trees (e.g., only trees killed during or after the fire event, excluding trees already dead during the fire event) were added together and titled "BA_killed". In the next step, the values of "BA_alive" and "BA_killed" were added together and titled "BA_alive_before_fire". Then, the values of "BA_alive" were subtracted from "BA_alive_before_fire", and the results were titled "BA_gone". Lastly, the proportional change of basal area was calculated by dividing "BA_gone" by "BA_alive_before".

Standing tree volume from transect data was calculated with the respective species volume function (Skogskunksap 2023) for trees growing north of 60 degrees. High stumps (trees with a maximum height recorded as 1.3 m were excluded, though due to that only a few high stumps were found in the field inventory, their inclusion would not have had a high impact on the results).

For Scots pine:

(2) $V = 10^{-1,20914} * DBH^{1,94740} * (DBH + 20)^{-0,05947} * H^{1,40958} * (H - 1,3)^{-0,45810}$,

For Norway spruce:

(3) $V = 10^{-0,79783} * DBH^{2,07157} * (DBH + 20,0)^{-0,73882} * H^{3,16332} * (H - 1,3)^{1,82622}$,

For Birch:

$$(4)\ V = 10^{-0{,}84627} * DBH^{2{,}23818} * (DBH + 20{,}0)^{-1{,}06930} * H^{6{,}02015} * (H - 1{,}3)^{4{,}51472},$$

For Asp:

$$(5)\ V = 0{,}0355 * DBH * H + 0{,}0205 * DBH * H + 0{,}2177 * DBH - 0{,}0397,$$

Where V is the volume,
DBH is the diameter of breast height in cm of each tree, and
H is the height of each tree in m.

The volume unit is m^3 if the results of the calculations are divided by 1000. The results were then scaled to per ha values.

The volume of logs in transects was estimated using the line intersect method (Van Wagner 1968). In this method, a strip sample with the desired length is placed at random in a forest stand. The diameters of all wood pieces that the strip or here measuring tape crosses are measured (Van Wagner 1982). In the present study, all logs with a minimum diameter of 10 cm were measured, and their volume was calculated with formula 6:

$$(6)\ V = \frac{\pi^2 \sum D^2}{8 * \mathrm{L}},$$

Where V is the volume of logs per hectare,
D is the diameter of the wood piece where the tape crosses in dm, and
L is the length of the transect in m.

The total volume of deadwood with a minimum of 10 cm DBH, the total volume of deadwood created by fire, and the total volume of deadwood created by the fire event with a minimum diameter of 20 cm were calculated by summing the values of logs and standing deadwood volumes per ha of all species.

Regeneration was pooled across all measured eight 2 m^2 rectangles in each circular sample plot for each species separately, and mean values were scaled to per hectare values.

The proportion of birches killed during the fire event with *Daldinia loculata* was calculated (transects), as well as the proportion of alive pines with resin flow (plots) and the proportion of trees with signs of woodpecker food sourcing (transects).

2.4. Statistical analysis

The distribution of data was tested using the Shapiro Wilcoxon test in R studio, and a p-value greater than 0.05 was assumed to be normally distributed (Statology 2020). Not normally distributed variables were transformed using $\sqrt{x+1}$ or $\sqrt{x+\frac{3}{8}}$ for proportions and $\log(x+1)$ for the other variables to improve their fit to a normal distribution (Zar 1974). Slight deviations from normality were deemed acceptable. For statistical tests, Generalized linear models with normal, binomial, or poisson distribution (Quick-R by Datacamp 2017) were done using the R studio "car" package. For the regeneration data, a post hoc test using the R studio package "emmeans" was computed. The Aikaiki Information Criterion (AIC) was used to compare the likelihood of the models and Q-Q plots to see if the transformation of the variable or the chosen distribution led to a better fit to the normal distribution. Tests with a p-value below 0.05 were assumed to have a significant difference.

3. Results

In the following section, the results are presented. First, the results of tree mortality are presented, then the proportional change of living trees' basal area. Third, I display the results of the total, standing, and downed deadwood. Further, the regeneration of birch, aspen, goat willow, and pine, the proportion of alive pines with resin flow, as well as the proportion of fire killed birch trees with *Daldinia loculata* fruit bodies are shown. Lastly, the proportion of dead trees with signs of woodpeckers' feeding activity is presented. I present both mean and standard error for each variable, as well as the smallest and greatest proportion, count, or volume to give a perspective of the variation between sites.

3.1. Tree mortality

The fire generated tree mortality between sites exposed to wildfire and prescribed burnings varied depending on tree species. There was a difference in the mortality of trees between the wildfire and the prescribed burning for pine (p-value=0.004, t-value=3.315, DF=18). In the wildfire sites, the mean proportion of pines killed by the fire was twice as high as the mean proportion of pines killed by the fire in the prescribed burning sites (93% greater in the wildfire) (Figure 9.). The lowest proportion was determined in the prescribed burning site Södra Bastunäset (0.12), whilst the highest proportion was found in the wildfire site Norra Björkvallsberget (0.74).

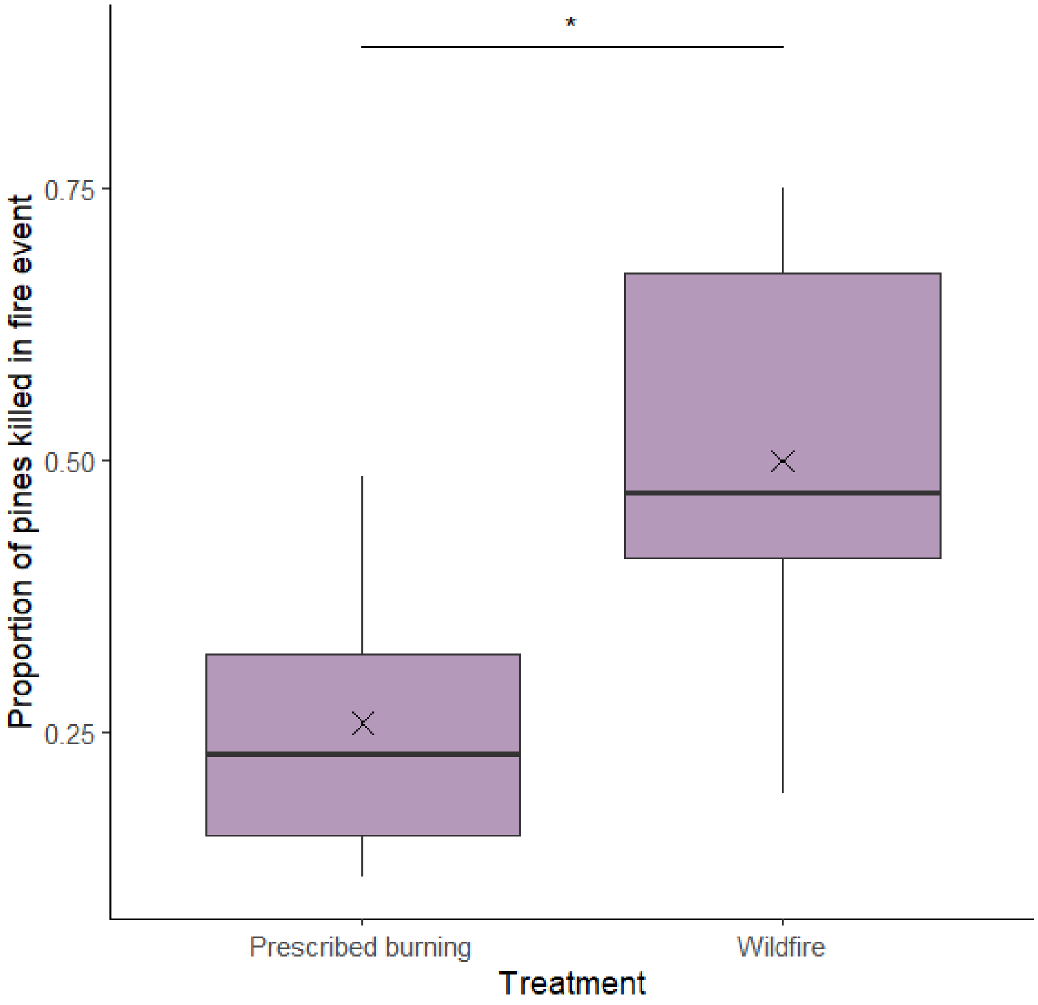

*Figure 9. Boxplot illustrating the proportion of pine mortality (e.g., the proportion of pines killed by the fire event or in the 3-5 years after the fire event). Mean proportion wildfire ± SE: 0.50 ± 0.05, mean proportion prescribed burning ± SE: 0.26 ± 0.03. The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes.*

For the other tree species for which the mortality could be tested, no difference was established between the two fire types (Table 3.). The mortality of spruce was near 100% in both fire types. For birch, the proportion of killed trees was slightly higher in the wildfire sites, but the difference was not statistically significant.

Table 4. Table of the mean proportional values, standard errors, t- and p-values as well as degrees of freedom for non-significant tree species mortalities. WF decodes for wildfire sites, and PB decodes for prescribed burning sites (n=10 for both).

Variable	Mean WF +/- Standard error	Mean PB +/- Standard error	t-value	DF	p-value
Proportion of spruce mortality	0.99±0.00	0.95±0.04	1.301	18	0.21
Proportion of birch mortality	0.88±0.05	0.72±0.07	1.725	14	0.106

For aspen and goat willow, no figures or statistical tests were produced, as there were too few (no aspen recorded in the prescribed burning sites) observations to conduct statistical analyses.

3.2. Change in basal area

The proportional change of living trees' basal area in m^2 was different between the surveyed fire types (p-value=0.003, t-value=3.354, DF=18). In the wildfire sites, the proportional change of the basal area was more than twice as high as in the prescribed burning sites (122% greater proportional change of basal area in the wildfire) (Figure 10.). The smallest change in proportion (0.08) was recorded at Stora Sundsjöberget (prescribed burning) and the greatest change (0.80) was recorded at Norra Björkvallsberget (wildfire).

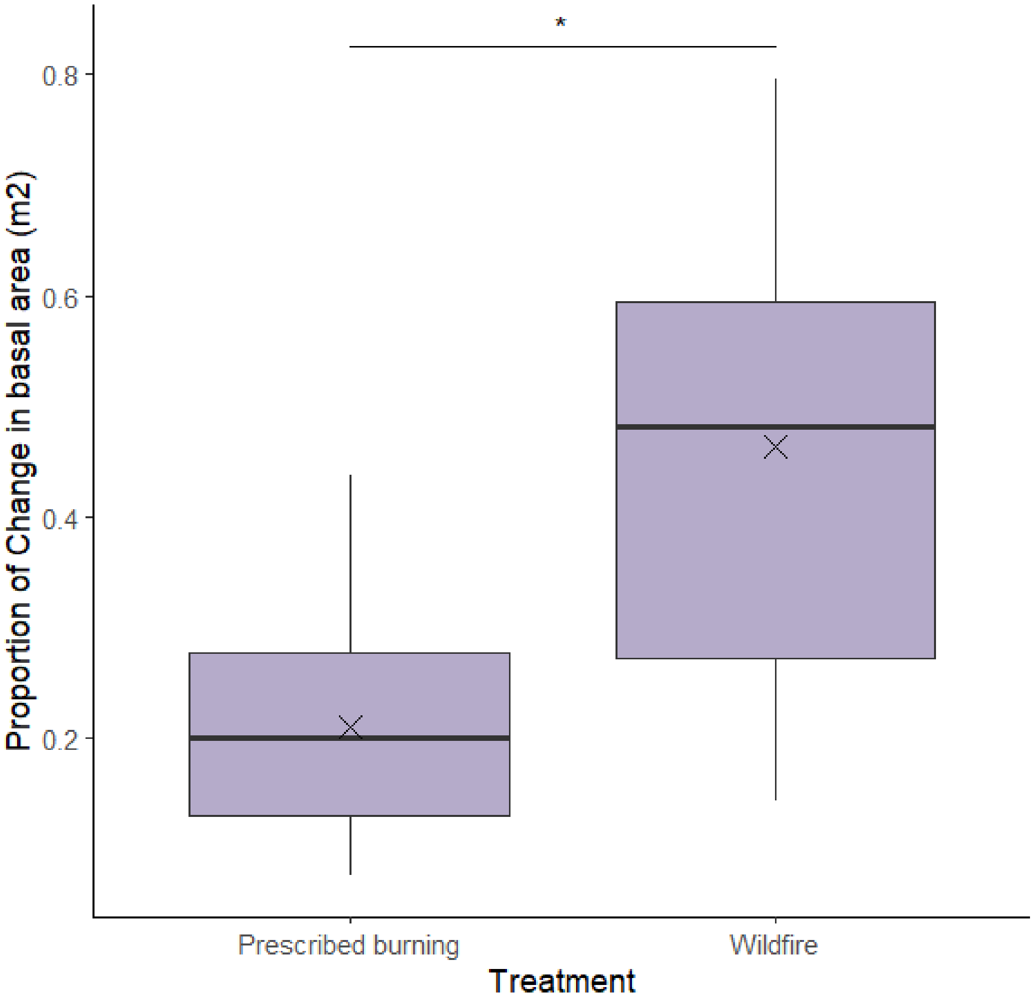

*Figure 10. Proportional change of the basal area of living trees in m^2, e.g., the change of the living trees' basal area inflicted by the fire event. Data presented as boxplots on change in basal area (m^2) in areas exposed to prescribed burning and wildfire. Significant difference ($p < 0.05$) is indicated by * above the boxes. The mean proportions ± SE (wildfire: 0.45 ± 0.07, and prescribed burning: 0.21 ± 0.04) are marked by a × within the boxes.*

3.3. Deadwood

3.3.1. Total deadwood with minimum diameter 10 cm

The statistical test showed a difference in the total volume of coarse deadwood, e.g., the volume of both standing and downed deadwood with a minimum diameter or DBH of 10 cm (p-value=0.001, t-value=3.571, DF=18). The total coarse woody debris (CWD) volume in the sampled wildfire areas was more than double that in the prescribed burnings (137% greater in the wildfire) (Figure 11.). The lowest volume was found in the prescribed burning area Södra Sundsjöberget and was estimated to be 6.12 m^3/ha. The highest volume of CWD was found in the wildfire area Gommorsberget and added up to 212.39 m^3/ha.

