Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Ecology
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Historic range of variability in the fire regime of a Fennoscandian boreal forest - the Trillemarka-Rollagsfjell Nature Reserve

Historisk variasjon i brannregimet i en Fennoskandinavisk boreal barskog - Trillemarka-Rollagsfjell naturreservat

Ylva-li Blanck

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Contents

Preface

This thesis is submitted in partial fulfilment of the degree Doctor Scientiarum at the Norwegian University of Life Sciences, Department of Ecology and Natural Resource Management. The Miljø 2015 Program at the Research Council of Norway has financed the majority of the work (grant no. 184059-LAND). I have received additional funding from the Ministry of Agriculture and Food and the Norwegian Forest and Landscape Institute.

It takes more than one person to complete a thesis, and several people have been important in the process up to completion, a process that lasted a bit longer than planned. First of all, I am most thankful to my supervisors at the Norwegian Forest and Landscape Institute, Jørund Rolstad and Ken Olaf Storaunet, for patiently helping me and encouraging me through practical and scientific challenges. Thanks for interesting and inspiring discussions and for teaching me into the mysteries of ecology in general and of forest fire in particular.

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Big thanks also to Isabella Kasin and Mikael Ohlson for good cooperation, discussions and nice field trips together to Trillemarka. Also thanks to colleagues and friends at both Norwegian Forest and Landscape Institute and at INA for inspiring discussions. Thanks also to all of you organising and participating in field-weeks, courses and conferences on dendrochronological and forest ecological issues during these years. I will never forget the most exciting trip in my life to Nepal!

I would also like to thank Ann-Mari Fransson, for deepening my interest in vegetation ecology. Thanks for believing in my abilities and for encouraging me to apply for a PhD-education.

My warmest gratitude goes to mother for always being there for me and prepared to help and all my love to my two wonderful children. Finally, but most importantly, I am indepted to my dearly beloved Eric for your patience, help and always encouraging words when work with the thesis have been time consuming and tough.

Abstract

Fire is the principal natural disturbance process in the boreal forest. Thus, knowledge about the historical fire regime is essential for understanding present day forest ecosystems, which in turn is important for implementing ecosystem management. In this thesis, I document spatial and temporal aspects of forest fire history (*i*) to better understand the historic range of variability (*ii*) to improve sampling procedures and evaluate methodological issues regarding how fire scar records should be interpreted and applied in retrospective studies, and (*iii*) to see to what extent human activity, climate and vegetation change has influenced the fire history. The fire regime, characterised by the numbers, frequency, rotation, severity, seasonality, as well as spatial extent of fires occurring in a given area, were compared with historical climate proxies, vegetation maps, and historical written sources. The research has been carried out in the southern part of Trillemarka-Rollagsfjell Nature Reserve in south-central Norway, where 650 samples with 1391 fire scars were collected and successfully cross-dated from stumps, snags and living trees of Scots pine (*Pinus sylvestris* L.). The work is primarily based on dendrochronological methods applied to fire scars (Paper I, II and III). In addition, the fire-scar datings were combined with datings of charcoal layers in peat columns to reveal fire history over the Holocene (Paper IV).

In the first and second paper (I and II), cross-dated fire chronologies spanning 700 years, were developed to describe the fire history at two different spatial scales, one detailed small scale area (3.6 km^2) and one large scale area (74 km^2) encompassing the small one. The results revealed patterns consistent with a predominantly natural fire regime up till AD 1625, followed by periods of strong anthropogenic impact that increased fire frequency in the 1600-1700s, and diminishing fire impact during the last two centuries. This was documented by (*i*) an abrupt shift towards more frequent and smaller fires from 1625 and a cease of fire after 1800, (*ii*) a sudden increase in early-season fires from 1625, (*iii*) a marked shift in fire return intervals and hazard of burning post 1625, (*iv*) a decreasing fire severity, (*v*) a positive relationship between summer temperature and annual burnt area pre-1625, whereas this was far less pronounced post-1625, and finally, (*vi*) written historical sources that support the results of anthropogenic forest fires and slash-and-burn cultivation expanding with the increasing population from the late 1500s and subsequently diminished due to increasing timber values during 1700s and 1800s. I also found that Norway spruce (*Picea abies* L. Karst.) forests burnt less often (rotation 250-1000 years) than pine forests (150-300 years).

Thus, it is clear that fire has been a dominating disturbance factor prior to ca. 1800, both natural and man-made. It is also clear that the last 200-year fire-free period is unprecedented during the last 700 years.

Little is known about the growth responses of Scots pine following fire. Therefore, I used the fire-scar data to quantify changes in tree growth after historical forest fires in the third study (III). Basal area increments (BAI) 10 years pre-, 5 years post-, and 11-20 years post-fire were calculated to distinguish between short-, medium-, and long-term growth effects. The results showed that recurring fires maintained high tree growth in remnant Scots pines, most probably due to a reduction in tree density and thus decreased competition.

In the fourth study (IV), I combined the fire-scar data with charcoal data from peat deposits to reveal the fire history further back in time. The dendrochronological dating revealed the fire history over the last 600 years, and AMS radiocarbon dating and charcoal records of 20 peat columns from four peatlands were used to elucidate the fire history over the Holocene. The results revealed that recent fires showed up to a low degree in the peat columns. I suggest several mechanisms that may explain this lack of conformity; (*i*) distances to the mire edges have been too long at the time of fire, (*ii*) different peat accumulation rates at the sites have caused imprecise datings, *(iii*) many of the historical fires have been of low severity that do not produce macroscopic charcoal record in the peat. Finally, the correspondence may have improved if we had included smaller fractions of the macroscopic charcoal record in the analysis. Nonetheless, I conclude that the two methods complement each other.

The results of this thesis document the importance of fire in the development of the forest landscape in Trillemarka-Rollagsfjell Nature Reserve during 700 years, and relate the large changes in fire regime to human activity. Hopefully, this knowledge contributes to a better understanding of the forest ecosystem variability over time, and to an ecological basis for managing both protected nature reserves and commercially utilised forests in the future.

Keywords: Boreal forest, dendrochronology, fire regime, forest fires, *Pinus sylvestris*, fire history, historical variability

Sammendrag

Skogbrann er den viktigste naturlige økologiske forstyrrelsesprosessen i den boreale barskogen. Kunnskap om det historiske brannregimet er derfor avgjørende for å forstå dagens skogøkosystem, som i sin tur er viktig for å kunne gjennomføre en bærekraftig skogforvaltning. I denne avhandlingen har jeg studert historiske skogbranner i tid og rom (*i*) for å dokumentere den historiske variasjonen i brannregimet, (*ii*) for å vurdere metodiske tilnærmingsmåter for hvordan brannlyrer i trær kan tolkes og anvendes i slike studier, og (*iii*) for å se i hvilken grad menneskelig aktivitet og klima- og vegetasjonsendringer har påvirket brannhistorikken. Begrepet brannregime innbefatter bl.a. antall branner, brannstørrelse, deres hyppighet, omløpstid, intensitet, brannsesong, samt deres romlige fordeling i landskapet. Disse egenskapene er sammenholdt med historiske klimadata, vegetasjonskart og historiske skriftlige kilder. Undersøkelsene er gjort i den søndre delen av Trillemarka-Rollagsfjell naturreservat mellom Sigdal og Numedal i Buskerud fylke i perioden 2006-2010. Her er tilsammen 650 prøver med 1391 brannlyrer samlet inn og datert fra stubber, gadd og levende furutrær (*Pinus sylvestris* L.) for dendrokronologisk datering av branntidspunkt og utbredelse i terrenget (artikkel I, II og III). I artikkel IV er dateringene fra brannlyrene sammenholdt med trekull-dateringer fra torvprofiler for å se hvordan de sammenfaller, og for å se på brannhistorikken i et lengre tidsperspektiv.

I artikkel I og II beskrives brannhistorikken gjennom daterte brannkronologier de siste 700 år på to romlige skalaer, ett småskala-område (Heimseteråsen, 3,6 km^2) og ett storskala område (74 km^2) som omslutter småskala-området. Resultatene viser et mønster med et overveiende naturlig brannregime fra 1300 til 1625, etterfulgt av perioder med sterk menneskelig påvirkning som økte brannhyppigheten gjennom 1600- og 1700-tallet men som reduserte den til nesten fraværende etter 1800. Dette er dokumentert gjennom (*i*) en dramatisk økning i antall små branner fra 1625 og et nesten opphør av branner etter 1800, (*ii*) et markant innslag av branner tidlig på sommeren fra 1625, (*iii*) et klart skifte fra lengre til kortere brannintervaller etter 1625, (*iv*) en avtagende brannintensitet over tid, (*v*) en klar sammenheng mellom høye sommertemperaturer og årlig brent areal før 1625, men i mindre grad etter 1625, og til slutt (*vi*) skriftlige kilder som beskriver svedjebruk og brenning for bedring av beiteforholdene som følge av den økende befolkningen fra slutten av 1500-tallet, men som avtok sterkt igjen på grunn av økt tømmerverdi gjennom 1700- og 1800-tallet. Videre har granskogen (*Picea abies* L. Karst.) brent mindre (brannrotasjonstid 250-1000 år) enn

furuskogen (rotasjonstid 150-300 år). Dette viser at skogbranner har vært den dominerende forstyrrelsesfaktoren fram til 1800-tallet, både gjennom naturlige og menneskeskapte branner. Det er også klart at den siste 200 års nesten brannfrie perioden er unik de siste 700 år.

Få studier har sett på tilvekstrespons hos furu etter brann. I artikkel III er data fra brannkronologiene brukt til å kvantifisere endringene i trærnes vekst etter de historiske brannene. Grunnflatetilvekst (BAI) 10 år før, 5 år etter, og 11-20 år etter brann ble beregnet for å se på mulige tilveksteffekter på kort og lang sikt. Resultatene viser at furutrærne opprettholdt en høy tilvekst ved gjentatte branner, mest sannsynlig på grunn av mindre konkurranse fra et åpent tresjikt.

I den siste artikkelen (IV) kombineres data fra brannkronologiene med data fra trekull i torvprofiler for å se på brannhistorikken i et lengre tidsperspektiv. For å belyse brannhistorikken i Holocen periode sammenholdes brannkronologiene med AMS 14C dateringer av kull-lag i 20 torvprøver fra fire myrkanter i småskala-området ved Heimseteråsen. Resultatene viser, med noen unntak (1499- og 1575-brannene), at nyere historiske branner etter 1300-tallet bare i liten grad viser seg som kull-lag i torvprofilene. Det er sannsynligvis flere grunner til denne dårlige overensstemmelsen: (*i*) avstanden til myrkanten kan ha vært for lang ved branntidspunktet, (*ii*) variasjon i akkumuleringen av torv kan ha bidratt til upresise dateringer, og (*iii*) at mange av de seneste historiske brannene har hatt for lav intensitet til at de har brent myrvegetasjonen. Kanskje ville det vært bedre samsvar om mindre trekullpartikler hadde blitt analysert. Likevel konkluderer jeg med at disse to metodene kompletterer hverandre i brannhistorikkstudier.

Resultatene fra denne avhandlingen viser hvor viktig brann har vært for utviklingen av skoglandskapet i Trillemarka-Rollagsfjell naturreservat de siste 700 årene, og hvor store endringer som har skjedd som følge av menneskelig aktivitet. Forhåpentligvis bidrar resultatene til en større forståelse av hvordan skogtilstanden har endret seg over tid, og til en kunnskapsbasert forvaltning både av naturreservater og kommersielt drevne skoger.

List of terms and nomenclature for plants

Fire regime: A collective term describing the spatial pattern, temporal frequency, and behavioural characteristics of fires confined to a certain spatially defined area and temporally defined time period.

Fire frequency: A general term for the number of fires occurring in a given time period in a given area.

Annual burnt area: The area burnt each year, typically reported as "mean percentage annual burnt" in a spatially defined area and temporally defined period.

Fire rotation period (fire cycle): The time it takes to burn an area equivalent to the study area. The entire area does not burn during this period; some sites burn several times and others not at all. This is the inverse of percentage annual burnt area.

Fire (return) interval: The number of years between successive fires at a given site (point fire interval) or a well-defined area (composite fire interval). Often said to be "site-specific", as opposed to recurrence intervals that are "size-specific" and related to fires of certain sizes.

- **Scar-based fire interval:** Time between successive fires as recorded by scars in single wooden samples.

- **Map-based fire interval:** Time between successive fires as determined from spatially overlapping burnt areas delineated on a map.

- **Mean fire (return) interval (MFI):** Average of all fire return intervals recorded at a site or a well-defined area.

Cumulative survival function: The proportion of freshly burnt area remaining unburnt over time, calculated from the distribution of the fire return intervals.

Hazard of burning: The yearly probability of a new fire occurring at a site with increasing time since the last fire, calculated as the instantaneous mortality from the cumulative survival function.

Fire recurrence interval: The average time interval between occurrences of a fire of a given or greater size within a defined spatial area. It is the inverse of the probability that a fire of a given size will be equalled or exceeded in any given year. Said to be “size-specific” as opposed to fire return intervals that are “site-specific”.

Fire severity: The severity by which a fire burns a forest stand commonly categorised in 3 classes:

- **Low-severity fire**: Fires that burn only the lowest vegetation layer.
- **Mixed/Moderate-severity fire:** The severity varies between nonlethal understory and lethal stand-replacing fire in a mosaic-like pattern.
- **High-severity fire**: A fire that kills most of the dominant above ground vegetation and substantially changes the vegetation structure.

Scientific names of vascular plants follow Lid and Lid (2005).

List of papers

The following four papers comprise the basis of this PhD thesis and are referred to in the text by their Roman numerals:

(I) Blanck, Y., Rolstad, J., Storaunet, K.O. Historic range of variability in the fire regime of a Fennoscandian boreal forest – a 700-year dendroecological reconstruction from Trillemarka Rollagsfjell Nature Reserve in southcentral Norway. Manuscript.

(II) Storaunet, K.O., Rolstad, J., Toeneiet, M., Blanck, Y. 2013. Strong anthropogenic signals in historic forest fire regime: a detailed spatiotemporal case study from south-central Norway. Canadian Journal of Forest Research 43(9): 836-845.

(III) Blanck, Y., Rolstad, J., Storaunet, K.O. 2013. Low- to moderate-severity historical fires promoted high tree growth in a boreal Scots pine forest of Norway. Scandinavian Journal of Forest Research 28(2): 126-135.

(IV) Kasin, I., Blanck, Y., Storaunet, K. O., Rolstad, J., Ohlson, M. 2013. The charcoal record in peat and mineral soil across a boreal landscape and possible linkages to climate change and recent fire history. Holocene 23(7): 1052-1065.

The published papers are printed with kind permissions from the publishers:
Paper II: NRC Research Press, Canadian Science Publishing
Paper III: Taylor & Francis Group
Paper IV: SAGE Publication

Table 1: *Table of contributions.*

Paper	I	II	III	IV
Idea and planning	JR, KOS	JR, KOS	JR, KOS	MO, IK, (JR, KOS)
Fieldwork	YB, KOS, JR	MT, KOS, JR	MT, KOS, JR, (YB)	IK, YB
Lab work	YB, KOS, (JR)	MT, KOS, (JR, YB)	MT, YB, KOS	IK, (YB)
Analyses	JR, YB, KOS	KOS, JR	YB, JR, KOS	IK, MO
Discussions	YB, JR, KOS	KOS, JR, MT, YB	YB, JR, KOS	IK, MO, JR, KOS, YB
Manuscript preparation	YB, JR, KOS	KOS, JR, MT, (YB)	YB, JR, KOS	IK, (MO, JR, KOS, YB)

YB: Ylva-li Blanck, KOS: Ken Olaf Storaunet, JR: Jørund Rolstad, MT: Målfrid Toeneiet, IK: Isabella Kasin, MO: Mikael Ohlson

Introduction

Fire is the most important natural disturbance factor in the boreal coniferous forest (Heinselman 1973, Zackrisson 1977, Bergeron et al. 2002). Fire increases stand heterogeneity and affect succession by killing trees and other organisms, thereby releasing space and nutrients (Rowe and Scotter 1973, Esseen et al. 1997). Furthermore, fire enhances forest regeneration and creates structural elements such as charred and decaying wood that are important for biodiversity (Esseen et al. 1997, Granström 2001, Bergeron et al. 2002). Thus, knowledge about historical fires, causes of fires, and the processes controlling the natural development of the vegetation after a forest fire, is important to understand the function of the natural forest under present conditions and may serve as a guideline for future management (Swetnam et al. 1999, Gillson and Willis 2004, Scheller et al. 2005, Bergeron et al. 2006, Willis et al. 2007).

The pattern in which fires occurs in an area, known as the fire regime, influences the vegetation mosaic within a forest landscape. Knowledge about historical fire regimes can elucidate the historical variation, how the condition of today differs from historical conditions and how the forest ecosystem has varied through time, i.e. its historic range of variability, HRV (Morgan et al. 1994). Understanding the historical fire regime is necessary for those managers who want to restore an ecosystem similar to natural processes and conditions (Fulé et al. 1997). This often leads to the question of how to define “natural” (see e.g. Gillson and Willis 2004, Willis and Birks 2006). Since there is a suite of conditions that could be considered natural, the terms “reference conditions” and “range of natural variability” are often used to describe what is natural (Fulé et al. 1997, Moore et al. 1999). This description often includes the structure, composition and functions of an ecosystem and must be defined for a specific region and a period of time (Stephenson 1999). The determination of HRV in North American fire studies has mainly dealt with land-use changes due to the pre-EuroAmerican settlement (Nonaka and Spies 2005, Sherriff and Veblen 2007). In Fennoscandia however, studies have shown strong human impact on fire frequencies and forest structures during several centuries (Segerström et al. 1994, Niklasson and Granström 2000, Groven and Niklasson 2005, Molinari et al. 2005, Wallenius 2011).

A fire regime generally characterises the spatial and temporal patterns of fire and the concept consists of many variables such as seasonal timing, frequency, cycle, fire interval, severity as well as spatial extent of fires occurring in a given area (Agee 1990, 1993, Weber and Flannigan 1997). Variations in frequency and severity of fire have greatly affected the forest structure and species composition in the boreal forest (Bergeron et al. 2002, Ryan 2002). For example, it has been shown that more frequent forest fires favours *Pinus sylvestris* on the expense of *Picea abies* (Lehtonen 1998, Pitkänen et al. 1999), while the opposite is the case when fire is lacking or supressed by man (Linder et al. 1997). Variations in fire frequency and severity may also affect post-fire tree growth in surviving trees in many different ways. Therefore, both increases (Wyant et al. 1983, Reinhardt and Ryan 1988), decreases (Wooldridge and Weaver 1965, Johansen and Wade 1987), and no change at all (Waldrop and Van Lear 1984, Hunt and Simpson 1985) in tree growth following fire have been reported.

A fire regime with stand-replacing fires creates a landscape with a mosaic of forests with different ages (Johnson et al. 1995) with the proportion of old forests depending on the fire frequency and the spatial patterning of the fire. Assuming that the probability of burning is independent of stand age, the age class distribution will follow a negative exponential distribution, or a Weibull function, suggesting that the area of forest age-classes decreases exponentially with age (Van Wagner 1978). However, since large Scots pine trees often survive low-to moderate severity fires, is it unlikely that Fennoscandian pine-dominated forest age distributions have a form of a negative exponential function, and the forest age distribution would instead peak in older age classes (Pennanen 2002). Fire regimes of boreal North America are often characterised by large stand-replacing fires (Johnson 1992), whereas Fennoscandian forest fires for the most part seem to have been low- to moderately severe (Zackrisson 1977, Engelmark et al. 1994). Presence of several fire-scarred live trees within multi-aged and multi-layered forest stands further indicates that Scots pine commonly survives fire events in Fennoscandia (Groven and Niklasson 2005, Hellberg et al. 2004, Wallenius et al. 2002).

Even though there are large differences in severity between the continents, historical fire cycles have been relatively similar (Heinselman 1973, Zackrisson 1977) and average fire return intervals have shown to vary from some decades to about one hundred years between 1500-1850 in Europe as well as North America (Heinselman 1973, Zackrisson 1977, Weir et al. 2000). However, fires decreased rather abruptly in both Fennoscandia during the 1800s (Lehtonen and Kolström 2000) and in the coniferous forests of North America in the beginning of the 1900s (Tande 1979, Bergeron et al. 2001). This has resulted in estimated fire cycles of several thousands of years in Fennoscandia (Zackrisson 1977, Niklasson and Granström 2000) and several hundreds or thousands of years in most North American coniferous forests (Heinselman 1973, Weir et al. 2000, Bergeron et al. 2001). These abrupt decreases in forest fires have been explained by effective fire suppression (Heinselman 1973, Zackrisson 1977), global climatic change (Bergeron 1991, Flannigan et al. 1998) and by a decrease in anthropogenically caused fires combined with more careful use of fire due to increased timber value (Wallenius et al. 2004). While increased fire suppression locally may have reduced the number of fires, the abrupt decrease in human caused fires appears to be the more general explanation for the decline of fires in Fennoscandia (Wallenius 2011).

Knowledge about past variation in fire frequency can be inferred from analysis of tree rings, fire scars, and charcoal records from peat and soil. Tree rings represent a valuable, long-term record of tree growth for many forest ecosystems. These records are capable of providing not only reconstructions of prior climates (Fritts 1976), but also ecological reconstructions of forest history (Frelich 2002). However, whereas tree-ring information gives detailed reconstructions of fire events such as fire years, season, frequencies and location during shorter time periods (about 300-800 years) (Zackrisson 1977, Fulé et al. 1997, Niklasson and Granström 2000, Groven and Niklasson 2005, Wallenius et al. 2007), charcoal records from sediments and peat can be used to reconstruct much longer fire histories (throughout millennia) (Ohlson et al. 2013), although with lower temporal and spatial precision (Olsson et al. 2010). This thesis combines dendrochronology and charcoal data to delineate the spatial and temporal pattern of historical forest fires. Possible drivers and determinants influencing the fire regime, such as climate, landscape characteristics and anthropogenic activity are further discussed.

Objectives

The specific objectives of the work behind this thesis were:

(1) To reconstruct and describe the historic fire regime at two different spatial scales over the last 700 years, and to see to what extent climate, landscape characteristics and human activity have influenced the fire regime (Paper I and II).

(2) To evaluate growth responses of remnant Scots pine trees surviving fire, and differentiate between short, medium and long-term effects on tree growth (Paper III).

(3) To combine fire-scar data with charcoal data to explore the spatial and temporal resolution of historic forest fire activity (Paper IV).

Study area

The study area was located in Trillemarka-Rollagsfjell Nature Reserve (Fig. 1), a 147 km^2 protected area situated in Buskerud county, south-central Norway. It was protected in 2008 since it is one of the last relatively undisturbed forested areas in southern Fennoscandia. The area has been little influenced by large-scale commercial forestry and technical developments (Bendiksen 2004). However, it has a long history of anthropogenic utilisation, such as high-grading timber harvesting, summer dairy farming, grazing, and slash-and-burn cultivation (Skatvedt 1914, Mørch 1954). Thus, several traces from past human activity, including cut stumps (Storaunet et al. 2005), old tracks, and historical summer dairy farms can be found in the area. In addition to this, historical forest fires, storm felling and natural development in the forest landscape have provided a mosaic and variation in vegetation and forest types of different ages. Characteristics of old-growth forest, such as very old trees, abundant dead standing and fallen trees, and the presence of rare and threatened species, are present at several localities in the reserve (Bendiksen 2004, Hofton 2003, 2004, Storaunet et al. 2005, Castagneri et al. 2013).

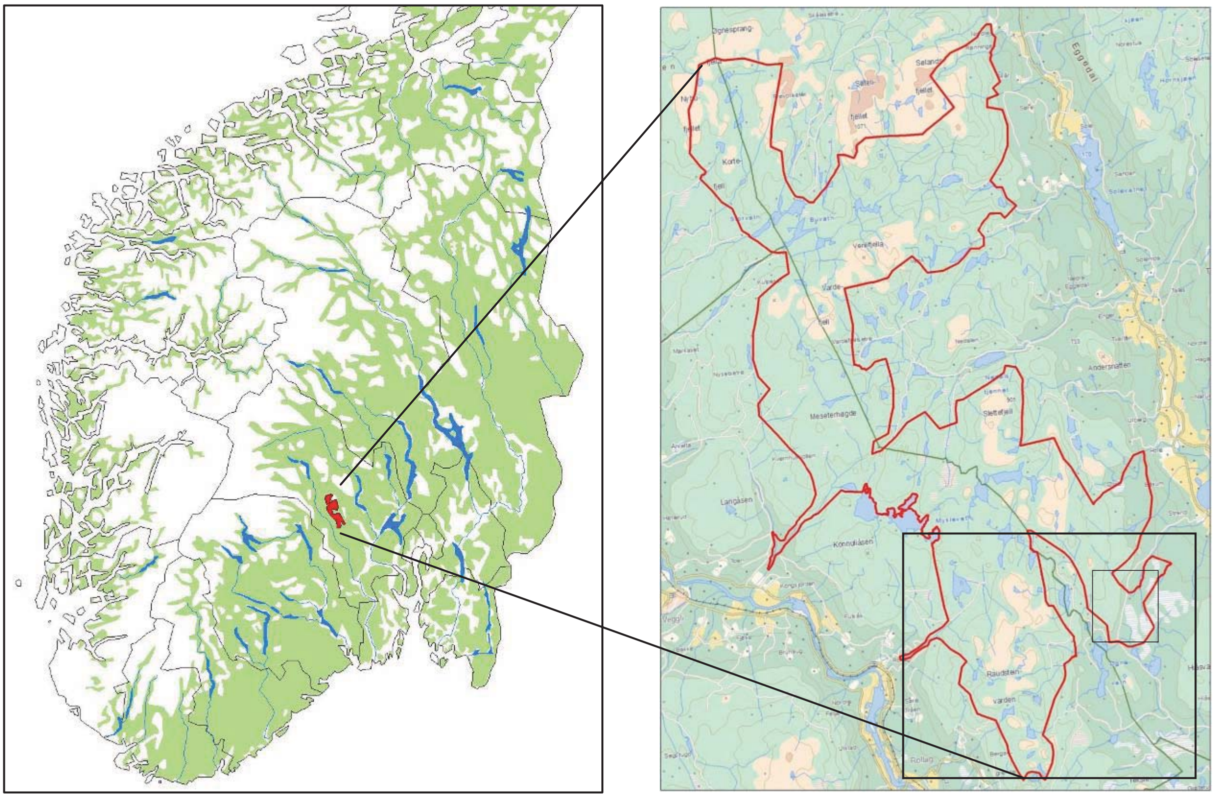

Figure 1: *Map of Trillemarka-Rollagsfjell Nature Reserve. Rectangles in right map outline the study area for the "southern part of the reserve" (74 km^2) (Paper I) and Heimseteråsen (3.6 km^2) (Paper II and III and IV), respectively.*

The reserve is situated in the middle-northern boreal zone with climate being intermediate oceanic to continental. The average annual precipitation is 800 mm, and snow covers the ground from November-December to mid-May but with large variations due to elevation and aspect. The mean annual temperature is +4°C, with mean monthly temperature variations from -4°C in January to +15°C in July (www.eklima.met.no). Altitude ranges from about 300 to 900 m a.s.l. but even though the area is below the regional tree line, most of the terrain above 750-800 m lacks closed-canopy forest stands and the mountain tops are usually barren. Mires are common in depressions and on flat ground.

