

TREE MORTALITY, FIRE SCAR FORMATION AND
REGENERATION 8 YEARS AFTER LOW-INTENSITY
FIRE IN MANAGED *PINUS SYLVESTRIS* STANDS

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Tiivistelmä — Referat — Abstract <p>Fire is an important driver of the boreal forest ecosystem, and a useful tool for the restoration of degraded forests. However, we lack knowledge on the ecological processes initiated by prescribed fires, and whether they bring about the desired restoration effects. The purpose of this study was to investigate the impacts of low-intensity experimental prescribed fires on four ecological processes in young commercial Scots pine (<i>Pinus sylvestris</i>) stands eight years after the burning. The processes of interest were tree mortality, dead wood creation, regeneration and fire scar formation. These were inventoried in twelve study plots, which were 30 m x 30 m in size. The plots belonged to two different stand age classes: 30-35 years or 45 years old at the time of burning. The study was partly a follow-up of study plots researched by Sidoroff et al. (2007) one year after burning in 2003.</p> <p>Tree mortality increased from 183 stems ha⁻¹ in 2003 to 259 stems ha⁻¹ in 2010, corresponding to 15 % and 21 % of stem number respectively. Most mortality was experienced in the stands of the younger age class, in smaller diameter classes and among species other than Scots pine. By 2010, the average mortality of Scots pine per plot was 18%, but varied greatly ranging from 0% to 63% of stem number. Delayed mortality, i.e. mortality that occurred between 2 and 8 years after fire, seemed to become more important with increasing diameter. The input of dead wood also varied greatly between plots, from none to 72 m³ ha⁻¹, averaging at 12 m³ ha⁻¹.</p> <p>The amount of fire scarred trees per plot ranged from none to 20 %. Four out of twelve plots (43 %) did not have any fire scars. Scars were on average small: 95% of scars were less than 4 cm in width, and 75% less than 40 cm in length.</p> <p>Owing to the light nature of the fire, the remaining overstorey and thick organic layer, regeneration was poor overall. The abundance of pine and other seedlings indicated a viable seed source existed, but the seedlings failed to establish under dense canopy. The number of saplings ranged from 0 to 12 333 stems ha⁻¹.</p> <p>The results of this study indicate that a low intensity fire does not necessarily initiate the ecological processes of tree mortality, dead wood creation and regeneration in the desired scale. Fire scars, which form the basis of fire dating in fire history studies, did not form in all cases.</p>			
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Contents

1. INTRODUCTION.....	2
1.1. Fire in Finnish forests.....	3
1.2. Characteristics of forest fires	4
1.3. Ecological importance of fire	5
1.3.1. Fire and tree death	8
1.3.2. Fire scar formation and fire history analysis	9
1.3.3. Regeneration after fire.....	10
1.4. Fire in forest restoration.....	12
1.5. Research questions.....	14
2. MATERIALS AND METHODS.....	15
2.1. Study location.....	15
2.2. Experimental plots.....	15
2.3. Background data.....	19
2.4. Field measurements	19
2.4.1. Tree mortality	20
2.4.2. Fire scar formation.....	21
2.4.3. Regeneration	21
2.5. Data handling, computations and statistical analyses.....	22
3. RESULTS.....	24
3.1. Tree mortality.....	24
3.1.1. Amount of dead wood	27
3.2. Fire scars	29
3.3. Regeneration.....	33
4. DISCUSSION	36
4.1 Limitations of the study.....	36
4.2 Comparison with previous studies.....	37
4.2.1 Tree mortality.....	37
4.2.2 Fire scar formation	38
4.2.3 Tree regeneration.....	39
4.3 Implications.....	41
5. CONCLUSION.....	44

1. INTRODUCTION

Tree mortality after fire has been widely studied in the last few decades and many species have been the subject of research. Most studies have focused on the immediate mortality after a fire event (Ryan and Reinhardt 1988, Swezy and Agee 1991, Kolström and Kellomäki 1993, Regelbrugge and Conard 1993, Linder et al. 1998, Stephens and Finney 2002, McHugh and Kolb 2003, Hély et al. 2003, Beverly and Martell 2003, van Mantgem and Schwartz 2004), but studies on fire-induced delayed mortality are scarce (e.g. Ryan et al. 1988, Mutch and Parsons 1998) or results of modelling (e.g. Keane et al. 1990). Post-fire Scots pine (*Pinus sylvestris*) mortality in the boreal forest has been studied by some, but the research period has been limited to one year after fire (Kolström and Kellomäki 1993, Linder et al. 1998, Sidoroff et al. 2007).

Previous studies on the use of prescribed burning for management purposes, especially the ones conducted in North America, have focused on the reduction of surface fuels diminishing the intensity and severity of subsequent wildfires (Fernandes and Botelho 2003). However, there is increasing interest in the use of prescribed burnings for restoration purposes in the boreal forest (Granström 2001, Kuuluvainen et al. 2005, Vanha-Majamaa et al. 2007).

Effective fire suppression in Fennoscandia has decreased the annual average burnt area to less than 0.1% of forested land (Granström 2001). It is not until recently that the positive effects of fire on biodiversity have been identified (Vanha-Majamaa et al. 2007, Berglund et al. 2011). Fires help create a mosaic of different successional stages in the landscape, induce dead wood generation and enhance heterogeneity on several spatial and temporal scales – all important features of natural boreal forests (Kuuluvainen et al. 2002). In order to protect biodiversity on a large enough scale in the boreal landscape, management must focus on both commercial stands and forest reserves. There is an increasing need to introduce fire or fire-mimicking activities to all types of forests (Esseen

et al. 1997). This, however, cannot be done without adequate knowledge of the consequences of fire on the ecosystem.

1.1. Fire in Finnish forests

Fires have throughout time played a significant role in shaping the boreal landscape (Zackrisson 1977). Lightning is the most common natural cause of fires, although the ignition density in boreal forests has been found to be fairly low. Larjavaara et al. (2005) estimated the average ignition probability in Finland to range from 0.1 ignitions per 10 000 hectares on the south coast to 0.01 in northern Finland.

In the last centuries, humans have increasingly affected fire regimes to meet their needs. Before that, the fire return interval is estimated to have been much longer, even hundreds of years (Pitkänen et al. 2002). Even before shifting cultivation, wildfires may have been started by hunters either deliberately to mobilise game animals or when failing to put camp fires out (Parviainen 1996). However, supposedly due to the intricate mosaics of lakes, wetlands or recently burned ground acting as fire breaks, and differences in climate, forest fires mostly remained fairly small in Fennoscandia compared to for example Canada and Siberia (Parviainen 1996).

The earliest evidence of forest being burnt to obtain agricultural land in Finland is from the 16th century, but it was the 18th and 19th centuries when the peak of *slash and burn* was experienced. By the beginning of the 20th century, 50-75% of Finnish forests had been affected by slash and burn (Heikinheimo 1915). This period coincides with the rise of the Finnish forest industry and, subsequently, there was widespread concern of losing forest cover. The Private Forest Act passed in 1929 allowed slash and burn only if absolutely necessary.

The cessation of slash and burn practices altered the Finnish forest landscape. The amount of pioneer broadleaved species declined and there was a marked increase in Norway spruce (*Picea abies*) (Finnish Forest Research... 1992). In the 1920s and especially

in the 1950s and 60s after the Second World War, fire was used as site preparation for enhanced regeneration. It is estimated that prescribed burning has affected 2-3% of Finland's forests. The aerial size of a forest fire has decreased from 60-80 hectares a decade ago to an average of 0.5 ha (Parviainen 1996). Presently, severe forest fires in Finland are rare due to the effective fire prevention and control system. The popularity of fire use for site preparation has declined as mechanized options are safer and less costly. A clear-cut final felling method has been adopted on the basis that it imitates stand-replacing fire in the landscape (Johnson 1992). Today this is opposed by many, because essential differences exist and stand-replacing fires have actually been fairly rare in the Finnish boreal forest.

The high amount of anthropogenic forest fires in the 18th and 19th century has altered the landscape to this day. Therefore, the forest structures that are viewed today as pristine, may in fact be more heavily impacted by man-made fires than a real "*natural*" boreal forest ecosystem would be (Granström 2001). However, presently the amount of fires is higher than it would no doubt be naturally, but due to effective fire suppression, the area burnt remains small. The intensive forest management that is currently practiced, has also altered the fuel conditions of the forest, possibly reducing further the area burnt (Tanskanen 2007).

1.2. Characteristics of forest fires

In forest fire regimes, the most important variables are the return interval, intensity, severity and size (Vaillancourt et al. 2009). Spurr and Barnes (1980) classify fires into ground, surface and crown fires depending on the stratum at which they burn. Surface fires are the most common type of wildfire in Finland (Kolström and Kellomäki 1993); according to a study by Saari (1923), 27.7% of fires were stand-replacing in 20-60-year-old pine forests in Southern Finland. The probability and characteristics of a forest fire are determined by the fire environment, which has three main elements: fuel, weather and topography (Countryman 1972).

The live and dead biomass make up the total fuel load, and the preceding weather conditions determine the fuel available for combustion (Chandler et al. 1983). Fuel is further divided into fine, medium and heavy classes (Van Wagner 1987), of which the fine fuel contributes most to the ignition potential and fire spread (Viegas 1998), and the medium and heavy fuels increase fire intensity, severity and residence time (Ryan 2002).

Fire intensity refers to its energy release and is most commonly expressed as heat energy released per unit time per unit length of fire front (Byram's fireline intensity, Byram 1959). Fire severity measures qualitatively the impact of the fire on the ecosystem and is not directly dependent on fire intensity. For example, a fire with a similar fire line intensity (kW m^{-1}) may have more severe impacts on a spruce stand than a pine stand, because the energy needed for a surface fire to develop into a crown fire is lower for spruce (Johnson 1992). High intensity fires typically have a fireline intensity above 4000 kW m^{-1} (Alexander 1982) and result in the complete or near-complete combustion of the humus layer and the exposure of the mineral soil (Johnson 1992). This leads to favourable conditions for seedling germination and establishment, as mineral soil is less prone to desiccation, which is a major cause of mortality among seedlings (Johnstone and Chapin 2006). Low-intensity fires generally have a fireline intensity below 550 kW m^{-1} (Alexander 1982) and the surface vegetation is usually burnt, but the underlying humus layer left unburned.

1.3. Ecological importance of fire

Various disturbances in the ecosystem work on a temporal and spatial scale resulting in a dynamic mosaic of forest types and ages (Zackrisson 1977, Esseen et al. 1997).

Disturbances can range from the death of a single tree to stand-level and landscape level mortality. Disturbances and their variation create structural and compositional diversity in the ecosystem (Frelich 2002), which in turn induces higher biodiversity. However, biodiversity has been observed to be highest at medium levels of disturbance intensity or frequency, known as the *intermediate disturbance hypothesis* (e.g. Horn 1975, Huston

1979, Connell 1978, Petraitis et al. 1989, Roxburgh et al. 2004). A forest has four main structural components: living trees, dead wood, soil and regeneration. Different disturbances vary in their impacts on these components.