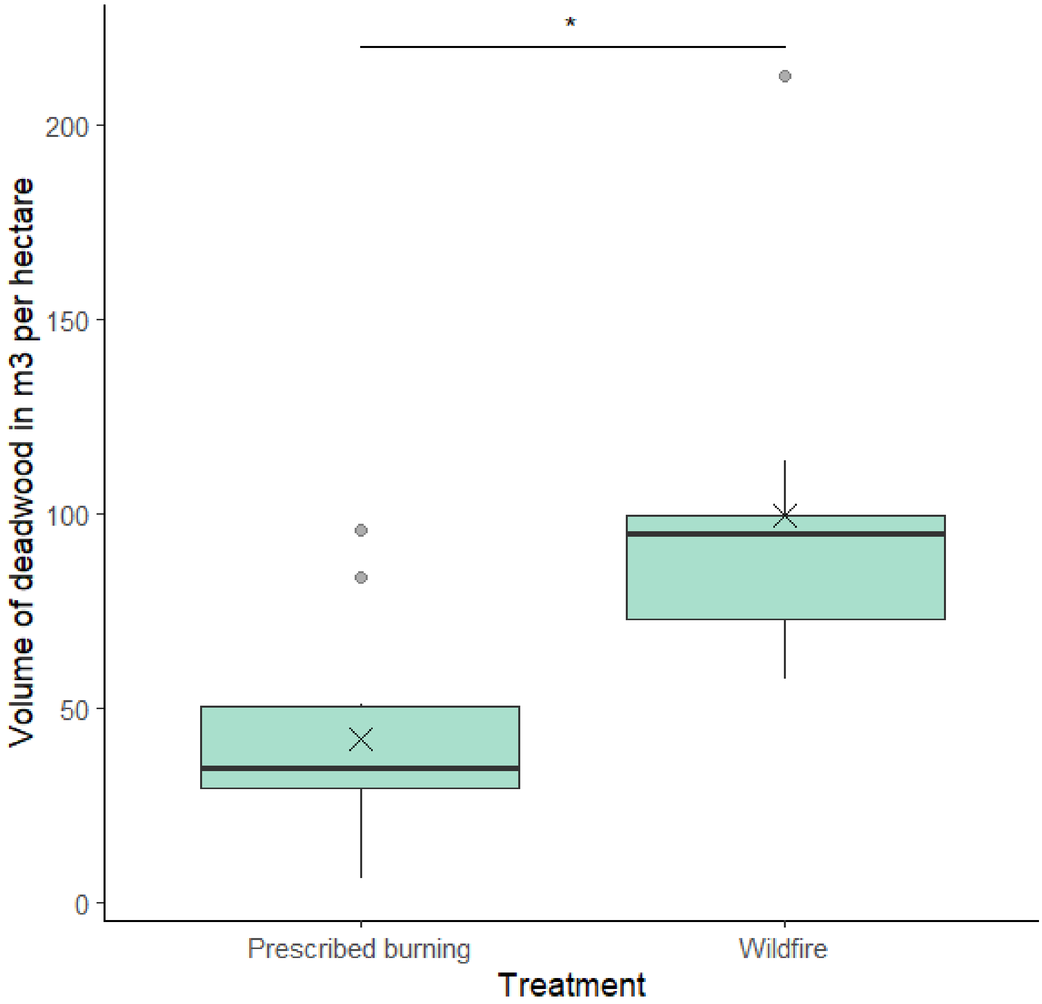

*Figure 11. The total volume of coarse deadwood in m^3 per ha, with a minimum diameter of 10 cm (both old and new, and both logs and dead standing wood). Mean total volume of CWD ± SE in wildfire: 99.40 ± 13.76 m^3/ha, mean total volume of CWD ± SE in prescribed burning: 41.85 ± 9.25 m^3/ha). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

3.3.2. Deadwood created by the fire event with minimum diameter 10 cm

Likewise, there was a difference in the total volume of CWD with a minimum diameter or DBH of 10 cm produced by the fire event between the two fire types (p-value=0.0004, t-value=4.372, DF=18). In this case, the mean volume produced in the wildfire sites was three times as high as in the prescribed burnings (211% greater in the wildfire) (Figure 12.). In the prescribed burning in Gåsberget

Stockåstjärn, the lowest volume of 2.93 m^3/ha was detected. Again, the highest volume was found in the wildfire area Gommorsberget with a mean of 193.85 m^3/ha.

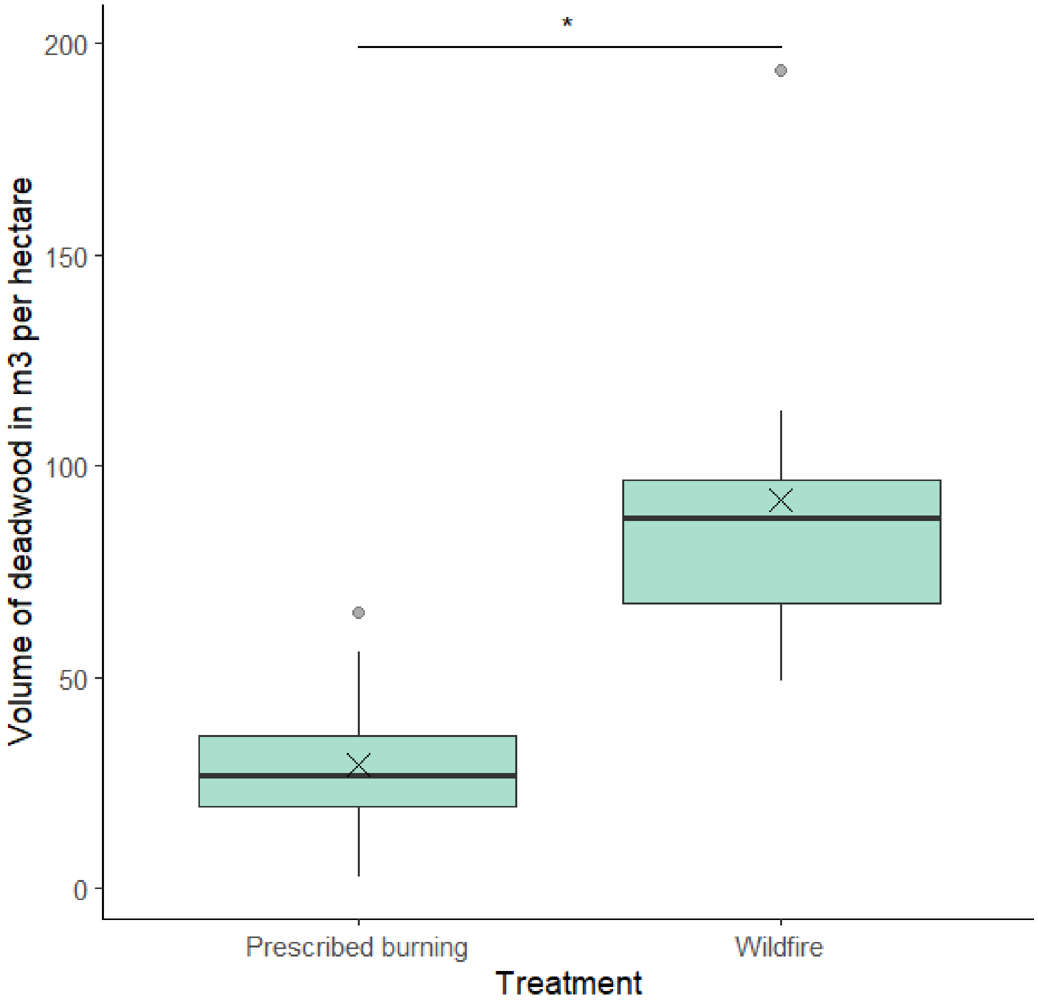

*Figure 12. Boxplot illustrating the volume of logs and dead standing wood in m^3/ha with a minimum diameter of 10 cm, only CWD created due to or after the fire event (mean volume ± SE in wildfire: 92.14 ± 12.83 m^3/ha, mean volume ± SE in prescribed burning: 29.58 ± 6.33 m^3/ha). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

3.3.3. Deadwood created by the fire with minimum diameter 20 cm

According to the statistic test, there was a difference in the volume of CWD with a minimum diameter or DBH of 20 cm that was created by the fire event (p-value=0.0006, t-value=4.051, DF=18). In similar fashion, the volume of CWD created by the fire with a minimum diameter or DBH of 20 cm was nearly four times as high in the wildfire sites compared to the prescribed burnings sites (276% greater in the wildfire) (Figure 13.). Again, the lowest volume was found in the prescribed burning Gåsberget Stockåstärn, where no CWD with a minimum of 20 cm was added by the fire event according to my survey. The highest volume of CWD with a minimum of 20 cm created by the fire was found in the wildfire site Gommorsberget and estimated to be 136.29 m^3/ha.

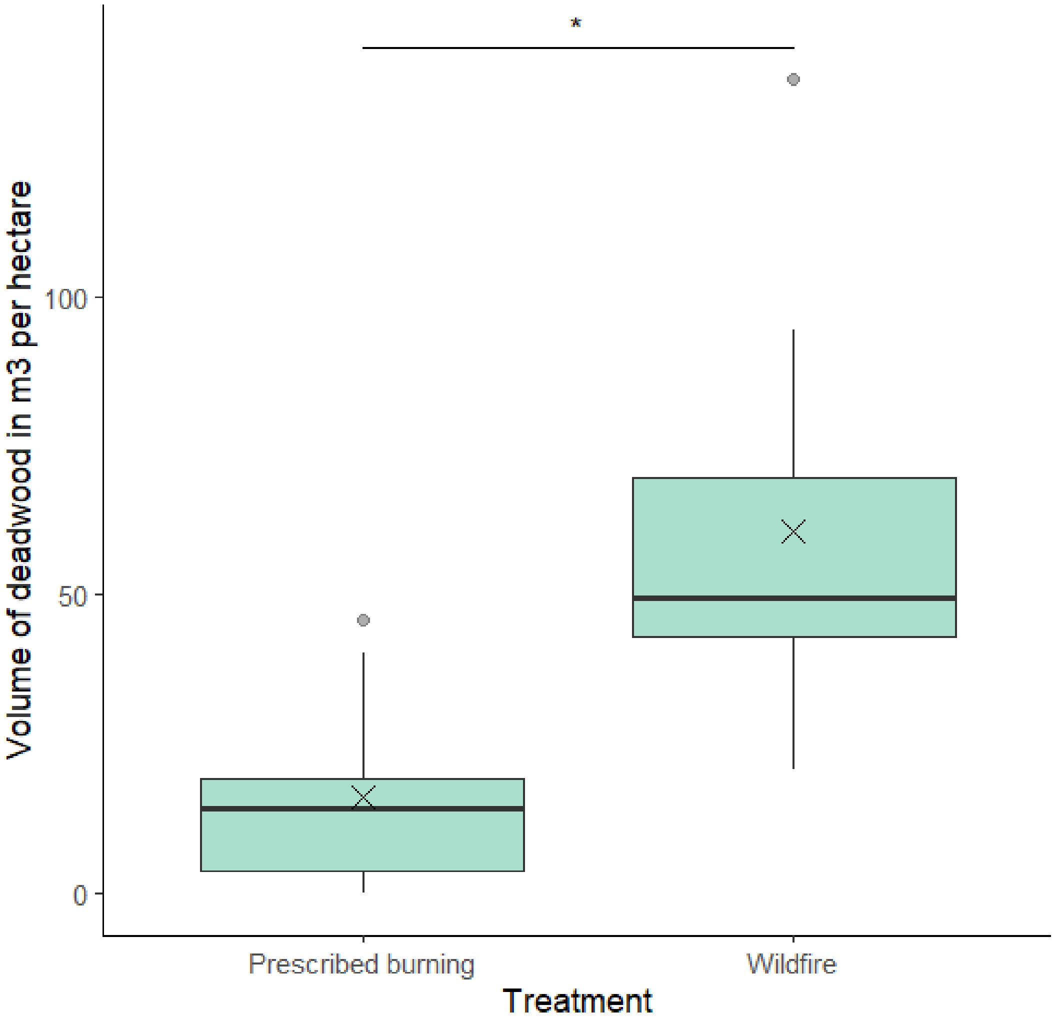

*Figure 13. The volume of coarse deadwood created by fire event in m^3 per ha, with a minimum of 20 cm in diameter (mean volume ± SE in wildfire: 60.67 ± 10.49 m^3/ha, mean volume ± SE in prescribed burning: 16.09 ± 4.99 m^3/ha). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