Forests mainly consist of two types, Scots pine forest and Norway spruce forest, largely depending on variation in topography, soil and hydrology. The pine-dominated forest (>50 % Scots pine trees in upper canopy layer) often border the larger mire systems and commonly occupies the nutrient-poor and dry sites (Fig. 2). It is characterised by various lichen (*Cladonia* spp.), heather (*Calluna vulgaris*), and dwarf-shrub communities (*Vaccinium* spp.).

The spruce-dominated forest (>50 % Norway spruce trees in upper canopy layer) occupies the more fertile mesic- moist sites, and is characterised by bilberry (*V. myrtillus*) but also various grass and herb species (Fig. 3). Deciduous tree species that occur sparsely are grey alder (*Alnus incana*), downy birch (*Betula pubescens*), aspen (*Populus tremula*) and rowan (*Sorbus aucuparia*).

Figure 2: *Pine-dominated forest and mire from Heimseteråsen study area. Photo: J. Rolstad.*

Figure 3: *Spruce-dominated forest from the southern part of the reserve. Photo: J. Rolstad.*

The large-scale study area (Paper I), the “southern part of the reserve”, covers a 74 km^2 area of forested and mountainous land in the southern part of Trillemarka-Rollagsfjell Nature Reserve between the Sigdal and Numedal valleys (59°59’-60°04’N, 09°19’-09°29’E) (Fig. 4). It includes a 38.6 km^2 southern part of the reserve and 35.3 km^2 of neighbouring private land. The topography is undulating with a Precambrian basement rock which consists of quartzite and granites. Some elements of gneisses can be found in the southern part. The dominance of nutrient-poor rocks gives a poor acidic podsol-type soil profile.

Figure 4: *View of the north-western part of the large-scale study area. Photo: J. Rolstad.*

The small-scale study area (Paper II, III and IV), Heimseteråsen (60°02’N, 09°26’E), covers a 3.6 km^2 large area encompassed by the large-scale study area. The topography here is characterised by north–south extending ridges of Precambrian rocks consisting of acid granites and gneisses and two east-facing slopes with deposits of richer glacial materials. A lower area in the eastern part and a central elevated plateau between the slopes consist of mires and forest stands dominated by Scots pine while Norway spruce predominates the slopes.

Methods

Fires from the past can be determined by dating fire scars in living and dead trees (Dieterich and Swetnam 1984). Fire scars of trees are the most accurate source of historic fire dates. Tree-ring dating, also called dendrochronology, is a dating method based on the analysis of tree-ring patterns. The application of the method to reconstruct past fire events depends on the capacity of the tree species to grow annual rings and to overgrow fire injuries (Swetnam et al. 1999). Scots pine is the most fire-tolerant tree species in the boreal forests of Europe and Asia (Uggla 1974). Among the Fennoscandian tree species, it is the only one that commonly survives fire and forms fire scars due to its bark thickness. A fire scar is formed when a fire kills a part of the cambium layer. After a fire, the tree starts to heal the injured part and new wood grows over the scar over time. If a tree has developed an open scar in previous fires, it will easily produce a new scar on the over-healing portion of the wood due to the much thinner bark in the over-healing wood (Gill 1974). The scar appears within the annual growth ring in which the fire occurred, so by using dendrochronological cross-dating techniques an accurate date of the fire event can be determined from the scar (Stokes and Smiley 1968, Arno and Sneck 1977, Dieterich 1980, Madany et al. 1982).

Cross-dating is the basis in dendrochronology and implies the matching of tree-ring series of an unknown age with a dated and known tree-ring chronology. By cross-dating series from dead trees, one may extend the chronology beyond the time span of living trees, and this methodology was applied in Paper I and II. However, samples may be difficult to date for many reasons, e.g., they have too few tree-rings, they are in too poor condition due to decay, they may have a complacent tree-ring pattern, or they may be injured by other things than fire. A scar is never charred in the first fire, only the outer bark which falls off after some years, implying that a tree with a charred scar surface has at least experienced two fires.

If the position of the scar within the ring is visible, even the season of the fire can be estimated by assessing the stage of ring development inside the scar lesion (Baisan and Swetnam 1990) (Fig. 5). We used five categories to represent the seasonal growth: dormant (D), early early wood (EEW), middle early wood (MEW), late early wood (LEW), and latewood (LW). Mork (1960) and Zumer (1969) studied the seasonal cambial growth period of Norway spruce at Hirkjølen (860 m above sea level), about 200 km north of our study area. They found that the growth started in the first half of June and ended during August depending on the temperature. By gaining this information, we assumed that EEW roughly corresponds to first half of June, MEW to last half of June, LEW to first half of July, and LW to the end of July and beginning of August.

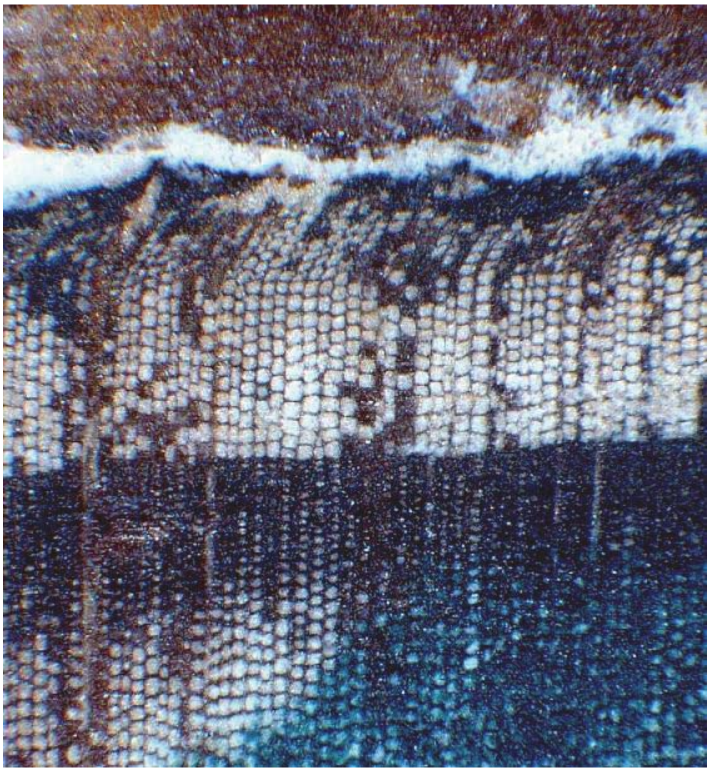

Figure 5: *Example of a fire scar showing collapsed cells after a LEW-fire in 1653 (year). Photo: K.O. Storaunet.*

Thus, fire scars provide a valuable and precise way to study fire history. However, it should be noted that several uncertainties make it difficult to apply a proper sampling method, to interpret scarred and unscarred trees correctly, and subsequently to estimate the fire regime characteristics. This is due to 1) the variable scarring susceptibility of individual trees (depending on size, age, bark thickness, etc.) 2) the high variability in the fire behaviour and 3) fire scars do not necessarily persist through time due to decomposition of dead-scarred material, and more recent fire events may have consumed older fire records. In addition to this, fire scars provide certain evidence of fire while lack of fire scars does not necessarily mean it did not burn it that location. However, we tried to remedy these problems by ensuring a well-distributed number of sample points (recorder trees) (Paper I and II) and by adjusting the number and size of fires for detection probability and proportional size within the recording transect (Paper I).

Sampling of fire-scarred material (Paper I and II)

We collected fire-scarred wood samples from Scots pine stumps, snags, logs and living trees during summer and fall 2006/2007 and 2009/2010 (Fig. 6). Most of the samples were from old cut stumps, whereas living trees with visible fire scars were uncommon (Fig. 7). A 2 – 5 cm thick partial cross-section was extracted with a chainsaw from the place where the fire record appeared to be most complete (Fig. 8). Multiple cross-sections were extracted in cases where scars on multiple sides or heights appeared to have recorded different fires.

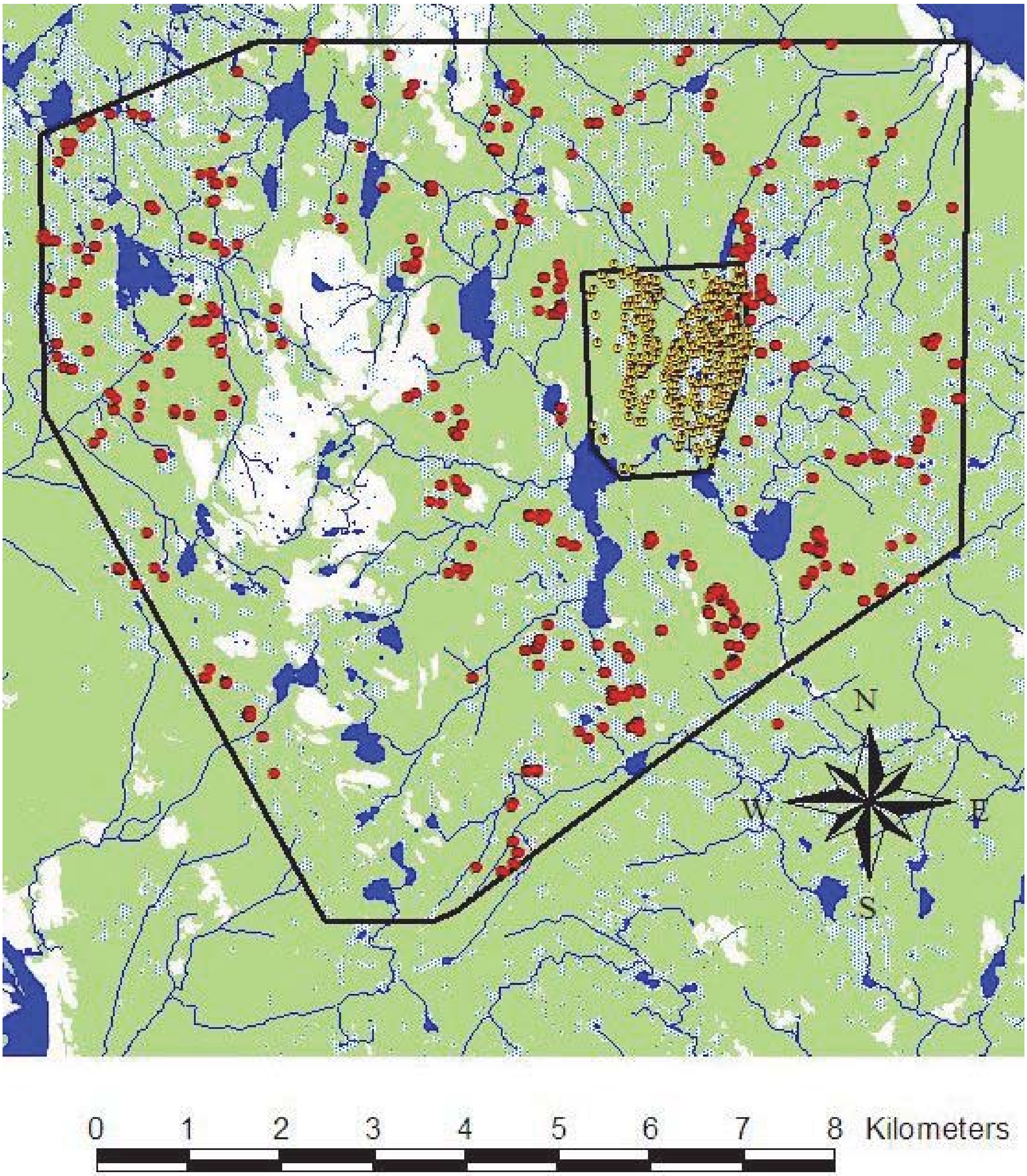

Figure 6: *Collected samples from the small scale study (3.6 km^2) (yellow dots) and the large scale study (74 km^2) (red dots).*

Figure 7: *Example of a typical fire-scarred stump with three fire scars (1590, 1639, 1690). Photo: J. Rolstad.*

Figure 8: *Sample 2016, as collected in the field from the large-scale study, having five fire scars (1624, 1667, 1711, 1744 and 1792). Photo: Y. Blanck.*

We collected a total of 854 wood samples. However, 143 of these were undated because they were in too bad condition due to decay, had too few tree rings to be cross-dated, or because they had a complacent tree-ring pattern. In addition, 61 samples were collected for other purposes (Paper II). Thus, we ended up with 650 samples containing a total of 1391 successfully cross-dated fire scars. Additionally, samples from 259 living trees without visible fire scars from another study (Storaunet et al. 2005) were included in Paper II. Most of the crossdated fire-scarred samples from Paper II were also utilised in Paper III and Paper IV.

In the large scale study (Paper I), we divided the study area into a 1x1 km grid and searched each square for fire-scarred material. Approximately 13% of the squares had no samples, whereas mean number of samples in the other squares was 7.0 (range 1 – 22). To estimate the total recording area we drew a buffer around our GPS tracklogs. This “recording transect” covered 38% of the total forest and mire area. In the small scale study (Paper II), we systematically searched throughout the study area and sampled all fire-scarred material that we could find. In addition to samples with distinct fire scars, we also collected samples from trees with irregular wooden structures indicating possible overgrown scars, from trees that had burnt after death, and from trees that appeared very old (for chronology building). However, sampling was impeded at some locations due to lack of available fire-scarred material, especially in spruce-dominated forests and at higher elevations. Furthermore, for locations with a high density of fire-scarred material, samples with the greatest number of visible fire scars and those that were least decayed were given priority.

Dendrochronological and seasonal dating of fire scars (Paper I and II)

All samples were brought to the laboratory, dried and sanded with a belt sander (down to grit 400) to make the tree-ring sequences appear clearer and so that tree rings and fire scars could be distinguished under a microscope (Fig. 9). Zinc paste and a scalpel were used when needed to assure better visibility of the tree-ring pattern. The annual ring widths were measured with an Addo micrometer (accuracy of 0.01 mm) and then cross-dated by using the program COFECHA (Holmes 1983, 1994): All samples were cross-dated against 3 different independently chronologies developed from the area: (1) Flesberg chronology (Eidem 1959) developed from 97 trees with a sample depth of ≥5 tree-ring series dating back to 1526, (2) Rollag pine chronology (45 trees with ≥5 tree-ring series from 1373), and (3) Sigdal pine chronology (117 trees with ≥5 tree-ring series from 1248). The suggestions from the statistical cross-dating were thereafter confirmed by the pointer-year method (Douglass 1941, Stokes and Smiley 1968, Yamaguchi 1991, Niklasson et al. 1994). When other signs of fire in the morphology of the tree-ring series, such as bands of traumatic resin ducts, strong growth depressions or releases occurred simultaneously with fire events dated in neighbouring trees, this was recorded as a positive fire indicator (Brown and Swetnam 1994).

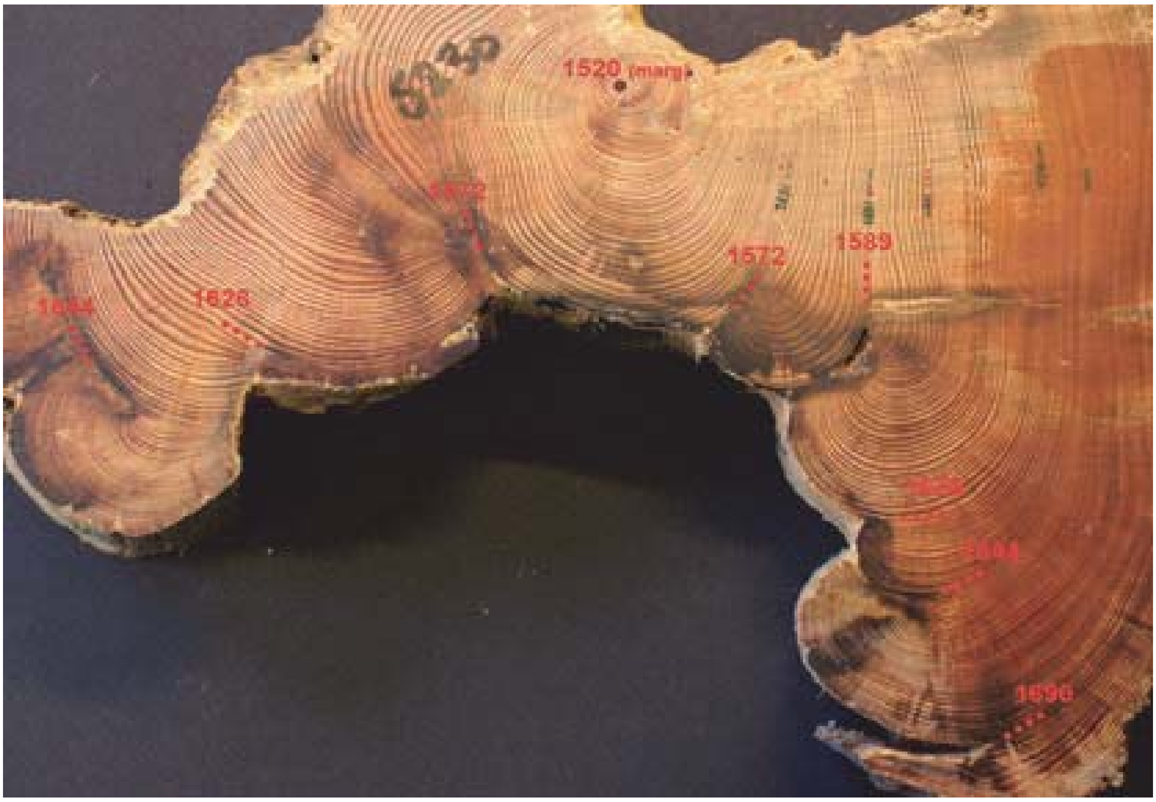

Figure 9: *Example of a prepared stem disc sample with 5 dated fire scars (1572, 1589, 1626, 1644 and 1690). Photo: K.O. Storaunet.*

Spatial delineation of fires (Paper I and II)

To delineate spatial distribution of individual fires, we used ArcView GIS 3.3 software (ESRI Inc., Redlands, CA, USA). Location of *recorder trees* was first identified. These were defined as: (*i*) samples having a fire scar the actual year, (*ii*) trees up to the age of 100 years, and (*iii*) trees scarred by a fire <150 years ago.

We used different methodologies to delineate individual fires in the two papers. In Paper I, we used ArcView to delineate boundaries and areas of individual fires, by drawing polygons around samples recording a fire. We drew a buffer around the fire-scarred samples, varying in size from 100 to 800 m. The buffer size was assessed in each case, after considering all available information on the map: 1) number, location and patterning of the scarred samples the actual year, 2) number, location and patterning of the available trees not having a scar, including the relative positions to the scarred samples, 3) calendar year (for fires after 1700 this included a judgement of living trees that we did not sample), 4) topographic elements like treeless mountain areas, mires, open water bodies and streams, and 5) terrain features like slope and aspect. In Paper II, we used the ArcView-extension “Animal Movement” (Hooge and Eichenlaub 2000) to outline the contours of individual fires. First, two contrasting kernel ranges were calculated; one for the scarred samples (fire-area) and one for the recorder trees without fire scars (no-fire-area). The no-fire area was then subtracted from the fire area to estimate the actual fire perimeter. Further, we estimated for all fire years the spatial coverage of the recorder trees (termed *recording area*), using the same GIS kernel procedure. Finally, the relative fire size was calculated as the ratio between the fire area and the recording area the actual year. For both applications, we adjusted the borders in the end to make sure that fires occurring closely in time (<15 years) were not spatially overlapping (except when multiple fire scars in single trees indicated otherwise). This was because very few of the scar intervals in our samples were of shorter duration.

Fire intervals, survival and hazard of burning (Paper I and II)

Time intervals between fires, cumulative survival and hazard of burning were calculated as scar-based and map-based, and for two separate time periods, i.e. pre- and post-1625 (Paper I) and pre- and post-1600 (Paper II). These time periods were chosen based on the timing of the anthropogenic influence on the fire regime. For the scar-based intervals, we used time periods between successive scars within the same tree sample. Map-based intervals were calculated based on successive overlapping fires from the map.

The fire intervals, survival and hazard are “site-specific” fire characteristics, i.e. defined at a specific site or a restricted area. However, in order to measure how often a fire of a certain size burns in an area, size-class frequency distribution of fires and recurrence intervals were used (Paper I). Fire recurrence intervals are based on the annual probability that in a defined spatial area, a given size event will be equalled or exceeded (Malamud et al. 2005). Thus, size-frequency distributions and recurrence intervals are size-specific characteristics of a fire regime as opposed to site-specific characteristics.

Growth responses of fire-scarred trees (Paper III)

Little is known about the growth response of Scots pine trees following fire in boreal forests. In paper III, we used 225 tree samples (25 from Paper I and 200 from Paper II) containing 439 fire scars to assess changes in tree growth after 61 of the historical fire events occurring from AD 1210 to 1866. We measured growth 10 years pre-, 5 years post-, and 11-20 years post-fire for all fire events (Fig. 10). The 10 years pre-fire period also served as an index of the long-term growth pattern (21-120 years) when it was preceded by a previous fire. Thus, we distinguished between short- (1-5 years), medium- (11-20 years) and long-term (21-120) effects.

To avoid influence of callus tissue on the tree-ring widths, we selected only samples where the tree rings were measured >4 cm from the fire scar. Furthermore, we only included samples with ≥5 measured tree rings pre-fire and ≥15 tree rings post-fire. Finally, we only measured growth responses in remnant fire-scarred trees and not trees that might have been subject to fire without getting scarred.

When testing for possible influence of fire return intervals, we used time since previous fire as an explanatory variable. This was estimated as the number of tree rings between multiple scars, or for those with only one scar, as the most likely last fire event based on the mapped fires in Paper II. Possible covariates that was used in the statistical analyses included diameter and age of the tree when it was scarred as well as the total age of the tree.

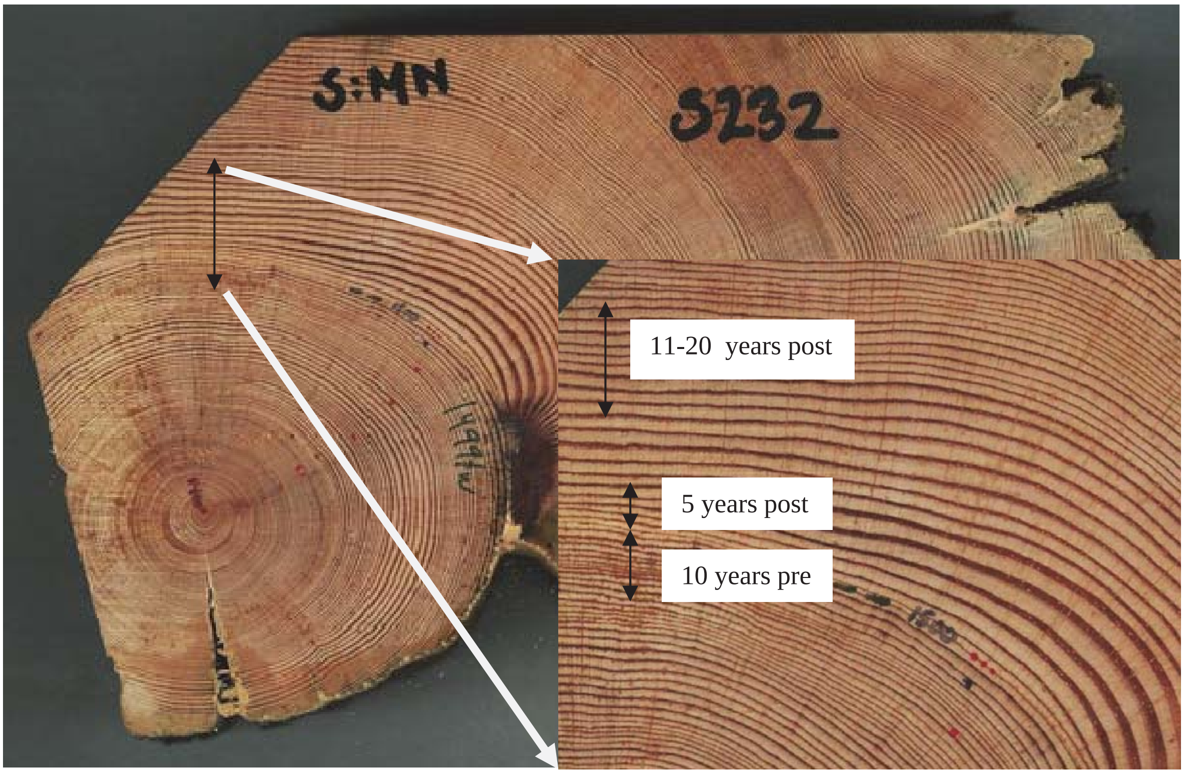

Figure 10: *An example approximately showing how the growth 10 years pre-, 5 years post-, and 11-20 years post-fire was measured (fire scar 1499).*

Whereas tree-ring width is used in dendrochronology, BAI (basal area increment) is more useful in growth modelling since it is a better estimate of the three-dimensional mass increment (Motta et al. 2006, Biondi and Qeadan 2008) and also reduces the age-related variation in radial growth (Leblanc et al. 1992). Thus, we used BAI to measure absolute as well as relative growth (post versus pre fire growth) 10 years pre-, 5 years post-, and 11-20 years post-fire and tested differences between growths, as influenced by time since previous fire, by using ANOVA, ANCOVA and partial regression.

Combining tree-ring and charcoal data (Paper IV)

We collected peat and soil samples during 2010 adjacent to nearby successfully dated fire-scarred pine stumps or snags. We used a Russian peat corer (Jowsey 1966) to sample 20 peat columns (Fig. 11). The banding pattern of charcoal layers in the peat was recorded (Ohlson et al. 2006), and in the laboratory each cm of the peat columns was searched for macroscopic charcoal (longest axis ≥0.5 mm). The charcoal extracted from the peat was thereafter dried to constant mass and weighed. We used AMS ^{14}C radiocarbon dating to estimate the age of organic materials. Site-specific age-depth models were obtained by linear interpolation with the CLAM software (Blaauw 2010). From these models, the age of the individual charcoal layers could be estimated. Since the radiocarbon dates of wood charcoal indicate the time period of wood formation, they always predate the fire event in which the charcoal was formed. GIS was used to measure distances between the peat sample sites on the mires and all fire-scarred stumps within a range 100 m from the peat sampling site and the correspondence between the dating of the charcoal layers and the fire scars was evaluated.

We also collected 100 soil samples by using a steel cylinder. The samples contained the entire organic layer and a few centimetres of the underlying mineral soil. The samples were then oven-dried in the laboratory and searched for macroscopic charcoal under a magnifying lamp. All macroscopic charcoal was extracted from the samples and weighed. A selection of charcoal fragments were radiocarbon dated.

In order to get an indirect date for a given level in each of the peat columns, we determined the level at which spruce pollen percentages exceeded 2% of the sum of tree pollen. Pollen analysis followed standard methods (Berglund and Ralska-Jasiewiczowa 1986). The approximate ages corresponding to this level was obtained from the age-depth models, and above this level we considered spruce to be established in the area (see Hafsten 1992).