Fires are considered an important stand- and landscape-level disturbance factor in boreal forests and a driver of various ecological functions. Fires affect nutrient cycling and soil chemistry (Ahlgren and Ahlgren 1960, Certini 2005), species composition, regeneration (e.g. Lehto 1956, Yli-Vakkuri, 1961), competition, succession (Ahlgren and Ahlgren 1960, Rowe 1983, Engelmark 1993) and the age structure of forests (Johnson 1992). As a disturbance factor, fires are selective: some trees are killed instantly, some with a delay, and some may not even be affected. Therefore, forest fires create a habitat mosaic both within stands and between them on a landscape-level. They also lead to stands of different ages and at different stages of succession (Johnson 1992, Turner and Romme 1994, Weir et al. 2000), which is vital for biodiversity.

In the face of disturbance, ecosystems respond with their properties of *resistance* and *resilience*, which are self-renewal mechanisms (Gauthier et al. 2009). In short, resistance is the ability of an ecosystem to withstand change, and resilience is the ability of an ecosystem to revert to previous conditions on its own.

Mechanical disturbances caused by current silvicultural practices have reduced the need for fire for the survival of some organisms that previously required fire (Granström 2001). However, a number of species depend specifically on fire for their existence, such as pyrophilous insects (Wikars 1997) and fungi (Dahlberg 2002). Engelmark and Hytteborn (1999) estimated that in Fennoscandian boreal forests, at least 60 species depend on fire in particular. In the Finnish red-list 2000, about 3 % of species were classed pyrophilic (Rassi et al., 2001), whereas Tikkanen et al. (2006) estimated that of forest dwelling red-listed species 3% are dependent on fire and 10% prefer it. However, historically forest fires probably occurred on a larger scale but less frequently, so pyrophilic species must have developed characteristics to cope with variable occurrences of fire in space and time (Granström, 2001). Therefore the current fire suppression regime may not necessarily threaten all fire-specialized species. Mobile species, such as pyrophilous beetles, can

move from a burnt patch to the next, even covering considerable distances. Immobile species and fire induced elements, such as fire-influenced soils or trees with fire scars, require fire returning to the same site periodically. This is rare in the current fire regime and thus these species and elements are disappearing from the landscape.

The more substantial ecological consequence of fires on biodiversity is the creation of dead wood. Siitonen (2001) estimated that 20-25% of forest-dwelling species in Finland depend on deadwood habitats. The volume of dead wood in industrial forests in Southern Finland is estimated at 1.2-2.9 m³/ha (Tomppo et al. 1999), whereas it is 60-120 m³/ha in natural pine forests (Siitonen 2001). The aim set for the volume of dead wood in Metsähallitus industrial forests is 10 m³/ha (Heinonen et al. 2004). For forest reserves, the target is higher, 30 m³/ha, and in addition the dead wood volume from fires should be 100 m³/ha (Hokkanen et al. 2005). The type and size distribution of dead wood must also be taken into consideration. Currently there is a severe lack of dead trees of deciduous species and of large diameter (Jonsson et al. 2005). However, large amounts of dead trees can encourage diseases and insect attacks on the stock reducing the profitability of forestry, and thus dead wood volume in the proximity of commercial forests is regulated.

The third ecologically important factor of fires is that it initiates a natural successional cycle dominated in the beginning by deciduous trees. The amount of deciduous trees and stands at the early stage of succession has been declining in the landscape, due to the sowing or planting of the desired species, most commonly spruce or pine (Finnish Forest Research... 2009).

Currently, the use of fire has been introduced in the forest certification criteria in Fennoscandia, and efforts are made to increase burnt area in both Finland (Forest Stewardship Council... 2010, PEFC Finland 2009) and Sweden (Granström 2001). How to achieve the desired ecological impacts using fire is still unclear. For example, the depth of burn, the level of desired tree mortality and other such issues are debated and more research is needed on this matter.

1.3.1. Fire and tree death

Tree mortality after fire is largely determined by the scope of physical damage to the crown, trunk and roots (Stephens and Finney 2002). The flames of a forest fire can either kill the tree directly by girdling the tree or scorching the crown. Or, flames can cause sufficient cell necrosis that leads to the tree being unable to acquire enough resources and keep up all physiological processes and defences (Franklin et al. 1987). Thus, the tree is either directly killed by the fire or weakened as it is more susceptible to attacks by pathogens. Tissue and cell necrosis occur at exponentially increasing rates as the temperature rises (Dickinson and Johnson 2001). Hare (1961) estimated the lethal temperature of the cambium at 60°C. Cheney et al. (1992) established a *critical residence time* of a flame that would cause necrosis of the cambium around the entire circumference of the bole. They estimate that for a tree with a bark thickness of 5 mm, the critical residence time would be 20 seconds (Cheney et al. 1992).

In the Scandinavian boreal forest, tree mortality after fire has been studied previously by, for example, Kolström and Kellomäki (1993), Linder et al. (1998) and Sidoroff et al. (2007). From the empirical data, various probabilistic models predicting tree death from certain parameters have been constructed. For example, Kolström and Kellomäki (1993) estimated that a pine of 20 cm diameter at breast height had a 50% probability of surviving a low intensity fire, assuming the fire does not spread to the crown. It was also concluded that Scots pine is the only tree species able to some extent survive forest fires.

Many studies have found crown scorching to be a significant contributor to tree mortality. In low-intensity fires, the crown is rarely damaged at all. Therefore other variables must be considered. Sidoroff et al. (2007) found a correlation between mortality and tree characteristics such as bark thickness and diameter at breast height, as well as with fire-induced damage, such as charred stem ratio. Ryan et al. (1988) concluded that in low-intensity fires, cambium injury is more important than crown scorch.

Whether forest fires lead to the directional evolution of increased resistance to fire of species is both defended (e.g. Zackrisson 1977) and questioned (e.g. Rowe 1983). The

development of a thick, heat-insulating bark, rapid height growth that lifts the crown from the forest floor and the lower branches dying out and falling off, however, are important features of fire resistance. Due to its height and the lack of lower branches, surface fires in pine forests rarely develop into more destructive crown fires due to the lack of "ladder fuel" (Sannikov and Goldammer 1996). The cambium of pines also has an extraordinary ability of recovering after damage, and pine possesses a high resistance to pathogen attacks following damage (Zackrisson 1977). It is likely that the deep rooting of pine, compared to for example spruce, may contribute to reduced root damage during fire, but this has not been confirmed (Flinn and Wein 1977). In Finland, Scots pine forests have a high ignition potential and fire spread rate compared to Norway spruce (Tanskanen 2007).

1.3.2. Fire scar formation and fire history analysis

Trees that are damaged by fire but survive may develop fire scars. A fire scar is formed if lethal temperatures linger at the surface of the stem for a sufficient amount of time and cause cell death in the bark, cambium and xylem (McBride 1983). The cambium is a sensitive layer of cells that are responsible for tree growth (Larson 1994), thus its destruction decreases the probability of tree survival. In the years following the fire, the bark covering the scar falls off exposing the sapwood, which is vulnerable to pathogens and subsequent fires. However, the tree may start a rejuvenation process. The remaining cambium will grow from the sides forming a callus that eventually covers the scar, and will start producing new wood and bark (Zackrisson 1977, McBride 1983). The damaged area will be entirely covered by new wood, if another fire does not disrupt the healing process.

The occurrence of fire scars can be dependent on tree species (Lachmund 1921, Show and Kotok 1924), bark thickness and tree diameter (Gill 1974, Tunstall et al. 1976, Guyette and Stambaugh 2004) or fire intensity (Vines 1968). Disturbances other than fire may produce scars very much similar to scars caused by fire (McBride 1983). Other causes include hits

by falling neighbouring trees, lightning, floods or mechanical damage by storms, animals or man. A fire scar can be identified by the presence of black charcoal flecks or black crust on the scar margins.

Fire scar formation in Scots pine has not been studied. According to Madany and West (1980), ponderosa pines (*Pinus ponderosa*) are most susceptible to scarring between the ages of 10 and 80 years. Younger trees will not survive the fire, and older trees will likely have developed a bark thick enough to insulate the heat. For Scots pine, the corresponding range may be different.

Determining the fire history of an area is important background information for the planning of management practices, especially if it involves re-introducing fire (e.g. McBride 1983). The most common method has been the dating of fire scars. This includes selecting fire scarred trees or stumps to be examined, extracting a sample from them, analysing the tree rings and dating the fire scars (Arno and Sneek 1977). The sample is typically and preferably a whole cross-section, but due to its destructive nature, other samples can also be taken into account. According to Zackrisson (1980), a sample taken from the root neck of the tree provides a more accurate estimate than ones taken at breast height (1.3 m). It is not uncommon for a tree to have several fire scars buried in the heartwood (Zackrisson 1977).

1.3.3. Regeneration after fire

Post-fire regeneration often can occur immediately after the disturbance or with a delay (Yli-Vakkuri 1961, Engelmark 1993, Johnstone et al. 2004, Charron and Greene 2002).

Regeneration consists of several stages: flowering, fruiting, dispersal, storage, germination and establishment (Wagner and Lundqvist 2005). The amount of recruitment depends on the degree of seed tree and seedling mortality rates. Germination is mainly dependent on the available microsites and their temperature, moisture and light conditions. For the regeneration of Scots pine, ideal conditions would be in areas with an

open canopy, available seed sources and a good seed year, sparse understory vegetation cover, exposed mineral soil and enough moisture for establishment.

In general, tree species in Finland do not form a persistent seed bank and seeds are usually destroyed in forest fires (Vanha-Majamaa et al. 1996), although pine seeds can partially preserve germinability even when charred (Sannikov and Goldammer 1996). Scots pine, Norway spruce, silver and pubescent birch (*Betula pendula* and *B. pubescens*) and rowan (*Sorbus aucuparia*) regenerate from seeds originating from trees that survived the fire. The birches, rowan and aspen (*Populus tremula*) can also regenerate vegetatively from underground parts (Vanha-Majamaa et al. 1996)

Several studies have found that the severity of the burn, exposure of mineral soil and reduced duff layer have a positive effect on post-fire seed germination and seedling establishment (eg. Dyrness and Norum 1983, Charron and Greene 2002, Johnstone and Chapin 2006). Often, the deeper the burn and the more mineral soil exposed, the higher the seedling recruitment as reported by e.g. Charron and Greene (2002). A study on four common North American boreal species by Johnstone and Chapin (2006) found that the establishment of small-seeded species, such as pines, was low on lightly burned soils. In northern USA, Little and Moore (1953) concluded that unburned or unprepared soils are a poor seedbed for pitch pine (*Pinus rigida*) regeneration, and natural occurrence of seedlings can be close to zero. On the other hand, after a severe fire, up to 56 300 pitch pine seedlings were found per hectare. Charron and Greene (2002) found that the establishment rate is more dependent on the seedbed than the tree species. They also found that in four years, post-fire recruitment of jack pine (*Pinus banksiana*), black spruce (*Picea mariana*) and white spruce (*Picea glauca*) declined to almost zero. Duchesne and Sirois (1995) found that recruitment success of black spruce and jack pine in the Canadian boreal forest was strongly correlated with soil moisture content, whereas Herr and Duchesne (1995) found shading, organic layer removal and ash removal to enhance regeneration of jack pine. According to a study by Johnstone et al. (2004) in the Alaskan boreal forest, regeneration rates were highest in the first five years after fire and no net recruitment was observed ten years after fire.