3.3.4. Standing deadwood

There was a difference in the total volume (both dead prior to and after the fire event) of dead-standing pines CWD (with a minimum diameter of 10 cm) between the wildfire and prescribed burning sites (p-value=0.047, t-value=2.213, DF=18). In the wildfire sites, the total volume of standing pine CWD was more than double as high as in the prescribed burning sites (118% greater in the wildfire) (Figure 14.). The lowest standing pine CWD volume was found in the prescribed burning of Stora Sundsjöberget and summed up to 0.82 m^3/ha. In the wildfire area Östra Ängrabrännan, the highest standing pine CWD volume was estimated to be 107.56 m^3/ha.

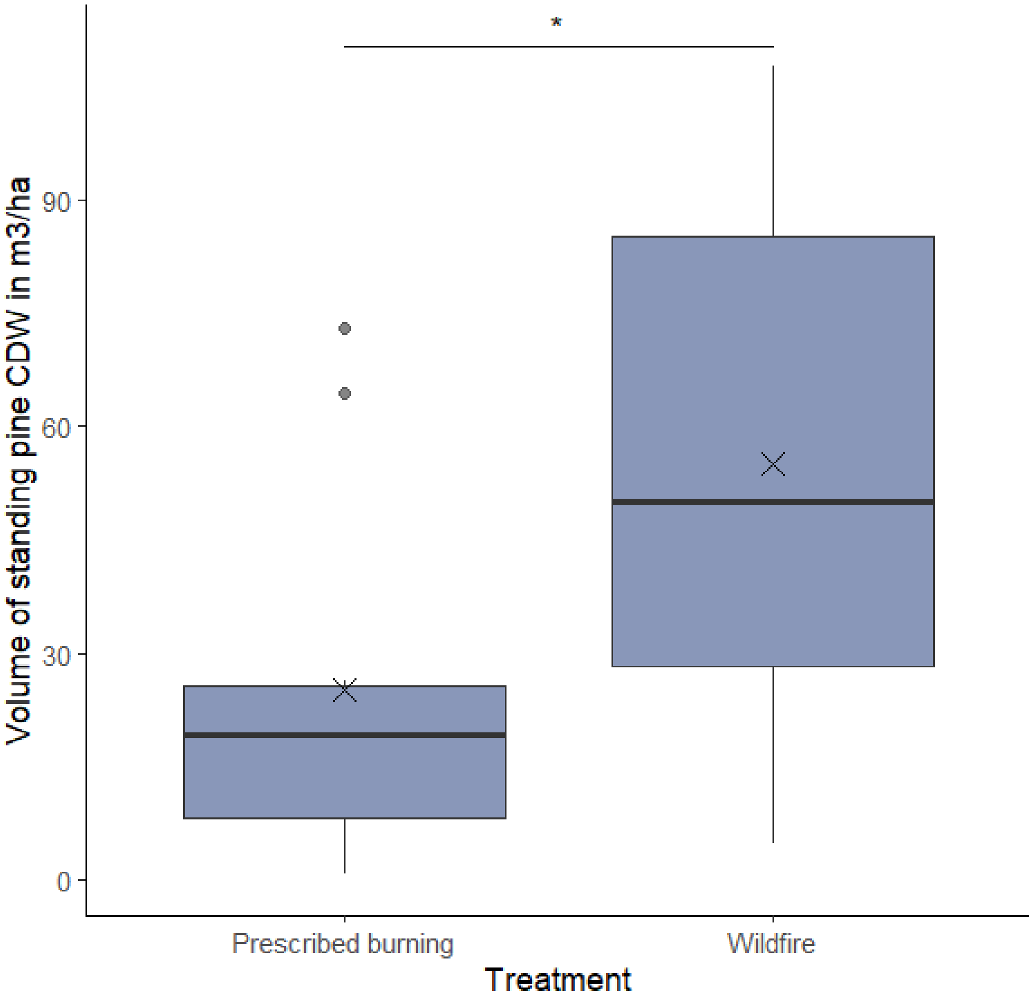

*Figure 14. The volume of total dead standing pine coarse deadwood (with a minimum DBH of 10 cm) in m^3 per ha, both deadwood prior to the fire and deadwood created by the fire event (mean dead standing pine volume ± SE in wildfire: 55.01 ± 10.86 m^3/ha, mean dead standing pine volume ± SE in prescribed burning: 25.17 ± 7.71 m^3/ha). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

Regarding the creation of standing CWD by the fire event, there was also a difference for pine between fire types (p-value=0.011, t-value=2.853, DF=18). The volume of CWD originating from pines created by the fire event in the wildfire sites was more than 3.2 times as high as the volume created in the prescribed burning sites (222% greater in the wildfire) (Figure 15.). The lowest volume of standing pine CWD created by the fire event was in Stora Sundsjöberget (prescribed burning), where the fire event added no new standing CWD. In Östra Ängrabrännan (wildfire), the newly created standing pine CWD amounted to 107.56 m^3/ha, which was the highest volume of newly created standing CWD.

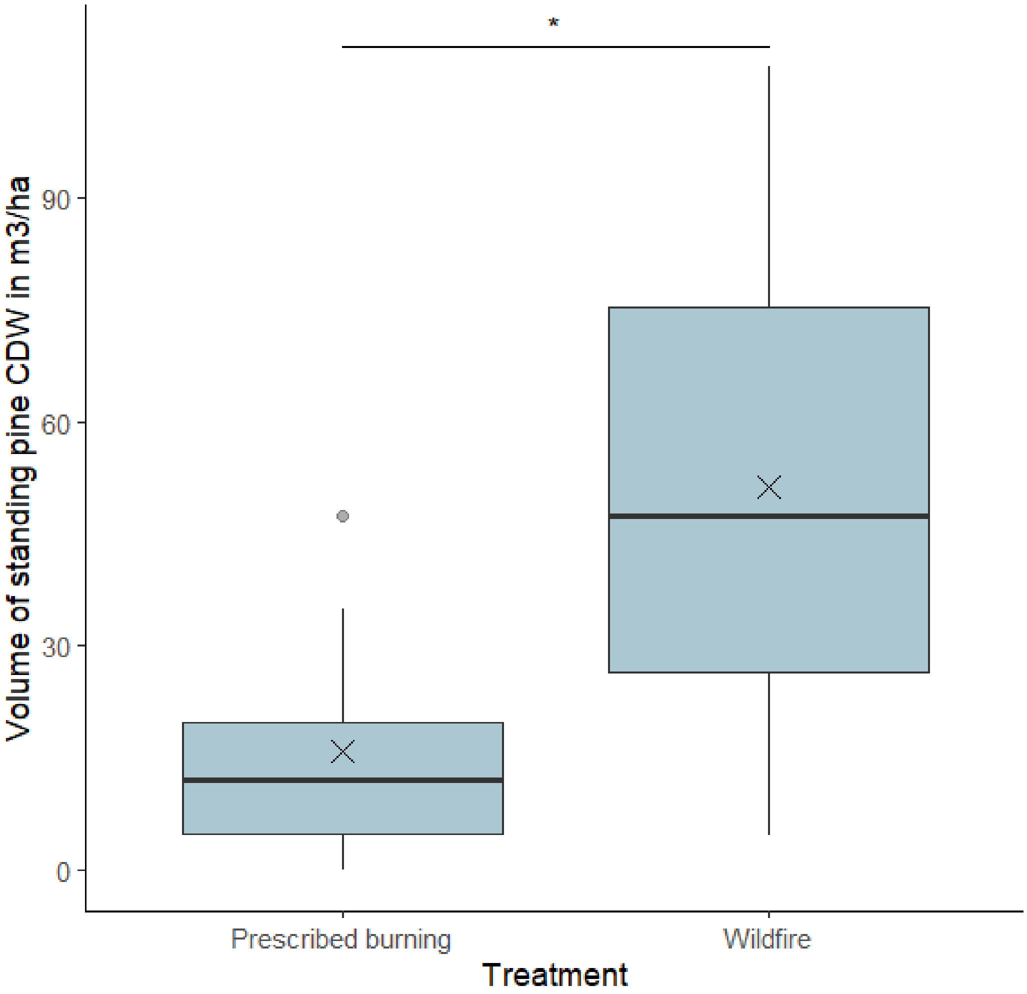

*Figure 15. Boxplot displaying the volume of dead-standing pine (with a minimum DBH of 10 cm) in m^3 per ha, created during/after the fire event only (without standing pines dead before the fire event). Mean volume ± SE in the wildfire: 51.33 ± 10.58 m^3/ha, mean volume ± SE in the prescribed burning: 15.91 ± 4.77 m^3/ha. The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

For spruce, birch, and aspen, there were no differences in the total volume of standing CWD or the volume of newly created standing CWD between the prescribed burnings and the wildfire (Table 4.). However, the same trend as for standing pine CWD could be observed, as the volume created in the wildfire sites was in all cases higher than in the prescribed burning sites. For CWD of spruce type, the total volume of standing CWD was nearly three times as high in the wildfire sites compared to the prescribed burning sites. Similarly, the volume of newly created standing spruce CWD was more than three times as high in the sampled wildfire areas. Similarly, the CWD volume of standing birch and aspen was higher in the wildfire sites than in the prescribed burning sites, but the difference was not as big as for the other tree species. Birch and goat willow snags were not found in all sites and no snags were found to have been dead before the fire event.

Table 5. Depicting the mean volumes in m^3/ha, standard errors as well as t- and p-values and degrees of freedom for non-significant standing deadwood. Wildfire is shortened as "WF", and prescribed burning is shortened as "PB" (n=10 for both).

Variable	Mean WF +/- Standard error	Mean PB +/- Standard error	t-value	DF	p-value
Total standing CWD volume of spruce in m^3/ha	34.01±8.84	12.13±3.49	1.774	18	0.092
Standing CWD volume of spruce in m^3/ha created by fire	34.01±8.84	10.87±2.83	1.896	18	0.073
Standing CWD volume of birch in m^3/ha created by fire	3.03±1.09	2.64±0.94	0.151	18	0.880
Standing CWD volume of aspen in m^3/ha created by fire	2.02±1.40	0±0	1.542	18	0.141

3.3.5. Downed deadwood

There was a difference between the coarse volume of downed dead pine created by the fire event in wildfire sites and prescribed burning sites (p-value=0.046, t-value=2.128, DF=18). According to the field inventory and calculations, the coarse pine logs volume was ten times higher in the wildfire areas than in the prescribed burning areas (or 959% greater in the wildfire) (Figure 16.). However, in several wildfire areas and prescribed burning areas I recorded no pine logs that were created during the fire event. The highest pine logs volume was found in the Gommorsberget site (wildfire) and estimated to 1.43 m^3/ha.