Figure 11: *Peat core with charcoal layers sampled with a Russian peat corer. Photo: J. Rolstad.*

Historical archives (Paper I and II)

To gain knowledge about historical sources, we searched the National Archives of Norway for documents, diplomas, and old maps covering the reserve and its vicinity. Historic maps gave information about locations of summer dairy farms, old roads, tracks, and rivers used for log floating. We also searched old agricultural textbooks and reports with more general descriptions of forest and land use.

The fire chronologies extended back to the early 1300s (Paper I, Paper II), coinciding with the Black Death epidemic that came to Europe during 1348 – 1350. This epidemic extinguished between half and two thirds of the Norwegian population and many farms were abandoned. It was not until the mid-1600s that the population had recovered to pre-1350 level (Benedictow 2002). The authorities invited farmers to recolonise and cultivate the agricultural and forested land that had been abandoned. In a legislative decree from 1490, the National Council ordered all farm owners to practice slash-and-burn cultivation to sow rye (Tveite 1964). The basis for all swidden agriculture is utilisation of the large stores of nutrients bound up in trees and humus layers in the forest. When these nutrients are converted and released by fire, they may be used for crop yields of useful plants (Asheim 1978, Tvengsberg 1995). The slash-and-burn cultivation, as well as burning to create and improve livestock grazing conditions, were therefore important in Norway as people settled the countryside (Bleken et al. 1997).

However, from the mid-1600s, a concern rose for the future timber supply due to the extensive logging in southern Norway. The use of fire on forested land had become so common that the first legislation against it came in 1683 to impede damage to timber and forests (Skogdirektøren 1909). This was due to the gradually increasing value of the timber, since there was an increasing demand for timber in Europe (Fryjordet 1992), and locally also because the Kongsberg Silver Mines (45 km south of the reserve) opened in 1623 (Berg 1998, 2001) and the establishment of the Modum Cobalt Mines (25 km southeast of the reserve) in 1776 (Fryjordet 1992).

Climate (Paper I)

We downloaded historical climate data (reconstructed annual mean summer temperature and precipitation) from the Climate Explorer of the Royal Netherlands Meteorological Institute (KNMI) (Luterbacher et al. 2004, Pauling et al. 2005) to explore relationships with the long term fire chronology in Paper I. The gridded reconstructions were then calibrated against local instrumental records from nearby meteorological stations downloaded from the Norwegian Meteorological Institute (www.eklima.met.no).

Main results and discussion

Fire history at two spatial scales in Trillemarka-Rollagsfjell Nature Reserve (Paper I and II)

To describe, delineate and evaluate the historic fire regime we sampled and cross-dated fire-scarred material from Scots pine at two different spatial scales. We delineated 61 and 254 individual fires (Fig. 12) in the small (Paper II) and large (Paper I) scale study, respectively, from the 1300s and up till today.

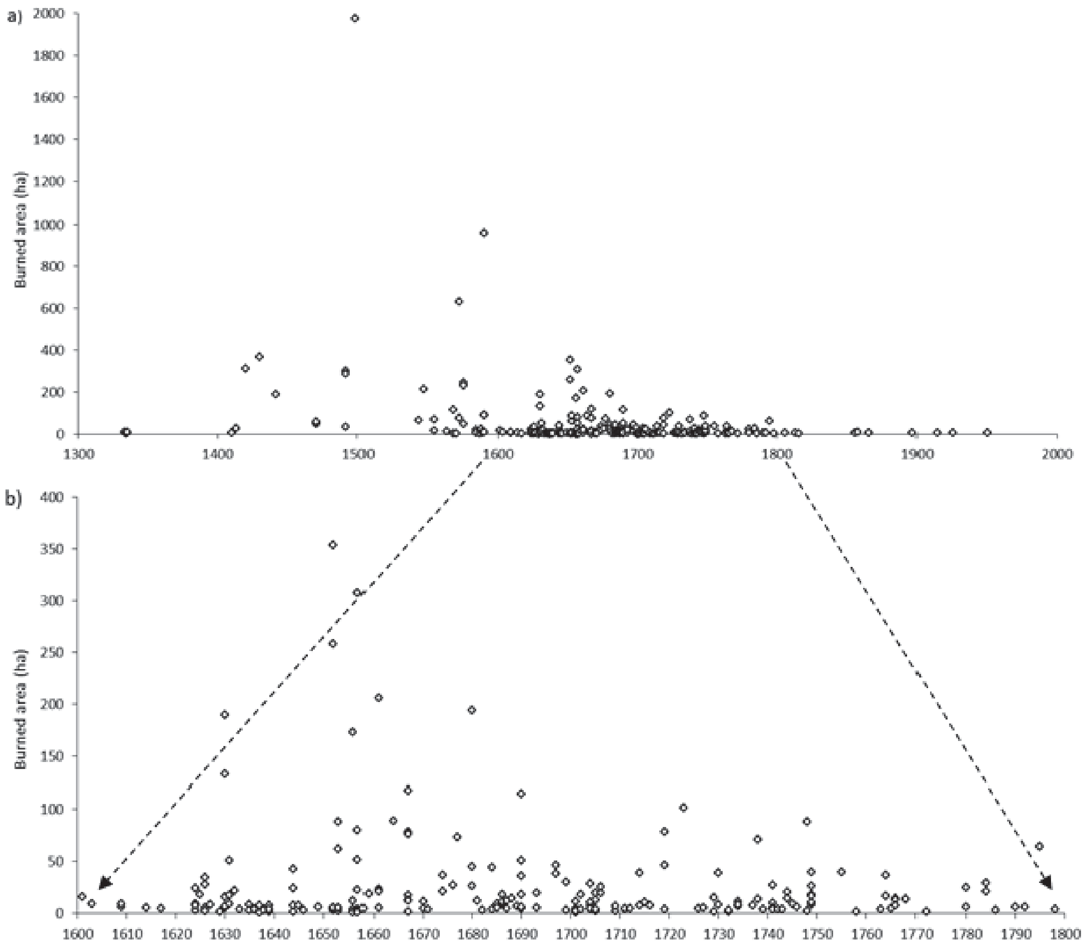

Figure 12: *Size (ha) of all recorded fires during a) 1300-2009 and b) 1600-1800 within a 74 km² southern section of the Trillemarka-Rollagsfjell Nature Reserve.*

The main results of these studies show that historical forest fires have been a major factor influencing the boreal forest structure in Trillemarka-Rollagsfjell Nature Reserve. Our data allowed for detailed reconstruction of both numbers and sizes of individual fires. We found a general pattern of relatively few, but many of them large, fires in the landscape up to the beginning of the 1600s, followed by a period of greatly increased number of fires that were progressively smaller in size over time during 1600-1800, and with an almost total lack of fires from the 1800s and up till today (Fig. 13). This is a general pattern that has been described also in other parts of Fennoscandia, although with some differences in the timing of the events (Groven and Niklasson 2005, Niklasson and Granström 2000, Wallenius et al. 2004). The observed changes could be caused by climate changes (Bergeron 1991, Swetnam 1993), human activity (Clark and Royall 1995, Lehtonen and Huttunen 1997) or a combination of both (Zackrisson 1977, Johnson et al. 1990). However, our results show several lines of evidence that point to a shift from climatic (or natural) driven fires to human caused influence in the beginning of the 1600s.

a) 1492-1568 (77 yrs) b) 1652-1667 (16 yrs) c) 1778-1866 (89 yrs)

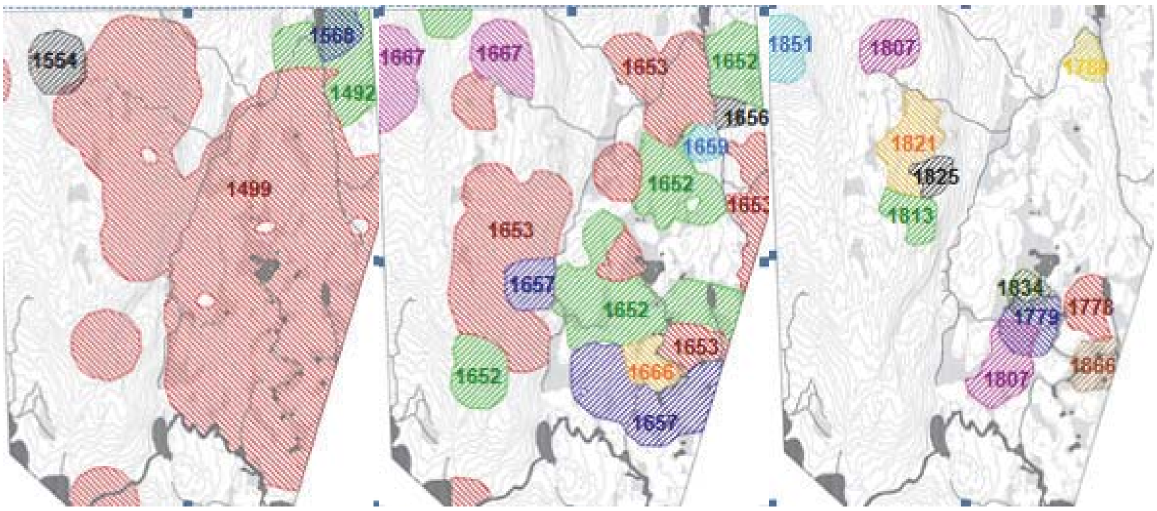

Figure 13: *Delineation of fires in the small scale study during three different time periods (from Paper II); a) 1492-1568 (77 yrs), b) 1652-1667 (16 yrs), and c) 1778-1866 (89 yrs).*

Notably, we found an abrupt increase in number of fires from the beginning of the 1600s that lasted to the mid-1700s (Fig. 14a). Although mean fire size varied considerably, we found a general trend of decreasing fire size during the period (Fig. 14c). Concurrently, fire severity showed a decreasing trend over time, also after fire size was accounted for (Paper II). The counteracting effects of an increasing number of successively smaller fires resulted in mean annual burnt area being not very different pre and post 1625 (Fig. 14b). It has been found that natural fire regimes tend to be dominated by fewer and larger fires compared to human-caused fires (Johnson 1992). However, human caused fires may shift this pattern towards smaller fires with lower intensities (Niklasson and Granström 2008). This is because human ignitions are set under less severe weather and therefore leading to small fires. It may also be due to active suppression of large fires, and/or too little fuel for fires to spread since forests were repeatedly burnt (Schimmel and Granström 1997).

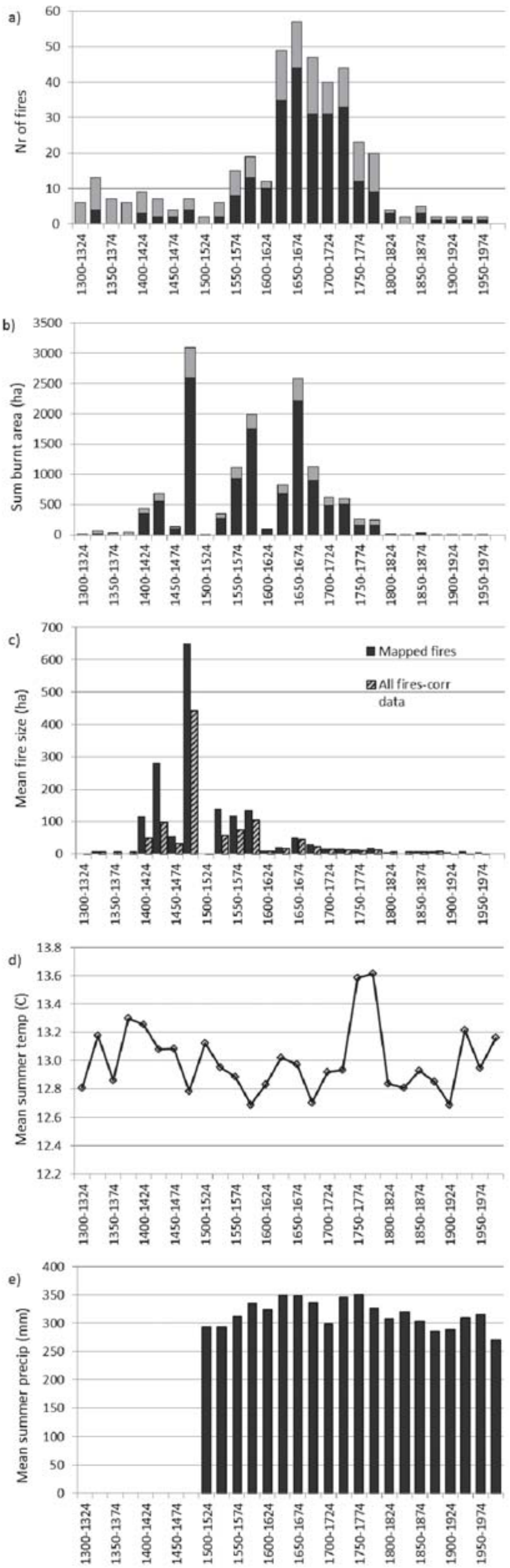

Figure 14: *a) Total number of fires, b) sum of total burnt area (ha), c) mean fire size (ha), d) mean summer temperature (°C), and e) mean summer precipitation (mm), within 25 year periods. In a) and b) black and grey bars show recorded and added adjusted fires, respectively. The hatched bars in c) show mean fire size of all fires (both recorded and added ones) (from Paper I).*

We also found a sudden appearance of early season fires starting in 1625 (Fig. 15), which supports human interference with the fire regime. Due to these time-related changes in fire pattern (increasing number of fires, decreasing fire sizes, fires earlier in the season, and decreasing fire severity) we split the dataset into one early period and one late period for further analyses: pre and post 1625 (Paper I) and pre and post 1600 (Paper II).

Lightning strikes is the only natural cause of forest fire in Fennoscandia, and in southeastern Norway, the main period of lightning is June to August, peaking in July and being more common in August compared with June (Rokseth et al. 2001). This corresponds well with the early period, where most fires occurred mid-late in the growing season. However, human-caused fires, with slash-and-burn cultivation and summer grazing burns, were probably more common in spring/early summer, possibly because fires were easier to control and the previous year's dead organic material was dry and the new vegetation had not yet started to grow.

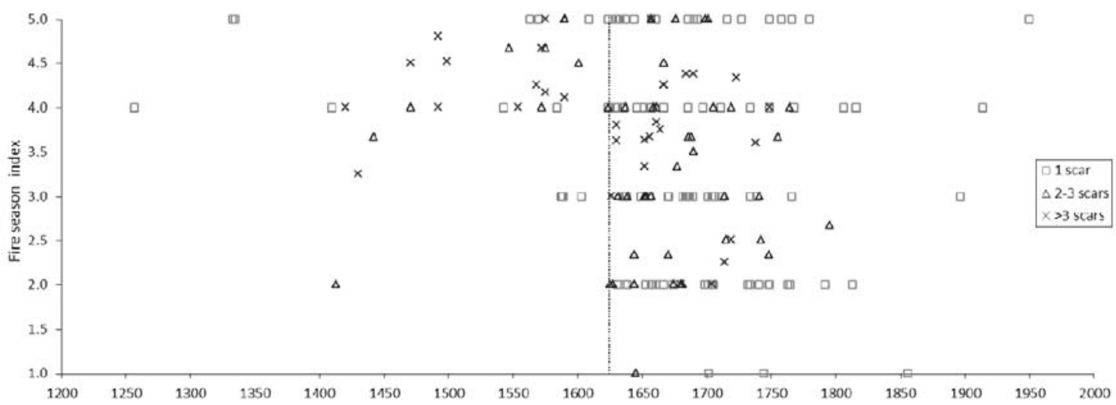

Figure 15: *Fire season index values (1 corresponds to dormant season, and 5 corresponds to latewood season) for each individual fire. Dashed line represent the year 1625 (from Paper I).*

We found few short intervals (< 15 years) and a strong mosaic-shaped pattern in forest fires, indicating that recently burnt areas had too little fuel to burn over again. The hazard rates differed substantially between the early and the late period. The hazard of burning peaked later (60-100 years since last fire) in the early period compared to the late period (20-40 years) (Fig. 16). Niklasson and Granström (2000) found similar results with a peak in the hazard of burning post-1650 much earlier (20-30 years since last fire) than pre-1650 (about 70 years). It has been shown that it takes at least 20 years after a fire in Scandinavian *P. sylvestris* forest stands before enough fuel builds up for a new fire to spread, followed by a progressive rise in fire risk up to 50 years, after which the risk levels off at a fairly constant rate (Schimmel and Granström 1997). This corresponds well with our early period results. Notably, our data showed marked decline in fire risk above 75 years, since a significant part of the study area did not burn during the recording period.

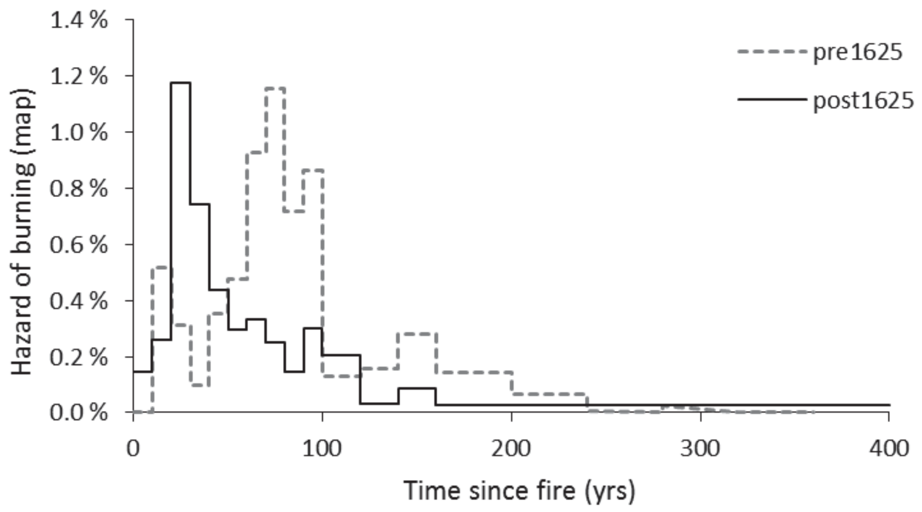

Figure 16: *Estimated hazard of burning (i.e., yearly probability of a new fire occurring with increasing time since the last fire) for map-based data, drawn separately for pre-1625 (dashed grey) and post-1625 (solid black) time periods (from Paper I).*

In Paper I, we compared our fire data with historical climate proxies. On a 25-year period basis, indicating possible multi-annual patterns, neither fire frequency (number of fires) nor sum of burnt area showed any relationship with mean summer temperature (Fig. 14). On a yearly basis, however, we found a rather strong positive relationship between summer temperature and annual burnt area pre-1625 whereas this relationship was far less pronounced post-1625 (Fig. 17). Thus, we suggest that the 1625 shift in fire regime was not due to a shift in the long-term trends of summer temperature. Rather, it implies that fires pre-1625 for the most part were driven by warm summers whereas many fires post-1625 were lit by man during both cold and warm summers. Several other studies from Fennoscandia have found similar shifts in the fire regime, but during different time periods, which further strengthens our conclusion that these changes were due to human activities rather than climate (Engelmark 1984, Lehtonen and Kolström 2000, Niklasson and Granström 2000, Groven and Niklasson 2005). Surprisingly, we found a higher number of fires and sum burnt area during 25-year periods with more precipitation, despite that we found no relationship between burnt area and precipitation on a yearly basis. Notably, the periods with high precipitation for the most part occurred during the 1600s and 1700s. Thus, we interpret the correlation between precipitation and number of fires on a 25-year basis as coincidental rather than causal.

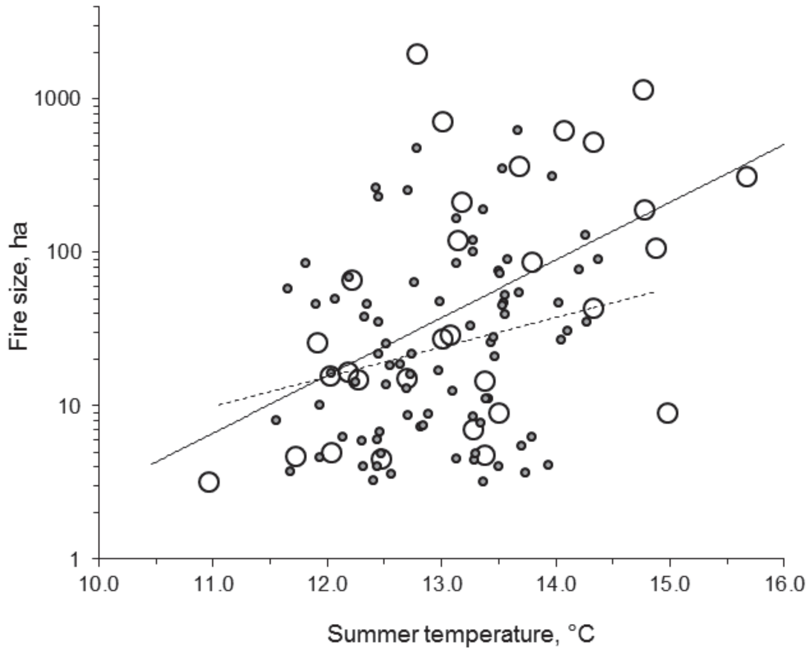

Figure 17: *Fire size (ha) versus summer temperature for pre-1625 (1300-1624) (open circles and solid line) and post-1625 (1625-1799) (filled dots and dashed line) (from Paper I). Note the logarithmic scale on the y-axis.*

Finally, the sudden increase in number of fires during the early 1600s corresponds well with written history of the area. The written sources describe a history where anthropogenic forest fires and slash-and-burn cultivation expanded with the increasing population from the late 1500s. During the 1700s, however, timber resources increased in value, gradually forcing slash-and-burn cultivators to abandon fires on forest land (see further information in *Historical archives* p. 20).

Both the small-scale and large-scale study revealed an abrupt ending of fires from the 1800s and up till today. Similar pattern has been observed in almost all fire history studies performed in Fennoscandia, although the timing differ somewhat (Zackrisson 1977, Niklasson and Granström 2000, Lehtonen 1998, Lehtonen and Kolström 2000, Groven and Niklasson 2005). Several hypotheses have been proposed to explain this decline, such as fire suppression (Heinselman 1973, Zackrisson 1977) and global climate change (Bergeron 1991, Flannigan et al. 1998). However, it is unclear whether effective fire fighting was effective in remote areas in the 1800s without motorised equipment (Wallenius 2011). Thus, we believe that active fire suppression presumably played a minor role in the cessation of fires.

Furthermore, a sudden change in climate as explanation for the decrease in fires also appears unlikely because the cease of fires were not synchronous in time and our summer temperature and precipitation data showed no climatic trends that could explain the almost total cessation of forest fires. Rather, we believe that a decrease in anthropogenic burning due to increased timber value was the predominant reason for the almost total lack of forest fires in recent times. The first legislation in Norway against use of fire came in 1683, and a circumference for timber supply was established around the silver mines of Kongsberg in 1723, undertaken special legislations against burning of forests. Thus, by the late 1700s, slash-and-burn cultivation was basically forbidden and consequently abandoned.

Another possible contributing factor to the decline in fire activity may have been an increasing dominance of Norway spruce. It has been suggested that the reduction of fires took place during or immediately after the spruce invasion and that the reasons for this was because it made the forest denser, darker and cooler and thus locally more humid with moister soil conditions, all reducing flammability and fire activity (Ohlson et al. 2011). Even though our study covers a time period with spruce forests already established in the region (Giesecke and Bennett 2004), we found that spruce-dominated forests burnt less often (rotation 250-1000 years) than pine forests (150-300 years). We also found that percent annually burnt areas decreased with increasing elevation, implying considerable spatial variation in fire susceptibility (Table 2).

Table 2. *Percent annually burnt area within four different time periods for adjusted and unadjusted data and for different altitudes (m a.s.l) within pine- and spruce-dominated forests (from Paper I).*

	1300-1624	1625-1699	1700-1799	1800-2009
Adjusted data, total area	0.42%	1.03%	0.30%	<0.01%
Unadjusted data, total area	0.35%	0.86%	0.23%	<0.01%
Pine-dominated (<480 m)	0.52%	1.58%	0.27%	<0.01%
Pine-dominated (480-660 m)	0.51%	1.03%	0.28%	<0.01%
Pine-dominated (>660 m)	0.28%	0.49%	0.18%	<0.01%
Spruce-dominated (<480 m)	0.35%	0.98%	0.25%	<0.01%
Spruce-dominated (480-660 m)	0.21%	0.54%	0.22%	0.01%
Spruce-dominated (>660 m)	0.08%	0.25%	0.13%	<0.01%

Finally, we calculated normalised fire size-frequency distributions by means of power-law statistics for the early and the late period to describe the relative contribution of small vs. large fires (Paper I). To our knowledge, our study is the first to document this in Fennoscandia. In North America such statistics have been calculated for recent time periods, but historical records are lacking (Malamud et al. 2005, Jiang et al. 2009). We found that fire frequency was 7 times higher during our early period and >20 times higher during 16-1700s compared with recent fire frequencies in North-America. We also found that small fires in Trillemarka-Rollagsfjell Nature Reserve historically outnumbered the large ones to a larger degree than what has been seen in recent years in North America. Thus, we conclude that it has burnt more often in the past in our study area compared to present wildfire ecoregions of North America.

Historical fires promoted high tree growth (Paper III)

Even though there are large variations in individual growth responses following fire, we found a general pattern of a slight temporary growth reduction 5 years post-fire compared to the 10 years pre-fire values. However, growth 11-20 years post-fire returned to, and often exceeded, pre-fire growth levels, suggesting that the negative effects only occurred temporarily. Beyond 20 years post-fire, the long-term tree growth declined steadily up to ca.

120 years (Fig. 18), resulting in relative growth responses (post- /pre-fire ratios) being affected by time since previous fire in the individual trees.

The absolute growth 5 years post-fire (short-term effects) decreased slightly with increasing time since previous fire, whereas the peak in growth 11-20 years post-fire (medium-term effects) was independent of this. This implies that tree growth slowly declined in the long-term absence of fire (>20 years), which to a certain degree also seemed to ‘carry over’ and kept the growth low 5 years following the next fire. However, 11-20 years post-fire, growth returned to the same relatively high values, independent of the fire return intervals.