After fire, conditions are often adverse for Scots pine regeneration, as the surface soil is subject to large temperature variations and high evaporation. Weather conditions following fire are one of the most crucial factors of recruitment success (Thomas and Wein 1985). Pine seedlings, especially those under two years, are prone to drought. For example, in a study by Little et al. (1958), 81% of pitch pine seedlings died in a summer drought in New Jersey, USA.

1.4. Fire in forest restoration

Restoration is defined as actively re-establishing the structure, function and dynamics of a damaged or degraded ecosystem to a state that previously existed in the area (Stanturf 2005). A degraded area is disturbed beyond self-renewal or beyond the thresholds of the ecosystem's resistance and resilience. Restoration requires conscious human action that accelerates the achievement of the desired structure and dynamics.

Before any restoration efforts, the previous *pristine* state must be determined (Bradshaw 2005). This can prove extremely difficult, especially in areas with long human influence, like Finland. In practice, no reference of a natural ecosystem exists for fertile lowland forests. The pristine state is not static, but rather a range of natural variability (Landres et al. 1999, Kuuluvainen 2002, Vaillancourt et al. 2009), so restoration goals should be wide enough to cover this variation as much as possible. The appreciation that ecosystems are internally highly heterogenous, complex and dynamic on both a temporal and spatial scale is referred to as the nonequilibrium or new ecological paradigm (Fiedler et al. 1997, Landres et al. 1999).

Restoration efforts are often single actions, but they aim at inducing long-term processes (Kuuluvainen et al. 2002). The scale of restoration efforts can range from single-organism focus to landscape-level modifications, such as can be induced by fire. The ultimate aim of restoration is to return the ecosystem to a natural state. In addition, it is necessary to establish practical, short-term goals and a monitoring framework that

measures success at various temporal and spatial scales (Block et al. 2001). The restoration actions should be adjusted to the results of monitoring and emerging knowledge.

In Finland, large tracts of managed, species-poor Scots pine or Norway spruce monocultures dominate the landscape (Finnish Forest Research... 2009). Restoration efforts must include setting aside land as reserves, but also improving the ecological quality of industrial forest by introducing new management practices and encouraging a natural-like successional forest dynamics (Hanski 2000). Due to the history of forest utilization in Finland, conservation areas often have traces of human influence (Kuuluvainen et al. 2002). Thus, even conservation areas can be ecologically degraded compared to truly pristine forest. Fire could be a useful tool in hastening the restoration process. It could also be used in the vicinity of pristine habitats to create buffer zones.

Fire can be used as a restoration agent, because it creates dead wood, leads to the start of a natural succession cycle and encourages heterogeneity within and between stands (Johnson 1992). It has been stated that fires will be essential in restoring boreal forests (Kuuluvainen et al. 2005). However, improved understanding of the ecological consequences is required for the effective use of fire as a restoration agent. As pointed out by Ryan (2002), fires vary greatly in space and time, and make the outcome hard to predict. Using fire for restoration purposes is costly, laborious and risky, so there is the need to make certain the desired outcomes are achieved by its use. It is often not economically or socially feasible to use fire as a restoration agent on a large scale. The historical, natural fire regime occurred over such a large scale that restoring it in its entirety is not possible today. Therefore, restoration by fire requires careful, long-term planning to achieve the desired goal of a post-fire habitat mosaic on a smaller scale.

Strict conservation areas are not large enough to maintain some fundamental processes of the boreal forest, such as meta-population dynamics or a natural fire regime (Granström 2001). Therefore, the establishment of buffer zones and improvement of the ecological state of commercial forests is imperative, especially in Southern Finland. Restoration can, thus, be seen as complementary to a network of reserves.

Post-fire ecology has been studied widely all around the boreal zone, but research on the effects and success of prescribed fires as restoration agents has been limited. The Evo experiment examined extensively the various impacts of fire on commercial spruce forests (Vanha-Majamaa et al. 2007), Sidoroff et al. (2007) investigated the effects on commercial pine stands, and De Chantal and Granström (2007) studied the regeneration of aspen and willow in coniferous old growth forests. It has been recommended that 5% of the area harvested on dry and mesic sites should be burnt in Finland and Sweden (Granström 2001, Kuuluvainen et al. 2002). Whether prescribed restorative fires succeed in their aim of enhancing biodiversity, and in what situations it succeeds or fails, is still lacking evidence.

Scots pine makes up 50% of Finnish forests by volume (Finnish Forest Research... 2009), so they are likely to be subjected to restoration efforts. However, little information is available on the impacts the use of fire for restoration purposes will have in Scots pine stands.

1.5. Research questions

The aim of the study was to examine the tree mortality, fire scar formation and regeneration after low-intensity experimental fires on commercial Scots pine stands. This study was partly a follow-up of the study plots researched by Sidoroff et al. (2007) on the immediate effects of low intensity fires on tree mortality. The specific research questions were:

- What was the tree mortality eight years after fire? What proportion of the dead trees were killed instantly and what proportion died with a delay?
- What was the volume of created dead wood?
- Did the fire leave fire scars, and if so, what kind?
- What was the regeneration pattern in the burned plots?

2. MATERIALS AND METHODS

2.1. Study location

The study area is located in Southern Finland in the Evo region (61.3 N, 25.2 E, 140-180 m a.s.l.). Bioclimatically, the region belongs to the southern boreal zone (Ahti et al., 1968). Nine of the twelve plots were located in Evo and three in Vesijako. The average temperature is 3.9°C, ranging from -7.3°C in February to 16.2°C in July. The annual precipitation is approximately 631 mm, of which roughly 250 mm falls as snow. The length of the growing season is approximately 170 days, the temperature sum is above 1200 d.d. and the region has permanent snow cover typically from mid-December until the beginning of April (averages 1971 to 2000, Drebs et al. 2002). However, the past decade has been warmer than the long-time average and five of the years between the burnings in 2002 and inventory in 2010 have been exceptionally warm (Finnish Meteorological Institute 2009).

2.2. Experimental plots

The study consisted of 12 experimental plots 30 x 30 m in size. The plots belonged to one of two age classes at the time of burning: (1) five plots were stands that had not undergone their first thinning and had been between 30 and 35 years old, and (2) seven of the plots had undergone first thinning and had been 45 years old. Henceforth the plots will be referred to as “younger stands” and “older stands” respectively. This is slightly inaccurate, because the plot size so small that it cannot be called a stand. However, it can still be considered representative of a stand. The plots were established on even ground

on dry *Vaccinium vitis-idaea* (L.) site type according to Cajander's site type classification (Cajander 1926). Stand density ranged between 600 and 2200 trees ha⁻¹ and average tree diameter at breast height from 12 to 24 cm (Table 1). The area has a long history of industrial wood production and therefore the plots are reasonably homogenous.

Plots were coded by giving a letter corresponding to the age class (Y for the younger stands and O for the older ones) and giving a rolling number starting from 1. Below is a description of the visual appearance of each plot 8 years after the fire. See also stand characteristics in Table 1.

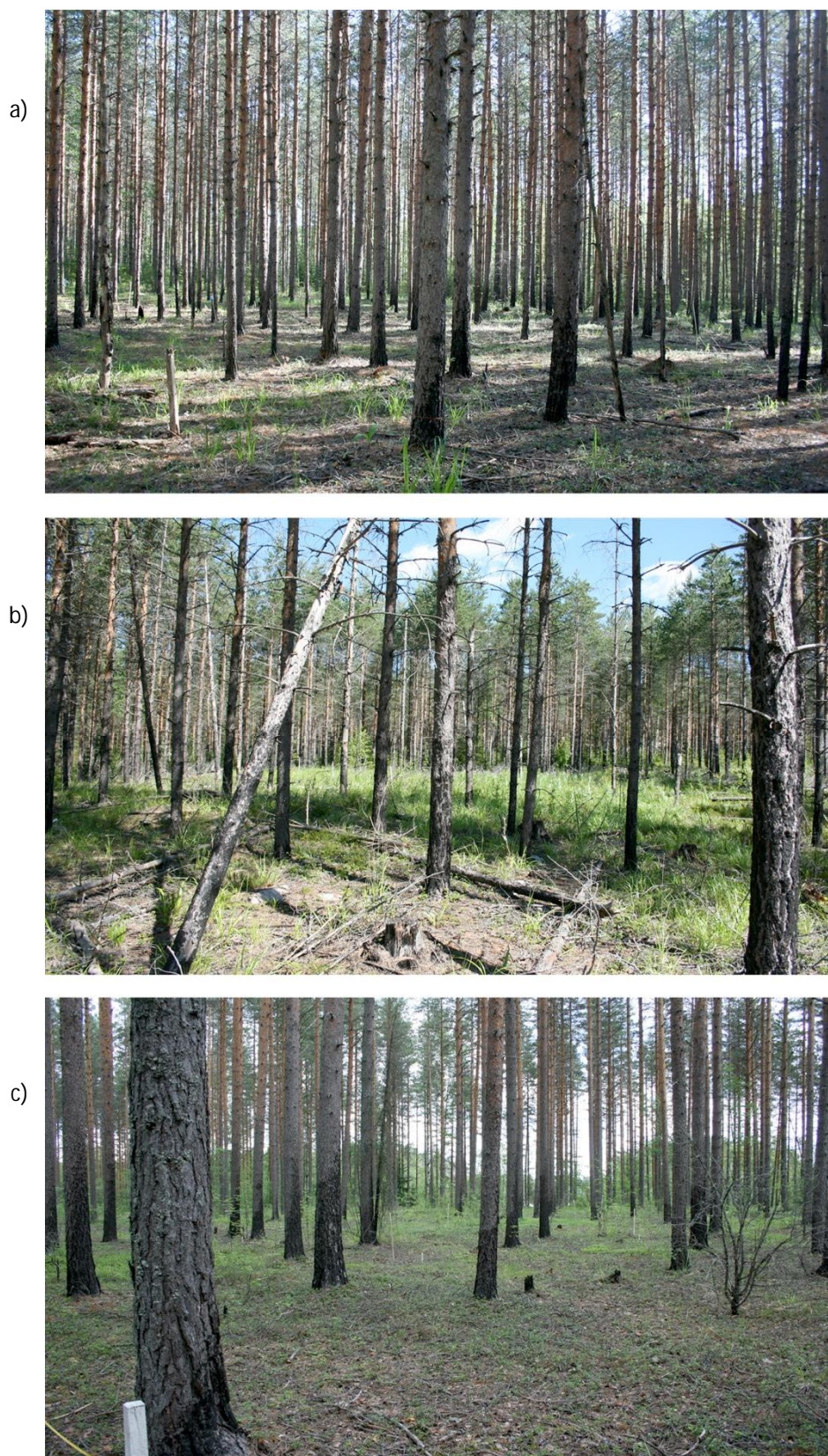
- Y1: High stand density and shading, no canopy openings. The forest floor is almost void of vegetation save some grasses and lingonberry (*Vaccinium vitis-idaea*). (See picture 1a.)
- Y2: High stand density, but less shading than in plot Y2. The forest floor is almost entirely covered with grasses.
- Y3: High mortality of trees and large quantities of dead wood around the plot. A large canopy opening in the middle of the plot. Regeneration of various species of ground vegetation and trees. (See picture 1b.)
- Y4: High mortality of trees and large quantities of dead wood, but the stand density is lower than in Y3. The canopy has opened up fairly uniformly inside the entire plot.
- Y5: Very low mortality except for some small spruces. The canopy cover is dense and the plot is shaded. Yet there is regeneration of especially grasses.
- O1: The trees are charred, but most are still alive. The ground is almost bare of vegetation.
- O2: Similar to O1, the trees are charred, but have not died, and the ground has scarce vegetation cover.
- O3: The ground is more uneven than in other plots. There is clear evidence of the fire on the ground and on the trees, but almost no trees in the plot have died.
- O4: The trees and ground vegetation do not show much sign of the fire. Bases of trees are not even charred. The vegetation is almost recovered to normal.