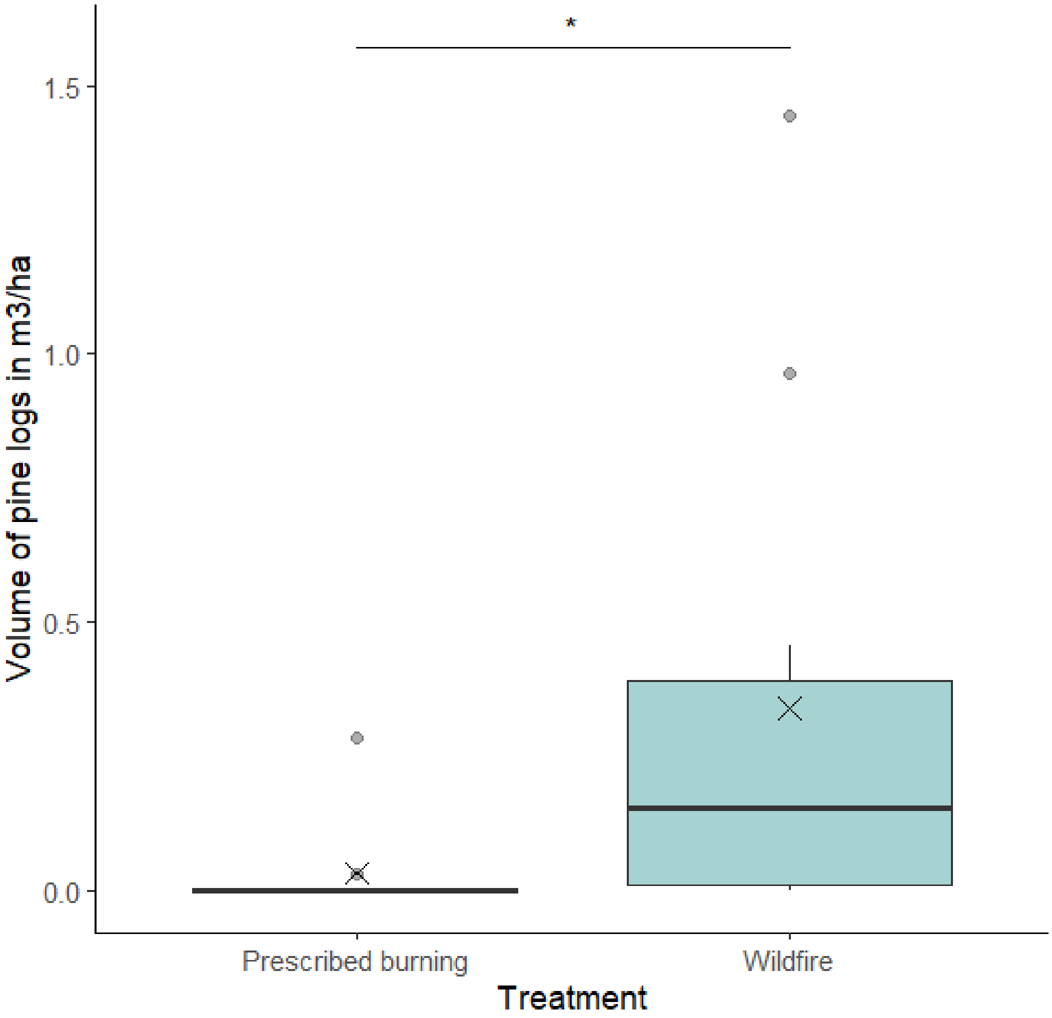

*Figure 16. Pine logs in m^3 per ha, only logs created during/after the fire event with a minimum diameter of 10 cm (mean pine logs volume ± SE in wildfire: 0.34 ± 0.16 m^3/ha, mean pine logs volume ± SE in prescribed burning: 0.02 ± 0.03 m^3/ha). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

There were no significant differences regarding the logs volume of spruce, birch, or goat willow (Table 5.). The trend for the total pine, spruce, and birch logs was however similar as for pine logs created by fire, with higher volumes in the wildfire sites compared to the prescribed burning sites. Contrastingly, there was a tendency towards higher volumes of downed deadwood for both birch and goat willow logs (both total logs volume and logs volume created by fire), there was a higher volume in the prescribed burning areas than in the wildfire areas (Table 5.).

Table 6. Depicting the mean logs volumes in m^3/ha, standard errors, t- and p-values as well as degrees of freedom of non-significant logs. WF denotes wildfire, and PB denotes prescribed burning (n=10 for both).

Variable	Mean WF +/- Standard error	Mean PB +/- Standard error	t-value	DF	p-value
Total pine logs volume in m^3/ha	2.13±0.70	1.78±0.70	0.415	18	0.683
Total spruce logs volume in m^3/ha	3.10±2.33	0.05±0.03	1.521	18	0.146
Spruce logs volume in m^3/ha created by fire event	1.37±0.89	0.05±0.03	1.480	18	0.156
Total birch logs volume in m^3/ha	0.08±0.03	0.05±0.02	0.591	18	0.562
Birch logs volume in m^3/ha created by fire event	0.03±0.02	0.05±0.02	-0.090	18	0.929
Total goat willow logs volume in m^3/ha	0.01±0.01	0.01±0.02	-0.916	18	0.3718
Goat willow logs volume in m^3/ha created by fire event	0±0	0.01±0.01	-1.000	18	0.331

3.4. Regeneration

There was a difference between the fire types regarding the regeneration of all sampled tree species (Figure 17.). The difference was greatest for aspen (estimate=-1.366, p-value=<0.0001, t ratio=-9.379). The mean number of seedlings per ha in the wildfire areas was 4166 ± 1057.78 (SE), while the mean number of seedlings per ha in the prescribed burning areas was 427.1 ± 274.08 (SE). Thus, the number of aspen seedlings per ha was almost 10 times as high in the wildfire than in the prescribed burning sites (875% greater in the wildfire). In several prescribed burning sites, no aspen regeneration was recorded. The highest number of aspen seedlings per ha was found in Södra Nötberget (wildfire, 12857.13 seedlings per ha).

For goat willow saplings, there was a statistical difference between both fire types (estimate=-1.101, p-value=<0.0001, t ratio=-7.556). The mean number of seedlings ± SE per hectare was 3240 ± 318.19 in wildfire sites, whilst the mean number of seedlings ± SE in the prescribed burning sites was 430.79 ± 171.89. Hence, the number of goat willow saplings was more than 7.5 times as high in the wildfire sites compared to the prescribed burning sites (652% greater in the wildfire). The lowest number of goat willow seedlings per ha was 0 in several prescribed burning sites, whilst the highest number of seedlings was found in the wildfire sites Norra Björkvallsberget and summed up to 4897.96 seedlings per ha.

Also for birch, I found a clear statistical difference between wildfire and prescribed burning sites (estimate=-0.835, p-value=<0.0001, t ratio=-5.735). Birch regeneration was nearly 3.7 times higher in the sampled wildfire areas than in the sampled prescribed burnings areas (267% greater in the wildfire, mean ± SE in the wildfire 4819.5 ± 1374.44 seedlings per ha, and mean ± SE in the prescribed burnings: 1311.9 ± 392.59 birch seedlings per ha). The lowest seedlings count per ha was found in Gåsberget Stockåstjärn, which is one of the prescribed burning sites (0). In the wildfire site Gommorsberget, the highest count with 10918.37 birch seedlings per ha was calculated.

The difference between the two fire types was smallest for pine seedlings (mean ± SE in the wildfire 3993 ± 876.73 pine seedlings per ha, and mean ± SE in the prescribed burnings: 1321.9 ± 316.35), but there were still significantly more seedlings in sites exposed to wildfire (estimate=-0.776, p-value=<0.0001, t ratio=-5.33). The pine regeneration was roughly three times as high in the wildfire sites compared to the prescribed burning sites (202% greater in the wildfire). The lowest was found in the prescribed burning site Stensjön (312.5), whereas the highest was found in the wildfire site Södra Nötberget and summed up to 9795.92.

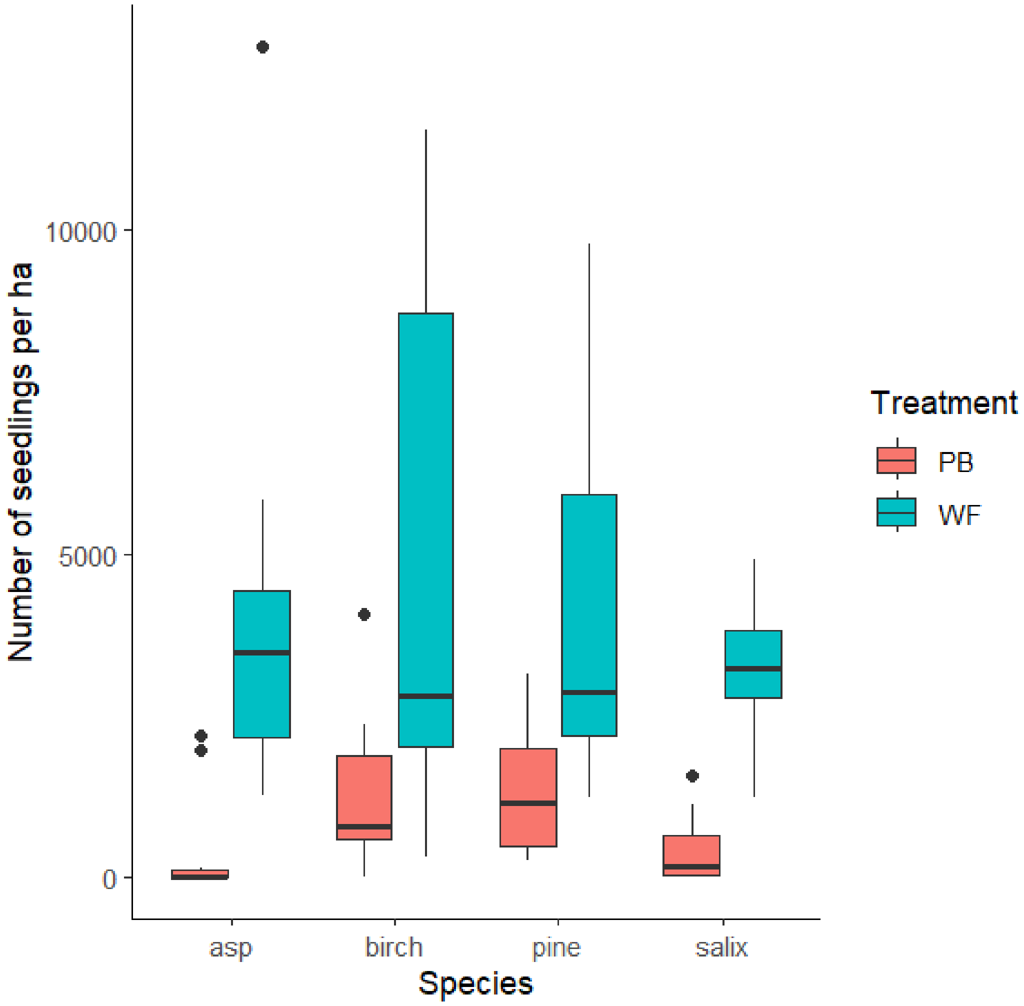

Figure 17. Regeneration of tree saplings measured in circular sample plots scaled to the number of seedlings per hectare. All differences between prescribed burning sites and wildfire sites were statistically significant (<0.0001). WF denotes wildfire sites, and PB denotes prescribed bruning sites. Outliers are marked by dots.

3.5. Resin Flow

Regarding the proportion of alive pines with resin flow, there was no difference between the fire types (p-value=0.381, t-value=-0.899, DF=18). The proportion of alive pines with resin flows tended to be slightly higher in the prescribed burnings compared to the wildfire (18% greater in the prescribed burning sites) (Figure 18.).