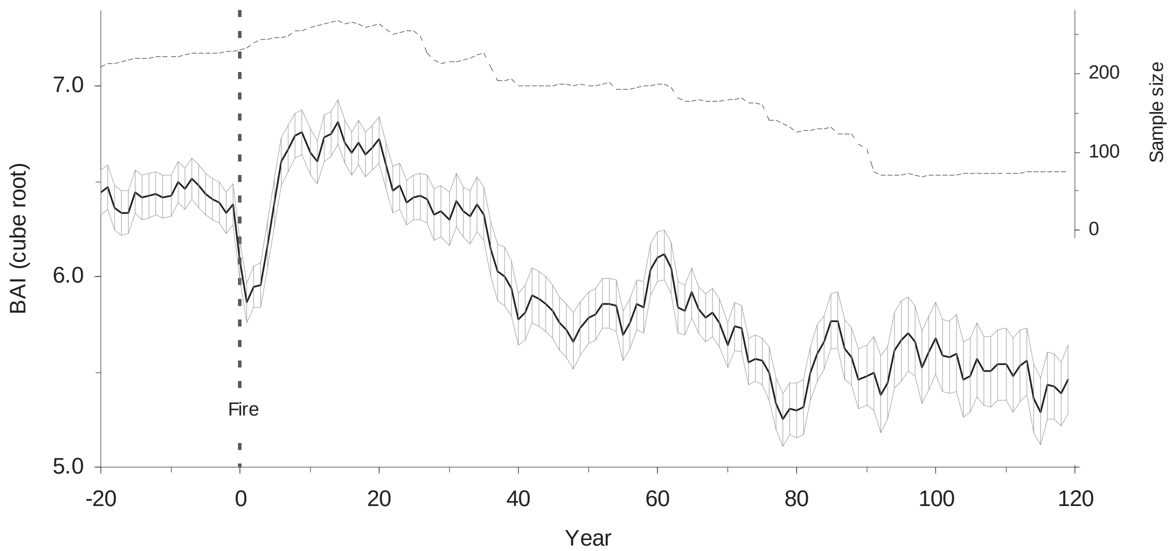

Figure 18: *Average BAI growth (mm^2 year^{-1}, scaled to cube root) (±1 SE) related to fire year, of fire-scarred pine trees in Trillemarka-Rollagsfjell Nature Reserve. BAI-series with ≥2 fire events were used, the series were aligned according to the first fire, and the series were cut from the next fire event. Sample size (dotted line) shown on right y-axis (from Paper III).*

The results of this study indicate that recurring fires maintained high tree growth in remnant Scots pines and we believe this mostly was due to a reduction in tree density and thus decreased competition. Previous studies have reported both reductions (Peterson et al. 1991), increases (Reinhardt and Ryan 1988), or lack of prolonged growth response (Keyser et al. 2010). This is not surprising since a fire of low-to-moderate severity often creates a mosaic of burnt and unburnt areas and might not influence all of the trees within the fire boundary in the same way (DeBano et al. 1998).

Since the historical data did not allow us to positively identify non-scarred surviving and new recruiting trees, only growth responses of remnant individual trees after fire as opposed to the total productivity of the whole stand, was measured. However, we conclude that due to the almost total lack of fires in Fennoscandia during the last two centuries, a retrospective comparative approach as the one applied is the only applicable method to gain knowledge about long-term effects of fire.

Correspondence between charcoal data and fire scars (Paper IV)

The results from this study showed that the correspondence between the charcoal record in the peat and in the tree-ring data for the time span where they overlap was rather vague. We found that charcoal traces from the period covered by the dendrochronological analysis of fire scars were nearly absent in the peat, although fires had been documented on mineral soil in the vicinity. A charcoal banding pattern matching all fire events in the fire-scar data could not be found at any site. However, at one site (P3), situated in the western part of Heimseteråsen study area and in the middle of a 15 m wide protrusion of a mire complex surrounded by pine forest and with ombrotrophic vegetation dominated by *Sphagnum* spp. and *Eriophorum vaginatum* species, three peat columns showed fire activity that may correspond to the tree-ring dated fires AD 1499 and AD 1575 (Fig. 19 and 20).

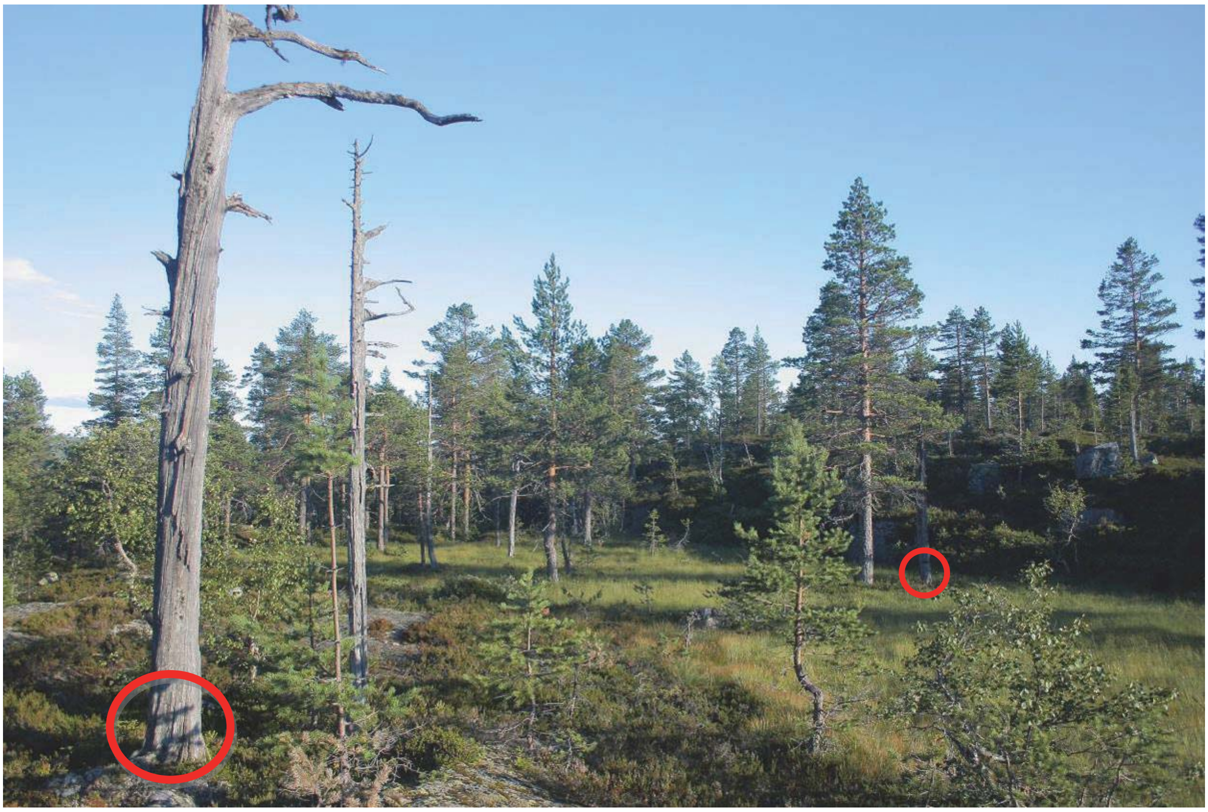

Figure 19: *Picture illustrating peat sample site P3, with the fire years 1499 and 1575 in the left front snag and fire year 1575 in the right back snag.*

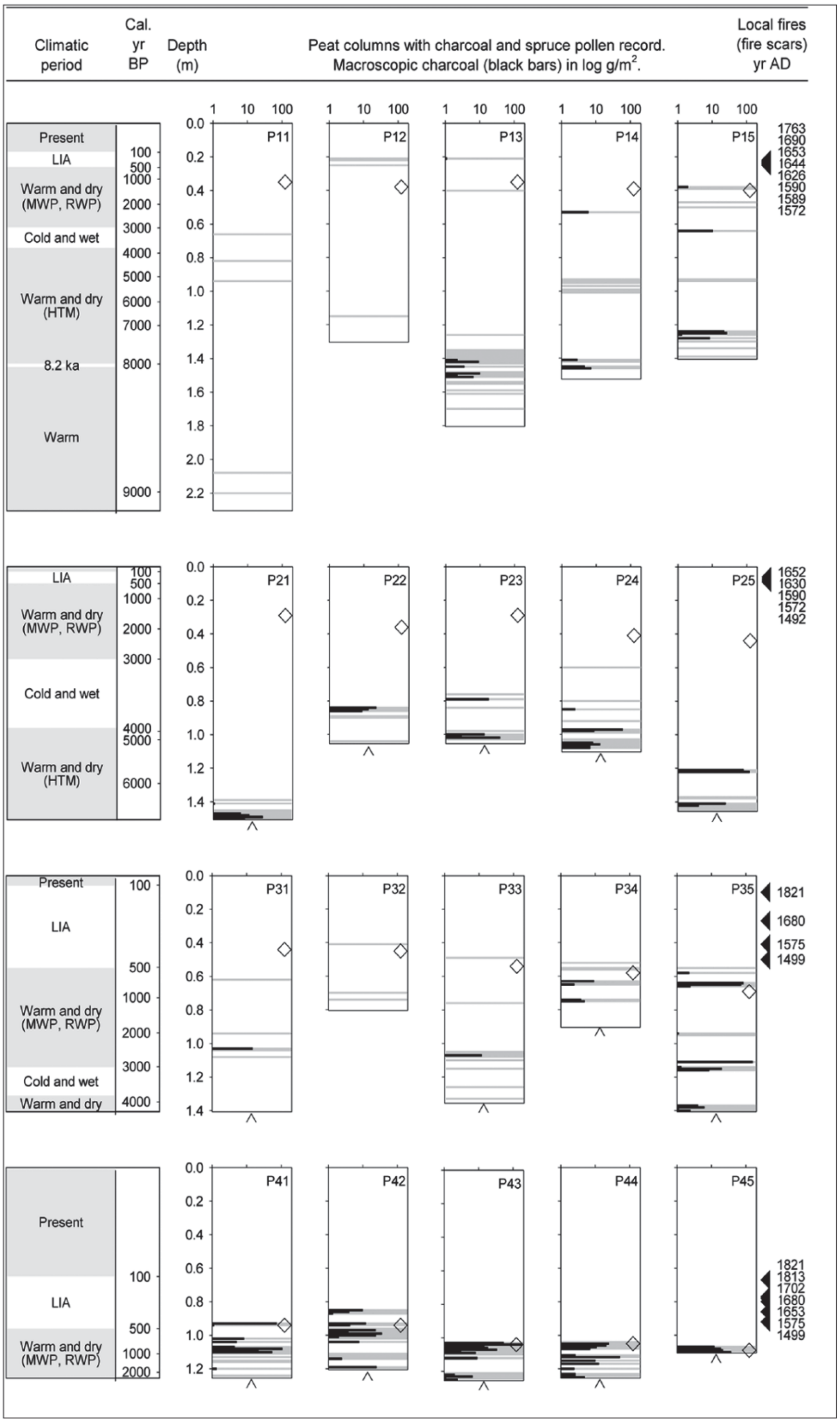

Figure 20: *Peat charcoal record, local fire history (fire scars) and establishment of Norway spruce (Picea abies). The four panels represent the four sites with five peat columns each. Black vertical bars: amount (mass) of macroscopic charcoal (note the logaritmic scale). Grey lines: fire activity. Open diamond: the local establishment of spruce. Arrowheads at the bottom of peat columns mark that samples reached mineral soil. Local fires documented through the analysis of fire scars are indicated at the right hand side (yr AD) (from Paper IV).*

We suggest different mechanisms that may explain why recent fires showed up to a low degree in the peat columns; (*i*) distances from the mire edges to the forest on the mineral soil may have been too large at the time of the more recent historic fire events, (*ii*) different peat accumulation rates at the sites have caused imprecisely datings, *(iii*) many of the historical fires have been low-severe fires that do not produce macroscopic charcoal record in the peat. Higuera et al. (2005) for example found that many moderate and low intensity fires were missing in sediment charcoal records. Finally, the match between charcoal and tree-ring data might have been better if we had included smaller fractions of the macroscopic charcoal record, i.e. sizes down to 0.15 mm wide, in the analysis (Higuera et al. 2005).

Although the peat and tree-ring data showed weak correspondence in our study, we conclude that the two methods still complement each other. Only tree-ring analysis provides proof of recent fires, but the peat provides information about the fire history at the scale of millennia. Thus, we agree with Niklasson et al. (1998) who concluded that this combination of methods has great potential for high resolution studies in fire and vegetation history.

Conclusion

This thesis documents a high spatial and temporal resolution of historical forest fires in Trillemarka-Rollagsfjell Nature Reserve. The results strengthen earlier studies showing that recurring fires, anthropogenically or naturally caused, historically have been a major disturbance factor affecting the structure and composition of the boreal forests of Fennoscandia. However, historical studies from Fennoscandia report large spatial and temporal variations in the fire regime due to variations in climate, topography and anthropogenic influence (Engelmark 1987, Niklasson and Granström 2000, Pitkänen et al. 2003, Hellberg et al. 2004).

We found relatively few, but often rather large, fires in the landscape from 1300s up to the beginning of the 1600s, a period supposedly representing a relatively natural fire regime, possibly influenced by humans already from the late 1500s. Thereafter, number of fires increased abruptly and stayed high till late 1700s. The temporally and spatially occurrence of fires, together with the signs of past human influence, indicate that the most likely reason for the sudden increase and following decline in fire frequency was due to changes in human-caused fires. It appears unlikely that the observed decline in fires could be due to active fire suppression or climate change.

When Trillemarka-Rollagsfjell Nature Reserve, the largest forest reserve in Norway, was put under protection in 2008, the purpose was to “preserve a large and continuous natural forest with natural flora and fauna and natural processes that take place in the forest” (Forvaltningsstyret 2014). This thesis shows that the historical fire frequency has been “unnaturally” high for 200 years (1600s and 1700s) and then “unnaturally” low for 200 years (1800s and 1900s) , strongly affected by anthropogenic influence. This substantial increase and decrease in fires in the past has probably had considerable impacts on structure and composition of the forests. Hopefully, this knowledge will be taken into account when evaluating present-day forest and nature reserve management.

References

Agee, J. K. 1990. The historical role of fire in Pacific Northwest forests. *In* J. D. Walstad, S. R. Radosevich, and D. V. Sandberg. (eds). Natural and prescribed fire in the Pacific Northwest. Oregon State University Press, Corvallis, OR. pp. 25-38.

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington D C.

Arno, S. F. and K. M. Sneck. 1977. A method for determining fire history in coniferous forests of the mountain west. USDA Forest Service General Technical Report INT-42. Intermountain Forest and Range Experiment Station, Ogden, UT.

Asheim, V. 1978. Kulturlandskapets historie. Oslo: Universitetsforlaget. [In Norwegian.]

Baisan, C. H. and T. W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research 20: 1559-1569.

Bendiksen, E. 2004. Barskogsundersøkelser med hensyn til biologiske verdier i forbindelse med verneplan for Trillemarka - Rollag Ostfjell. Norwegian Institute for Nature Research,Oppdragsmelding 830. [In Norwegian.]

Benedictow, O. J. 2002. Svartedauden og senere pestepidemier i Norge. Unipub forlag Oslo, Norway. [In Norwegian.]

Berg, B.I. 1998. Gruveteknikk ved Kongsberg Sølvverk 1623–1914. STS Report 37. Centre for Technology and Society, Norwegian University of Science and Technology, Trondheim, Norway. [In Norwegian.].

Berg, B.I. 2001. Far from O.K. Corral - Crime and court practice in the eighteenth century - Norwegian mining town of Kongsberg. *In:* J.E. Fell, P.D. Nicolaou, and G.D. Xydous (eds.). Book of Proceedings - 5th International Mining History Congress. Milos Conference Center, Milos Island, Greece. pp. 422-426.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72: 1980-1992.

Bergeron, Y., D. Cyr, C. R. Drever, M. Flannigan, S. Gauthier, D. Kneeshaw, E. Lauzon, A. Leduc, H. Le Goff, D. Lesieur, and K. Logan. 2006. Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. Canadian Journal of Forest Research 36: 2737-2744.

Bergeron, Y., S. Gauthier, V. Kafka, P. Lefort, and D. Lesieur. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Canadian Journal of Forest Research 31: 384-391.

Bergeron, Y., A. Leduc, B.D. Harvey, and S. Gauthier. 2002. Natural fire regime: a guide for sustainable management of the Canadian boreal forest. Silva Fennica 36: 81-95.

Berglund, B. E. and M. Ralska-Jasiewiczowa. 1986. Pollen analysis and pollen diagrams. *In:*B.E. Berglund (ed.). Handbook of Holocene Palaeoecology and Palaehydrology. Chichester: John Wiley & Sons Ltd. pp 455-484.

Biondi, F. and F. Qeadan. 2008. A theory-driven approach to tree-ring standardization: defining the biological trend from expected basal area increment. Tree-Ring Research 64: 81-96.

Blaauw, M. 2010. Methods and code for ‘classical’ age-modelling of radiocarbon sequences. Quaternary Geochronology 5: 512-518.

Bleken, E., I. Mysterud, and I. Mysterud. 1997. Forest fire and environmental management: A technical report on forest fire as an ecological factor. Directorate for Fire & Explosion Prevention and Department of Biology, University of Oslo, Norway.

Brown, P. M. and T. W. Swetnam. 1994. A cross-dated fire history from Coast Redwood near Redwood National Park, California. Canadian Journal of Forest Research 24: 21-31.

Castagneri, D., K. O. Storaunet, and J. Rolstad. 2013. Age and growth patterns of old Norway spruce trees in Trillemarka forest, Norway. Scandinavian Journal of Forest Research 28: 232-240.

Clark, J. S. and P. D. Royall. 1995. Transformation of a northern hardwood forest by aboriginal (Iroquois) fire: charcoal evidence from Crawford Lake, Ontario, Canada. The Holocene 5: 1-9.

DeBano, L. F., D. G. Neary, and P. F. Ffolliott. 1998. Fire`s Effects on Ecosystems. John Wiley & Sons, New York.

Dieterich, J. H. 1980. The Composite Fire Interval - a tool for more accurate interpretation of fire history. Pages 8-14 *in* Proceedings of the Fire History Workshop. General Technical Report RM-GTR-81. Ft. Collins, CO: USDA, Tucson, Arizona, 20-24 October 1980. 142 pp.

Dieterich, J. H. and T. W. Swetnam. 1984. Dendrochronology of a fire-scarred ponderosa pine. Forest Science 30: 238-247.

Douglass, A. E. 1941. Crossdating in dendrochronology. Journal of Forestry 39: 825-831.

Eidem, P. 1959. En grunnskala til tidfesting av trevirke fra Flesberg i Numedal. Blyttia 17: 69-85. [In Norwegian.]

eklima.met.no: Norwegian Meteorological Institute. Oslo, Norway. Accessed Oct. 10, 2013.

Engelmark, O. 1984. Forest fires in the Muddus National Park (northern Sweden) during the past 600 years. Canadian Journal of Botany 62: 893-989.

Engelmark, O. 1987. Fire history correlations to forest type and topography in northern Sweden. Annales Botanici Fennici 24: 317-324.

Engelmark, O., L. Kullman, and Y. Bergeron. 1994. Fire and age structure of Scots pine and Norway spruce in northern Sweden during the past 700 years. New Phytologist 126: 163-168.

Esseen, P.-A., B. Ehnström, L. Ericson, and K. Sjöberg. 1997. Boreal forests. Ecological Bulletins 46: 16-47.

Flannigan, M. D., Y. Bergeron, O. Engelmark, and B. M. Wotton. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469–476.

Forvaltningsstyret. 2014. Forvaltningsplan for Trillemarka-Rollagsfjell naturreservat. [In Norwegian].

Frelich, L. E. 2002. Forest dynamics and disturbance regimes: studies from temperate evergreen-deciduous forests. Cambridge University Press, Cambridge.

Fritts, H. C. 1976. Tree Rings and Climate. Academic Press, London.

Fryjordet, T. 1992. Skogadministrasjon i Norge gjennom tidene. Bind I. Skogforhold, skogbruk og skogadministrasjon fram til 1850. Norwegian Department of Agriculture and Directorate of State Forests, Oslo, Norway. [In Norwegian].

Fulé, P. Z., W. W. Covington, and M. M. Moore. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine. Ecological Applications 7: 895-908.

Giesecke, T. and K. D. Bennett. 2004. The Holocene spread of *Picea abies* (L.) Karst. in Fennoscandia and adjacent areas. Journal of Biogeography 31: 1523–1548.

Gill, A. M. 1974. Toward an understanding of fire-scar formation: field observation and laboratory simulation. Forest Science 20: 198-205.

Gillson, L. and K. J. Willis. 2004. 'As Earth's testimonies tell': wilderness conservation in a changing world. Ecology Letters 7: 990-998.

Granström, A. 2001. Fire management for biodiversity in the European boreal forest. Scandinavian Journal of Forest Research 16: S3: 62-69.

Granström, A. and M. Niklasson. 2008. Potentials and limitations for human control over historic fire regimes in the boreal forest. Philosophical Transactions of the Royal Society 363: 2351-2356.

Groven, R. and M. Niklasson. 2005. Anthropogenic impact on past and present fire regimes in a boreal forest landscape of southeastern Norway. Canadian Journal of Forest Research 35: 2719-2726.

Hafsten, U. 1992. The immigration and spread of Norway spruce (*Picea abies* (L.) Karst.) in Norway. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography 46: 121 - 158.

Heinselman, M. L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Research 3: 329-382.

Hellberg, E., M. Niklasson, and A. Granström. 2004. Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. Canadian Journal of Forest Research 34: 332-338.

Higuera, P. E., D. G. Sprugel, and L. B. Brubaker. 2005. Reconstructing fire regimes with charcoal from small-hollow sediments: A calibration with tree-ring records of fire. The Holocene 15: 238–251.

Hofton, T. H. 2003. Trillemarka-Rollagsfjell: en sammenstilling av registreringer med hovedvekt på biologiske verdier. [Trillemarka-Rollagsfjell: Field inventories with emphasis on biological values]. Siste Sjanse-rapport 2003–5. Oslo. [In Norwegian.]

Hofton, T. H. 2004. Supplerende biologiske registreringer i Trillemarka-Rollagsfjell [Supplementary biological inventories of Trillemarka-Rollagsfjell]. Siste Sjanse-notat 2004-2. Oslo. [In Norwegian.]

Hooge, P. N. and B. Eichenlaub. 2000. Animal Movement extension to ArcView, ver. 1.1. Alaska Biological Science Center, U.S. Geological Survey, Anchorage, AK.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and mesurement. Tree Ring Bulletin 43: 69-78.

Holmes, R. L. 1994. Dendrochronology program library. User manual. Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona.

Hunt, S. M. and J. A. Simpson. 1985. Effects of Low Intensity Prescribed Fire on the Growth and Nutrition of a Slash Pine Plantation. Australian Forest Research 15: 67-77.

Jiang, Y. Y., Q. L. Zhuang, M. D. Flannigan, and J. M. Little. 2009. Characterization of wildfire regimes in Canadian boreal terrestrial ecosystems. International Journal of Wildland Fire 18: 992-1002.

Johansen, R. W. and D. D. Wade. 1987. Effects of crown scorch on survival and diameter growth of slash pines. Southern Journal of Applied Forestry 11: 180-184.

Johnson, E. A. 1992. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University Press, Cambridge, UK.

Johnson, E. A., G. I. Fryer, and M. J. Heathcott. 1990. The influence of man and climate on frequency of fire in the interior wet belt forest, British-Columbia. Journal of Ecology 78: 403-412.

Johnson, E. A., K. Miyanishi, and J. M. H. Weir. 1995. Old-growth, disturbance and ecosystem management. Canadian Journal of Botany 73: 918-926.

Jowsey, P. C. 1966. An improved peat sampler. New Phytologist 65: 245-248.

Keyser, T. L., F. W. Smith, and W. D. Shepperd. 2010. Growth Response of Pinus ponderosa following a Mixed-Severity Wildfire in the Black Hills, South Dakota. Western Journal of Applied Forestry 25: 49-54.

Leblanc, D. C., N. S. Nicholas, and S. M. Zedaker. 1992. Prevalence of individual-tree growth decline in red spruce populations of the Southern Appalachian Mountains. Canadian Journal of Forest Research 22: 905-914.

Lehtonen, H. 1998. Fire history recorded on pine trunks and stumps: influence of land use and fires on forest structure in North Karelia. Scandinavian Journal of Forest Research 13: 462-468.

Lehtonen, H. and P. Huttunen. 1997. History of forest fires in eastern Finland from the fifteenth century AD - The possible effects of slash-and-burn cultivation. The Holocene 7: 223-228.

Lehtonen, H. and T. Kolström. 2000. Forest fire history in Viena Karelia, Russia. Scandinavian Journal of Forest Research 15: 585-590.

Lid, J. and D. T. Lid. 2005. Norsk Flora. Elven, R. (ed) 7th ed. Det Norske Samlaget, Oslo. [In Norwegian.].

Linder, P., B. Elfving, and O. Zackrisson. 1997. Stand structure and successional trends in virgin boreal forest reserves in Sweden. Forest Ecology and Management 98: 17-33.

Luterbacher, J., D. Dietrich, E. Xoplaki, M. Grosjean, and H. Wanner. 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303: 1499-1503.

Madany, M. H., T. W. Swetnam, and N. E. West. 1982. Comparison of two approaches for determining fire dates from tree scars. Forest Science 28: 856-861.

Malamud, B. D., J. D. A. Millington, and G. L. W. Perry. 2005. Characterizing wildfire regimes in the United States. Proceedings of the National Academy of Sciences of the United States of America 102: 4694-4699.

Moen, A. 1999. National atlas of Norway: Vegetation. Norwegian Mapping Authority, Hønefoss.

Molinari, C., R. H. W. Bradshaw, O. Risbøl, M. Lie, and M. Ohlson. 2005. Long-term vegetational history of a *Picea abies* stand in south-eastern Norway: Implications for the conservation of biological values. Biological Conservation 126: 155-165.

Moore, M. M., W. W. Covington, and P. Z. Fule. 1999. Reference conditions and ecological restoration: A southwestern ponderosa pine perspective. Ecological Applications 9: 1266-1277.

Morgan, P., G. H. Aplet, J. B. Haufler, H. C. Humphries, M. M. Moore, and W. D. Wilson. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry 2: 87-111.

Mork, E. 1960. On the relationship between temperature, leading shoot increment and the growth and lignification of the annual ring in Norway spruce (*Picea abies* (L.) Karst). Meddelelser fra Det Norske Skogforsøksvesen 16: 225-261.

Motta, R., M. Morales, and P. Nola. 2006. Human land-use, forest dynamics and tree growth at the treeline in the Western Italian Alps. Annals of Forest Science 63: 739-747.

Mørch, A. 1954. Sigdal og Eggedal. Bind III. Gard og slekt. Sigdal og Eggedal historielag, Drammen, Norway. [In Norwegian.].

Niklasson, M., O. Zackrisson, and L. Östlund. 1994. A dendroecological reconstruction of Saami use of Scots pine (Pinus sylvestris L.) innerbark around Lake Sädvajaure, N. Sweden. Journal of Vegetation History and Archaeobotany 3: 183-190.

Niklasson M., G. Hörnberg, and O. Zackrisson. 1998. Age structure and disturbancehistory in a boreal *Pinus-Picea* forest, N. Sweden. Silvestria 52, Doctoral thesis. Umeå: Swedish University of Agricultural Sciences, 14.

Niklasson, M. and A. Granström. 2000. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81: 1484-1499.

Nonaka, E. and T. A. Spies. 2005. Historical range of variability in landscape structure: A simulation study in Oregon, USA. Ecological Applications 15: 1727-1746.

Ohlson, M., A. Korbøl, and R. H. Økland. 2006. The macroscopic charcoal record in forested boreal peatlands in southeast Norway. The Holocene 16: 731-741.