- O5: The trees are blackened from the base and the ground has been burnt. There is very little regeneration of either trees or ground vegetation.
- O6: Similar to O5, the trees show sign of fire, and the ground is still bare.
- O7: The tree trunks are blackened, but no trees have died. The ground vegetation is scarce comprising mainly of lingonberry and small Scots pine seedlings. (See picture 1c.)

Inside each plot, 9 circular sub-plots for regeneration measurements had been established in 2003 and the centre marked with white plastic tubes. They were placed at 7.5 m from the sides of the plot and 7.5 m from each other. Comparison plots were set up outside the plot. In some cases, the original comparison plot was not found, so an area as similar as possible to the experimental plot was chosen.

Table 1. Essential characteristics of the experimental plots. The plots were classed into younger (Y) and older (O) stands according to their age at time of burning.

Plot	Number of trees (pines)	Age at burning (a)	Average dbh (cm)	Stand density (trees ha ⁻¹)
Y1	170 (168)	30-35	14,41	1889
Y2	182 (180)	30-35	12,78	2022
Y3	199 (198)	30-35	12,74	2211
Y4	92 (73)	30-35	14,89	1022
Y5	102 (85)	30-35	17,63	1133
O1	95 (93)	45	19,42	1056
O2	96 (93)	45	20,02	1067
O3	81(74)	45	19,62	900
O4	91 (91)	45	17,97	1011
O5	75 (75)	45	19,03	833
O6	85 (80)	45	20,26	944
O7	56 (53)	45	24,00	622



Pictures 1. a-c. Examples of burnt plots. a) Y1: A younger stand with low tree mortality and poor regeneration of trees or ground vegetation. b) Y3: A younger stand with high mortality, canopy opening and regeneration. c) O7: An older stand with low mortality and poor regeneration.

2.3. Background data

One aim of this study was to continue the tree mortality research on study plots examined by Katja Sidoroff (Sidoroff et al. 2007). The information relevant to this study is summarized below, but for more details, see Sidoroff et al. (2007). The study plots were burned between June and August 2002 by igniting the windward side with drip-torches and extinguishing the fire outside the plot. Climatic variables such as wind speed, air humidity, temperature and Finnish Forest Fire Index (FFI) during burning were monitored. Flame height ranged from 0.5 m to 1.3 m, meaning the burn was a surface fire. Tree stand parameters such as age, stand density, stand volume and average diameter at breast height were measured before burning. Trees that had died before the burning were omitted from the data.

After the burning, tree mortality and morphological characteristics were recorded in 2003 (Sidoroff et al. 2007). For each individual tree, the diameter at breast height, location of the tree in the plot, bark thickness and tree height were measured. Fire-induced variables were measured and damage to the roots and field layer estimated. The aim was to link mortality with tree characteristics or fire-induced damage. Tree mortality was found to increase with decreasing diameter and bark thickness and increasing damage to the tree stem and ground layer (Sidoroff et al. 2007).

2.4. Field measurements

Tree mortality, fire wound formation and tree regeneration were inventoried in July and October 2010. The difference in inventory times was due to the location information of the Vesijako plots missing, and the appropriate maps were only found in August. The difference in measurement times does not affect fire scar formation and is likely to have a negligible effect on mortality, but affected regeneration results, which is discussed later.

2.4.1. Tree mortality

In each experimental plot, each tree above 5 cm in diameter had been given a number in 2003 by either stapling weather resistant paper or by painting on the bark, and their location in the plot had been recorded (measuring the distance and direction from plot centre). Consequently, it was possible to compare the data of individual trees between 2003 and 2010. A total of 1301 trees were inventoried in 2010.

Some numbers on the trees had fallen off or were otherwise not identifiable. Therefore, during the inventory for this study, a tree map was also drawn to help identify unknown trees by comparing their location data of the 2003 inventory. 21 trees were not found during the inventory, perhaps because they went unnoticed, they were dead and buried under litter or they were on the border and considered out of bounds. However, most of them were dead already in 2003 and would thus be so presently as well. For one of the plots, background data was missing for about 35 trees. Most of these trees were still alive and thus would have been so in 2003 too. As a result, whether a tree was dead or alive was unclear in 11 cases. This constitutes less than 1 % of all inventoried trees.

In accordance with the previous study by Sidoroff (2007), a tree was classed *dead* if it had no green needles on it and *alive* if even some were green, even if the tree was severely damaged. In addition, two health classes were introduced: *weakened* and *dying*. A tree was classed as *dying* if it had mostly brown needles (> 50%) and *weakened* if it had some brown needles (<50%) or fewer branches than a healthy tree of its size. The position of the dead trees was recorded as *standing*, *lying*, *leaning* or *broken*. In the case of a broken tree, the height of the broken trunk was estimated. The diameter at breast height (1.3 m) was measured with callipers for analysis of stand volume.

2.4.2. Fire scar formation

Fire scars are defined as debarked areas exposing the sapwood. It was also noted whether there was indication of the tree attempting to heal the wound. In practice, this meant the presence of resin and the thickening of the bark surrounding the scar (a sign of cambial growth starting to cover the wound).

Living trees were examined for possible fire scars by observation of the surface, and by tapping the bark to find points where the vascular cambium has been burned, but the bark not fallen off yet. Such points sounded hollow when tapped. They may also show hints on the outside, for example, the bark is not curved along the circumference of the stem, but is straight, or even concave. Hidden fire wounds were revealed by debarking around the wound with a knife.

The width and length of the scar were measured at a point that, by eye, represented the average. For scars that reached above two metres, the scar length was estimated to the nearest metre. However, sometimes the highest point of such scars could not be established, because the bark had not fallen off yet. The height between the ground and the lowest point of the scar was recorded. In addition, compass direction was recorded for each fire wound. Many fire scars seemed to form adjacent to the knots of the lower dried out branches. This was, however, not recorded in a systematic manner and remains a personal observation. Analysing from the pictures taken of each fire scar, the proportion of scars adjacent to knots

2.4.3. Regeneration

Regeneration was measured from nine circular sub-plots within each plot. The sub-plots were 3.56 m in diameter giving an approximate area of 10 m². Regeneration was divided into seedlings and saplings. Seedlings were defined as having germinated in the growing season of 2010, but not established, being less than 5 cm in height and having a high

turnover rate. Saplings are defined as established, more than one year old and greater than 5 cm in height. All saplings were inventoried, their species and height recorded. The age of pine and spruce saplings was estimated by the number of nodes. Seedlings of each species were counted, but not recorded separately. A comparison plot was established in a similar manner outside each experimental plot.

2.5. Data handling, computations and statistical analyses

In most analyses, only Scots pine was included, due to the small number of trees of other species. For general comparison, some results are reported with all species included to give a more holistic and realistic picture, but these results have less statistical power and should be considered only approximate.

Mortality percentages are presented on the basis of stem number unless otherwise specified. Immediate mortality is the amount or percentage of trees that had died up to 1 year after the fire, and were thus dead in the study by Sidoroff et al. (2007). Delayed mortality is defined as the amount of trees that have died 2-8 years after the fire, i.e. between the 2003 and 2010 inventories. The percentage of delayed mortality is the amount of trees that have died with a delay out of all the dead trees. Total mortality is the sum of immediate and delayed mortality.

Dead trees were divided into diameter classes at 2.5 cm intervals starting from 5 cm, which was the minimum diameter included in the original study. Some dead trees had lost their bark or decayed sufficiently for their diameter to be less than 5 cm. These were included in the smallest diameter class. The volume of dead wood was estimated from diameter (d) measurements using Laasasenaho's volume equations (Laasasenaho, 1982):

$$\text{Pine} \quad \ln(v) = -5,39417 + 3,48060 \times \ln(2 + 1,25 \times d) - 0,039884 \times d \quad (\text{Eq. 1})$$

$$\text{Spruce} \quad \ln(v) = -5,41948 + 3,57630 \times \ln(2 + 1,25 \times d) - 0,0273199 \times d \quad (\text{Eq. 2})$$

$$\text{Birch} \quad \ln(v) = -5,41948 + 3,57630 \times \ln(2 + 1,25 \times d) - 0,0395855 \times d \quad (\text{Eq. 3})$$

Deadwood was also divided into diameter classes.

The rate of occurrence of fire scars was then calculated as the number of scarred trees from all inventoried trees. The relationship between fire wounds or scars and its health (dying/weakened) was assessed. Two different types of scars were detected, and due to their physiological differences, they were analysed separately. The chosen defining parameter was height, and the cut-off point was set at 2 m, because beyond that point measurements and observations became inaccurate.

For the analysis of differences between young and old forest plots, the Kolmogorov-Smirnov statistical test was used.

3. RESULTS

3.1. Tree mortality

A total of 1324 alive and dead trees were inventoried, of which most were Scots pine ($n=1263$) and the rest other species ($n=61$), mainly Norway spruce and silver birch. The number of dead trees, all species included, rose from 183 stems ha^{-1} one year after fire to 259 stems ha^{-1} eight years after. Respectively, the average mortality increased from 15 % to 21 % on the basis of stem number, but there was great variation between plots and age classes. The majority of the dead trees had fallen down (59 %), followed by standing dead (19 %), broken (15 %) and leaning (3 %). Among dead tree species were Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), silver birch (*Betula pendula*) and grey alder (*Alnus incata*).

The mortality among Scots pine had increased from 12% one year after fire to 18 % eight years after, and for the other species from 74% to 80% respectively. However, the small number of other species, and their small diameter on average, made analysis impossible and only Scots pine was considered for the rest of the study. This is in accordance with the previous study by Sidoroff et al. (2007). Pine mortality per plot ranged between 0 and 63 % (Fig. 1). Omitting other species than pine from the data analysis affected most the mortality of plots Y5 and O4, whose tree mortality consisted almost entirely of species other than pine.

As was discovered by Sidoroff (2007) for immediate mortality, diameter also correlated strongly with delayed tree mortality (Fig. 2). The diameter of dead trees ranged from 4 to 22 cm, with the smaller diameter classes dominating (Table 2.). The number of dead trees by diameter is seen in Table 3. The highest amount of dead trees were found in the smallest category (<7.5 cm), and in the third category (10-12.5 cm). However, the percentage of dead trees decreased steadily from smaller trees to larger ones (Fig. 2.).