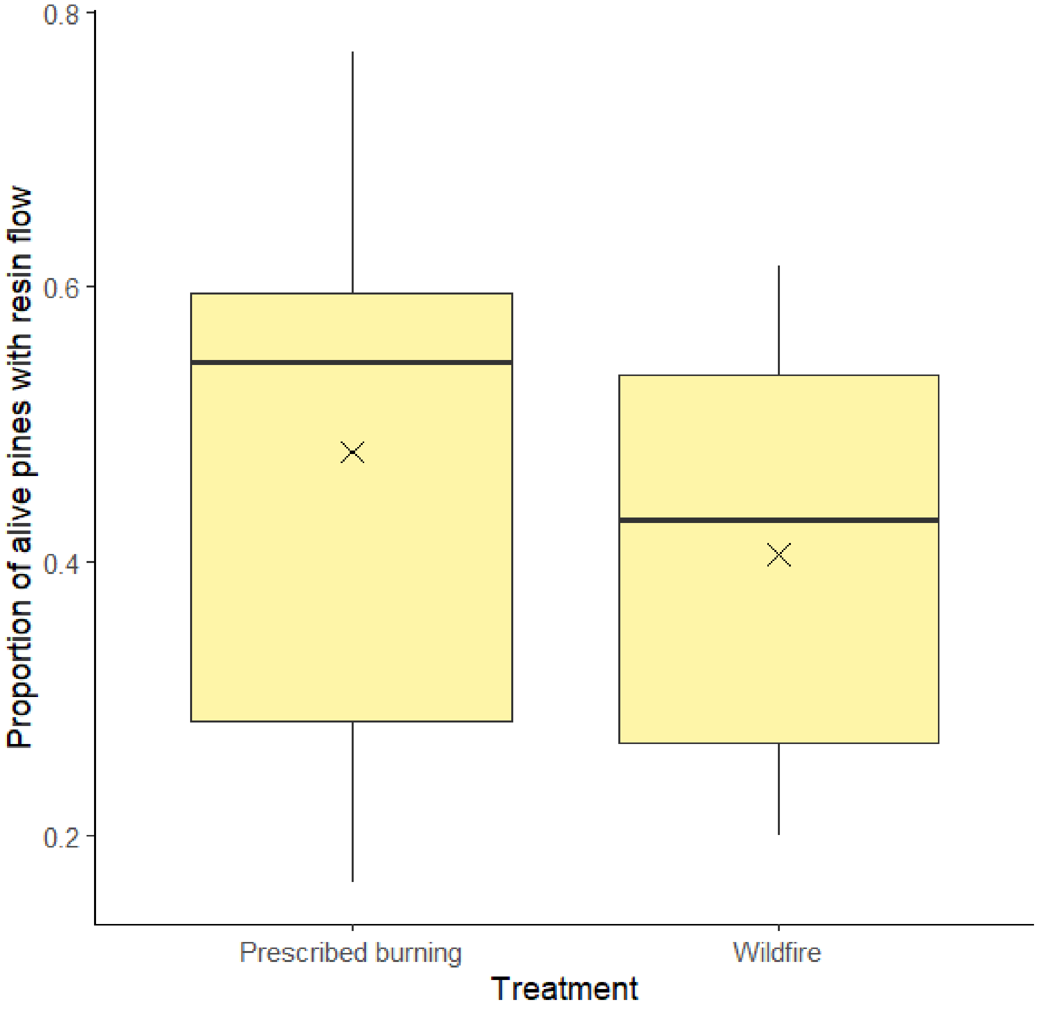

Figure 18. Boxplot representing the proportion of alive pines with resin flow (no significant difference, thus no star, mean proportion ± SE in wildfire 0.41 ± 0.05, mean proportion ± SE in prescribed burnings 0.48 ± 0.07). The mean values for each category are marked with a × (within the boxes).

3.6. *Daldinia loculata* on fire killed birch

The proportion of dead birches with *Daldinia loculata* was higher in wildfire sites than in the prescribed burning sites (p-value=0.001, t-value=4.171, DF=13). In the wildfire sites, the proportion of fire killed birches with *D. loculata* was more than 26 times as high as in the prescribed burning sites (Figure 19.). However, the variation among sites was high, and in several prescribed burnings and wildfire sites there was no record of *D. loculata* on fire killed birches. In the wildfire sites Sveaskog, Södra Nötberget, and Östra Ängrabrännan, *D. loculata* were found on all fire killed birches.

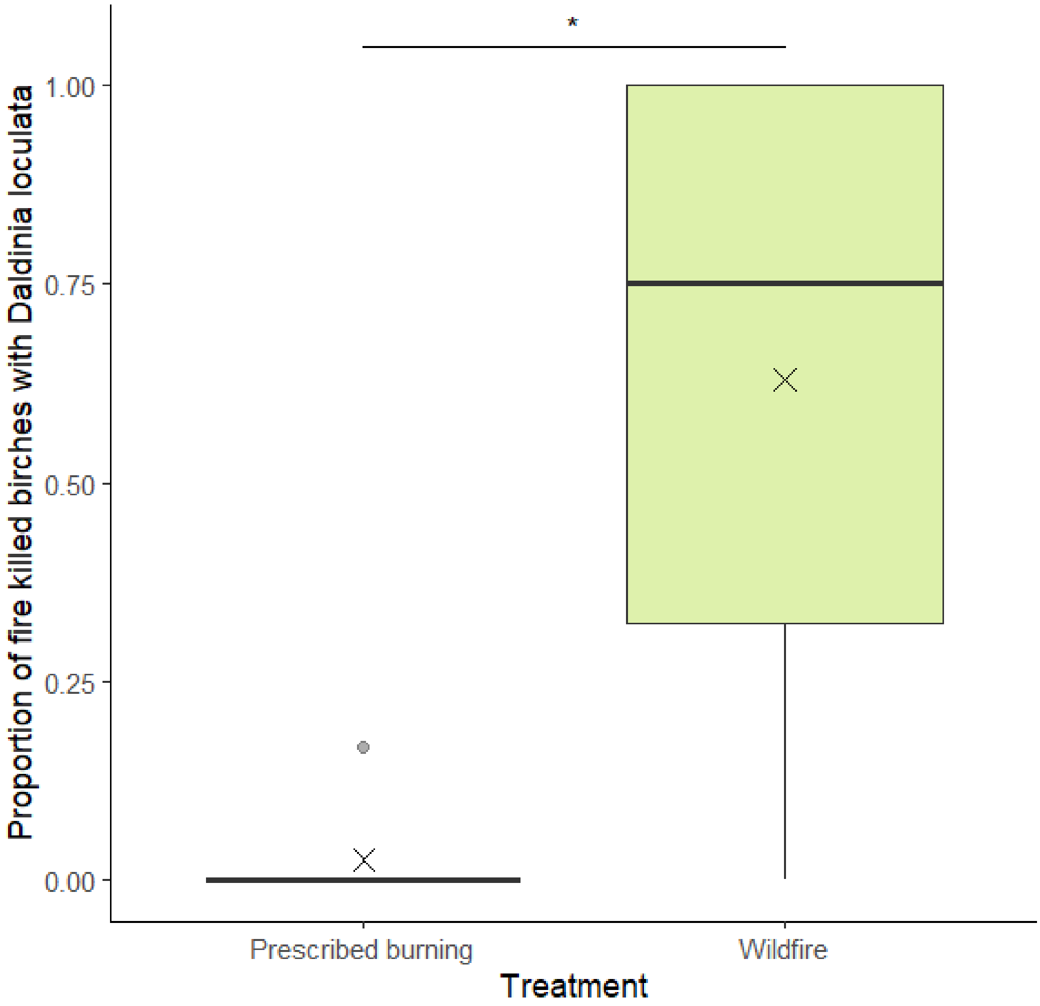

*Figure 19. The proportion of birches killed by the fire event with Daldinia loculata in transects (mean proportion ± SE in wildfire sites 0.62 ± 0.13, mean proportion ± SE in prescribed burning sites 0.01 ± 0.01). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

3.7. Woodpeckers' feeding activity

In regard to the woodpeckers' feeding activity, there were differences in feeding activity in dead pine, spruce, and birch. There was a significant difference in the woodpeckers' feeding activity on dead pines between prescribed burning and wildfire sites (p-value=0.0271, t-value=2.405, DF=18). In the wildfire sites, the proportion of dead pines with signs of woodpeckers' feeding activity was more than 50% higher than that in the prescribed burning sites (Figure 20.). The lowest proportion in several prescribed burning areas was 0, whilst the highest proportion was found in Södra Nötberget, which is one of the wildfire areas and accounted to 0.91.

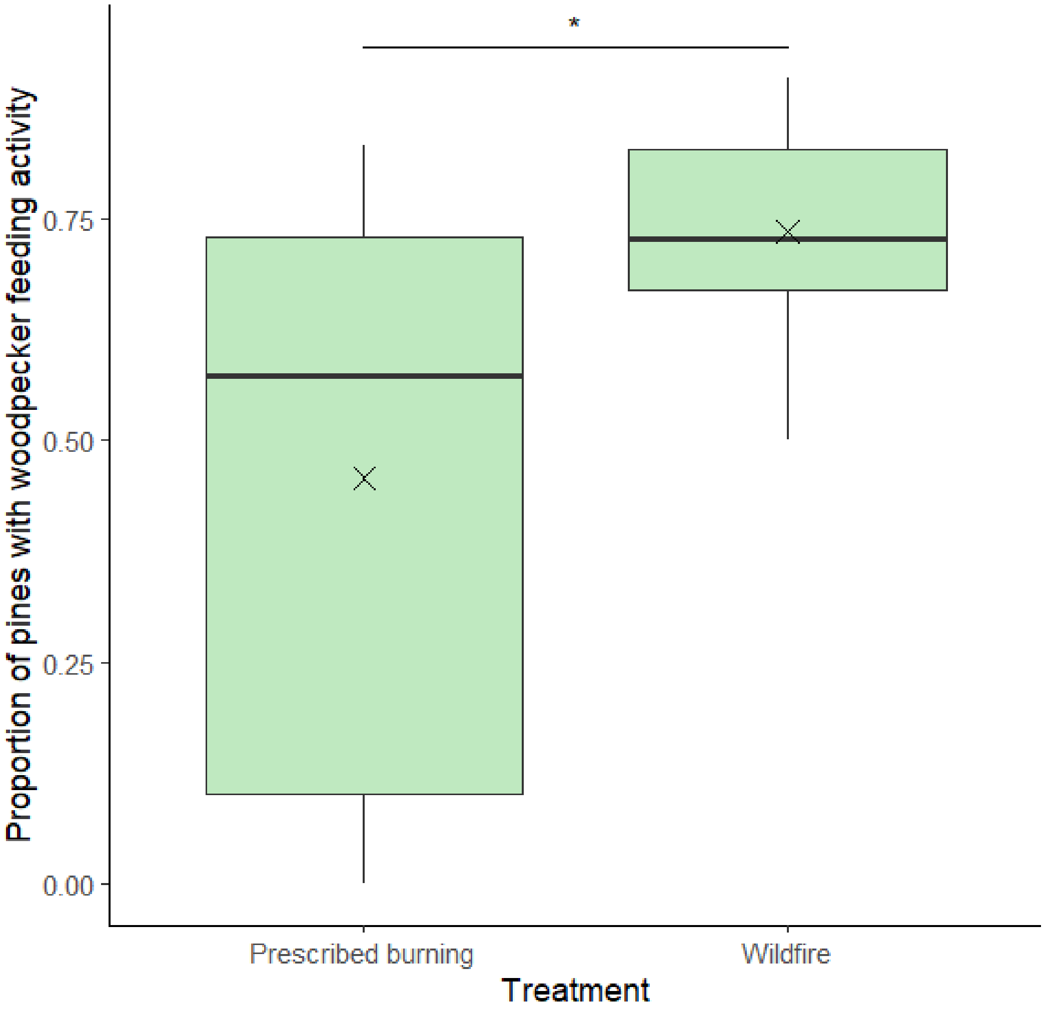

*Figure 20. The proportion of dead pine in transects with signs of woodpeckers' feeding activity (mean proportion ± SE in the wildfire sites 0.74 ± 0.04, mean ± SE in the prescribed burning sites 0.46 ± 0.11). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes.*

According to the statistical test, there was a difference between the two fire types regarding the proportion of dead spruces with signs of woodpeckers' feeding activity (p-value=0.038, t-value=-2.247, DF=16). Differently from the results of feeding on pine, the feeding activity on spruces was nearly 50% higher in the prescribed burnings compared to the wildfire (Figure 21.). The lowest proportion was present in the wildfire site Ängraån (0), whereas the highest proportion was present in the wildfire site Östra Ängrabrännan, as well as in the prescribed burning sites Stensjön, Stora Sundsjöberget, and Tänningbrändan and accounted to 1.0.