Ohlson, M., K. J. Brown, H. J. B. Birks, J. A. Grytnes, G. Hörnberg, M. Niklasson, H. Seppä, and R. H. W. Bradshaw. 2011. Invasion of Norway spruce diversifies the fire regime in boreal European forests. Journal of Ecology 99: 395-403.

Ohlson, M., I. Kasin, A. Nordtug Wist, and A. E. Bjune. 2013. Size and spatial structure of the soil and lacustrine charcoal pool across a boreal forest watershed. Quaternary Research 80: 417-424.

Olsson, F., M.-J. Gaillard, G. Lemdahl, A. Greisman, P. Lanos, D. Marguerie, N. Marcoux, P. Skoglund, and J. Wäglind. 2010. A continuous record of fire covering the last 10,500 calender years from southern Sweden: The role of climate and human activities. Palaeogeography, Palaeoclimatology, Palaeoecology 291: 128–141.

Pauling, A., J. Luterbacher, C. Casty, and H. Wanner. 2005. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Climate Dynamics 26: 387-405.

Pennanen, J. 2002. Forest age distribution under mixed severity fire regimes – a simulation-based analysis for middle boreal Fennoscandia. Silva Fennica 36: 213–231.

Peterson, D. L., M. J. Arbaugh, and L. J. Robinson. 1991. Regional growth changes in ozone-stressed ponderosa pine (*Pinus ponderosa*) in the Sierra Nevada, California, USA. The Holocene: 50-61.

Pitkänen, A., P. Huttunen, K. Tolonen, and H. Jungner. 2003. Long-term fire frequency in the spruce-dominated forests of the Ulvinsalo strict nature reserve, Finland. Forest Ecology and Management 176: 305-319.

Pitkänen, A., J. Turunen, and K. Tolonen. 1999. The role of fire in the carbon dynamics of a mire, eastern Finland. The Holocene 9: 479-488.

Reinhardt, E. D. and K. C. Ryan. 1988. Eight-year tree growth following prescribed underburning in a western Montana Douglas-fir/ Western larch stand. Research Note INT-387. 6 pp. US: US Forest Service.

Rokseth, O., A. Pleym, and F. Dahlslett. 2001. Sammenstilling av lyndata for perioden 1996-2001. Sintef Energy Research, Technical Report TR A5503. [In Norwegian.]

Rowe, S. J. and G. W. Scotter. 1973. Fire in the boreal forest. Quaternary Research 3: 444-464.

Ryan, K. C. 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica 36: 13-39.

Scheller, R. M., D. J. Mladenoff, R. C. Thomas, and T. A. Sickley. 2005. Simulating the effects of fire reintroduction versus continued fire absence on forest composition and landscape structure in the Boundary Waters Canoe Area, northern Minnesota, USA. Ecosystems 8: 396-411.

Schimmel, J. and A. Granström. 1997. Fuel succession and fire behavior in the Swedish boreal forest. Canadian Journal of Forest Research 27: 1207-1216.

Segerström, U., R. Bradshaw, G. Hörnberg, and E. Bohlin. 1994. Disturbance history of a swamp forest refuge in northern Sweden. Biological Conservation 68: 189-196.

Sherriff, R. L. and T. T. Veblen. 2007. A spatially-explicit reconstruction of historical fire occurrence in the ponderosa pine zone of the Colorado Front Range. Ecosystems 10: 311-323.

Skatvedt, T. 1914. Sigdal og Eggedal. Historisk beretning. Grøndahl & Søns Boktrykkeri, Kristiania, Norway. [In Norwegian.]

Skogdirektøren. 1909. Skogvæsenets historie - Utgit i anledning av det offentlige skogvæsens 50-aarige virksomhet 1857-1907. 1. del - Historik. Grøndahl & Søns Boktrykkeri, Kristiania, Norway. [In Norwegian].

Stephenson, N. L. 1999. Reference conditions for giant sequoia forest restoration: Structure, process, and precision. Ecological Applications 9: 1253-1265.

Stokes, M. A. and T. L. Smiley. 1968. An introduction to tree-ring dating. University of Chicago Press, Chicago.

Storaunet, K. O., J. Rolstad, I. Gjerde, and V. S. Gundersen. 2005. Historical logging, productivity, and structural characteristics of boreal coniferous forests in Norway. Silva Fennica 39 :429-442.

Swetnam, T. W. 1993. Fire history and climate-change in Giant Sequoia Groves. Science 262: 885-889.

Swetnam, T. W., C. D. Allen, and J. L. Betancourt. 1999. Applied historical ecology: Using the past to manage for the future. Ecological Applications 9: 1189-1206.

Tande, G. F. 1979. Fire history and vegetation pattern of coniferous forests in Jasper National Park, Alberta. Canadian Journal of Botany 57: 1912-1931.

Tveite, S. 1964. Skogbrukshistorie. *In:* H. K. Seip (ed.). Skogbruksboka. Bind 3: Skogøkonomi. Skogforlaget, Oslo, Norway. pp. 17-75. [In Norwegian.]

Tvengsberg, P. M. 1995. Det värmlandsfinske svedjebruket. *In:* B. Larsson (ed.). Svedjebruk och röjningsbränning i Norden. Nordiska museet. Skrifter om skogs- och lantbrukshistorie 7: 109-18. [In Swedish.]

Uggla, E. 1974. Fire ecology in Swedish forests. In: Proceedings annual Tall Timbers fire ecology conference; 1973 March 22-23; Tallahassee, FL. No. 13: 171-190.

Van Wagner, C. E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8: 220-227.

Waldrop, T. A. and D. H. Van Lear. 1984. Effect of crown scorch on survival and growth of young loblolly Pine. Southern Journal of Applied Forestry 8: 35-40.

Wallenius, T. H., T. Kuuluvainen, and I. Vanha-Majamaa. 2004. Fire history in relation to site type and vegetation in Vienansalo wilderness in eastern Fennoscandia, Russia. Canadian Journal of Forest Research 34: 1400-1409.

Wallenius, T. H., S. Lilja, and T. Kuuluvainen. 2007. Fire history and tree species composition in managed *Picea abies* stands in southern Finland: Implications for restoration. Forest Ecology and Management 250: 89-95.

Wallenius, T. 2011. Major decline in fires in coniferous forests - reconstructing the phenomenon and seeking for the cause. Silva Fennica 45: 139-155.

Weber, M. G. and M. D. Flannigan. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environmental Reviews 5: 145–166.

Weir, J. M. H., E. A. Johnson, and K. Miyanishi. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. Ecological Applications 10: 1162-1177.

Willis, K. J. and H. J. B. Birks. 2006. What is natural? The need for a long-term perspective in biodiversity conservation. Science 314: 1261-1265.

Willis, K. J., M. B. Araujo, K. D. Bennett, B. Figueroa-Rangel, C. A. Froyd, and N. Myers. 2007. How can a knowledge of the past help to conserve the future? Biodiversity conservation and the relevance of long-term ecological studies. Philosophical Transactions of the Royal Society B: Biological Sciences 362: 175-186.

Wooldridge, D. D. and H. Weaver. 1965. Some effects of thinning a ponderosa pine thicket with a prescribed fire, II. Journal of Forestry 63: 92-95.

Wyant, J. G., R. D. Laven, and P. N. Omi. 1983. Fire effects on shoot growth characteristics of ponderosa pine in Colorado. Canadian Journal of Forestry 13: 620-625.

Yamaguchi, D. K. 1991. A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research 21: 414-416.

Zackrisson, O. 1977. Influence of forest fires on the North Swedish boreal forest. Oikos 29: 22-32.

Zumer, M. 1969. Årringdannelse hos gran i fjellskog. Meddelelser fra Det Norske Skogforsøksvesen 27: 161-184. [In Norwegian.]

PAPER I

Historic range of variability in the fire regime of a Fennoscandian boreal forest – a 700-year dendroecological reconstruction from the Trillemarka-Rollagsfjell Nature Reserve in south-central Norway

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Abstract. Knowing the historic range of variability in fire regimes is pivotal to succeed in predicting what may happen in the future. By cross-dating 745 fire-scars in 378 samples of remnant Scots pines we delineated the spatial pattern of 254 individual forest fires during the past 700 years in a 74 km^2 section of Trillemarka-Rollagsfjell Nature Reserve in south-central Norway. Their size, numbers, and frequency were compared with historical climate proxies, vegetation maps, and written sources. The results revealed patterns consistent with a predominantly natural fire regime up till 1625, followed by periods of strong anthropogenic impact that increased fire frequency during 1600-1700s and diminished fires during 1800-1900s. This was documented by (*i*) an abrupt shift towards more frequent and smaller fires from 1625 and a cease of fire after 1800, (*ii*) a sudden increase in early-season fires from 1625, (*iii*) a marked shift in fire return intervals and hazard of burning post 1625, (i*v*) a positive relationship between summer temperature and annual burnt area pre-1625, which was far less pronounced post-1625, and (*v*) written sources that described anthropogenic forest fires and slash-and-burn cultivation expanding with the increasing population from the late 1500s and subsequently diminishing due to increasing timber values during 1700s and 1800s. Spruce forests burned less often (rotation 250-1000 years) than pine forests (150-300 years). Finally, we found our pre-1625 historical fire recurrence intervals notably shorter than recent intervals from North America and Canada, indicating that it burnt more often in the past in the Trillemarka-Rollagsfjell Nature Reserve than present wildfire ecoregions of North America. We conclude that fire has been a dominating disturbance factor prior to ca. 1800, both natural and man-made, and that the last 200-year fire-free period is unprecedented during the last 700 years.

Key words: anthropogenic influence; climate; Fennoscandian boreal forest; fire history; fire recurrence intervals; fire return intervals; Norway; Trillemarka-Rollagsfjell Nature Reserve.

Introduction

Being the most important disturbance agent in the boreal forest (Heinselman 1973, Zackrisson 1977, Ryan 2002), fire of variable severity creates a mosaic of burnt and unburnt patches, affects the species composition and age-class distribution of stands (Zackrisson 1977, Zackrisson and Östlund 1991), and thereby enhances spatial heterogeneity (Bergeron et al. 2002). For example, in the Fennoscandian boreal forests, frequent fires tend to favour Scots pines (*Pinus sylvestris* L.) and birch (*Betula* spp.), whereas lack of fire tends to favour shade-tolerant late-successional species like Norway spruce (*Picea abies* (L.) Karst.) (Viro 1974, Oliver and Larson 1990, Granström 1991, Bradshaw 1993). Furthermore, fire opens up the forest and releases nutrients, benefits forest regeneration and creates structural elements such as charred and decaying wood that are important for biodiversity (Esseen et al. 1997, Granström 2001, Bergeron et al. 2002). Thus, forest fire is of vital importance in maintaining diverse and productive ecosystems, especially in the boreal forest (Hirsch and Fuglem 2006).

On the other hand, high-severity fires also can be detrimental and possess a major threat to human settlements and forest industry. Each year fires cause millions of hectares of forest to be destroyed, a large amount of forest fire fighting expenses, and loss of lives and recreational value. For example, in Canada, about 8,600 wildland fires, covering an annual burnt area average of about 2.5 million hectares of forest and wooded land, have occurred over the past three decades with an annual cost for suppression and wildland fire management exceeding 500 million Canadian dollars (Taylor et al. 2006). Thus, sustainable management of fire-dependent ecosystems requires optimising both the socio-economic effects of fire and its ecological benefits. In this respect, it has frequently been suggested that an understanding of natural disturbances, such as fire, can provide important guidance for present forest management and restoration of ecosystems (Angelstam 1998, Bergeron et al. 2002).

Fire regime is used as a collective term describing the spatial pattern, temporal frequency, and behavioural characteristics of fires confined to a certain spatially defined area and temporally defined time period. Fire frequency is probably the most commonly reported characteristic of the fire regime. However, the term has been used in the literature with a variety of different meanings. Here we use fire frequency either in a general sense for temporal characteristics of a fire regime, or in a narrow sense where we clearly define its meaning. Annual percent burnt incorporates both number and size of fires per unit area per unit time. However, a general problem using annual percent burnt is that even though it indicates that fires have burnt a proportion annually within the period measured, it says nothing about the nature of fires (Li 2000), i.e. the number or sizes of individual fires. The same area burnt can thus result from either a large number of small fires or a small number of large fires, which complicates the interpretation of fire history by only using area burnt (Niklasson and Granström 2000). The reciprocal of percent annual burnt area is the fire rotation period, which is the time required to burn an area equal to a defined area of interest (Grissino-Mayer 1999).

Forest fires typically exhibit robust size-frequency power-law behaviour (Niklasson and Granström 2000, Malamud et al. 2005, Jiang et al. 2009). In order to measure how often a fire of a certain size burns in an area, size-class distribution of fires and recurrence intervals are often used. Fire recurrence intervals are based on the annual probability that in a defined spatial area, a given size event will be equalled or exceeded (Malamud et al. 2005). Thus, size-frequency distributions and recurrence intervals are size-specific characteristics of a fire regime. Finally, some characteristics are defined at a specific site or a restricted area, i.e. they are site-specific as opposed to size specific characters. This incorporates the fire return interval, defined as “the number of years between the occurrence of fires at a given point” (Merrill and Alexander 1987), its counterpart hazard of burning (or instantaneous mortality), i.e. the yearly probability of a new fire in relation to time since the previous fire, and the corresponding survival distribution, i.e. the proportion of newly burnt area remaining unburnt over time (Johnson and Gutsell 1994).

Fire regimes are dynamic, varying in response to changes in climate, vegetation and human influence. Many fire history studies have reported a regime of frequent fires with average fire return intervals ranging from some decades to about 100 years during the period 1500-1850 (Heinselman 1973, Zackrisson 1977, Lehtonen and Kolström 2000). From the 1800s, there has been a marked reduction in forest fires in Fennoscandia and different hypotheses for this decline has been discussed, including fire suppression, climate change, overgrazing and human influence (Wallenius 2011). Variation in fire regime characteristics may spatially be explained by responses to parameters such as vegetation types or topographic breaks (Zackrisson 1977). For example, in Fennoscandia, dry pine-dominated forests have historically burnt at intervals of 20–60 years on average (Zackrisson 1977, Lehtonen and Kolström 2000, Niklasson and Drakenberg 2001), whereas some spruce-dominated swamps seem to have escaped fire for thousands of years (Hörnberg et al. 1995, Ohlson and Tryterud 1999).

Climatic or human caused influences on the fire regime are an important issue in many fire history studies (Niklasson and Granström 2000, Grissino-Mayer et al. 2004). Good estimates of historic numbers and sizes of fires may assist in separating the effects of climatic versus human influence (Grissino-Mayer and Swetnam 2000, Niklasson and Granström 2000, Hellberg et al. 2004). Changes in climate may modify both numbers and sizes of fires, which have been observed in several studies from North America (Bergeron 1991, Johnson 1992, Weber and Flannigan 1997). However, studies from Fennoscandia show that anthropogenic burning, with slash-and-burn techniques and burning to improve grazing conditions played an important role explaining the increase in the number of historical fires (Lehtonen and Huttunen 1997, Niklasson and Drakenberg 2001, Storaunet et al. 2013).

In North America, where high-intensity stand-replacing fires are common (Johnson 1992, Payette 1992), fire intervals may be calculated from the distribution of age classes (time since last fire) in the landscape (Van Wagner 1978, Johnson and Gutsell 1994). However, this method measures only a relatively short time period since each new fire destroys evidence of past burns. In low- to medium-severity fires, which often leave fire-scarred Scots pines behind (Zackrisson 1977, Engelmark et al. 1994, Kuuluvainen 2009, Wallenius et al. 2010), fire intervals can be calculated map-based (i.e. as the time between successive fires determined from spatially overlapping burnt areas delineated on a map) or scar-based (i.e. as the time between successive fires recorded by scars in single wooden samples). Tree-ring reconstructions of fire history may cover relatively long time periods (ca. 300-800 years) and may also offer precise information regarding fire years and season (Zackrisson 1977, Niklasson and Granström 2000, Groven and Niklasson 2005). Thus, by using fire scars and dendrochronological dating methods, the spatial and temporal fire history regime in an area can be rather accurately assessed (Fritts and Swetnam 1989). In this study, we used an intensive sampling of fire-scarred material that covered an extended period, to document past human and climatic influence on the fire regime. To our knowledge, no other study from boreal Eurasia has estimated and compared fire size distributions and fire recurrence intervals.

The study was performed within and around a nature reserve in south-central Norway, with a diverse topography, and dominated by the Scots pine (*Pinus sylvestris*) and Norway spruce *(Picea abies*). The general aims were: (1) to combine cross-dated fire-scarred pine woods to delineate the spatial and temporal pattern of individual forest fires as far back as possible, (2) to estimate fire regime characteristics, such as numbers and sizes of fires, percent annually burnt area, season, fire intervals, survival and hazard, and (3) to explore possible drivers and determinants influencing the fire regime, such as climate, landscape characteristics and anthropogenic activity.

MATERIAL AND METHODS

Study area

The study area encompasses 74 km^2 of forested and mountainous land between the Sigdal and Numedal valleys in Buskerud county, south-central Norway, bounded by parallels 59°59'-60°04'N and meridians 9°19'- 9°29'E (Fig. 1). It includes a 38.6 km^2 southern part of the Trillemarka-Rollagsfjell Nature Reserve and 35.3 km^2 of neighbouring private land. The reserve that was established in 2002 covers 147 km^2 altogether and it is one of a few large and relatively undisturbed forested areas remaining in southern Fennoscandia. Nonetheless, many remains and traces of past anthropogenic activity exist, including cut stumps, old tracks, and historic summer dairy farms (Storaunet et al. 2005). Notably, historical forest fires, windstorms and natural successions in the forest landscape have provided a mosaic and variation in vegetation and forest types. The area was chosen due to the presence of numerous remnants of fire scarred Scots pine, historical features that are rare to find in many managed landscapes of today. A detailed small-scale study of the fire history emphasised that anthropogenic forest fires were common during the 1600-1700s (Storaunet et al. 2013).

The area is located in the mid-boreal vegetation zone (Moen 1999) and the climate is intermediate oceanic and continental, characterised by long winters and short summers with an average annual precipitation of 800 mm. Snow covers the ground from November-December to mid-May but with large variations due to elevation and aspect. Mean annual temperature is +4°C, with mean monthly temperatures varying from -4°C in January to +15°C in July (eklima.met.no). Altitude ranges from 300 to 900 m a.s.l., but even though the area is below the regional tree line, most of the terrain above 750-800 m lacks closed-canopy forest stands and the mountain tops are usually barren. Mires are common in depressions and on flat ground. Topography is undulating with a Precambrian basement rock that consists of quartzite and granites, with some elements of gneisses in the southern part. The dominance of nutrient-poor rocks gives a poor acidic podsol-type soil profile.

For the purpose of this study, we categorized the study area in four main vegetation types: pine-dominated forest, spruce-dominated forest, mire, and mountain (Moen 1999). The pine-dominated forest (>50% Scots pine trees in upper canopy layer) occupies the nutrient-poor and dry sites and also areas bordering larger mire systems. It is characterised by various lichen (*Cladonia* spp.), heather (*Calluna vulgaris*), and dwarf-shrub (*Vaccinium* spp.) communities. The spruce-dominated forest (>50% Norway spruce trees in upper canopy layer) is found on the more fertile mesic and moist sites, characterised by bilberry (*V.*

myrtillus) but also various grass and herb species. Mires consist of treeless bogs >1 ha, mostly ombrotrophic in nature, and characterised by peat moss depositions (*Sphagnum* spp.) and various species of sedge (*Carex* spp.) and cottongrass (*Eriophorum* spp.). Mountain comprises various high elevation vegetation types, mostly treeless, but often includes a narrow zone of downy birch (*Betula pubescens* Ehrh.) and scattered patches of stunted spruce trees. No larger patches of pure deciduous forest exist in the area. However, tree species that occur sparsely and scattered within the pine and spruce forests include downy birch, rowan (*Sorbus aucuparia* L.), aspen (*Populus tremula* L.), and grey alder (*Alnus incana* (L.) Moench).

Sampling

Excluding larger bodies of open water and treeless mountainous areas, the area of forest and mires was 59 km^2. From the outset, we divided our study area into a 1x1 km grid and we searched each square for fire-scarred material with a primary aim to collect 5-6 samples per km^2. In locations with a high density of fire-scarred material, samples with the greatest number of visible fire scars and those that were least decayed were given priority. Sampling was impeded at some locations due to lack of available fire-scarred material, especially in spruce-dominated forests and at higher elevations. Approximately 13% of the 1 km-squares had no samples, whereas mean number of samples in the other squares was 7.0 (range 1 – 22).

During summers and falls of 2009 and 2010, we collected fire-scarred material from stumps, snags, down logs and living trees of Scots pine using a chainsaw (Arno and Sneck 1977, McBride 1983). Samples were collected on average 0.4 m above ground. Most samples were taken from old stumps and the tree pith was included whenever possible. Living trees with fire scars were rare, with only 5% of samples coming from living or recently dead trees. The oldest living pine sampled was 494 years old. A 2-5 cm thick partial cross-section was extracted from the region of the tree that appeared to have the most complete fire record. In cases where scars on multiple sides or heights appeared to have recorded different fires, multiple cross-sections were extracted.

We collected wood samples from a total of 410 pine trees, of which 81 samples could not be dated because they were in too bad condition due to decay, or because they had a complacent tree-ring pattern. We also included 49 dated fire-scarred samples randomly drawn from a total of 321 samples previously collected in a 3.6 km^2 subsection of our study area (Storaunet et al. 2013). This sample density (13-14 per km^2) was approximately the same as those parts of our study area where we found the most samples. Altogether this amounted to 378 samples having a total of 745 fire scars (Fig. 1, Fig. 2).

To estimate the total recording area we drew a buffer around our GPS tracklogs. Since we only brought one GPS during fieldwork, we used buffer-zones of 30, 50 and 70 metres when we were 1, 2 or 3 persons, respectively. This "recording transect" covered 38% of the total forest and mire area (Fig. 1).

Dendrochronological and seasonal dating

Wood samples were brought to the laboratory where they were dried and sanded down to grit 400 with a belt sander to make the tree ring sequences appear clear and so that tree rings and fire scars could be easily distinguished under a microscope. Zinc paste and a scalpel were used when needed to assure better visibility of the ring pattern. The annual ring widths were measured with an Addo micrometre (accuracy of 0.01 mm) and the tree-series were cross-dated against three different chronologies using the program COFECHA (Holmes 1983, 1994): (1) Flesberg chronology (Eidem 1959) was developed from 97 trees with a sample depth of ≥5 tree-ring series dating back to 1526, (2) Rollag pine chronology (45 trees with ≥5 tree-ring series from 1373), and (3) Sigdal pine chronology (117 trees with ≥5 tree-ring series from 1248). The suggestions from the statistical cross-dating were thereafter confirmed by the pointer-year method (Douglass 1941, Stokes and Smiley 1968, Yamaguchi 1991, Niklasson et al. 1994). When other signs of fire in the morphology of the tree rings (e.g. bands of traumatic resin ducts and strong growth depressions or releases) occurred simultaneously with fire events dated in neighbouring trees, this was recorded as a positive fire indicator (Brown and Swetnam 1994).

Fire season can be determined by assessing the stage of tree ring development within the scar lesion (Baisan and Swetnam 1990). When the heat from the fire has killed the outermost row of living cells, these dead cells appears as collapsed under magnification. The collapsed cells relative position within the tree-ring reveals the season of the fire. Five categories were used to represent the seasonal growth: dormant (D), early early wood (EEW), middle early wood (MEW), late early wood (LEW), and latewood (LW). Mork (1960) and Zumer (1969) studied the seasonal cambial growth period of Norway spruce at Hirkjølen (860 m above sea level), about 200 km north of our study area. They found that the growth started in the first half of June and ended during August depending on the temperature. The approximate same seasonal cambial growth pattern was found in Scots pine in southern Finland (Schmitt et al. 2004). Using this information, we assumed that EEW roughly corresponds to first half of June, MEW to last half of June, LEW to first half of July, and LW to the end of July and beginning of August. This corresponds well to the authors' experience from coring living trees and subsequently studying the development of the current tree-ring. Few scars (2%) were classified to dormant season (D), and these were assumed to be early season fires instead of late fires occurring after growth season the previous year. This was done because in most cases other seasonal datings the same fire year were already classified to EEW and MEW. Fire season was determined for 60% of all dated fire scars and for 74% of all individual fires. A fire season index between 1 (dormant) and 5 (latewood) was calculated for each individual fire by averaging the individually dated scars.

Delineation of individual fires

We used ArcView GIS 3.3 software (ESRI Inc., Redlands, CA, USA) to delineate boundaries and areas of individual fires, by drawing polygons around samples recording a fire according to the following procedure. For each fire year, we first identified locations of all *recorder trees*, including fire-scarred samples, young trees, and trees previously scarred by a fire (see Storaunet et al. 2013 for further details). Then, we drew a buffer around the fire-scarred samples, varying in size from 100 to 800 m. The buffer width was assessed in each case, after considering all available information on the map: 1) number, location and patterning of the scarred samples the actual year, 2) number, location and patterning of the available trees not having a scar, including the relative positions to the scarred samples, 3) present vegetation and living trees that we did not sample, being increasingly important with time post 1700, 4) topographic elements like treeless mountain areas, mires, open water bodies and streams, and 5) terrain features like slope and aspect. Finally, the borders of individual fires were adjusted to make sure that fires occurring closely in time (<15 years) were not spatially overlapping (except when multiple fire scars in single trees indicated otherwise). The 15 years limit was chosen because only 1.8% of the scar intervals in our samples were of shorter duration.

Adjusting number and size of fires

Number and size of fires were underestimated back in time due to lower density of recorder trees. We applied a correction procedure to arrive at an adjusted estimate accounting for undetected small fires and underestimated fires sizes. Fires <3 ha were excluded from the procedure and subsequent analyses since these were assumed too small to be detected within our recording transect (i.e., when randomly distributing 3-ha fires within the study area, only

50% had >1 ha of their area within the transect). On the other hand, we believe to have recorded practically all fires >30 ha within the transect (i.e., when randomly distributing 30-ha fires, more than 95% had >1 ha of their area within the transect).

First, the number of fires that are discovered by a point sampling scheme within an area depends on the density of sample points since not all fires are large enough to contact ≥1 point. Assuming that fires occur randomly in the landscape, and that the sample points were randomly distributed within the recording transect (R = 0.95, Z = –1.65), the probability that a fire of area A will go undetected within the transect is the zero category of a Poisson distribution $e^{-\lambda A}$, with λ being the number of recorder trees divided by the total transect area. Detection probability is the complement $1 - e^{-\lambda A}$. In our data, the number of recorder trees increased gradually during the 1300s, being approximately 70 during the 1400s, and after 1492 it increased rapidly (Fig. 3), averaging 70 recorders during the period between 1300 and 1550. With 70 sample points and a transect area of 2 236 ha (forest and mire), the detection probability for fires of e.g. 10 ha is 0.27 (Table 1). After 1550 the number of recorder trees increased even more, to >250 during the 1600s, illustrating that scarred dead trees and stumps from this period had still not decayed. Additionally, we did not sample the huge numbers of non-scarred living trees that existed in the study area during the last two centuries (Storaunet et al. 2013). Thus, although the number of sampled recorder trees fell rapidly after 1750, the actual number of possible recorder trees observed in the field was >1 000. With 250 sample points, the detection probability of 10-ha fires is 0.67. Therefore, we choose to adjust number and size of fires for detection probability within transects only in the period 1300-1550.