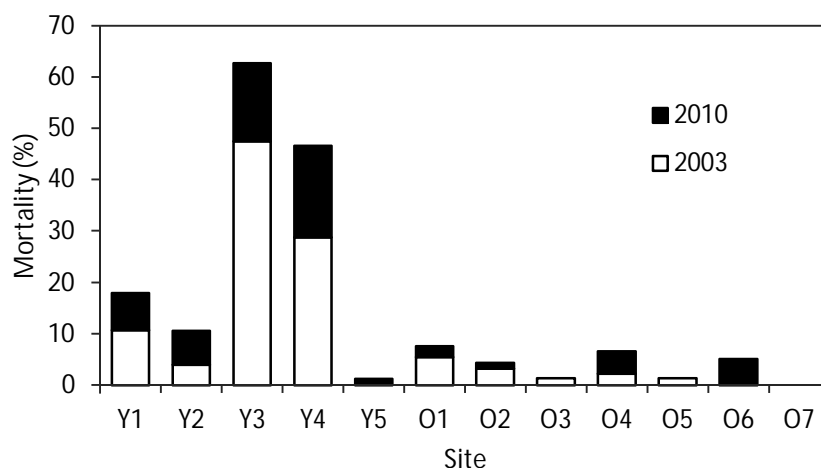


Fig. 1. The mortality (percentage of dead trees from all trees) of Scots pine in the inventory years 2003 (one year after fire) and 2010 (eight years after fire). In plot codes, Y refers to the younger age group (30-35 years at time of burning) and O to the older age group (45 years at the time of burning).

Table 2. Number of dead pines (stems ha^{-1}) by diameter class (cm) by study plots eight years after fire.

Plot	<7.5	$7.5 \leq x < 10$	$10 \leq x < 12.5$	$12.5 \leq x < 15$	$15 \leq x < 17.5$	$17.5 \leq x < 20$	$20 \leq x < 22.5$
Y1	167	111	33	22	-	-	-
Y2	12	56	22	11	-	-	-
Y3	89	178	589	411	112	-	-
Y4	78	11	78	33	144	33	-
Y5	-	-	11	-	-	-	-
Subtotal (Y)	346	356	733	478	256	33	-
O1	22	22	11	-	1	-	-
O2	-	-	33	11	-	-	-
O3	-	-	1	-	-	-	-
O4	11	11	33	11	-	-	-
O5	11	-	-	-	-	-	-
O6	-	-	22	-	-	11	11
O7	-	-	-	-	-	-	-
Subtotal (O)	44	33	111	22	11	11	11
TOTAL	500	389	844	500	267	44	11

Delayed mortality seems to become more prominent with diameter (Fig. 3). Of all the dead pines of the smallest diameter (<7.5 cm), 82 % died immediately (up to 1 year after the fire) and only 18 % died with a delay (between 2-8 years after the fire). For higher (7.5-20 cm) diameter classes only on average 64 % had died immediately and 36 % with a

delay. The effect of tree size on delayed mortality becomes more pronounced when all species are taken into account (Fig. 3). The low number of dead trees in the highest diameter classes makes comparisons difficult, and a study including more trees would be needed in order to verify this trend.

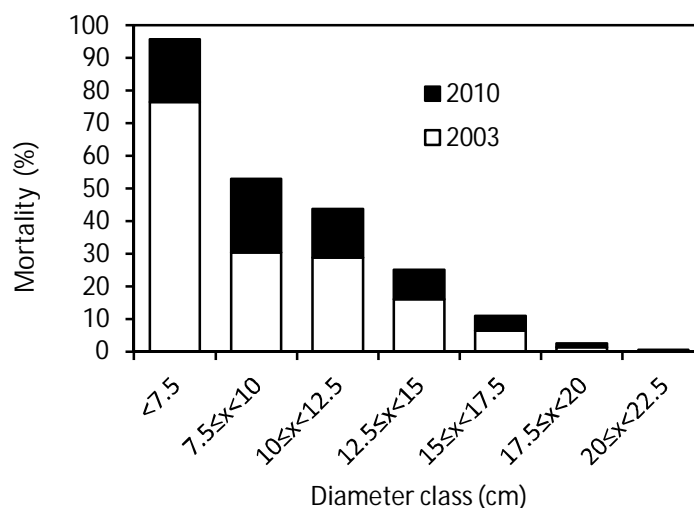


Fig. 2. The percentage of mortality for pine, inventoried in 2003 and 2010, in different diameter classes in the study plots.

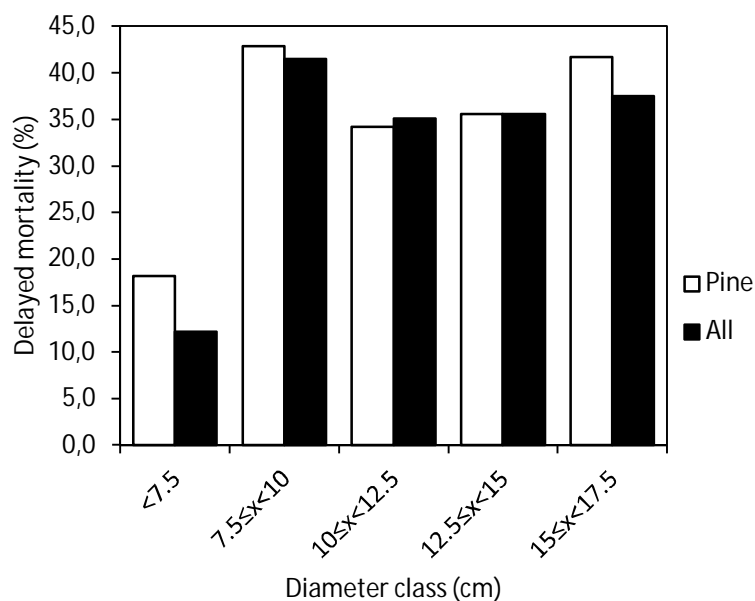


Fig. 3. Delayed mortality, i.e. percentage of dead trees that have died two to eight years after fire, for pine and all species in different diameter classes.

As would be expected, the mortality of pine was significantly higher in the younger stands (30 %) than in the older stands (4 %) (Fig. 4.), and this result is statistically significant ($p < 0.05$, Kolmogorov-Smirnov test). In the older stands, both overall mortality and the difference in mortality between plots were smaller than in younger stands, ranging from 0 % to 7.5 %. In younger stands, mortality varied from 1.2 % to 62.6 % (Fig. 1.).

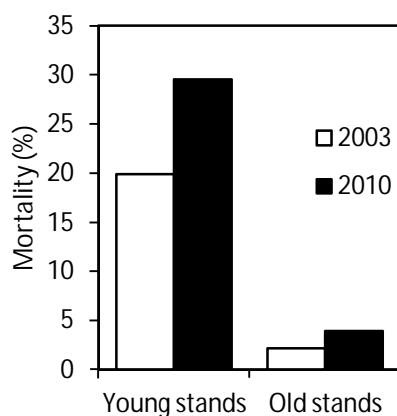


Fig. 4. The percentage of dead pines in young (30-35 years at time of burning) and older stands (45 years at time of burning)

3.1.1. Amount of dead wood

Due to the high variability in tree mortality between plots, the production of dead wood also varied greatly, ranging from $0.14 \text{ m}^3 \text{ ha}^{-1}$ to $71.56 \text{ m}^3 \text{ ha}^{-1}$. The average dead wood produced per plot was $11.85 \text{ m}^3 \text{ ha}^{-1}$, but is non-representative of the whole picture, as only two plots were above that amount (Table 3.).

The largest amount in volume of dead wood was created in the 10-17.5 cm diameter classes (Fig. 5.). Trees that had fallen down constituted 60 % of the dead wood volume.

Table 3. Amount of dead wood created ($\text{m}^3 \text{ha}^{-1}$) per plot eight years after fire.

Site	Total	Pine	Spruce	Deciduous
Y1	6.93	6.92	-	0.01
Y2	4.57	4.50	-	0.07
Y3	71.56	71.55	-	0.01
Y4	33.38	33.05	0.02	0.31
Y5	2.39	0.04	2.35	-
Average (Y)	23.76	23.21	0.47	0.08
O1	2.52	2.52	-	-
O2	3.68	3.55	0.13	-
O3	8.56	0.05	8.50	-
O4	2.67	2.67	-	-
O5	0.14	0.14	-	-
O6	5.61	5.60	0.01	-
O7	0.22	-	0.22	-
Average (O)	3.34	2.08	1.27	-
Average (total)	11.85	12.64	0.87	0.04

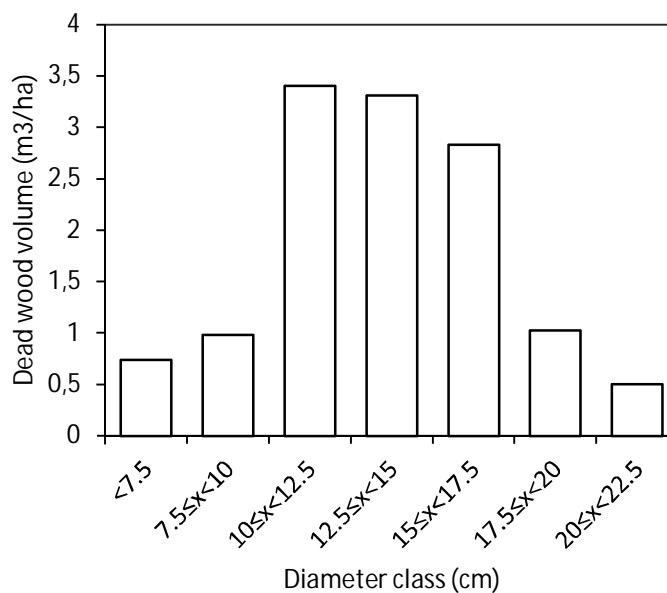


Fig. 5. The distribution of dead wood volume produced in the study plots by diameter class eight years after fire.

3.2. Fire scars

A total of 217 fire scars were recorded in 142 trees. The number of separate scars per tree ranged from 1 to 6, with most 67 % of the trees having just one scar. The proportion of fire scarred trees out of all trees per plot ranged from 0 % to 30 %, averaging 16.5 % in young stands and 2.8 % in older stands. However, the percentage of scarred trees out of remaining living trees could be up to 81 %. Four out of the twelve plots did not have any trees with fire scars, and these were all in the older age group. This means that in the older stands, only in three cases out of seven (43%) did the fire leave scars from which fire history can potentially be established afterwards (Fig. 6.).

There were 65 scars that reached above two metres and these were only found in two plots, Y3 and Y4. These scars were very different to the rest of the scars, as they extended up to heights where the flames had not reached, and never showed signs of healing. They were also wider and formed lower to ground (Fig. 7b and 7c). Due to this, and the inaccuracy of the height measurement, averages of scar dimensions will be reported separately for these types of scars and the rest.