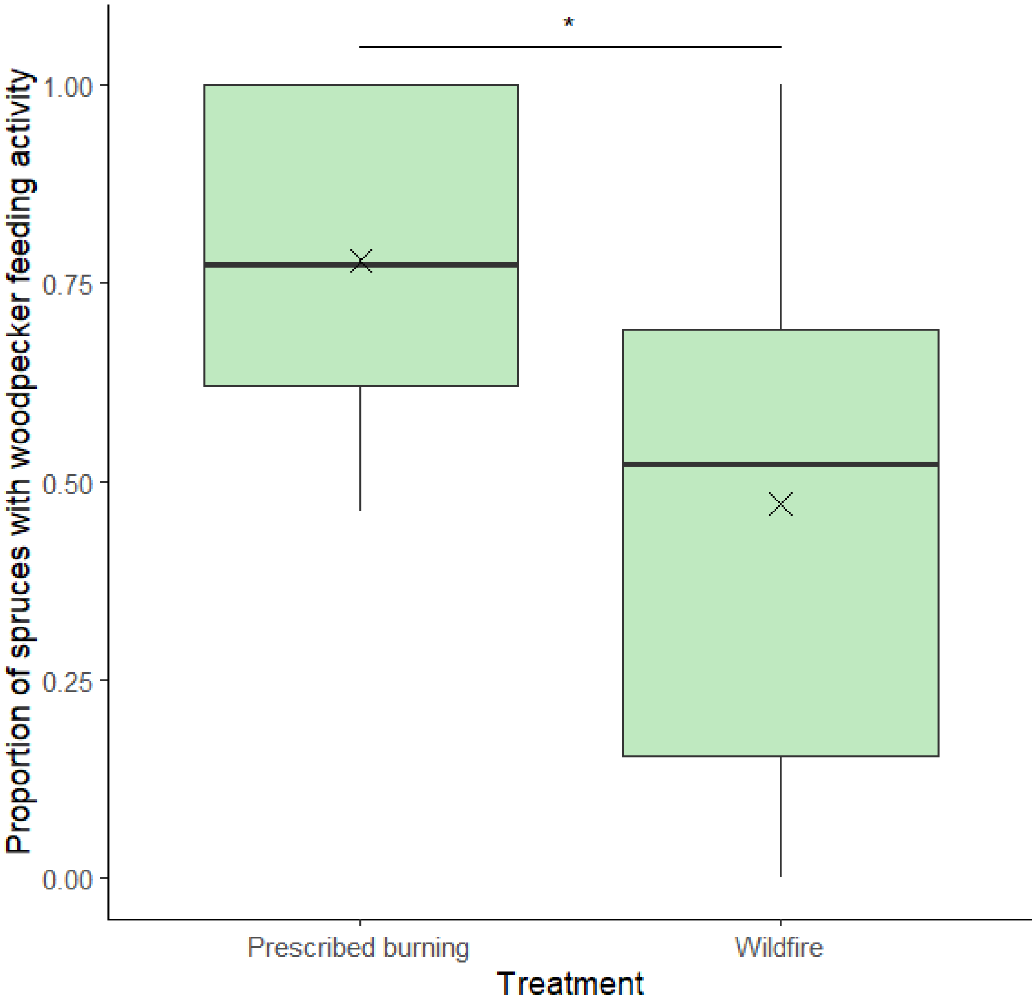

*Figure 21. Boxplot illustrating the proportion of dead spruces in transects with signs of woodpeckers' feeding activity (mean ± SE in wildfire sites 0.46 ± 0.11, mean ± SE in prescribed burning sites 0.78 ± 0.06). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes.*

Also, feeding activity on dead birches was found to significantly differ between the prescribed burnings and the wildfire (p-value=0.003, t-value=-3.764, DF=12). In comparison to pine and spruce, the proportion of dead birches with feeding activity of woodpeckers was more than five times higher in the prescribed burning sites compared to the wildfire sites (435% greater in the prescribed burning sites) (Figure 22.). The lowest proportion was 0 in several wildfire areas and one prescribed burning area. The proportion of birches with feeding signs was highest in the prescribed burnings Börningsberget, Ensjölokarna, Hagåsen, and Stensjön, where all birches showed signs of feeding activity by woodpeckers.

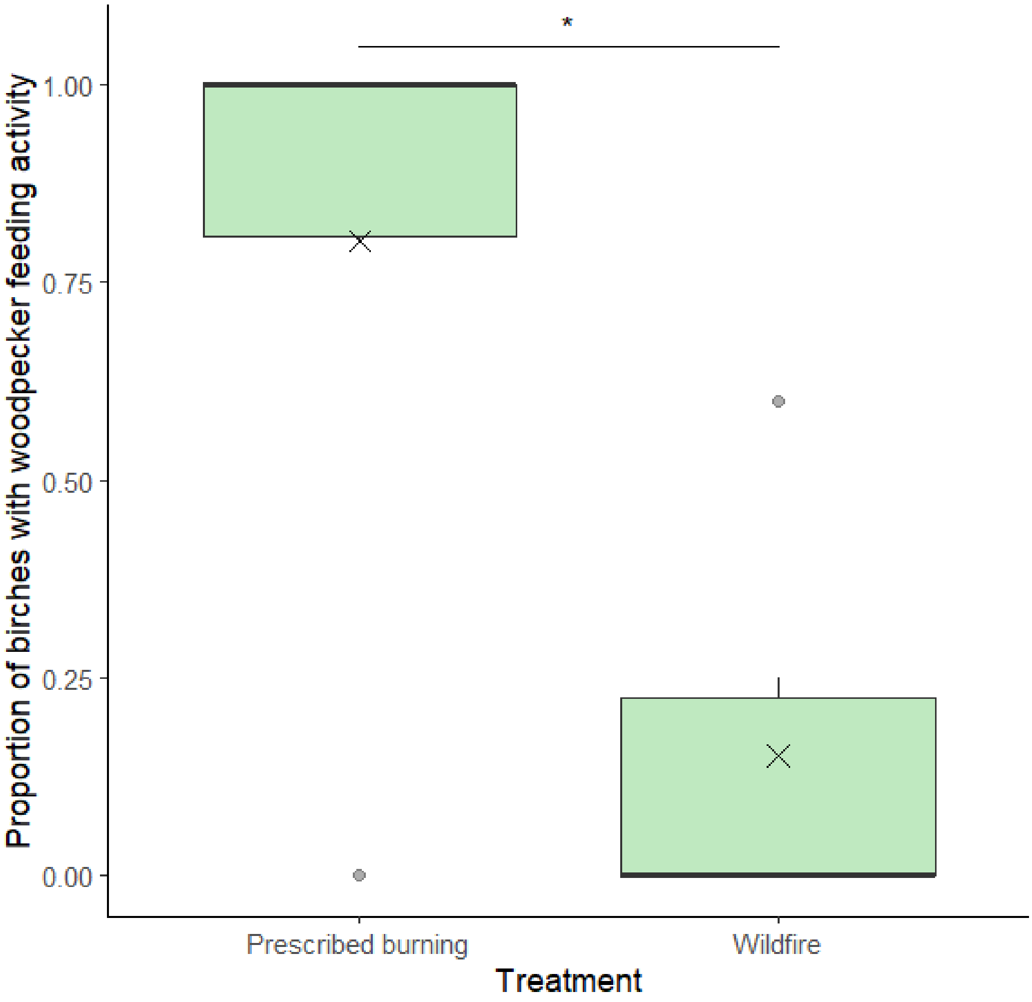

*Figure 22. The proportion of dead birches in transects with signs of woodpeckers' feeding activity (mean ± SE in the wildfire sites 0.14 ± 0.07, mean ± SE in the prescribed burning sites 0.79 ± 0.14). The mean values for each category are marked with a × (within the boxes) and significant difference between the categories is indicated by a * above the boxes. Outliers are marked by dots.*

For dead aspen and dead goat willow with signs of woodpeckers feeding activity, there were too few observations to make reliable comparisons (5 dead standing aspen with 0 signs of woodpeckers feeding activity in wildfire sites, 0 dead standing aspen in prescribes burning sites; 0 dead standing aspen and goat willow in both fire type areas).

4. Discussion

The aim of this study is to describe and compare differences and similarities between natural fires and prescribed burnings in Sweden. In the first part of the discussion, I present results for the individual response variables that I included and compare my results to the findings of others. Further, this study aims to identify if, and which goals of prescribed burnings can be reached. For goals that are difficult or not possible to achieve with prescribed burning, I discuss what changes that may improve the results and what possible alternative measures can be undertaken to achieve such goals. These questions and implications for prescribed burning from a conservation perspective will be discussed in the second part of the discussion.

This study points out that the stand effects of prescribed burnings and wildfires differ in many of the variables interesting to nature conservation. This is in accordance with Lindberg et al. (2020, p. 2) stating that prescribed burnings cannot fully mimic wildfires, however, do "create similar structural elements such as charred and decaying wood" and general input of deadwood. Also, Fredriksson (2021) concluded that prescribed burnings did not lead to effects directly comparable to those generated by wildfires.

4.1. Tree mortality

As far as tree mortality is concerned, the fire types had a different impact on the proportion of pines killed in the fire event only. The pine tree mortality generated by the wildfire was significantly higher than the mean proportion killed in the prescribed burnings. There are very few studies focusing on comparisons of wildfires and prescribed burns, and also few studies focusing on the effects of wildfire in Fennoscandia. However, my results are in accordance with the limited number of studies that have compared the effects of the two types of fires. For example, Fredriksson (2021) also noted higher tree mortality in the wildfire sites inventoried in her study. Moreover, Linder et al. (1998) state that wildfires are thought to have a more variable impact but are also generally considered to be of higher intensity, thus leading to higher tree mortality which is also in consonance with my results.

According to Sidoroff et al. (2007), pine tree mortality was highly variable in an experimental low-intensity prescribed burning. The researchers observed that mortality was dependent on diameter and height, thus tree age. Mortality was highest in trees with a DBH of 5-7 cm (70%) and decreased rapidly for trees already with DBH of 7-9 cm (20%). Sidoroff et al. (2007) highlight that the increased tolerance to fire could have to do with the increasing bark thickness of older trees, which protects the trees' cambium against lethal temperatures. In addition, tree mortality is also highly dependent on wind speed during burning (Sidoroff et al. 2007). Sidoroff et al. (2007) also state that mortality increases when the burning is conducted downwind when wind speed is low. In addition, Linder et al. (1998) studied the effects of low-intensity prescribed burning and found the same trend as Sidoroff et al. (2007). I did not analyze the mortality of different diameter classes, but generally, the observed pine mortality seems in line with other studies' results in prescribed burnings.

For spruce and birch, mortalities did not differ significantly. Interestingly, spruce mortality was very similar in both fire types, and in almost all sites (except for one sampled wildfire area, and two prescribed burning areas), the proportion of spruces killed was 100%. This is in line with Sidoroff et al. (2007), who reported over 80% mortality for spruce. den Herder et al. (2009) observed far higher mortality in spruce compared to pine trees after prescribed burning. The results are in line with the general perception that pine trees are more tolerant to fire disturbances than spruce trees (for example Zackrisson 1977; Esseen et al. 1997).

4.2. Volume of coarse woody debris

The studied sites that were exposed to wildfire had higher volumes of coarse woody debris than sites exposed to prescribed burning. The results were the same irrespectively of the fraction of CWD studied, i.e., >10 cm in diameter, > 20 cm in diameter, or if I included all present CWD or only CWD generated by the fire. These results demonstrate that prescribed burning generates less amount of deadwood and that even though wildfires may consume more of the already existing CWD, the net effect is still a substantially increased volume. Fredriksson (2021) found a similar trend, where the wildfires had higher amounts of CWD, and prescribed burnings had deadwood volumes similar to the amount found in unburned control stands.

In a study by Kyaschenko et al. (2022), the CWD volume in production forests in central northern Sweden was reported to be ca. 11 m^3/ha, while the volume in protected areas was around 25 m^3/ha. Prescribed burnings added between 2.8 to 65.6 m^3/ha or a mean of 29.6 m^3/ha to the protected areas studied in the present study. This shows that prescribed burning may more than double the volume of CWD in a protected area. This is in accordance with Siitonen (2001), who states that natural disturbances, such as fire, can increase deadwood volumes significantly. According to Hekkala et al. (2016), threshold volumes for the presence of saproxylic species have been established to be 20-30 m^3/ha in boreal forests. Hekkala et al. (2023) compared richness of red-listed species in a study in two different sites in Sweden and found thresholds of 20 m^3/ha in the northern sites and 22.4 m^3/ha in the southern sites. Penttilä et al. (2004) suggest a threshold of 20 m^3/ha for the occurrence of threatened fungi in boreal forests. My study revealed that in all but three prescribed burning sites (Stora Sundsjöberget, Stensjön, and Gåsberget Stocksåstjärn), the input of CWD volume by the fire event was at least 20 m^3/ha, thus most prescribed burnings generate CWD within the suggested thresholds. Nonetheless, Hekkala et al. (2016, p. 1122) highlight that threshold values should be treated with caution, as "the suitability of deadwood as a habitat varies in space and time, and different deadwood-dependent species may show different thresholds". Comparing the results of the input of CWD with other prescribed burning studies, for example Sidoroff et al. (2007) noted that prescribed burnings generated slightly smaller inputs of deadwood (10 m^3/ha). However, the authors of that study highlight that the volume of fire-created deadwood is largely variable. Additionally, Linder et al. (1998) observed deadwood inputs of 21 m^3/ha in a low-intensity prescribed burning, which is closer, but still lower than the mean input of CWD calculated in the present study, even though Linder et al. (1998) included deadwood of all diameter classes.