Second, we divided the recorded fires ≥3 ha in four size classes: 3-5 ha, 5-10 ha, 10-30 ha, and >30 ha. Since we searched for fire scarred material only in 38% of the study area (i.e. the recording transect), we used the ratio between fire size within the transect and the mapped fire size within forest and mire to correct for missing fires occurring fully or partially outside the recording transect. E.g. for small recorded fires, possibly occurring completely within the transect, this ratio was 2.64 (1 / 0.38). Although this ratio decreases continuously with increasing fire size, we assumed this to be negligible within each fire size class. We therefore used the median value of the ratio within each fire size class as a correction factor (Table 1).

Finally, for simplicity, fires between 3 and 30 ha were adjusted by numbers only, whereas fires ≥30 ha were adjusted only by size. Number of fires was adjusted within five time periods (1300-1549, 1550-1624, 1625-1699, 1700-1799, and 1800-2009) based on the recorded number of fires in each size class. E.g. in size class 3-5 ha, two fires were recorded during 1300-1549 and the correction factor was 16.3 (Table 1), which gives an adjusted number of 33 fires. The 31 additional fires were given the same sizes as the recorded ones, and added randomly within the actual time period. Fires ≥30 ha had correction factors of 1.12 and 1.17 before and after 1550 (Table 1), respectively. Assuming that all fires of such sizes were recorded by our sampling, these fires were only increased in size with the corresponding factors.

Since we had no knowledge of where these additional fires were located in the study area, all analyses requiring site-specific information of individual fires were performed with unadjusted data only.

Size -specific frequencies and recurrence intervals

The inverse cumulative size distribution of all recorded fires and a normalised size-frequency distribution were calculated pre-1625 (1300-1624) and post-1625 (1625-1799) based on the timing of the anthropogenic influence on the fire regime (see Results section and Storaunet et al. 2013). To characterise the relationship between number (N_F) and size (A_F) of fires we defined the frequency density according to Malamud et al. (2005):

$$f\,(A_F) = \Delta N_F / \Delta A_F \qquad (1)$$

where ΔN_F is the number of fires in a "bin" of width ΔA_F, with log-equidistant bins of unit 1 km^2 and normalised by the period length (yr) and the size (km^2) of the study area (A_{SA}). Thus, the normalised frequency density is presented as the number of fires per km^2 unit bins per km^2 of the study area per year of the time period ($km^{-4}\ yr^{-1}$).

Following Malamud et al. (2005) we least-square fitted inverse power-law functions to the normalised size-frequency distributions and used the slope (β) and intercept (α) parameters to calculate size-specific fire recurrence intervals (T):

$$T\,(\geq A_F) = (\tau + 1 / \tau) \cdot (\beta - 1 / \alpha) \cdot A_F^{\,(\beta-1)}) / A_{SA} \qquad (2)$$

where A_F and A_{SA} are the size (km^2) of the fire and study area, respectively, and τ is the time period of interest (yr). Avoiding the outmost small and large fires, due to very small fires being overlooked and very large fires extending beyond the study area, fire recurrence intervals were calculated for fires ≥0.1 km^2, ≥1 km^2, and ≥10 km^2. Associated 95% confidence intervals were approximated with ±2 SDs from the least-square fitted power-law functions.

Site-specific return intervals, survival and hazard of burning

Fire return intervals (the site-specific return intervals as opposed to the size-specific recurrence intervals) were calculated based on successive overlapping fires from the map

(map-based) and from intervals between successive fire scars in each multiple-scarred tree sample (scar-based). The map-based intervals included the overlap area within the recording transect only, excluding open water bodies and tree-less mountainous areas. Frequency distributions were calculated pre-1625 (1300-1624) and post-1625 (1625-2009).

Cumulative survival functions and hazard of burning (or instantaneous mortality, Johnson and Gutsell 1994) were calculated pre- and post-1625 from all intervals using a life table survival analysis (actuarial algorithm of Statview 5.0, SAS Institute Inc., Cary, NC, USA). A censored observation is a minimum estimate of the true time-since-fire, used when the last fire event is unknown. All time intervals between successive overlapping fires were uncensored. For intervals crossing the year 1625, these were grouped to pre-1625 if more than half of the interval occurred pre-1625 (same for post-1625). If only one fire occurred pre 1625, the period between 1300 and the fire, the period between the fire and 1625, as well as the period 1625-2009, were all treated as censored intervals. A similar approach was used if only one fire occurred post-1625. All areas without fire were censored at 325 and 384 years pre- and post-1625, respectively. The scar-based analysis included only true (uncensored) intervals, with intervals crossing 1625 allocated to the period where most of the intervals occurred.

Climate

Gridded (0.5° × 0.5° resolution) reconstructed annual mean summer temperature (JJA) and precipitation sum extending back to 1500 AD were downloaded from the Climate Explorer of the Royal Netherlands Meteorological Institute (KNMI) (climexp.knmi.nl, Luterbacher et al. 2004, Pauling et al. 2005). The temperature series was extended further back to 1300 AD using a longer time series from The Netherlands (climexp.knmi.nl, Van Engelen et al. 2001) that correlated well with the Luterbacher series ($y = 0.93x - 1.07$, $R^2 = 0.81$). These reconstructions were based on comprehensive data sets including seasonally resolved proxy data from sea-ice, Greenland ice cores, and Scandinavian tree ring chronologies for the earlier centuries, and a large number of instrumental records from 1659 and onwards (Luterbacher et al. 2004). The gridded reconstructions were calibrated against local instrumental records from nearby meteorological stations. Temperature was adjusted to a combined Svene-Lyngdal 1927-2006 series ($y = 1.04x - 0.78$, $R^2 = 0.8$; St.nr. 28560, 59°46’12”N, 9°35’00”E, and St.nr. 28800, 59°54’31”N, 9°31’25”E), and precipitation was adjusted to the Hiåsen 1895-2013 series ($y = 1.03x + 2.67$, $R^2 = 0.74$; St.nr. 26240, 60°00’44”N, 9°30’36”E), all downloaded from the Norwegian Meteorological Institute (eklima.met.no). From the annual temperature and precipitation series we derived means and cumulative sums, respectively, for successive 25 year periods.

RESULTS

Numbers and sizes of fires

Altogether, we dated and outlined 254 individual fires within 130 separate fire years covering 753 years (AD 1257-2009). The pith year of the oldest living and dead Scots pine was AD 1515 and AD 1070, respectively. As many as 146 fires (57%) were recorded only in one tree sample with most of them occurring during the 1600s and 1700s. Only one fire (1257) was recorded before AD 1300, which seems to have been a small fire. However, due to low sampling depth in this early period, this fire was excluded from further analyses. From 1300 onwards, the observed number of recorder trees was assumed numerous enough to estimate the extent of individual fires throughout the study area (Fig. 4, Fig. 5). The largest fire occurred in 1499, covering 34% of the study area. Other large fires occurred in 1430, 1572, 1590 and 1652. Eleven out of 23 fires >100 ha (48%) appeared to have extended beyond the border of the study area.

Adjusting the dataset for undetected small fires increased the total number of fires from 254 to estimated 412. Compared to the recorded fires, this presumably gives a more unbiased picture of the temporal distribution. Number of fires within the study area (estimated) was rather low from 1300 to mid-1500s, mostly <10 fires per quarter of a century intervals (Fig. 6a). It rose slightly from the mid-1500s and in 1625 the numbers increased dramatically to 40-60 fires per quarter. This high number remained so for five quarters till 1750, after which it decreased to <5 fires per quarter from 1800 and onwards. Although mean fire size varied considerably, especially during the early period, the general trend was a gradual decrease in size throughout the period (Fig. 6c).

Taken together, the counteracting effects of an increasing number of successively smaller fires resulted in mean annual burnt area being not very different pre and post 1625 (Fig. 6b, Fig. 7, Table 2). Estimated annual percentage area burnt was 0.42% (adjusted data) pre 1625, increased to 1.03% during 1625-1700, decreased to 0.30% during the 1700s and fell to insignificant <0.01% from the 1800s and up till today. This represents rotation cycles of 236, 98, 335, and 11 000 years, respectively. During the peak fire period, 1625-1675, 1.16% of the area burnt annually (rotation cycle 86 years). Percent annually burnt area for the adjusted data was 20-30% higher than for the unadjusted data (Table 2).

Fire season

Most of the fires in the early period occurred in late season. This changed markedly during the first half of 1600s when early season fires became equally abundant as late season fires (Fig. 8). The appearance of early season fires occurred rather abruptly, starting with the 1625 fire. Pre 1625, only five out of 39 fires had a season index of 1-3, whereas this was the case in 77 of 148 fires post-1625 (Fisher's exact test: $p < 0.0001$). There were no long-term trends in the season index within the two time periods (pre-1625: slope = 0.0008, $R^2 = 0.008$, $t = 0.55$, $p = 0.59$, n = 39; post-1625: slope = -0.0008, $R^2 = 0.002$, $t = -0.50$, $p = 0.61$, n = 148). Based on the time-related changes in the fire regime (increasing number of fires, decreasing fire sizes and fires earlier in the season), we split our data into two time periods, one early period (pre-1625) and one late period (post-1625) for further analysis.

Fire size distributions and size-specific recurrence intervals

The inverse cumulative size distribution, divided in pre-1625 and post-1625, showed that there was a higher proportion of small fires in the late period compared with the early period (Fig. 9a). The large differences in size and numbers of fires over the time periods are exemplified in Fig. 5 where all recorded fires are shown during the 1400s (100 year period) and for the peak period, 1625-1675 (50 years).

The normalised size-frequency distribution closely followed power-law relationships both pre and post 1625 (Fig. 9b) with coefficients of determination (R^2) >0.98. Log α, representing the density of fires, was significantly higher post-1625 than pre-1625, whereas the β values (slopes), representing the ratio of small to large fires, were not significantly different, being 1.6 and 1.7 pre- and post-1625, respectively (Table 3). Accordingly, fire recurrence intervals were shorter during the post-1625 period, with small (0.1 km^2) and medium-sized (1 km^2) fires being 4 and 3 times more frequent than pre-1625, respectively (Table 3). No large fires (>5 km^2) occurred post-1625.

Site-specific fire return intervals, survival functions and hazard of burning

Map-based fire return intervals ranged from 2 to 326 years. The frequency distribution was skewed to the right, mostly so for the post-1625 period. Mean fire intervals were 76 years pre-1625 and 54 years post-1625, with median values of 73 and 37 years, respectively. Only 1.4% of the intervals spanned <10 years and all occurred post 1625 (Fig. 10). Pre 1625, the area was strongly influenced by a few, large fires (e.g. 1420, 1492, 1499, 1572, 1575 and 1590) giving rise to a bimodal distribution of return intervals peaking at 15 years and 60-100 years (Fig. 10). Post 1625, the distribution of return intervals peaked at 20-40 years influenced by many fires with short intervals (Fig. 10). This resulted in cumulative survival curves dropping more rapidly post-1625 than pre-1625 (Fig. 11a). The hazard of burning pre-1625 peaked at 15 and at 75 years since fire, with rates of 0.5 and 1.2%, respectively (Fig. 11c). The post-1625 hazard function peaked at 20-30 years with a rate of 1.2%. The post-1625 shift towards shorter return intervals implies that parts of the area burnt repeatedly at shorter time intervals during the late period. The cumulative survival curves levelled off at approximately 50 and 60% pre- and post-1625, respectively, implying that these proportions of the study area remained unburnt during the respective time periods. For the same reason, hazard rates approached zero with increasing time (Fig. 11c).

The cumulative survival curves based on fire scars in individual trees followed the pattern of the map-based curves. However, because the unburnt areas were not accounted for, the scar-based curves fell to zero with increasing time (Fig. 11b). This influenced the hazard function in two ways. First, hazard rates were markedly higher compared to the map-based rates, and secondly, the rates stayed high at longer time periods (Fig. 11d). Pre-1625 hazard rates increased up to 6% at 60-70 years, varying between 2 and 5% at longer time since fire. Post-1625 the rates increased up to 3% at 20 years, varying between 2 and 5% at longer time since fire.

Vegetation, altitude and spatial distribution of fires

Percent yearly burnt areas of spruce- and pine-dominated forests at different altitudes were calculated based on the unadjusted data because the adjusted data was not site-specific. Percent yearly burnt was notably higher in pine-dominated compared to spruce-dominated forests (Table 2, Fig. 12). This was consistent both pre- and post-1625, but after 1700, when the burnt area fell markedly, the difference between pine and spruce forests was negligible. Expectedly, percent annual burnt decreased markedly (50-80%) at higher altitudes (>660 m) for both spruce- and pine-dominated forests, and for all time periods (Table 2).

Within the recording transect area, the spatial delineation of fires showed that 31% of the area had no signs of fire, 46% had burnt 1-3 times and 22% had burnt ≥4 times during the 700 years period. The maximum number of fire scars recorded in a single sample was seven. This fire overlap pattern was rather similar between the two time periods (pre and post 1625), with approximately 50 and 60% unburnt area, respectively (Fig. 13).

The historic summer dairy farms were rather regularly distributed within the study area, with mean distance to nearest neighbour of ca. 1 km (DNN = 965 m, R = 1.39, Z = 4.3, *p*

< 0.001, n = 34). They were also located to the most spruce-dominated forests (Fig. 12a). Prior to 1625, percent burnt area was rather evenly distributed with respect to distance from the dairy farms. Post 1625 there was a shift towards more burnt area at medium distances from the summer dairy farms (Fig. 12 and 13).

Climate

On a 25-yr period basis, indicating possible multi-annual patterns, we found no correlations between number of fires and mean summer temperatures ($R^2 < 0.001$, $t = -0.14$, $p = 0.89$, n = 28 time periods) nor between the sum of burnt area and mean summer temperatures ($R^2 = 0.01$, $t = -0.38$, $p = 0.71$, n = 28; burnt area was log-transformed) (Fig. 6). Surprisingly, number of fires and sum of burnt area were positively correlated with precipitation on a 25-yr period basis (number: $R^2 = 0.52$, $t = 4.37$, $p < 0.001$, n = 20; burnt area: $R^2 = 0.51$, $t = 4.32$, $p < 0.001$, n = 20) (Fig. 6).

On a yearly basis, however, we found a rather strong positive correlation between burnt area and mean summer temperature pre-1625 ($R^2 = 0.27$, $t = 3.18$, $p < 0.004$, n = 30). Post-1625, annual burnt area showed a weaker, but still statistically significant, correlation with summer temperature ($R^2 = 0.05$, $t = 2.08$, $p = 0.041$, n = 83) (Fig. 14). Removing the "effect" of temperature in a partial regression analysis revealed no additional "effect" of precipitation neither pre-1625 ($r_p = -0.22$, $t = -0.90$, $p > 0.20$, n = 19 fires) nor post-1625 ($r_p = -0.02$, $t = -0.20$, $p > 0.20$, n = 83 fires). It should be noted though, that temperature and precipitation was markedly correlated, with warmer summers for the most part being dryer and colder summers being wetter. This was most pronounced prior to 1659 when temperature and precipitation were based on indices from proxy data only (pre-1659: $R^2 = 0.35$, $t = -9.17$, $p < 0.0001$, n = 159), after which more accurate instrumental records were included in the climate reconstructions (post-1659: $R^2 = 0.03$, $t = -3.01$, $p < 0.003$, n = 342).

Discussion

This study documents that forest fire historically has been a major factor influencing the forest landscape of Trillemarka-Rollagsfjell Nature Reserve. Our data allowed for detailed reconstruction of both numbers and sizes of individual fires. We found a general pattern of relatively few fires of varying sizes up to the beginning of the 1600s, followed by two centuries of increased number of fires but with decreasing fire sizes over time. Finally, there was an almost total lack of fires after 1800.

Similar general pattern has been reported from other parts of Fennoscandia, although with some spatial and temporal variations (Engelmark 1984, Lehtonen and Kolström 2000, Niklasson and Granström 2000, Niklasson and Drakenberg 2001, Wallenius et al. 2004). In the most comprehensive study from northern Sweden, Niklasson and Granström (2000) revealed a gradual increase in fire frequency (proportion annual burnt per time unit) from the late 1600s and a sudden decrease in fires from the 1870s. In another study, conducted only 45 km SSW of our study area, Groven and Niklasson (2005) found an increased fire frequency (shorter fire intervals) from the 1550s and a decrease after 1750. From Russian Karelia, Wallenius et al. (2004) reported an abrupt increase in the number of fires in the late 1600s and a decrease in both number of fires and annually burnt area in the mid-1800s.

Climatic vs. human drivers of the fire regime

Climatic variation (Bergeron 1991, Swetnam 1993, Carcaillet et al. 2007), human activity (Clark and Royall 1995, Lehtonen and Huttunen 1997) or a combination of both (Zackrisson 1977, Johnson et al. 1990) is thought to be the major drivers of changes in fire regimes. In our study, several lines of evidence point to a shift from climate to human caused influence in the early 1600s.

First, we found a rather abrupt increase in number of fires from ca. 1625 lasting to the mid- 1700s. However, due to the counteracting effect of decreasing fire sizes, the percent annual burnt area (adjusted values) did not change much, averaging 0.4% pre-1625 and 0.6% post 1625 (1625-1800). This translated to size-frequency distributions showing a significantly higher number of small fires and a lack of large fires (>500 ha) post-1625 compared with pre-1625.

In general, compared to anthropogenic fires, natural fire regimes tend to be dominated by fewer and larger fires (Johnson 1992). Natural fires may become large since they often burn under conditions of rapid spread and high intensity. Human activity may shift this pattern towards smaller fires with lower intensities (Granström and Niklasson 2008). This could be due to one or a combination of different causes: human ignitions set under less severe weather and therefore leading to small fires, active suppression of large fires, and/or a negative feedback between ignitions and number of fires resulting from a slow build-up of fuels, i.e. there is not enough biomass for fires to spread to large fires in the landscape since forests are repeatedly burnt (Schimmel and Granström 1997).

Lightning is the only natural cause of fire ignition in Fennoscandian forests (Granström 1993, Gromtsev 2002). Using fire statistics from south-central Norway (1913-

1987) the background density of natural lightning-caused fires has been estimated to an average of 0.08 ignitions per 10 000 ha and year (Øyen 1998), which is very similar to a present density estimate of lightning-ignited fires of 0.05 fires per 10 000 ha and year from boreal forests of Sweden (Granström 1993). In our study, the density of fires (based on adjusted number of fires ≥3 ha) averaged 0.59 fires per 10 000 ha and year in the early period of 1300-1624. This rose to an average of 2.71 fires during 1625-1800, peaking during 1650-1675 with 3.85 fires. Niklasson and Granström (2000) found 0.10 fires per 10 000 ha and year on average in the early period of 1350-1650. Their estimate was also calculated from adjusted number of fires, but it applied to fires ≥100 ha only, which corresponds to a density of 0.07 fires in our study. Using fires ≥3 ha as a reference, the pre-1625 density of fires in Trillemarka-Rollagsfjell Nature Reserve was about 7 times higher than expected from present-day statistics. This could be due to natural lightning ignitions being higher historically, or that it is underreported in modern fire statistics. It is also possible that we added too many fires in the procedure to correct for low detection probability. Finally, there might actually have been some fire-related human activity during this early period. Anyway, the fire density during 1625-1800 was notably higher (34 times) than the present density of lightning-caused fires. The density after 1800 also was higher, with 0.16 fires per 10 000 ha and year.

Second, the sudden appearance of early season fires from 1625 and onwards was rather striking. In south-eastern Norway, the main period of lightning is June-August, peaking in July and being more common in August compared with June (Rokseth et al. 2001). Anthropogenically caused fires from slash-and-burn cultivation are known to be more common in spring and early summer, possibly because early fires were easier to control (Larsson 1995, Niklasson and Drakenberg 2001). Moreover, burning for cultivation or improving the grazing conditions was probably done in the early summer when dead organic material from the previous year still was dry and the new vegetation had not yet started to grow. Thus, the shift in seasonality of burns supports the view that many fires after 1625 were anthropogenically caused.

Third, fire intervals and corresponding hazard rates differed substantially pre- and post-1625, with map-based hazard of burning shifting from a peak at 60-100 years pre-1625 to a peak at 20-40 years post-1625. Niklasson and Granström (2000) found similar results with a peak in the hazard of burning shifting from about 70 years pre-1650 to 20-30 years post-1650. In northern Sweden, Schimmel and Granström (1997) found no or only marginal risk of fire spread up to about 20 years after fire, followed by a progressive rise in fire risk up to ca. 50 years, after which the risk levelled off at a fairly constant rate. However, our data showed a marked decline in fire risk above 75 years. This was due to the map-based analysis, which included areas without fire. The map-based cumulative survival function levelled off at 50% pre-1625 and 60% post-1625 implying that these proportions of the area did not burn during the respective time periods or that they have burnt without leaving fire-scarred legacies. The scar-based survival however fell to zero both pre- and post-1625 because no fire-free areas were incorporated in the analysis. This explains why the map-based hazard decreased while the scar-based levelled off at longer time since fire.

Fourth, changes in fire severity over time may indicate human interference with the fire regime. Our sampling protocol did not allow fire severity to be assessed. However, in the small-scale study that was encompassed by the present one, fire severity showed a decreasing trend over time (Storaunet et al. 2013). Although this change in fire severity was rather gradual, it indicates that fires post-1600 were less severe (scarred relatively fewer trees) compared with fires pre-1600.

Fifth, on a 25-year period basis, neither fire frequency (number of fires) nor sum of burnt area showed any relationship with mean summer temperature. On a yearly basis, however, we found a rather strong positive relationship between summer temperature and annual burnt area pre-1625 whereas this was far less pronounced post-1625. This finding indicates that the 1625 shift in fire regime was not triggered by a shift in the long-term trends of summer temperature. Rather, it suggests that fires pre-1625 for the most part were driven by warm summers whereas many fires post-1625 were lit by man during both cold and warm summers. Moreover, the fact that several other studies from Fennoscandia have found similar shifts in the fire regime, but during different time periods, further strengthens our conclusion that these changes were due to human activities rather than climate (Groven and Niklasson 2005, Niklasson and Granström 2000, Lehtonen and Kolström 2000, Engelmark 1984).

Unexpectedly, we found higher fire frequencies (number of fires) and sum burnt area during 25-year periods with more precipitation, despite that we found no relationship between burnt area and precipitation on a yearly basis. Notably, the periods with high precipitation for the most part occurred during the 1600s and 1700s. Thus, we interpret the correlation between precipitation and number of fires on a 25-year basis as coincidental rather than causal. Presumably it was a result of the contemporaneous timing of frequent human-ignited fires during an above average wet climatic period.

Finally, the sudden increase in number of fires during the early 1600s corresponds well with written history of the area (see Storaunet et al. 2013), indicating that the anthropogenic fires were due to various activities such as burning for improved livestock grazing conditions and slash-and-burn cultivation (Bleken et al. 1997). The Black Death epidemic spread to Norway in the 1349-50, subsequently reducing the population to between half and one third of what it once was. The country was thereafter struck by several epidemics that kept the population at a low level, resulting in an estimated low of ca. 200 000 around 1520. It was not until the mid-1600s that the population had recovered to the pre-1350 level (Benedictow 2002). Circumstantial evidence suggests that most of the forest and mountain areas became desolate after 1350. From the late 1500s and onwards the population increased and people recolonised the summer dairy farms, as indicated in local historical sources. The slash-and-burn cultivation was explicitly noted in 1632 when a local farmer was allowed to clear forested land by the use of fire. Gradually the timber resources increased in value and from the late 1600s several national and regional regulations banned the use of fire on forested land, implying that the slash-and-burn cultivation diminished during the 1700s (see Storaunet et al. 2013). Thus, we believe that the pre-1625 period by and large represents a natural fire regime, possibly slightly influenced by humans already from the late 1500s, while the post-1625 period was strongly influenced by man.

Why did fires cease after 1800?

From the 1800s and onwards, only scattered small fires occurred in the study area. This phenomenon has been documented in other parts of Fennoscandia (Zackrisson 1977, Engelmark 1984, Lehtonen 1998, Niklasson and Granström 2000) as well as North America (Heinselman 1973, Bergeron et al. 2001), although the timing of the decrease in fire frequency in most cases occurred a century later. This general trend with decreasing fires has been explained by a decrease in anthropogenically caused fires and increased timber value (Wallenius et al. 2004), effective fire suppression (Zackrisson 1977, Clark 1990), and climate change (Bergeron 1991, Flannigan et al. 1998).

The first legislation against use of fire in Norway came in 1683 to ensure timber availability (Skogdirektøren 1909). This legislation was due to the gradually increasing timber value, caused by increasing demand of timber in Europe (Fryjordet 1992), and regionally also from the Kongsberg Silver Mines, which opened in 1623 and was located 50 km south of the study area. This industry expanded after 1700, and in 1723 a circumference for timber supply was established around the silver mines. The circumference was undertaken a special legislations against burning of forest, and by the mid-1700s, the slash-and-burn cultivation was basically forbidden and consequently abandoned (for further details see Storaunet et al.

2013). This supports the view that a decrease in anthropogenic burning was a major reason for the almost total cessation of forest fires after 1800. Another contributing factor may have been a gradual increase in logging during the 1700s, as evidenced by the large number of cut stumps found in the area. This logging presumably created a mosaic-shaped forest landscape with less flammable fuel sources which may have reduced the fire risk during the 1800s.

Together with the increased demand for timber, the effort to suppress fires, both lightning-ignited and human-caused, also may have increased. The often observed decrease in annually burnt areas in northern coniferous forests has been attributed to effective fire suppression (Heinselman 1973, Zackrisson 1977). However, even if modern fire suppression practices are effective, it is unclear whether firefighting was effective in remote locations in the 1800s without motorized equipment (Wallenius 2011). Thus, we believe that active fire suppression presumably played a minor role in the cessation of fires.

Another possible explanation for the cessation of fires may be an increasing dominance of Norway spruce. Ohlson et al. (2011) suggested that a change in the dominant tree species had an important effect on the fire regime that exceeded the influence of climate change during the late-Holocene. They further suggested that the reduction of fires took place during or immediately after the spruce invasion and concluded that the reasons for this was because it made the forest denser, darker and cooler and thus locally more humid with moister soil conditions, all reducing flammability and fire activity (Ohlson et al. 2011). However, our study covers a more recent time period with spruce forests already established in the region (Giesecke and Bennett 2004). Nonetheless we found that spruce-dominated forests burnt less often (rotation 250-1000 years) than pine forests (150-300 years). We also found that percent annually burnt area decreased with increasing elevation, implying considerable spatial variation in fire susceptibility. Thus, in accordance with Wallenius et al. (2004), it seems evident that the high spatial variability in burnt areas in the past was largely due to the small-scale variation in vegetation and altitude.