The shape of scars was highly variable (see pictures 2 a-h), and therefore measuring the fire scar dimensions proved difficult. Excluding the scars above two metres, the scars were small: the average width and length were 4.4 cm and 34.8 cm respectively. Two

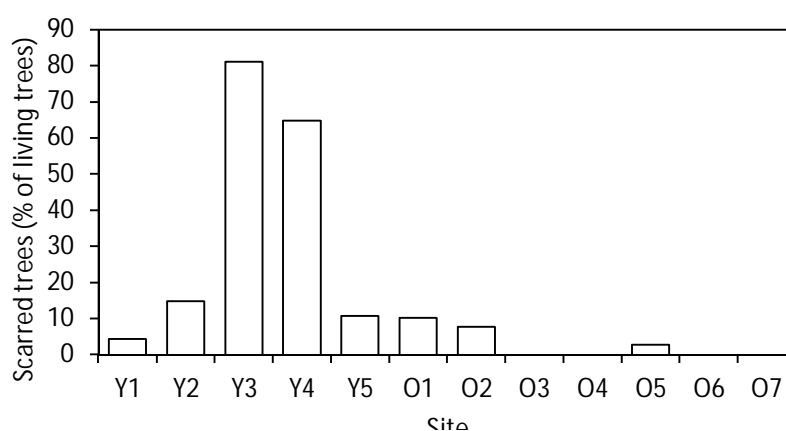


Fig. 6. The percentage of scarred trees out of remaining living trees per plot 8 years after fire. Y refers to the younger stand (30-35 years at time of burning) and O to the older age group (45 years).

thirds of the scars were less than 4 cm in width and the largest scar was 17 cm. Only 6 % of the scars were wider than 10 cm. 75% of scars were less than 40 cm in length. No correlation was found between the width of the fire scar and the size of the tree. For the scars above 2 metres, the average width was 14.2 cm

Opposite to the common understanding (McBride 1983), many of the scars did not form at the base of the tree. 43 % of the scars were located lower than 20 cm from the ground and the average height was 51 cm.

Again, large differences could be seen between the two stand age classes. Only 18 fire scars were found in the older stands, while 135 were found in the younger stands. Older trees also tended to have fewer scars than the younger ones. On average, the scars in the older trees were smaller in all dimensions than the scars in the younger ones (Table 4.).

The fire scars could also exhibit one or both of the following properties: 1) the edge of the scar is thin and craggy, and there is fresh (golden colour) or old (white colour) resin around it. This can be seen especially in pictures 2b, 2c and 2g. 2) A thickened edge has formed often in a vertical direction on one or both sides of the scar. The edge has a rope-like strand and there are still remains of old resin where it meets the scar. The edge is not blackened, indicating that it is new growth formed after the fire. This can be seen especially in picture 2f. The former is likely to be the first reaction of the tree to scarring, and in time a strand will develop, and grow over the scar.

Table 4. Amount of scarred trees and number of scars in each plot, and their average dimensions (cm) of scars below 2 metres. Figures in parentheses are including the scars above 2 m.

Plot	Number of scarred trees	Number of scars	Average width (cm)	Average length (cm)	Average height (cm)
Y1	6	10	3.3	22.5	38.3
Y2	24	43	3.5	22.7	86.6
Y3	13 (60)	22 (76)	6.4 (11.1)	79.5 (291.4)	30.9 (26.6)
Y4	17 (24)	35 (45)	5.6 (6.7)	38.9 (88.0)	63.1 (60.0)
Y5	9	18	4.2	22.8	67.2
Average (Y)	14 (25)	26 (38)	4.6 (5.8)	37.3 (89.5)	57.2 (55.7)
O1	9	14	3.4	27.0	45.6
O2	7	8	2.6	14.9	50.3
O5	2	2	4.0	8.5	19.0
Average (O)	6	8	3.4	16.8	38.3

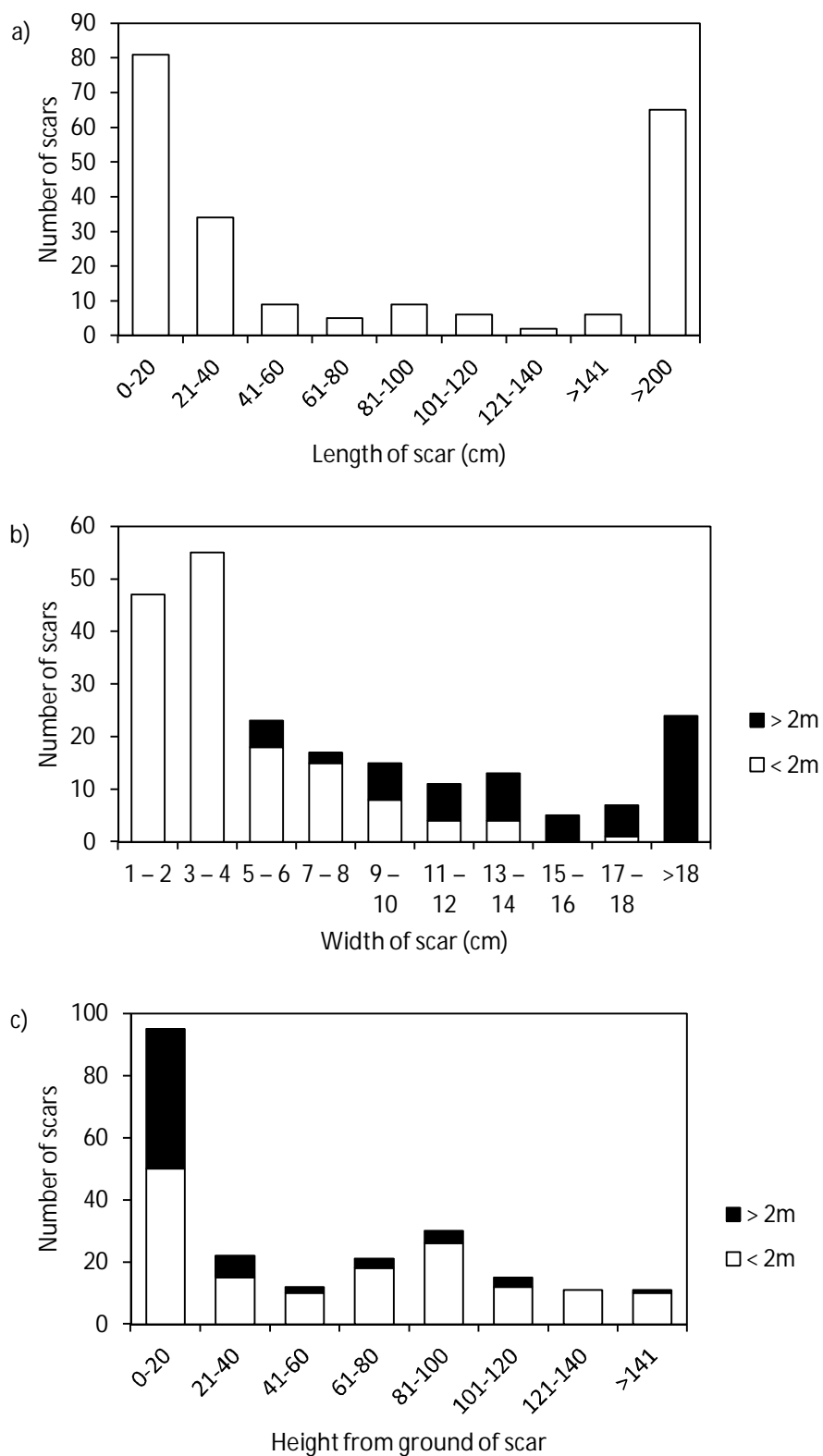
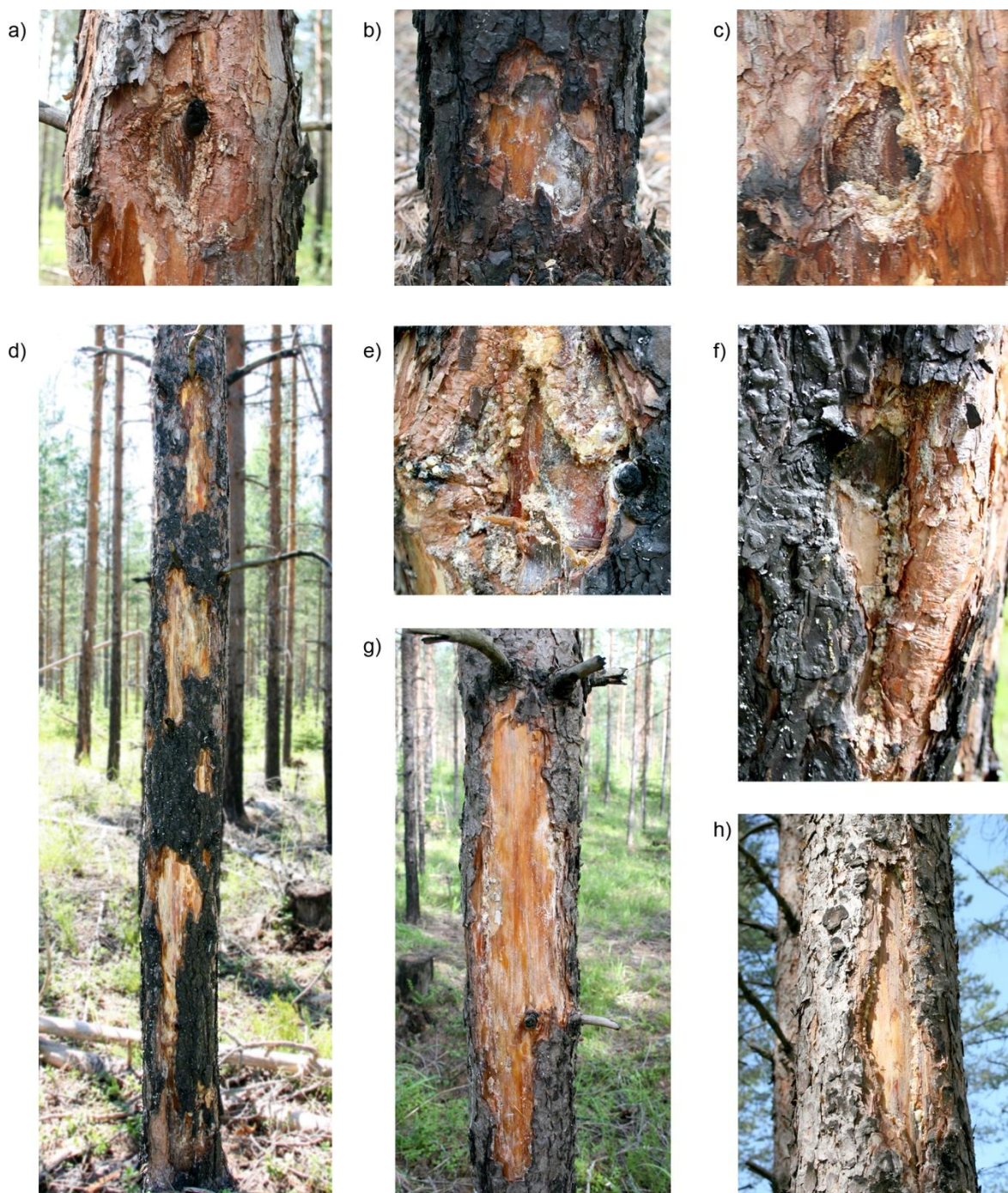


Fig. 7 a-c. The distribution of spatial dimensions of fire scars above and below two metres. a) Length distribution of fire scars. b) Width distribution of fire scars. c) Distribution of height from ground measured as height from ground to the lowest point of the scar.



Pictures 2. a-h. Examples of fire scars. a) Fire scar with clearly thickened edges and resin, formed underneath a branch (blackened branch stub). b) Scar of an irregular shape near the base of the tree. There is some resin, but the edges are not thickened. c) Typical small scar, 2 cm x 2 cm, with some resin on the sides and a branch stub on the right. Edges are not thickened. d) Three separate scars reaching up to 2.5 m. Some scars end underneath a branch. Some new growth can be seen at the base of the tree, on the left side (light coloured thickened edge). There is little resin. e) Scar with resin on the sides, and a thickened edge on the top left. There is a branch knot on both sides. f) Small fire scar with a clear rope-like thickened edge on the right. Clumps of resin can be seen and a branch stub on the left. g) Long scar with some resin but no sign of new growth (no thickened edges). The scar ends underneath a branch. h) Scar formed at the height of 2 metres. The bark is showing signs initiating new growth and there is resin along the edges.