Protected areas have due to their management history more trees with greater diameters than the average managed forest (Kysaschenko et al. 2022). Hence, it would not be that surprising if prescribed burns in reserves would generate more deadwood in the coarsest diameter class than a wildfire that occurs in a random location. However, this was not the case in my study, as the wildfire areas had a volume of deadwood with a minimum of 20 cm which was nearly four times greater compared to the volume in the prescribed burning sites. It seems that even though protected areas may have generally had more trees with greater diameters, not that many of these trees died from the prescribed burning, perhaps explained by the fire intensity. This is in accordance with the general claim that prescribed burns commonly have much lower fire intensity than natural fires (Linder et al. 1998). Nonetheless, Linder et al. (1998) noted that pines with diameters greater than 50 cm had higher mortality in their prescribed burning, as a high proportion of these trees had open fire scars. In the sampled areas, only very few trees with a greater diameter than 40 cm were recorded, which may explain the low level of coarse deadwood generated by prescribed burning in my study.

The distinction between the total volume of CWD and the volume of CWD created by the fire highlights that prescribed burnings do not consume deadwood completely. This aspect is mentioned by Hekkala et al. (2016), who state that fire may consume deadwood primarily in advanced decay classes, which is an especially important substrate for red-listed and specialized species. However, the present study did not analyze the amount of deadwood in different decay classes, which may be an interesting aspect for future studies.

According to Hekkala et al. (2016) stand-replacing wildfires may generate more than 200 m^3/ha of deadwood. In my study, the total volumes were in most cases lower. There was only one case in which the wildfire generated more than 200 m^3/ha CWD (Gommorsberget). Interestingly, this was the only prescribed burning site that was formally protected as a nature reserve before the fire event and might thus mirror the impact of wildfires on more natural forests.

4.3. Regeneration of aspen, goat willow, birch, and pine

Regeneration was for all species substantially higher in sites exposed to the wildfire than in sites exposed to prescribed burning, with a greater difference for deciduous trees than for pine. The greatest difference could be noted in the number of asp seedlings, significantly more seedlings were counted in the wildfire sites. This is in accordance with Åby Hedenius (2016) results, who found that aspen, goat willow, and pine seedlings were most abundant where the fire had been more intensive. Additionally, Schimmel & Granström (1996) found that birch and spruce seed establishment was favored when the majority of the mor layer had been consumed during the fire event. Also, Jakobsson (2017) reports that deciduous seedlings were most abundant where less than 2 cm of the humus layer remained. In my study, the higher recruitment is probably also related to the difference in fire severity between wildfire and prescribed burnings. The occurrence of patches with exposed mineral soil was much higher in sites exposed to the wildfire than those exposed to prescribed burning (personal observation), which likely explains the higher regeneration in the former.

Generally, there is a long tradition of using fire as a tool to enhance regeneration in Fennoscandia (Lindberg et al. 2020). This is due to that burning has positive effects on the establishment, survival, and growth of tree seedlings. For example, soil chemistry and pH changes, soil nutrient availability increases, competition from other vegetation decreases, allelopathic effects from ground vegetation are minimized, and the sapling roots have more space to develop (Johannesson & Dahlberg 2001; den Herder et al. 2009; Pasanen et al. 2015). Another important factor is that fire reduces the canopy cover in grown forest stands and thus increases light penetration to the ground, which also benefits seedlings (den Herder et al. 2009). Seedling establishment and diversity will have a large impact on the stand structure and tree species composition in the future, and impacts thus prerequisites for many species to a large extent as they form the characteristic of the future forest stand.

In regard to aspen, the mean number of seedlings recorded in the wildfire sites in this study was in accordance with Åby Hedenius (2016), who found 3565 aspen seedlings/ha two years after the Västmanland fire, which is somewhat lower than the aspen counts recorded in the present study. Jakobsson (2017), found a mean of 115000 and 158000 aspen seedlings/ha, which is far higher than the results presented in this study or by Åby Hedenius (2016). Hekkala et al. (2014) observed the aspen seedling establishment after prescribed burning and found that aspen only regenerated in the burned plots in their study. Pasanen et al. (2015) found the highest aspen seedling abundance in stands that were thinned and burned and observed 150 ± 50 (SE) seedlings/ha, which is far less than the amount observed in the prescribed burned sites in my study. (Tikkanen et al. 2006, p. 380) conclude that “sexual reproduction of Populus, for example, may be largely dependent on forest fires, because the seedlings cannot establish themselves easily in unburned soil”. Also, Lankia et al. (2012) found that todays mature aspen had established after fire events.

Åby Hedenius (2016) found 2625 goat willow seedlings/ha two years after the fire in Västmanland. This is somewhat less than the mean goat willow counts in this study. Jakobsson (2017) observed between 4170 to 37000 goat willow seedlings/ha, which is higher than this study’s results. This suggests that the fire intensity and microclimate of certain sites are very important for regeneration. I could not find other studies that had studied the rejuvenation of goat willow after prescribed burns.

Vanha-Majamaa et al. (1996), who also studied the regeneration of birch seedlings after prescribed burning, counted on average 2100 birch seedlings/ha one year after the fire event, which is somewhat higher than what I observed in the inventoried prescribed burning sites. Hermanson (2020) found that the number of birch seedlings was highly variable in prescribed burning sites, in some sites less than 200 birch seedlings/ha were found and 1107 birch seedlings/ha was the highest case, the latter being close to the levels of birch regeneration I observed. Concerning the birch seedling counts in studied wildfire sites, my records are somewhat lower than what Jakobsson (2017) found in their study. Jakobsson (2017) observed a mean of 6000 birch seedlings/ha in one site and a mean of 68000 seedlings/ha in the other site of the Västmanland wildfire. Åby Hedenius (2016) recorded as many as 57311 birch seedlings/ha in one area of the mega-fire in Västmanland in 2014. The site with the highest count of birch seedlings in the present study was Gommorsberget, where a total of 23571.43 seedlings per ha was found. This is still significantly lower than what Åby Hedenius (2016) reported. This may point out that wildfire's effects on regeneration can be very different, and also that the time of the study after the fire event may be an important aspect. The present study was conducted 5 years after the fire event, while Åby Hedenius (2016) inventoried seedlings regeneration two years after the event. In my study, some seedlings might have died due to competition already. Even though slightly more mature birch trees were killed in the wildfire areas compared to the prescribed burning areas in the present study, birch regeneration was greater in the wildfire sites. Regeneration may also be limited by dispersal limitation, i.e., there need to be some adult trees in the vicinity of the burn area to ensure high regeneration by seeds. However, the depth of burn has been demonstrated to be more important than distance to the nearest seedling source for the regeneration of boreal trees (Jakobsson 2017). Due to the fact that tree mortality, thus fire intensity was greater in the wildfire sites, a higher proportion of mineral soil was possibly exposed. Additionally, Jakobsson (2017) states that boreal tree seeds are mostly wind dispersed, and that burn depth is important for the microclimate and tree seedling establishment. The establishment was best where a large proportion of organic material had been consumed by the fire event. Jakobsson (2017) also highlights that seedlings growing surrounded by mineral soil are somewhat protected from predators.

Although there was a clear difference in seedling density between wildfire and prescribed burning also for pine, the difference was smaller than the deciduous species. Hermanson (2020) found in their prescribed burning sites that pine seedlings/ha counted between 1444 to 7332 seedlings/ha. In line with the present study, Hermanson (2020) also found that pine was the most abundant seedling species in prescribed burnings. In the present study, mean pine seedling counts per hectare varied between 408.162 to 3125 in the prescribed burnings, which is lower than the results reported by Hermanson (2020). Vanha-Majamaa et al. (1996) observed an average of 1717 pine seedlings/ha one year after a prescribed burning, which is slightly higher than the mean pine seedling count in my study. After the wildfire in Västmanland in 2014, Åby Hedenius (2016) reported only 743 pine seedlings/ha, which is much lower than the mean counts found in the wildfire sites in the present study. As for seedlings of deciduous species, Jakobsson (2017) reported higher counts than in the present study, with pine seedlings per hectare ranging from 77000 to 85000. In summary, this suggests that although effects on tree regeneration are highly variable among fires, the effect tends to be stronger in wildfires than in prescribed burning, and the effects are in general smaller for pine than deciduous species. That pine was the most abundant tree seedling in the prescribed burning sites insinuates that it is hard to rejuvenate almost pure deciduous stands ("lövbrännor") that have arisen after wildfires in the past.

4.4. Creation of fire scars

Although there were slightly more living pines with resin flow found in the prescribed burning sites, there was no significant difference in trees with resin flows between the two fire types. This indicates that the two types of fire have the same probability of generating fire scars. In Hermanson's (2020) study of prescribed burnings, the proportion of living pines with developing fire scars ranged from 0-34%. In the present study, living pines with resin flow varied between 17-76% in prescribed burning areas. Resin flow and consequently fire scar creation is dependent on several factors, such as tree age, diameter, bark thickness, moisture and density of bark, as well as fire intensity, wind speed, and temperatures on the tree's leeward side (Dickinson & Johnson 2001; Piha et al. 2013). Piha et al. (2013) observed that 16.5% of trees that had fire scars were 30-35 years old at the time of the fire event in their study, while the corresponding figure for trees older than 45 years was 2.8%. Also, Hammare (2017) concluded that resin flow and fire scar creation are highly variable between different prescribed burning sites (ca. 50% of pines had resin flow in one site, and only 5% in another site). In the prescribed burnings inventoried in the present study, I observed more old fire scars than in the inventoried wildfire sites. This shows that fires have shaped these protected forest stands in the past. Yet, very few fire scars were recorded (1 in the wildfire sites, 6 in prescribed burning sites on living pines, 6 on dead pines in prescribed burning plots, and 3 on dead pines in prescribed burning transects).

4.5. *Daldinia loculata* on fire killed birches

The proportion of fire killed birches with fruiting bodies of *Daldinia loculata* was higher in the wildfire transects in the present study. According to Wikars (2004), *D. loculata* is important for at least ten species of fire-dependent (pyrophilous) insects. He highlights that the number of deciduous trees with fruiting bodies has been shown to be well correlating with the number of fire-specialized insects in burned areas. My results contrast those of Wikars (2004), who could not identify a difference between the proportion of birch trees with *D. loculata* between wildfire and prescribed burning sites. However, in his study, there was no difference between burning intensity, or amount of burned trees between the fire types, indicating that the difference between the two fire types probably was smaller than in my study. The frequency of *D. loculata* may vary greatly within the same region over time due to the quality of burnings. It appears as if the responsiveness of *D. loculata* depends on the fire dynamics in the surrounding landscape, as increases in fruit body appearances seem to be more common in landscapes where many high-quality burns have been conducted compared to where few and low-quality burns have been executed (Wikars 2004).

4.6. Woodpeckers' feeding activity on pine, spruce, and birch

My results revealed, that there was a difference in the signs of feeding activity of woodpeckers between the two fire types. The proportion of pines with signs of feeding activity was higher in the inventoried wildfire sites, while the proportion of spruces and birches with signs of woodpecker's feeding activity was higher in the prescribed burning sites. In this study, I assume that the amount of feeding activity mirrors the amount of available insect prey. According to Versluijs et al. (2020), the feeding activity of Eurasian Three-toed woodpecker is mostly influenced by tree species, decay stage, and DBH of the tree. In the present study, each tree species was analyzed separately, and there were no major differences regarding the diameter of trees in wildfire and prescribed burning sites (mean pine DBH 18.9 cm in wildfire sites, 18.2 cm in prescribed burning; spruce 18.2 cm in wildfire sites, 15.4 cm in prescribed burning; birch 14.6 cm in wildfire sites, 15.0 cm in prescribed burning). Regarding birch, there were some sites with only 1 birch with signs of woodpecker feeding activity, and in three prescribed burning sites, 1 out of 1 birch was observed to have signs of woodpeckers foraging, thus the proportion of birches with feeding activity in this site was set to 100%. Thus, the results may not be mirroring proportions realistically.

Another factor may be to which degree trees were burned, as Nappi & Drapeau (2011) found that black-backed woodpeckers more frequently selected moderately burned snags for foraging. It is possible that the high tree mortality in the wildfire areas in my study was too high to create optimal conditions for woodpeckers, which may explain the trend of more signs of feeding activity in prescribed burning areas. Other possible explanations for the higher number of trees with feeding signs in prescribed burnings could be that those areas already prior to the fire harbored more woodpeckers as they are protected forest stands.