Finally, undoubtedly forest fire regimes are strongly influenced by climatic variations (Swetnam 1993, Kitzberger et al. 2001, 2007). Hence, climate change has been suggested as the main reason for the decrease in annually burnt area in Canada, despite the generally warming trend since the end of the Little Ice Age (Flannigan et al. 1998, Weir et al. 2000, Girardin et al. 2009). Here, the reduced fire frequency after the mid-1800s has been coupled to increasing summer moisture (Girardin et al. 2009) and changing dynamics of the large-scale teleconnection patterns related to the Pacific Decadal Oscillation/El Niño Southern Oscillation and the Arctic Oscillation (PDO/ENSO and AO) (Fauria and Johnson 2008), none of which seem particularly applicable to Scandinavia (Girardin et al. 2009). Our summer temperature and precipitation data showed no climatic trends that could explain the almost total cessation of forest fires from the 1800s and onward.

Methodological considerations

Dating fire scars by dendrochronology is an important method to reconstruct past fire events. However, whereas a fire scar proves the presence of fire, the absence of a scar does not necessarily mean that it did not burn at that location (Piha et al. 2013). This is due to the variable scarring susceptibility of individual trees (depending on size, age, bark thickness, etc.) and also the high variability in the fire behaviour. Also, fire scars do not necessarily persist through time due to decomposition of dead-scarred material, and because more recent fire events may have consumed older fire records. Such uncertainties make it difficult to apply a proper sampling method, to interpret scarred and unscarred trees correctly, and subsequently to estimate the fire regime characteristics. In our study we tried to remedy these problems by ensuring a well-distributed number of sample points (recorder trees) and by adjusting the number and size of fires for detection probability and proportional size within the recording transect.

Fire return intervals can be calculated map-based as the time between successive fires determined from spatially overlapping burnt areas delineated on a map, or scar-based as the time between successive fires recorded by scars in single wooden samples. In our study, there were profound differences between the map-based and scar-based survival and hazard functions, chiefly because the scar-based method does not include unburnt areas. This is not always acknowledged in scar-based studies (e.g. Niklasson and Granström 2000), resulting in hazard rates possibly being inflated at longer time intervals. This may be accounted for by sampling a relevant number of unscarred trees within a study area, but this usually is hampered by the fact that few living and dead unscarred trees cover the whole time period. On the other hand, map-based calculations based on historical delineated fires may underestimate hazard rates at longer time intervals because those areas designated as unburnt actually have burnt without leaving fire-scarred wooden samples.

When delineating the fires on the map we excluded overlap areas <15 years between fires. This was done because in our data, only 7 out of 390 scar-intervals were <15 years (all of which occurred after 1625). This probably was due to recently burnt areas having too little fuel to burn over again, a pattern which is in line with the conclusion of Schimmel and Granström (1997). The question is whether we have missed shorter intervals because Scots pine often retains the bark cover some years after the cambium has been damaged by a fire (Piha et al. 2013). However, Niklasson et al. (2010), in a study of historical fires in lowland Poland, found many scar-based intervals <10 years in Scots pine. Such short intervals are also commonly found in other pine species, e.g. *Pinus ponderosa* P. & C. Lawson (Brown et al. 1999, Farris et al. 2010). We therefore feel rather confident that the lack of short intervals in our study was real and not due to biased sampling.

We found no fire scars in other tree species than Scots pine, and only very few scarred legacies in the spruce-dominated forests. However, this does not necessarily mean that these areas did not burn. This problem might be alleviated by sampling macroscopic charcoal in closed-canopy soil and peat columns (Bradshaw 1988). However, the correspondence between charcoal record in peat and tree ring data for the time span where they overlap has been shown to be rather vague (Kasin et al. 2013).

Comparison of normalised size-frequency statistics

For the first time for Fennoscandian (and possibly Eurasian) boreal forests, we present normalised fire size-frequency distributions by means of power-law statistics. In North America these statistics have been calculated for recent time periods, but historical records are lacking (Malamud et al. 2005, Jiang et al. 2009). For comparable vegetation and climate regions in Canada and northern USA, *log-*α values range from -4.48 to -4.34 (Boreal Shield, Boreal Plains, Temperate Steppe Mountains) during the last 3-4 decades, corresponding to a density of ~0.009 fires $\geq$1 km^2 per 100 km^2 and year, or a recurrence interval of 110-120 years. In our study area *log-*α varied from -3.41 during 1300-1624 to -2.83 during 1625-1800, corresponding to 0.06 and 0.20 fires $\geq$1 km^2 per 100 km^2 and year, respectively, which translates to recurrence intervals of 16 and 5 years, respectively. Thus, fire frequency was 7 times higher during our early period and >20 times higher during 16-1700s compared with recent fire frequencies in North-America. However, after 1800, no fires >10 ha was recorded in our study area.

Our β-values, representing the ratio of small to large fires, were in the upper range (1.6 - 1.7) of what is reported from the North American boreal forest regions (1.4 - 1.5), inplying that in Trillemarka-Rollagsfjell Nature Reserve small fires historically outnumbered the large ones to a larger degree than what has been seen in recent years in North America. However, the differences are rather small and possibly not statistically significant. Additionally, small fires presumably were underreported in the North American fire statistics (Malamud et al.

2005, Jiang et al. 2009). On the other hand, half (Canada) and more than half (USA) of the North American fires are classified as anthropogenic, which makes the difference between present North American and our pre-1625 results even larger.

Possible explanations for our β-values being higher than those of North America may be that the landscape of Trillemarka –Rollagsfjell is more hilly and broken with barren mountain tops hampering fires from growing large. We also noted that several fires extended outside our study area, which thereby may underestimate the density of large fires, especially during the early (pre-1625) period. Finally, in the correction procedure, we may have overestimated the number of small fires in the early (pre-1625) period. Nevertheless, it seems clear that it has burnt more often in the past in our study area compared to present wildfire ecoregions of North America.

Our study of the historical fire regime in Trillemarka-Rollagsfjell Nature Reserve strengthens and expands the knowledge basis of fire as a fundamental ecological process in the boreal forests of Fennoscandia (Zackrisson 1977, Engelmark 1984, Engelmark et al. 1994, Lehtonen and Huttunen 1997, Niklasson and Granström 2000, Wallenius et al. 2004, Groven and Niklasson 2005). Our detailed reconstruction of both numbers and sizes of individual fires allowed us to compare size-frequency distributions showing historical fire frequencies similar to other parts of Fennoscandia (Niklasson and Granström 2000), and even shorter return intervals than recently recorded in boreal forests of North America (Malamud et al. 2005, Jiang et al. 2009). The anthropogenic signal in the fire regime in the early 1600s was convincing, although we should not exclude minor influence also in the earlier period. Notably, the last 200-year almost fire-free period is unprecedented during the last 700 years.

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the laboratory work; all authors participated in the analyses and discussion of the results; Y. Blanck prepared the manuscript in cooperation with K.O. Storaunet and J. Rolstad.

References

Angelstam, P.K. 1998. Maintaining and restoring biodiversity in European boreal forests by developing natural disturbance regimes. Journal of Vegetation Science 9: 593-602.

Arno, S.F. and Sneck, K.M. 1977. A method for determining fire history in coniferous forests of the mountain west. USDA Forest Service General Technical Report INT-42. Intermountain Forest and Range Experiment Station, Ogden, UT.

Baisan, C.H. and Swetnam, T.W. 1990. Fire history on a desert mountain-range - Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research 20: 1559-1569.

Benedictow, O.J. 2002. Svartedauden og senere pestepidemier i Norge. Unipub forlag, Oslo, Norway. (In Norwegian).

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72: 1980-1992.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P. and Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Canadian Journal of Forest Research 31: 384-391.

Bergeron, Y., Leduc, A., Harvey, B.D. and Gauthier, S. 2002. Natural fire regime: a guide for sustainable management of the Canadian boreal forest. Silva Fennica 36: 81-95.

Bleken, E., Mysterud, I. and Mysterud, I. 1997. Forest fire and environmental management: A technical report on forest fire as an ecological factor. Directorate for Fire & Explosion Prevention and Department of Biology, University of Oslo Oslo, Norway. (In Norwegian).

Bradshaw, R.H.W. 1988. Spatially-precise studies of forest dynamics. *In* Vegetation History. Edited by Huntley, B. and Webb III, T. Handbook of Vegetation Science Vol. 7, Kluwer Acad. Publ., Dordrecht, The Netherlands. pp. 725-751.

Bradshaw, R.H.W. 1993. Tree species dynamics and disturbance in three Swedish boreal forest stands during the last two thousand years. Journal of Vegetation Science 4: 759–764.

Brown, P.M., Kaufmann, M.R. and Shepperd, W.D. 1999. Long-term, landscape patterns of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecology 14: 513-532.

Brown, P.M. and Swetnam, T.W. 1994. A cross-dated fire history from Coast Redwood near Redwood National Park, California. Canadian Journal of Forest Research 24: 21-31.

Carcaillet, C., Bergman, I., Delorme, S., Hörnberg, G. and Zackrisson, O. 2007. Long-term fire frequency not linked to prehistoric occupations in northern Swedish boreal forest. Ecology 88: 465-477.

Clark, J.S. 1990. 20th-century climate change, fire suppression, and forest production and decomposition in northwestern Minnesota. Canadian Journal of Forest Research 20: 219–232.

Clark, J.S. and Royall, P.D. 1995. Transformation of a northern hardwood forest by aboriginal (Iroquois) fire: charcoal evidence from Crawford Lake, Ontario, Canada. Holocene 5: 1-9.

climexp.knmi.nl: KNMI Climate Explorer. Royal Netherlands Meteorological Institute. De Bilt, The Netherlands. Accessed Oct. 10, 2013.

Douglass, A.E. 1941. Crossdating in dendrochronology. Journal of Forestry 39: 825-831.

Eidem, P. 1959. En grunnskala til tidfesting av trevirke fra Flesberg i Numedal. Blyttia (Oslo) 17: 69-85. (In Norwegian).

eklima.met.no: Norwegian Meteorological Institute. Oslo, Norway. Accessed Oct. 10, 2013.

Engelmark, O. 1984. Forest fires in the Muddus National Park (northern Sweden) during the past 600 years. Canadian Journal of Botany 62: 893-989.

Engelmark, O., Kullman, L. and Bergeron, Y. 1994. Fire and age structure of Scots pine and Norway spruce in northern Sweden during the past 700 years. New Phytologist 126: 163-168.

Esseen, P.-A., Ehnström, B., Ericson, L. and Sjöberg, K. 1997. Boreal forests. Ecological Bulletin 46: 16-47.

Farris, C.A., Baisan, C.H., Falk, D.A., Yool, S.R. and Swetnam, T.W. 2010. Spatial and temporal corroboration of a fire-scar-based fire history in a frequently burned ponderosa pine forest. Ecological Applications 20: 1598-1614.

Fauria, M.M. and Johnson, E.A. 2008. Climate and wildfires in the North American boreal forest. Philosophical Transactions of the Royal Society, Series B 363: 2317-2329.

Flannigan, M.D., Bergeron, Y., Engelmark, O. and Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469–476.

Fritts, H.C. and Swetnam, T.W. 1989. Dendroecology - a tool for evaluating variations in past and present forest. Advances in Ecological Research 19: 111-188.

Fryjordet, T. 1992. Skogadministrasjon i Norge gjennom tidene. Bind I. Skogforhold, skogbruk og skogadministrasjon fram til 1850. Norwegian Department of Agriculture and Directorate of State Forests, Oslo, Norway. (In Norwegian).

Giesecke, T. and Bennett, K.D. 2004. The Holocene spread of *Picea abies* (L.) Karst. in Fennoscandia and adjacent areas. Journal of Biogeography 31: 1523–1548.

Girardin, M.P., Ali, A.A., Carcaillet, C., Mudelsee, M., Drobyshev, I., Hély, C. and Bergeron, Y. 2009. Heterogeneous response of circumboreal wildfire risk to climate change since the early 1900s. Global Change Biology 15: 2751-2769.

Granström, A. 1991. Skogen efter branden. Skog och Forskning 4: 32-38. (In Swedish).

Granström, A. 1993. Spatial and temporal variation in lightning ignitions in Sweden. Journal of Vegetation Science 4: 737-744.

Granström, A. 2001. Fire management for biodiversity in the European boreal forest. Scandinavian Journal of Forest Research, Supplement 3: 62-69.

Granström, A. and Niklasson, M. 2008. Potentials and limitations for human control over historic fire regimes in the boreal forest. Philosophical Transactions of the Royal Society, Series B 363: 2353-2358.

Grissino-Mayer, H.D. 1999. Modeling fire interval data from the American Southwest with the Weibull distribution. International Journal of Wildland Fire 9: 37-50.

Grissino-Mayer, H.D., Romme, W.H., Floyd, M.L. and Hanna, D.D. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, U.S.A. Ecology 85: 1708–1724.

Grissino-Mayer, H.D. and Swetnam, T.W. 2000. Century-scale climate forcing of fire regimes in the American Southwest. Holocene 10: 213-220.

Gromtsev, A. 2002. Natural disturbance dynamics in the boreal forest of European Russia: a review. Silva Fennica 36: 41-55.

Groven, R. and Niklasson, M. 2005. Anthropogenic impact on past and present fire regimes in a boreal forest landscape of southeastern Norway. Canadian Journal of Forest Research 35: 2719-2726.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Research 3: 329-382.

Hellberg, E., Niklasson, M. and Granström, A. 2004. Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. Canadian Journal of Forest Research 34: 332-338.

Hirsch, K.G. and Fuglem, P. (Technical Coordinators) 2006. Canadian wildland fire strategy: background syntheses, analyses, and perspectives. Canadian Council of Forest Ministers, Natural Resources Canada, Canadian Forest Service and Northern Forestry Centre, Edmonton, AB. 104 pp.

Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin 43: 69-78.

Holmes, R.L. 1994. Dendrochronology Program Library - User manual. Laboratory of Tree Ring Research, University of Arizona, Tuscon, USA.

Hörnberg, G., Ohlson, M. and Zackrisson, O. 1995. Stand dynamics, regeneration patterns and long-term continuity in boreal old-growth *Picea abies* swamp-forests. Journal of Vegetation Science 6: 291-298.

Jiang, Y.Y., Zhuang, Q.L., Flannigan, M.D. and Little, J.M. 2009. Characterization of wildfire regimes in Canadian boreal terrestrial ecosystems. International Journal of Wildland Fire 18: 992-1002.

Johnson, E.A. 1992. Fire and vegetation dynamics: Studies from the North American boreal forest. Cambridge University Press, Cambridge.

Johnson, E.A., Fryer, G.I. and Heathcott, M.J. 1990. The influence of man and climate on frequency of fire in the interior wet belt forest, British Columbia. Journal of Ecology 78: 403-412.

Johnson, E.A. and Gutsell, S.L. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25: 239-287.

Kasin, I., Blanck, Y., Storaunet, K.O., Rolstad, J. and Ohlson, M. 2013. The charcoal record in peat and mineral soil across a boreal landscape and possible linkages to climate change and recent fire history. Holocene 23: 1052-1065.

Kitzberger, T., Brown, P.M., Heyerdahl, E.K., Veblen, T.T. and Swetnam, T.W. 2007. Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Sciences of the United States of America 104: 543-548.

Kitzberger, T., Swetnam, T.W. and Veblen, T.T. 2001. Interhemispheric synchrony of forest fires and the El Niño Southern Oscillation. Global Ecology and Biogeography 10: 315-326.

Kuuluvainen, T. 2009. Forest management and biodiversity conservation based on natural ecosystem dynamics in Northern Europe: the complexity challenge. Ambio 38: 309-315.

Larsson, B. (Ed.) 1995. Svedjebruk och röjningsbränning i Norden - terminologi, datering, metoder. Skrifter om skogs- och lantbrukshistoria, Nordiska museet, Stockholm. (In Swedish).

Lehtonen, H. 1998. Fire history recorded on pine trunks and stumps: Influence of land use and fires on forest structure in North Karelia. Scandinavian Journal of Forest Research 13: 462-468.

Lehtonen, H. and Huttunen, P. 1997. History of forest fires in eastern Finland from the fifteenth century AD - The possible effects of slash-and-burn cultivation. Holocene 7: 223-228.

Lehtonen, H. and Kolström, T. 2000. Forest fire history in Viena Karelia, Russia. Scandinavian Journal of Forest Research 15: 585-590.

Li, C. 2000. Fire regimes and their simulation with reference to Ontario. *In* Ecology of a managed terrestrial landscape: patterns and processes of forest landscapes in Ontario. Edited by Perera, A.H., Euler, D.L. and Thompson, I.D. University of British Columbia Press, Vancouver, British Colombia. pp. 115-140.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M. and Wanner, H. 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303: 1499-1503.

Malamud, B.D., Millington, J.D.A. and Perry, G.L.W. 2005. Characterizing wildfire regimes in the United States. Proceedings of the National Academy of Sciences of the United States of America 102: 4694-4699.

McBride, J.R. 1983. Analysis of tree rings and fire scars to establish fire history. Tree-Ring Bulletin 43: 51-67.

Merrill, D.F. and Alexander, M.E. 1987. Glossary of forest fire management terms. Fourth edition. National Research Council of Canada and Canadian Committee on Forest Fire management. Ottawa, Ontario.

Moen, A. 1999. National atlas of Norway: Vegetation. Norwegian Mapping Authority, Hønefoss.

Mork, E. 1960. On the relationship between temperature, leading shoot increment and the growth and lignification of the annual ring in Norway spruce (*Picea abies* (L.) Karst). Meddelelser fra Det norske Skogforsøksvesen 16: 225-261.

Niklasson, M. and Drakenberg, B. 2001. A 600-year tree-ring fire history from Norra Kvills National Park, southern Sweden: implications for conservation strategies in the hemiboreal zone. Biological Conservation 101: 63-71.

Niklasson, M. and Granström, A. 2000. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81: 1484-1499.

Niklasson, M., Zackrisson, O. and Östlund, L. 1994. A dendroecological reconstruction of Saami use of Scots pine (*Pinus sylvestris* L.) innerbark around Lake Sädvajaure, N. Sweden. Journal of Vegetation History and Archaeobotany 3: 183-190.

Niklasson, M, Zin, E., Zielonka, T., Feijen, M., Korczyk, A.F., Churski, M., Samojlik, T., Jedrzejewska, B., Gutowski, J.M. and Brzeziecki, B. 2010. A 350-year tree-ring fire record from Białowieza Primeval Forest, Poland: implications for Central European lowland fire history. Journal of Ecology 98: 1319-1329.

Ohlson, M. and Tryterud, E. 1999. Long-term spruce forest continuity - a challenge for a sustainable Scandinavian forestry. Forest Ecology and Management 124: 27-34.

Ohlson, M., Brown, K.J., Birks, H.J.B., Grytnes, J.A., Hörnberg, G., Niklasson, M., Seppa, H. and Bradshaw, R.H.W. 2011. Invasion of Norway spruce diversifies the fire regime in boreal European forests. Journal of Ecology 99: 395-403.

Oliver, C.D. and Larson B.C. 1990. Forest stand dynamics. McGraw-Hill, New York.

Øyen, B.-H. 1998. Skogbrann i Norge de siste 200 år. Oppdragsrapport No. 8/98, Norsk institutt for skogforskning. (In Norwegian).

Pauling, A., Luterbacher, J., Casty, C. and Wanner, H. 2005. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Climate Dynamics 26: 387-405.

Payette, S. 1992. Fire as a controlling process in the North American boreal forest. *In* A systems analysis of the global boreal forest. Edited by Shugart, H.H., Leemans, R. and Bonan, G.B. Cambridge University Press, Cambridge, NY. pp. 144-169.

Piha, A., Kuuluvainen, T., Lindberg, H. and Vanha-Majamaa, I. 2013. Can scar-based fire history reconstructions be biased? An experimental study in boreal Scots pine. Canadian Journal of Forest Research 43: 669-675.

Rokseth, O., Pleym, A. and Dahlslett, F. 2001. Sammenstilling av lyndata for perioden 1996-2001. Sintef Energy Research, Technical Report TR A5503. (In Norwegian).

Ryan, K.C. 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica 36: 13-39.

Schimmel, J. and Granström, A. 1997. Fuel succession and fire behavior in the Swedish boreal forest. Canadian Journal of Forest Research 27: 1207-1216.

Schmitt, U., Jalkanen, R. and Eckstein, D. 2004. Cambium dynamics of *Pinus sylvestris* and *Betula* spp. in the northern boreal forest in Finland. Silva Fennica 38: 167-178.

Skogdirektøren. 1909. Skogvæsenets historie - Utgit i anledning av det offentlige skogvæsens 50-aarige virksomhet 1857-1907. 1. del - Historik. Grøndahl & Søns Boktrykkeri, Kristiania, Norway. (In Norwegian).

Stokes, M.A. and Smiley, T.L. 1968. An introduction to tree-ring dating. University of Chicago Press, Chicago.

Storaunet, K.O., Rolstad, J., Gjerde, I. and Gundersen, V.S. 2005. Historical logging, productivity, and structural characteristics of boreal coniferous forests in Norway. Silva Fennica 39: 429-442.

Storaunet, K.O., Rolstad, J., Toeneiet, M. and Blanck, Y. 2013. Strong anthropogenic signals in historic forest fire regime: a detailed spatiotemporal case study from south-central Norway. Canadian Journal of Forest Research 43: 836-845.

Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Science 262: 885-889.

Taylor, S.W., Stennes, B., Wang, S. and Taudin-Chabot, P. 2006. Integrating Canadian wildland fire management policy and institutions: sustaining natural resources, communities and ecosystems. Canadian Council of Forest Ministers, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton.

Van Engelen, A.F.V., Buisman, J. and Ljnsen, F. (Eds.) 2001. A millennium of weather, winds and water in the low countries. Kluwer Academic/Plenum Publishers, New York, NY.

Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8: 220-227.

Viro, P.J. 1974. Effects of forest fire on soil. *In* Fire and ecosystems. Edited by Kozlowski, T.T. and Ahlgren, C.E. Academic Press, New York. pp. 1-45.

Wallenius, T. 2011. Major decline in fires in coniferous forests - Reconstructing the phenomenon and seeking for the cause. Silva Fennica 45: 139-155.

Wallenius, T.H., Kauhanen, H., Herva, H. and Pennanen, J. 2010. Long fire cycle in northern boreal *Pinus* forests in Finnish Lapland. Canadian Journal of Forest Research 40: 2027-2035.

Wallenius, T.H., Kuuluvainen, T. and Vanha-Majamaa, I. 2004. Fire history in relation to site type and vegetation in Vienansalo Wilderness in eastern Fennoscandia, Russia. Canadian Journal of Forest Research 34: 1400-1409.

Weber, M.G. and Flannigan, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: Impacts on fire regimes. Environmental Reviews 5: 145-166.

Weir, J.M.H., Johnson, E.A. and Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. Ecological Applications 10: 1162-1177.

Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. Canadian Journal of Forest Research 21: 414-416.

Zackrisson, O. 1977. Influence of forest fires on the North Swedish boreal forest. Oikos 29: 22-32.

Zackrisson, O. and Östlund, L. 1991. Branden formade skoglandskapets mosaik. Skog och Forskning 1991(4): 13-21. (In Swedish).

Zumer, M. 1969. Årringdannelse hos gran i fjellskog. Meddelelser fra Det norske Skogforsøksvesen 27: 161-184. (In Norwegian).

TABLES

Table 1. Correction factors used for adjusting the number and size of fires. Correction factors in column 4 were used when adjusting fires during 1300-1550, whereas factors in column 3 were used during 1550-2009. (See Methods for details).

Fire size class (class center)	1) Detection probability within recording transect, with 70 sample points	2) Correction factor (1 / detection probability)	3) Ratio between fire size within transect and total mapped fire size (median)	4) Product of 2) and 3)
3-5 ha (4 ha)	0.118	8.49	1.92	16.3
5-10 ha (7.5 ha)	0.209	4.78	1.84	8.79
10-30 ha (20 ha)	0.465	2.15	1.39	2.99
≥30 ha (100 ha)	0.952	1.05	1.12	1.17

Table 2. Percent annually burnt area within four different time periods for adjusted and unadjusted data (i.e. the recorded fires), and for different altitudes (m a.s.l) within pine- and spruce-dominated forests.

	1300-1624	1625-1699	1700-1799	1800-2009
Adjusted data, total area	0.42%	1.03%	0.30%	<0.01%
Unadjusted data, total area	0.35%	0.86%	0.23%	<0.01%
Pine-dominated (<480 m)	0.52%	1.58%	0.27%	<0.01%
Pine-dominated (480-660 m)	0.51%	1.03%	0.28%	<0.01%
Pine-dominated (>660 m)	0.28%	0.49%	0.18%	<0.01%
Spruce-dominated (<480 m)	0.35%	0.98%	0.25%	<0.01%
Spruce-dominated (480-660 m)	0.21%	0.54%	0.22%	0.01%
Spruce-dominated (>660 m)	0.08%	0.25%	0.13%	<0.01%

Table 3. Fire recurrence intervals (T) of fires pre- and post-1625 obtained from power-law regressed normalized frequency size distributions, representing the average time between fires ≥0.1 km^2, ≥1 km^2 and ≥10 km^2 occurring in the study area. Confidence intervals (95%) are based on the number of 'bins' used in the least square fit of the regressions. (See Methods for details).