Many fire scars seemed to form adjacent to the knots of the lower dried out branches. This was not recorded in a systematic manner during field measurements, but analysed later from photographs taken of each fire scar. Of all scars, 49% were adjacent to branch knots. The scars are most often underneath the branch knot, sometimes on the sides, but never on top. There seemed to be two types of scars adjacent to branches. There were small, round scars, where the scar seems to have formed because of the branch, perhaps due to flames lingering there. This can be seen in picture 2a. Or, there are scars that have formed some distance underneath or to the side of the knot, and the knot has stopped the advancement of the scar. This can be seen in picture 2d and 2g.

3.3. Regeneration

In the burnt plots, eight species of seedlings (< 5 cm in height) and saplings (> 5 cm) were found: Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), silver birch (*Betula pendula*), downy birch (*Betula pubescens*), trembling aspen (*Populus tremula*), gray alder (*Alnus incana*), European rowan (*Sorbus aucuparia*) and willows (*Salix* spp.). In control plots, juniper (*Juniperus communis*) was also found. There was great variation in the regeneration numbers between burnt plots, ranging from 1 667 to 21 333 stems ha⁻¹, and averaging 8 120. The number of saplings (> 5 cm) ranged from 0 to 12 333 stems ha⁻¹. The level of regeneration in control plots was overall lower, and the variation was smaller, from 2 303 to 7 647 stems ha⁻¹ (Fig. 8.), but there was no statistical significance between burnt and control plots ($p=0.25$, Kolmogorov-Smirnov test). In the burnt plots, 60% of all regeneration was seedlings, whereas the figure in control plots was 7%, and this difference was highly significant ($p<0.05$).

The total regeneration (number of stems of seedlings and saplings) between the old and young burnt plots were similar, but considerably more saplings were found in the younger stands and more seedlings found in the older stands (Fig. 9.). The same pattern could be found in the control plots, but the number of saplings was much higher, and the number of seedlings much lower. There was also a clear difference in species growing in older and

younger stands. Pine saplings and birches were much more common in the younger stands, whereas occurrence of pine seedlings and aspen were significantly higher in older ones (Fig. 9.).

The regeneration count was affected by the time of inventory. Four older stands were inventoried in July and three in October. The regeneration of both saplings and seedlings were significantly different. This should be kept in mind when interpreting the results.

The establishment of pine was poor. Small pine seedlings, less than 5 cm in height and that had germinated the same year, were ample in most of the burnt plots and almost completely absent from the control plots. However, established pine seedlings more than one year old were found only in four plots, and in significant numbers only in one plot. One of these plots was an older plot and the rest were younger stands. No significant relationship was found between mortality and regeneration in this study. However, germination and establishment were highest in plots Y3 and Y4, which had the highest mortality, most disturbed soil and most open canopy (personal observation). Plot O7 had an unusual amount of pine seedlings and saplings of deciduous trees, but these are probably annual stems.

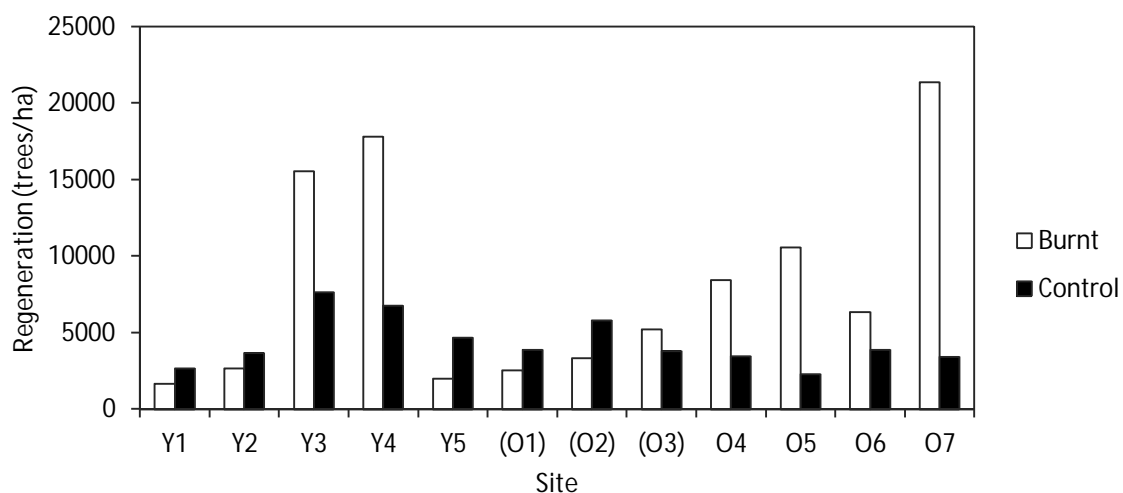


Fig. 8. The amount of seedlings ha⁻¹ in burnt and control plots. In plot codes, Y refers to the younger age group (30-35 years at time of burning) and O to the older age group (45 years at the time of burning). As it was evident that the time of inventory had an effect on regeneration results, plots O1, O2 and O3 are not reliable.

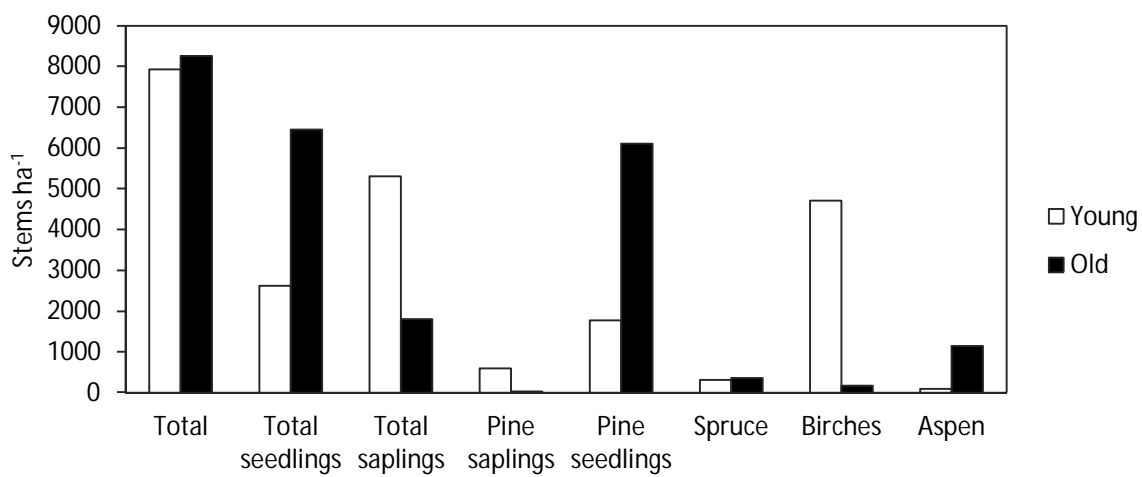


Fig.9. Total regeneration and regeneration by type and species in young and older stands.

4. DISCUSSION

4.1 Limitations of the study

This study reported the impact of fire on deadwood amounts on experimental plots one and eight years after the burning. According to several authors (Lynch, 1959, Wagener, 1961, Thies et al. 2005), most fire-induced mortality takes place within two to four years after the fire, after which no additional mortality caused by the fire can be detected. Annual average mortality rates for managed Scots pine stands have been observed in Switzerland at 0.4-0.5% of stand density (Dobbertin et al. 2004) and 0.24% of volume in Norway spruce stands in Finland (Hynynen et al. 2004).

This study was, to the author's knowledge, the first one to quantify post-fire delayed mortality in boreal Scots pine stands. However, the study does not shed light on the exact processes that lead to tree death, delayed or not, therefore it is difficult to make wide-reaching generalizations. On the other hand, quantifying delayed mortality is important information for effective restoration of this type of forest.

How is it possible to link observed tree death with the fire? Current models of tree mortality are probability functions based on binary empirical tree death data, where a tree is classed either dead (1) or alive (0), combined with physical tree features or damage. In order to fully comprehend the ecological consequences brought about by fire, the mechanistic and physiological processes that cause the critical amount of cell death, must be understood. Fire may not act as the primary disturbance agent, but as a weakening agent, and a set of other factors can contribute to mortality, such as natural self-thinning and competition, disease or fungal attack, pests (e.g. bark beetles), drought or physical damage (Franklin et al. 1987). Several studies indicate a significant increase in tree mortality by bark beetles after fire (Fettig et al. 2008, 2010). In a study by Ryan et al. (1988), 7 % of the dead Douglas firs did not have any measured damage to the crown or

bole indicating that the knowledge of mortality mechanisms, and thus modelling, is still lacking.

One shortcoming of the study is the limited scale. As noted by Ryan (2002), the use of fire for large-scale restoration purposes has not been quantified. Fires are variable in space and time, calling for a larger number of experimental plots. A small change in the intensity of the fire can greatly influence the ecological outcome (Ryan 2002). For a more comprehensive understanding on the use of fire for restoration purposes, a series of field experiments using fire of different intensities for forests of different ages, types and species is needed to be able to achieve restoration goals.

The comparison between the 2003 and 2010 dead wood volumes is not accurate, because the volume was previously calculated using Laasasenaho's volume equation by diameter and height (Sidoroff et al. 2007), as opposed to just diameter in this study.

From the twelve plots included in this study, two differed from all the others in their response to fire. They both had higher mortality, regeneration and fire scar formation than the others. The reasons for this were probably the initial stand structure, fuel load and the intensity of the prescribed fire. The two plots experienced highest flames (4.1 and 1.3 m), whereas flame height for other plots ranges between 0.5 and 1 m (Sidoroff et al. 2007).

4.2 Comparison with previous studies

4.2.1 Tree mortality

In general, the mortality rates observed in this study were lower than in previous studies. In this study, average mortality of Scots pine was 18.2 % eight years after a low-intensity surface fire. In a study by Kolström and Kellomäki (1993), Scots pine mortality after a surface fire was 82.2 % in two unmanaged stands, of which one was a 90-year-old mixed stand and the second a 40-year-old pine stand. Linder et al. (1998), observed a 90 % mortality rate in pines with diameter smaller than 10 cm in a multi-layered old-growth

Scots pine forest, whereas in this study the figure was lower, 70 %. This was probably due to the multi-layered structure of the forest, where understorey vegetation acted as ladder fuel resulting in higher mortality. For larger pines, mortality decreased with increasing diameter from 14 % in the 10-15 cm diameter class to 1.4% in the 40-50 cm class (Linder et al. 1998). In this study, mortality in the 10-15 cm diameter class was slightly higher, 22% one year after fire and 34 % eight years after fire.

As mentioned before, delayed mortality has not been widely studied. In this study, post-fire mortality of Scots pine one year after the fire was 11.2 % and 18.2 % eight year after fire. Research by Ryan et al. (1988), found that about 50% of Douglas-fir (*Pseudotsuga menziesii*) had died 8 years after a low-intensity surface fire in Montana, USA. They estimated that 42 % had died in the first two years, and 8 % in the remaining 6 years.