4.7. Targets and recommendations

In the present study, I analyzed differences and similarities between prescribed burning and wildfires. I found that prescribed burning and wildfire differed significantly in many aspects. Amongst the significant differing variables were pine tree mortality, change of living trees' basal area, creation of deadwood, total dead standing pine wood volume, dead standing pine wood volume created by the fire event, downed dead pine wood created by the fire event, regeneration of goat willow, asp, birch, and pine, as well as the proportion of fire-killed birches with *Daldinia loculata* and signs of woodpeckers' feeding activity. Except for the woodpeckers' feeding activity on spruce and birch, variables had considerably higher values in the inventoried wildfire sites. However, comparing prescribed burning targets from the burn summaries, prescribed burnings did have the effects on stand variables, such as spruce and pine mortality, as wished for.

Comparing the calculated mortality of pines in the prescribed burnings with the described targeted mortalities, show that the set targets were often reached. Targeted mortality varied between different sites, reports stated between 10% and up to 50% mortality. I calculated the proportions of pine mortality, and they varied between 12 and 49%. Thus, this target has clearly been met. Regarding the calculated results of this study and the set goals of spruce mortality, targets also have been met. Some burn summaries stated "over 75% of spruce mortality". In eight of ten inventoried prescribed burning sites, 100% of spruces were killed by the fire event in sample plots. Mortality of deciduous trees was mentioned in few reports of the County Administrative Board, but one stated that 20-50% mortality was targeted. As too few trees of aspen or goat willow were recorded, this can only be compared to the mortality of birch trees. In all but one site, mortality was higher than 50%, indicating that the mortality rate of deciduous trees in prescribed burning sites in my study was a bit higher than desired.

Turning to the change of basal area, prescribed burnings generally aim to produce more open, warm forest stands where the forest floor and deadwood can be reached by the sun. In my study, the basal area of living trees in the prescribed burnings changed between 7.5% and 43.8%. Thus, the controlled fire resulted in some degree of thinning in all sites. However, some burns were very patchy, with only small areas where fire had burned more intensely and caused high mortality, resulting in very variable effect on site openness. In areas within a planned prescribed burning site it could be recommendable to adapt a practice of girdling some trees before the fire (to increase the proportion of damaged trees) or felling some trees to improve the effectiveness of the burn (by facilitating deeper burns by creating drier conditions), and to better imitate the impacts of fires (Nilsson 2005). In some of the visited sites, the stand had been thinned and wood extracted, or partially left before the prescribed burning, to decrease the risk of high-intensity burns and crown fires and increase fire severity. In others, trees were girdled or manually felled some years after the fire event to increase tree mortality (probably to compensate for too low tree mortality during the burning).

In addition to thinning, burnings also aim to increase the amount of deadwood and create burned substrates. My results show that prescribed burning increases the input of deadwood, but due to low-intensity fires, big diameter trees with no stem damage from earlier fires are seldomly killed by the fire. Increasing the fire intensity of burnings may increase the input of CWD considerably, as the wildfire sites results prove. However, killing large trees may be suboptimal as they also may be important for supporting part of the biodiversity that needs protection.

Some CAB reports also specifically mentioned that they aimed to benefit the regeneration of deciduous trees and increase the proportion of deciduous trees with controlled fire. My results show that pines and deciduous trees regenerate after the fire, but that the number of seedlings may vary considerably between sample plots within one site and between different prescribed burns. There is concern that the intense herbivory will hinder successful regeneration, especially for deciduous trees (den Herder et al. 2009). In one of the sites included in my study (Tänningbrändan), a fence had been put up to reduce herbivory impact. This is also recommended by Nilsson (2005), especially in areas with great grazing pressure. Since my results indicate that prescribed burnings are suboptimal in terms of mimicking the effect of a wildfire when it comes to the regeneration of deciduous trees, one option would be to test whether it can be improved by adding a low-intensive soil scarification following the prescribed burning.

Some burn summaries mentioned that they wanted to create fire scars. In the present study, I observed that between 17% and up to 77% of living pines had resin flow after the prescribed fire, which means that this target is met. As mentioned before, both stand characteristics such as tree age and conditions during the fire event impact creation of fire scars.

Prescribed burning targets are not always clearly formulated in burn summaries, and even though some set targets have not been achieved in some cases, results are often still deemed satisfying after field visits by CAB personnel. However, if the prescribed burnings goals are to imitate wildfires (and to compensate for the low frequency of natural fires), their effects should be more similar to the effects achieved by wildfires. One way to achieve this is to ensure that burning takes place during warmer and drier conditions and thereby generates burns with higher severity. Focus sometimes may be to go through with the burn, even if the circumstances are not optimal, to have burned an area disregarding the quality of the burn. As prescribed burnings are a costly management tool, and as my results point out that there is a gap between the effects of wildfires and prescribed burning, I recommend waiting for optimal conditions to safeguard the achievement of high-quality burns. Targets should be clearly stated so that evaluations between achieved and set goals are possible.

The choice of sites suitable for prescribed burning is limited, as safety and minimized risk of spreading is highly important. Prescribed burning sites often have well defined borders, for example by bigger watercourses or lakes, mires, or forest roads. This highly limits which sites are chosen to be burned. Due to safety reasons, as well as personal experience of the executioners and public opinion, prescribed burnings are often conducted when natural fires would not take place (shorter from last precipitation, earlier during spring and summer, or in late summer or beginning of autumn). Additionally, the commonly used method of repeated ignition of strips keeps intensity low (Linder et al. 1998; Hermanson 2020). This limits the potential fire intensity that can be achieved with a prescribed burn, and thereby also the potential conservational value that it may add. As prescribed burnings are very costly, especially as they need a lot of present personnel and may require long supervision after the fire event, some targets may be better achieved by applying other methods, such as girdling and soil scarification.

According to Rubene et al. (2017), not only local factors but also landscape factors, such as the amount of deadwood within 2 km impact the effect that burning has on species richness. Research by for example Kouki et al. (2012) also highlight the importance to consider the landscape perspective. Kouki et al. (2012) found that species richness was greater after burnings in more easterly forest regions of southern Finland. They concluded that restoration success is higher in landscapes, and succeeds more easily, when the landscape is still quite natural, or does not have a long history of forest utilization. Kouki et al. (2012, p. 351) also highlight that species dispersal and origin matters, “historical patterns in forest management, assuming that the more recent is the initiation of modern forestry the higher is the currently remaining species pool”. Connectivity and close proximity to other restored or wildfire areas are thus important, as they ensure that colonizers can reach restored sites. Similarly, Larsson Ekström et al. (2021) mention that there were differences in the effect of restoration work in southern and northern Sweden, which the authors suggested was due to the difference in land-use history.

In accordance with Wikars (2004) and Fredriksson (2021), my results highlight that many prescribed burnings fail to create optimal habitat for fire-dependent species, and I concur with the recommendations that there is a need for more prescribed burnings with greater intensity (Fredriksson 2021). The differences between the two fire types detected in this study also highlight, that if prescribed burns are to mimic the effects of wildfire, controlled fire more often needs to be accompanied by for example manually damaging or girdling trees beforehand, as well as gap cutting conifers in advance, or manually removing humus layer to create exposed mineral soil. Fire-scarred wood, the input of charcoal and fire-killed birches can only be produced with fire, and are hard to mimic by alternative means. It may be possible to apply prescribed burning on a larger scale to benefit both conservation and wildfire management. Studies from the US have proven that prescribed burns reduce the risk of intense and spread of wildfires (Khabarov et al. 2016; Eales et al. 2018; Fang et al. 2018), and emit fewer submicron particles than wildfires (Liu et al. 2017), which means that their importance beyond nature conservation may increase in Europe. Studies on soil properties found that organic matter decomposes slower in burned sites, thus fixing carbon for longer (Holden et al. 2015).

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Popular science summary

Boreal forest ecosystems have been shaped by reoccurring fires. Wildfires have an important impact on the stand- and landscape diversity and create complex mosaics of forest stands with different age classes and species. Fires are also important as they thin out the existing tree layer and create both standing and downed dead wood, which is an important habitat for many forest-dwelling species. Generally, pine trees with their high crowns and thicker bark are better adapted to survive a fire event than spruces. Pines also can seal stem damages by producing resin, resulting in fire-scars, which makes them more resilient and long-lived. Birches that are killed by a fire event can grow fruiting bodies of the fungi *Daldinia loculata*, which is an important habitat and food source for many insects. On the ground, fire can consume thick humus layers, resulting in bare mineral soil. Deciduous trees such as aspen, goat willow, and birch are pioneer species that need mineral soil for successful germination and establishment. Therefore the stands that develops following a fire often have a high share of deciduous trees, contain a mix of old and young pines, i.e., multi-layered forest with high trees species richness, meaning trees of different age classes are found in the stand

Over the past centuries, forest utilization and timber value have increased. This has led to a change in the natural fire disturbance pattern, as fire suppression has become more and more effective in order to protect monetary values. Simultaneously, this has led to an extensive change in the forest's structure and complexity. Generally speaking, tree species variation has decreased, with even-aged monocultures focusing mainly on spruce and pine, with a low share of deciduous trees (at least in older forests). Shorter rotations are implied, which limit natural death and input of deadwood to the stand. As fire essentially is exempted, there is a lack of fire-shaped structures such as fire-scars and fire-killed birches that can produce fruiting bodies of *Daldinia loculata*. This simplification of forests has had consequences on many species, as they have lost much of their habitat and many of them are therefore today threatened.

Today, prescribed burning, or the controlled use of fire, has become a respected tool to restore and reintroduce fire as a disturbance in protected areas. Prescribed burning aims to mimic the effects wildfires had on the forest. Forest stands should be thinned by the fire event, some trees, especially spruce trees, should be killed by the fire, which favors the rejuvenation of deciduous trees. Prescribed burning also aims at creating structures such as fire-scars. However, few studies have compared the effects that wildfires and prescribed burns have on a forest stand.

The aim of this study is to describe and compare differences and similarities between natural fires and prescribed burnings in Sweden. The comparison focuses on the mortality, change in basal area, amount of dead wood above 10 cm diameter, rejuvenation of pine, birch, aspen, and goat willow, as well as the proportion of pines with resin flow, birches with *Daldinia loculata* and signs of woodpeckers' feeding activity. Further, the set targets of prescribed burns that are stated in the burning reports are compared to the targets reached by the fire event. For goals that are difficult or not possible to achieve with prescribed burning, I discuss what changes that may improve the results and what possible alternative measures can be undertaken to achieve such goals.

I found that wildfires and prescribed burnings generate different outcomes. Many of the variables studied proved to be significantly different. Pine mortality was much greater in the wildfire sites. Spruce and birch mortality did not differ significantly between the two fire types, but birch mortality was slightly higher in the sites that had experienced wildfire. Looking at the proportional change of living tree's basal area, as a measure of the stands thinning, the change was greater in the wildfire areas. Sites that were exposed to wildfire had far higher volumes of coarse woody debris than sites exposed to prescribed burning. The regeneration of aspen, goat willow, birch, and pine was significantly higher in wildfire sites. I found no difference between the two fire types in the proportion of living pines with resin flow, indicating the creation of a fire-scar. Further, the proportion of fire-killed birches with fruit bodies of *Daldinia loculata* was higher in the wildfire sites compared to the prescribed burning sites. Moreover, feeding activity by woodpeckers on pines was greater in the wildfire sites, whilst signs of feeding on spruce and birch was greater in the prescribed burning sites.

Because the targets of prescribed burns were not always clearly stated in the County Administrative Board reports, it was difficult to evaluate if desired outcomes of the burns were achieved or not. Differences in tree mortality, change in basal area, volumes of deadwood, and regeneration between wildfires and prescribed burns are likely due to higher fire intensity in wildfires. General targets such as creating fire-shaped forests with prescribed burning, enhancing the regeneration of deciduous trees, and creating deadwood can be reached. However, my results clearly show that prescribed burnings do not induce the same effects as wildfires. If the goal is to mimic wildfire, I propose that prescribed burnings are executed during hotter and drier conditions than today. However, this may be problematic as it may increase the risk that the prescribed burnings goes out of control, causing fire damages in adjacent forests outside the borders of protected areas. Another alternative to ensure higher tree mortality, and the creation of deadwood of larger diameters, may be the girdling and gap cutting of conifers prior to the planned burning. As a means to guarantee the regeneration of deciduous trees, the humus layer could be manually removed to expose more mineral soil.

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