In this study, a tree was defined dead, if no green needles were found on the tree. This is a common definition in tree mortality studies (e.g. Linder et al. 1998, Hély et al. 2003, Sidoroff et al. 2007). However, Thies et al. (2005) found several ponderosa pines that had been classed *dead* immediately after a fire in Oregon, USA, but started re-growing needles at the end of the growing season.

Due to the heterogenous microtopography of the forest floor, tree mortality can be highly variable within a stand. Even within a burnt area, unburnt patches can constitute up to 50-60% of the forest floor (Baker and Ehle 2001, Bergeron et al. 2002). In this study, plots were established on relatively even ground, so the effect of site heterogeneity was minimised, but even so, patches that had escaped fire completely could be found. The impact of a fire on a random area of managed forest, may vary even more than in this study, due to larger variation in the microtopography.

4.2.2 Fire scar formation

There are very few studies documenting the formation, quantity and other attributes of fire scars after a forest fire. This topic is important because establishing forest fire

histories is largely based on dating of fire scars. However, whether and how fire scars form in a certain fire is under obscurity. While the fact that some fires may not leave fire scars at all is acknowledged (e.g. Baker and Ehle 2001), it is uncertain to what extent this happens. In this study, scarring ranged from 0 to 30 % of trees per plot indicating high variation between sites. Studies on the fire scar formation in ponderosa pine have recorded scarring rates of 9% (Lachmund 1923), 20% (Morris and Mowat 1958) and 24 % (Lentile et al. 2005) after low-intensity surface fire. In this study, fire scars were in general small, averaging 4.4 cm in width and 34.8 cm vertically. There are no studies on fire scar dimensions that could be compared to this study. Fire scars also did not necessarily form at the base of the tree, as is generally thought. The shape of scars was highly variable.

There are two main reasons why a fire may not leave a scar (Baker and Ehle 2001). Firstly, the trees can escape the flames completely. Secondly, despite the fire reaching the tree, the intensity may be too low to cause cambial damage, due to low fuel loads, high fuel moisture content, shifting winds or sufficiently thick bark on the trees (Baker and Ehle 2001).

On some trees, the fire seemed to have almost completely girdled the tree. Especially pines with many fire scars or scars above 2 metres had a great proportion of their stem circumference damaged, yet the trees were still alive, and sometimes not even weakened. However, even when completely girdled, it can take several years for a tree to die, and if any connection is left between the roots and the crown, it may take even longer.

4.2.3 Tree regeneration

Post-fire tree regeneration was found to be poor overall, which is not surprising considering the low tree mortality and that plots were established in young, dense commercial stands. It is pointed out in Simard et al. (2005) that prescribed fires may not be enough to reduce the organic layer significantly to enhance regeneration. Some areas of the boreal forest accumulate significant amounts of organic matter. Forest productivity

has been observed to be negatively related to organic soil depth, which in turn is affected by the time since fire (Greene et al. 2007). Following this logic it has been argued that exclusion of fires decreases forest productivity in the long run (Simard et al. 2005). According to Kuuluvainen and Pukkala (1989), the proximity of living trees, despite being a seed source, is unfavourable to Scots pine seedling growth. On the other hand, the presence of dead trees is suggested to have a favourable effect on seedling establishment and growth (Engelmark 1993, Vanha-Majamaa et al. 1996). This is due to the reduced water and nutrient uptake as well as the more stable microclimatic conditions in the shade of dead trees. These patterns can be seen in the results of this study, as regeneration was greatest in the two plots with highest mortality and low in all other plots, where most of the trees were still alive.

The effect of germination substrate is of great importance. Research by Johnstone and Chapin (2006) on the regeneration of three boreal North American conifers indicates that organic layer thickness greater than 2.5 cm reduces significantly their establishment. The thickness of the humus layer was not measured in this study, but based on personal observation, it is likely to have been greater than 2.5 cm. Oleskog and Sahlén (2000) found that Scots pine seeds did not germinate on any substrate, when they were not irrigated. Once irrigation was started, germination occurred on all seedbeds, but to a lower extent on humus than on mineral soil.

According to some studies (e.g. Yli-Vakkuri 1961, Johnstone et al. 2004, Charron and Greene 2002), seedling establishment is low immediately after fire, but improves after 3-5 years. However, it is also reported in the same studies that after the peak, net recruitment declines to zero. In this study, even after 8 years, the occurrence of seedlings and saplings was low in all but two plots. In the two plots with significant regeneration of pine and spruce, the oldest saplings were 7 years old, indicating that regeneration had occurred since the first year after fire.

Seedling germination, establishment and growth varies significantly from year to year (Vanha-Majamaa et al. 1996), and seedling mortality rates are often high. Seedlings are vulnerable to climatic conditions, especially drought. The large number of seedlings, but

their poor establishment rates, suggests an adequate seed source is available, but that mortality is almost 100%. Mortality may be due to the competition with the living trees as suggested above, or due to desiccation from a thick humus layer that dries easily. Also, in the 8 years following the fire, 5 have been exceptionally warm and dry (Finnish Meteorological Institute 2009).

4.3 Implications

It is generally agreed that fire is an important driver of the boreal ecosystems and that fire is important in the restoration natural forest structures and processes (Zackrisson 1977, Angelstam 1998, Granström 2001, Kuuluvainen et al. 2002, Mielikäinen and Hynynen 2003, Kuuluvainen et al. 2005). It has also been noted that light fires may have very little impact on the ecosystems, while severe fires may be too destructive for restoration purposes (Vanha-Majamaa et al. 2007). Medium severity fires are estimated to best bring about the desired restoration effects (Petraitis et al. 1989, Vanha-Majamaa et al. 2007), although these of course depend on the restoration goals. This study supports the claim somewhat, but also highlights the impact stand density, fuel conditions, tree age and tree diameter have on the outcome.

The age difference between the two stand age classes in this study was only 10-15 years and the difference in average diameter about 5 cm. However, the younger stands (30 to 35 years at burning) were dense and had not yet undergone the first thinning, increasing the available fuel. The older stands (45 years at burning) had been thinned. Research by Tanskanen (2007) on some of the same and some additional plots in the area indicated that the younger stands had higher fire intensity and fire spread rates, and experienced more torching and crowning than the older stands. In addition, it should be noted that the fuel load of commercial forests is low and especially lacking in medium and heavy fuels (Tanskanen 2007), which would prolong the residence time of flaming combustion and increase the severity (Ryan 2002).

Depending on the restoration aim, the rate of dead wood production could be high enough in the younger stands for restoration purposes, but not so in the older ones. This has also been previously noted by Tanskanen (2007). Therefore, other methods of dead wood creation, such as using fire of higher intensity, girdling or felling trees directly, should be preferred in stands of a structure similar to the studied older stands. The combination of partial cutting, down wood retention and prescribed burning has been used with some preliminary success in a spruce-dominated stand, where results indicated that the severity of the burn can be partly controlled by the amount of downed wood (Lilja et al. 2005, Vanha-Majamaa et al. 2007). Considering the number of dying or weakened trees observed in the younger stands, the input of deadwood is likely to continue. In the older stands, no more input is expected.

The study highlights the need for quantifiable targets in restoration, and that the aims need to focus on the outcome rather than the operation. Targets should be determined as, for example, amounts of dead wood produced or severity of disturbance on soils, rather than hectares burned. In thinned commercial stands above a certain age, prescribed fire alone would not be enough to reach the target. However, a method of first increasing the fuel load by felling trees before burning, as has been done in the EVO experiment with Norway spruce (Vanha-Majamaa et al. 2007), could help bring about the desired outcome.

Many protected areas, especially in the South of Finland, have a history of human influence and few represent the natural state of the forest (Kuuluvainen et al. 2005). The slash-and-burn culture increased fire occurrence and current fire suppression has reduced it, altering the tree composition and natural processes in each period. Simply protecting an area will not be sufficient for biodiversity conservation due to past utilization. Kuuluvainen et al. (2002) listed the important features and processes that need to be restored in boreal forests, including dead wood, early successional stages and burnt features. Restoration efforts by fire should be able to create those features in order for it to be successful and efficient.

The width and height of fire scars both have a different, but important role in the ecology of the tree. The width of the scar determines the severity of the damage. The wider the scar, the more cambium is destroyed and the greater the implication on water and other resource transportation within the tree. However, when fully healed, a new vascular cambium will form in the callus (McBride 1983). The vertical length of the scar affects fire dating. When obtaining samples of the tree to find fire scars, the likelihood of finding a fire scar diminishes as scars become vertically shorter.

Traditionally, fire histories are determined based on samples taken from visible fire scars or by taking a cross-section of the tree at its base (McBride 1983). It has been acknowledged that low-intensity fires do not necessarily leave fire scars, and thus results based on fire scar dating may be inaccurate and underestimate the occurrence of low-intensity fires. There is evidence that above a certain diameter and bark thickness, scars do not form (Guyette and Stambaugh 2004). In natural forests, the probability of all trees being over that critical diameter is unlikely. However, quantified research on the extent to which low-intensity fires leave a record of themselves, has not previously been carried out. On four out of twelve burned plots, no fire scars were formed at all. In the rest of the plots, the number of fire scars was low, they were fairly small in width and will be overgrown in a short time. The large scars over 2 metres are likely to lead to substantial weakening of the tree. As no healing was observed, it is possible pathogens will kill them in the future. In addition, fire scars tended not to form at the base of the tree, as is often claimed. Therefore, even if a tree with fire scars was sampled, cross-sections would have to be taken at short intervals along the stem, and to as high as two metres in order to find the scars.

Regeneration was overall poor, except on two plots, where tree mortality was also highest. The number of seedlings was high, especially in some plots, indicating that there is a viable seed source available, but seedlings did not make past the first year. The reasons for the poor establishment rates can only be guessed at. The humus layer did not burn well, and the remaining layer is still thick, which leads to the drying of the regeneration substrate. Interception of precipitation by the dense canopy also plays a role. Since 2003, many of the summers have been abnormally dry and hot (Finnish

Meteorological Institute 2009), and drying out is one of the most important reasons for seedling death (Little et al. 1958). The mineral soil, the best substrate for Scots pine seedlings, was not exposed by the fire in any plots. In two plots, the soil had been slightly disturbed by the number of fallen trees.

5. CONCLUSION

A low-intensity prescribed burning in young managed Scots pine stands in southern Finland did create a continuum of dead wood input to the ecosystem, but the level of mortality was very low in general. One main observation of this study was that mortality among trees of larger diameter seemed to increase with time, whereas many small trees had died immediately after fire. However, the success of the burning was highly dependent on stand characteristics, which must be considered when planning restoration action. The pines in managed, thinned stands of 45 years at burning were highly resistant to fire, and other methods of dead wood production should be considered in those stands. Low-intensity fires did not necessarily leave any fire scars, especially in the older stands, and this should be kept in mind when establishing fire histories based only on fire scar dating. Post-fire regeneration was poor if the fire is not severe enough. To ensure the initiation of the regeneration process, a certain level of canopy opening and soil disturbance should be achieved. In addition to aiming for a certain area of burnt land, restoration efforts should also establish quantitative goals for the outcome of the burning.

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