Time period	Area, km^2	Yrs	log α	β (slope)	R^2	T ≥0.1 km^2, yr	T ≥1.0 km^2, yr	T ≥10 km^2, yr
1300-1624	58.93	325	-3.41 (-3.54; -3.28)	1.62 (1.49; 1.79)	0.986	6.5 (4.6; 9.1)	27.1 (17.5; 42.1)	113.6 (56.1; 230.1)
1625-1800	58.93	175	-2.83 (-2.91; -2.76)	1.73 (1.64; 1.81)	0.994	1.6 (1.4; 1.8)	8.4 (6.3; 11.2)	

FIGURES

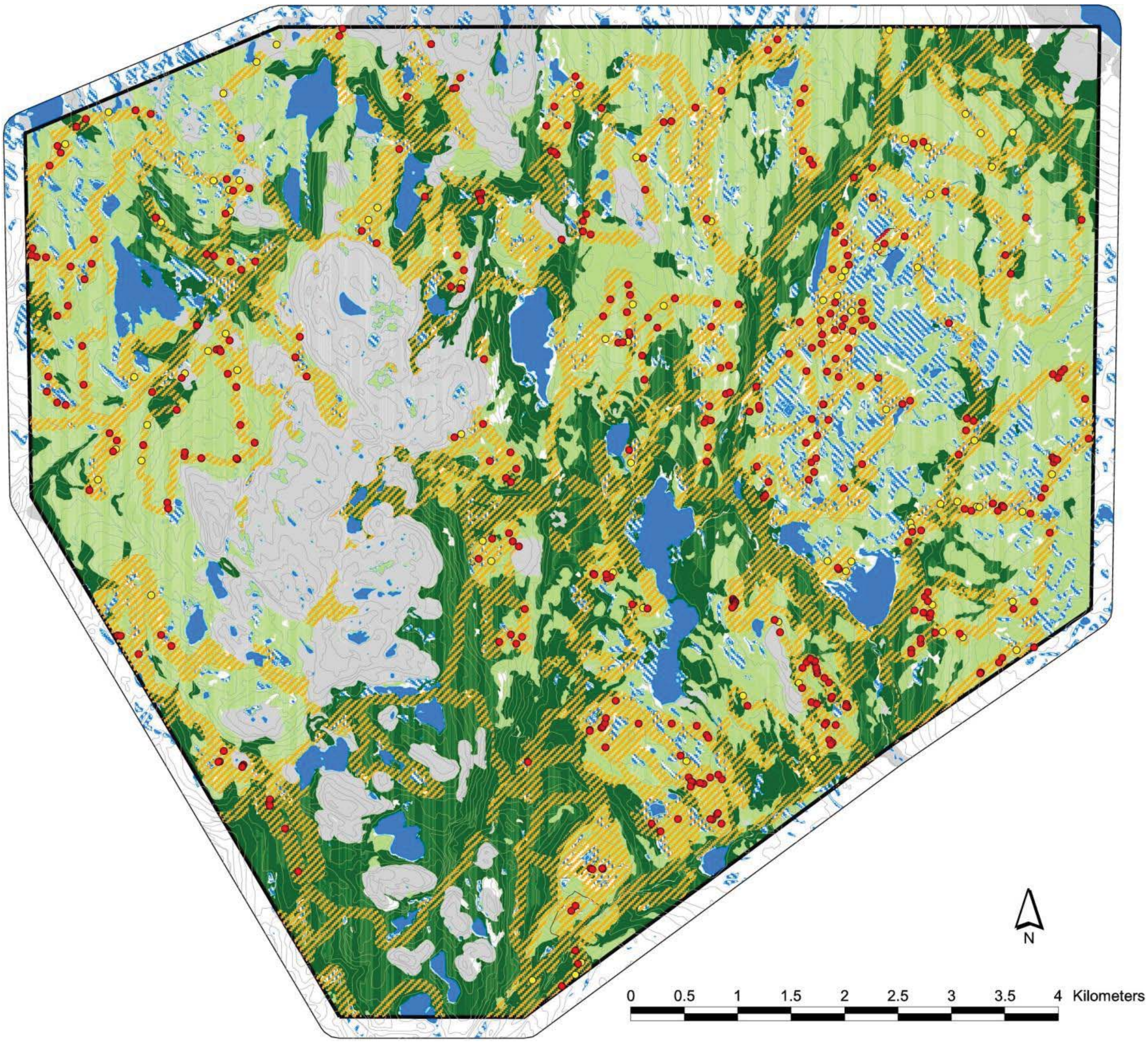
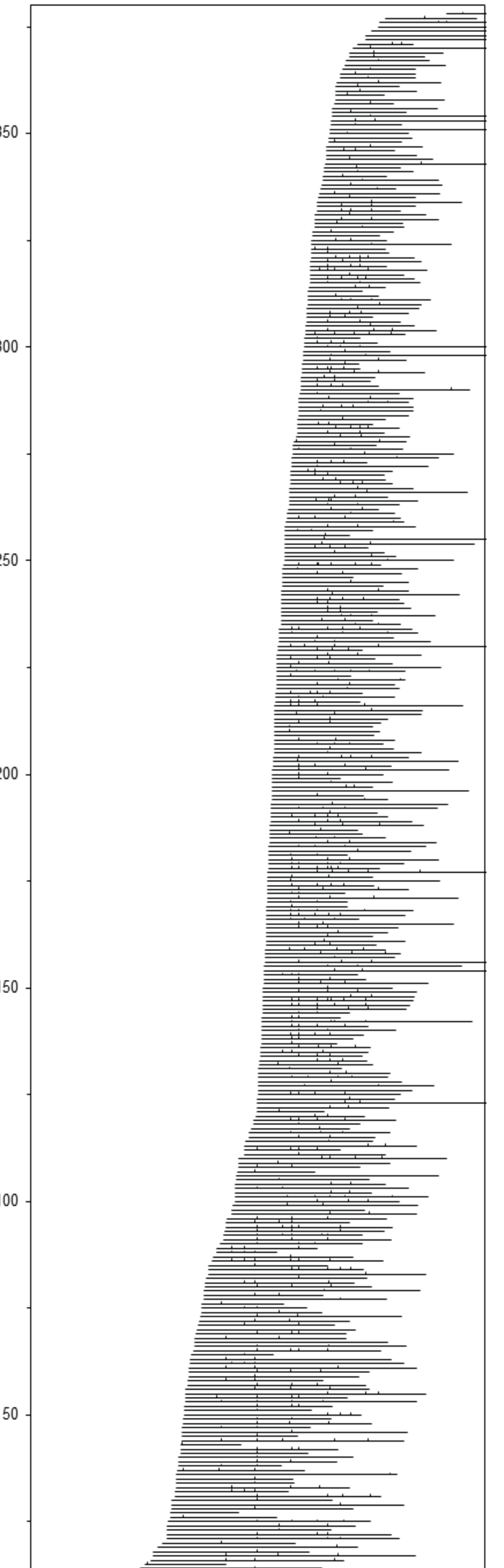


Fig. 1. Map of the 74 km^2 study area. Grey: mountainous area, solid blue: open water, hatched blue: mire, dark green: spruce-dominated forest, light green: pine-dominated forest. Hatched yellow shows the recording transect, whereas red and yellow dots represent successfully cross-dated and undated samples, respectively.



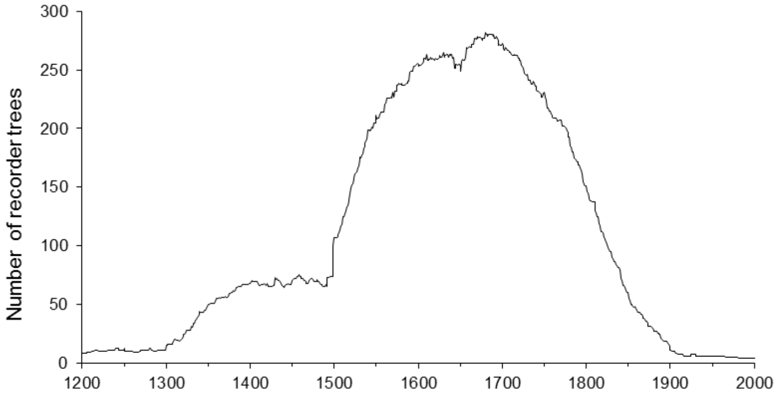


Fig. 3. Total number of recorder trees within the study area over time.

< Fig. 2. Time span of all cross-dated tree samples (n = 378) within the study area. Each horizontal line ranges from estimated germination year to estimated death and each vertical tick mark represent a fire scar (n = 745).

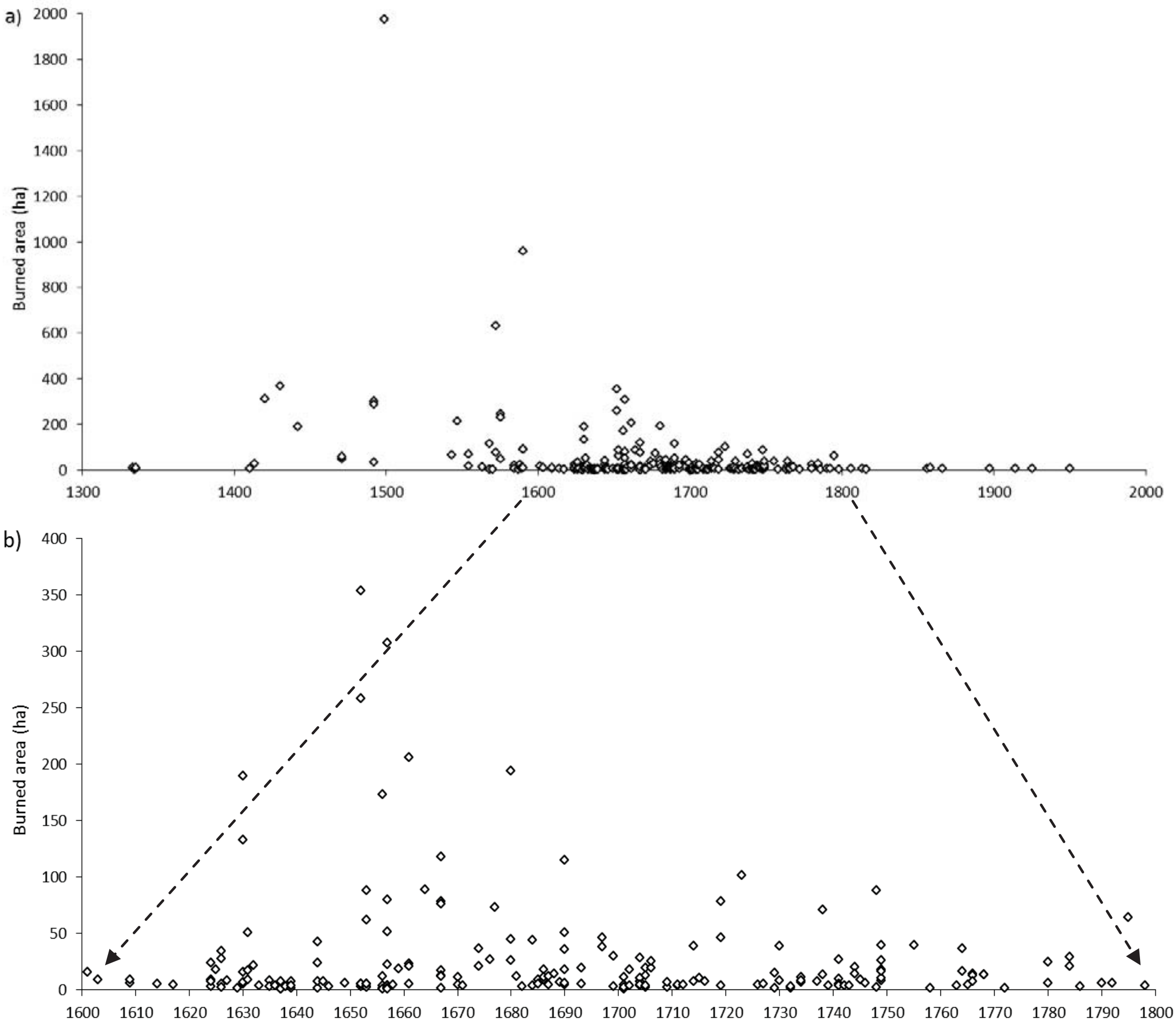
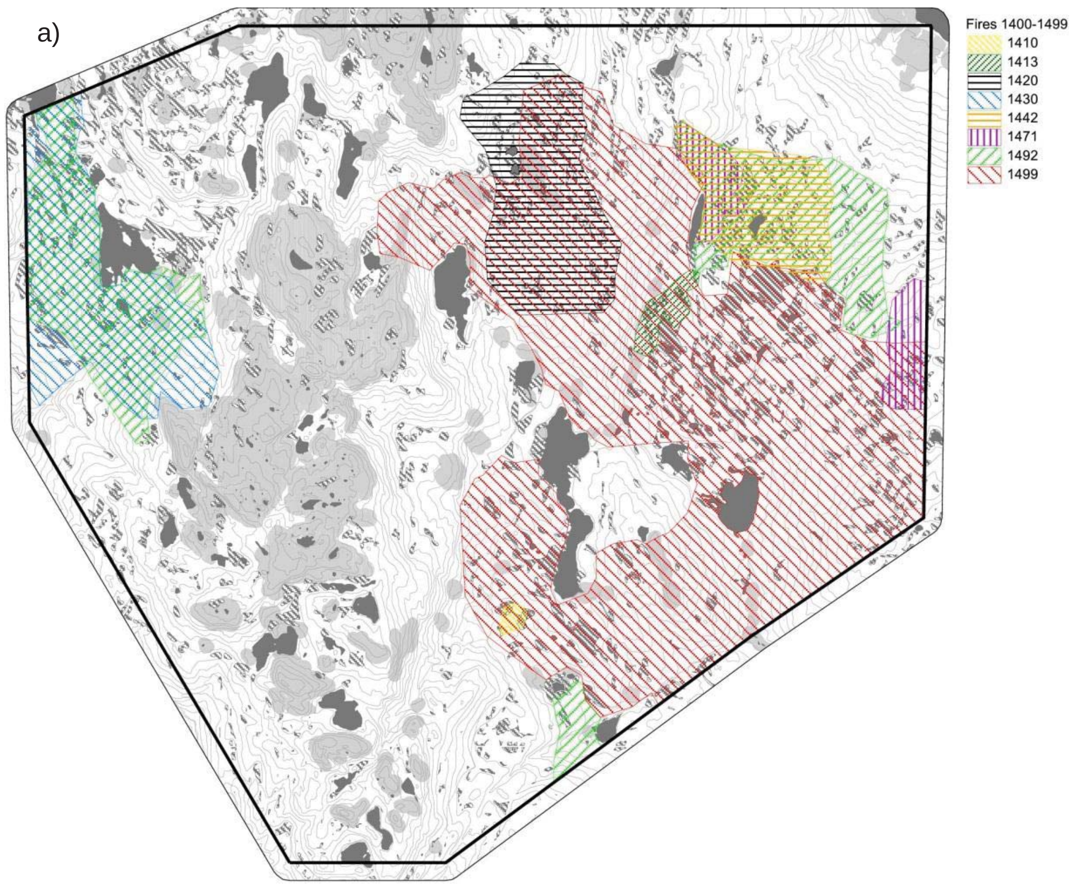


Fig. 4. Size (ha) of all recorded fires during a) 1300-2009 and b) 1600-1800.



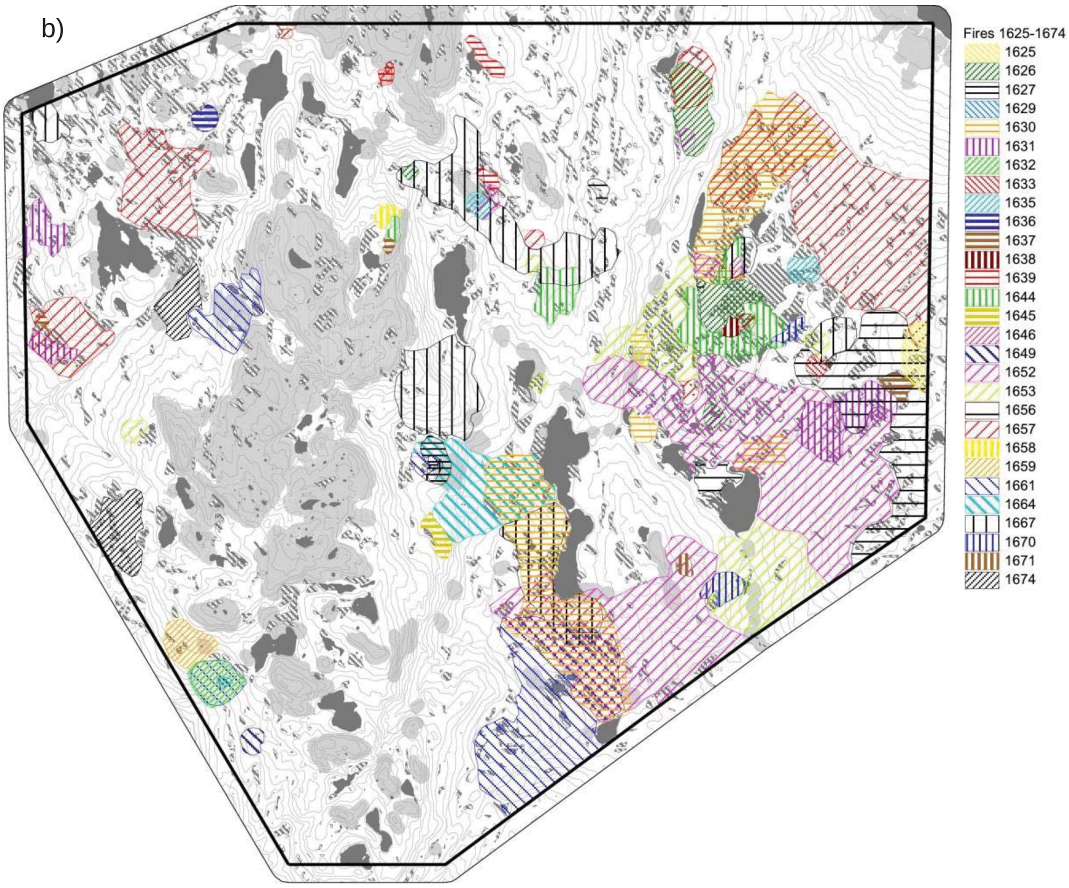


Fig. 5. All recorded fires within the study area in two different time periods: a) 1400-1499 (100 years), and b) 1625-1674 (50 years).

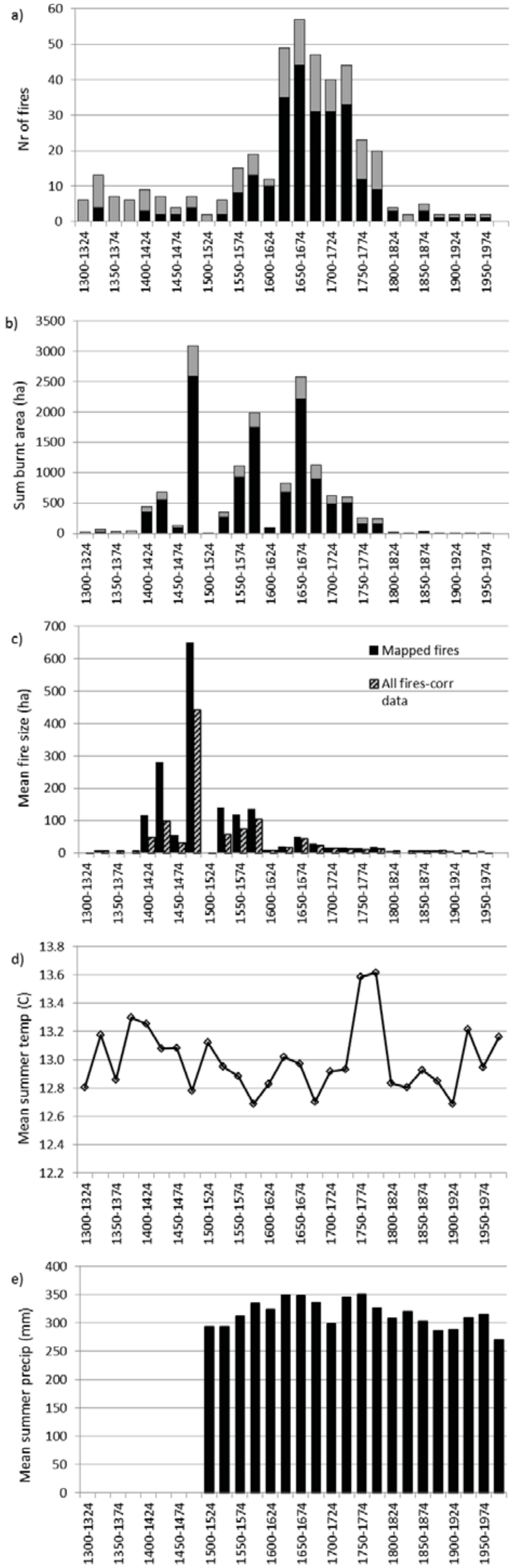


Fig. 6. a) Total number of fires, b) sum of total burnt area (ha), c) mean fire size (ha), d) mean summer temperature (°C), and e) mean summer precipitation (mm), within 25 year periods. In a) and b) black and grey bars show recorded and added adjusted fires, respectively. The hatched bars in c) show mean fire size of all fires (both recorded and added ones).

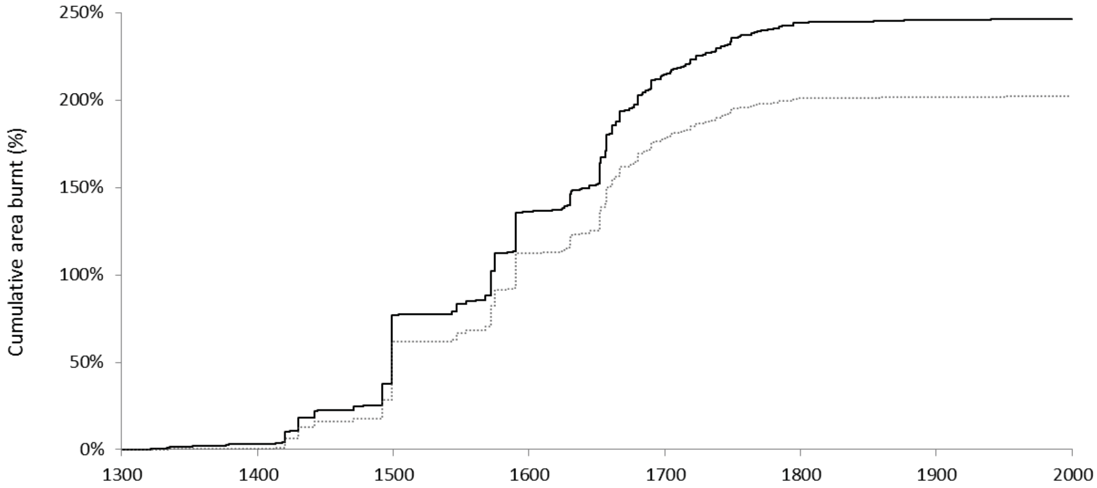


Fig. 7. Cumulative percent burnt area over time for the recorded fires (lower grey line) and for adjusted data (upper black line).

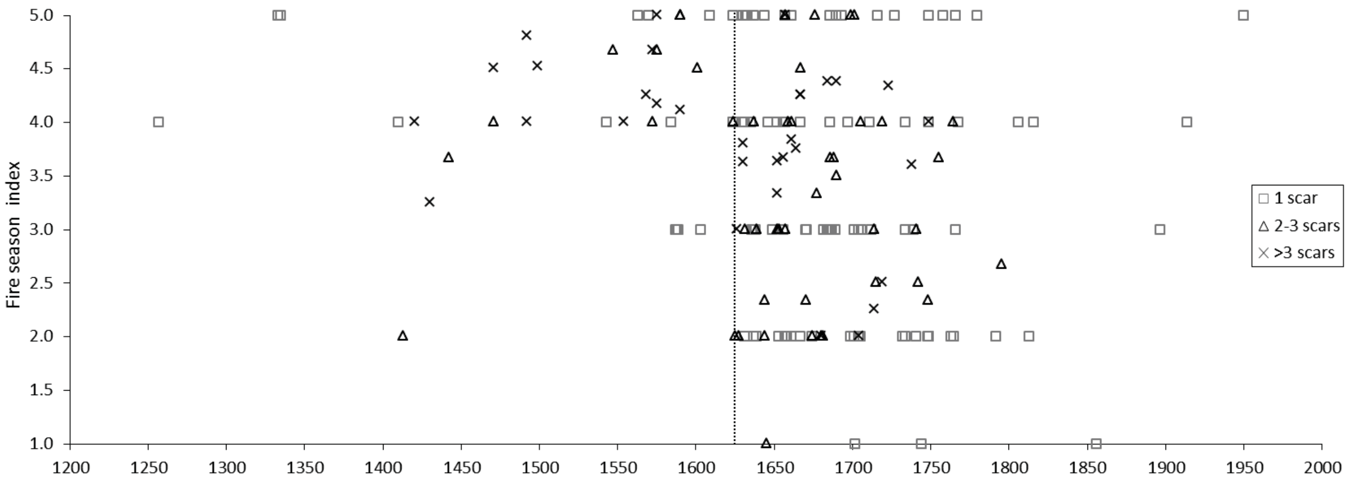


Fig. 8. Fire season index values (1 corresponds to dormant season and 5 corresponds to latewood season) for each individual fire. Dashed vertical line represent the year 1625.

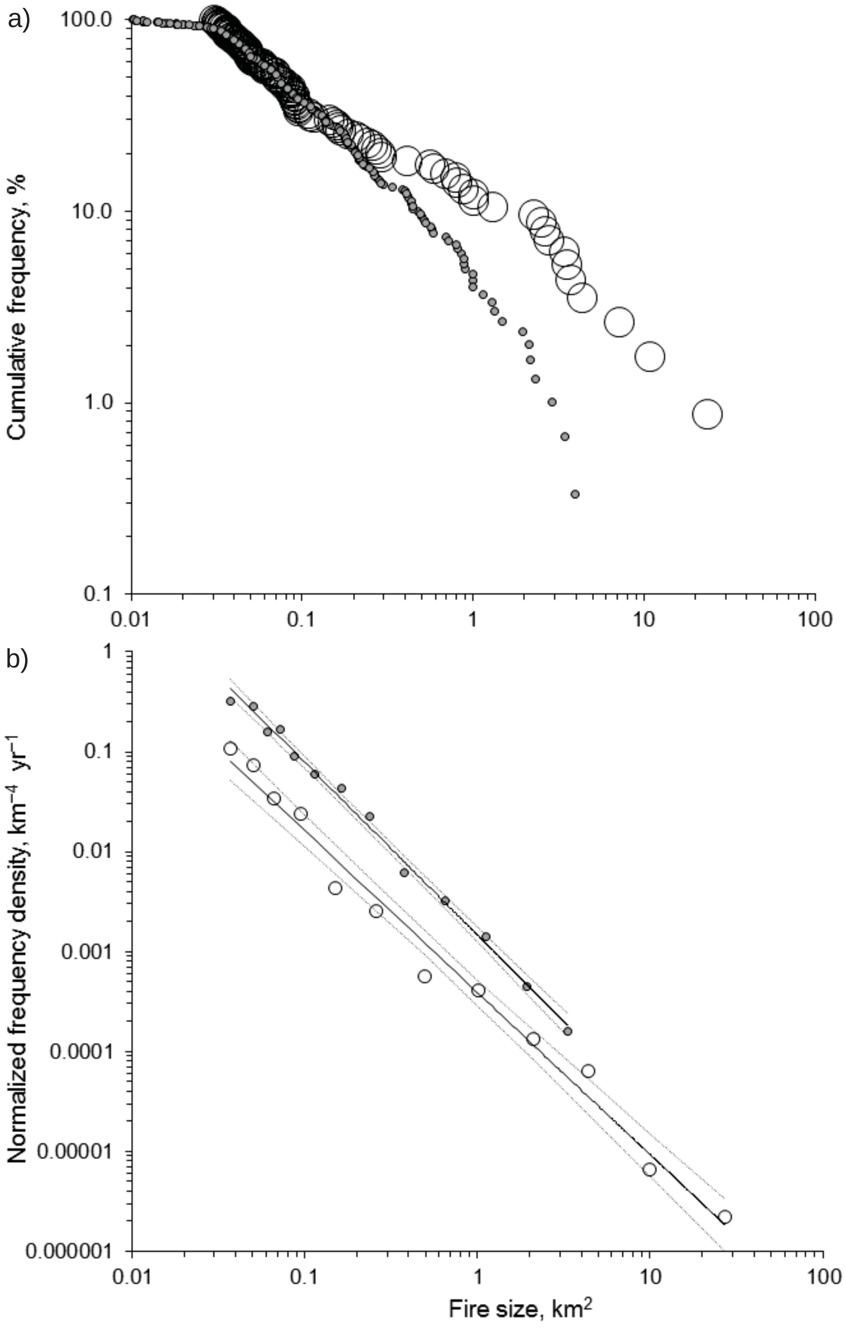


Fig. 9. a) Cumulative size-frequency distribution, and b) normalized density log-log plots, for pre-1625 (1300-1624) (open circles) and post-1625 (1625-1799) (filled dots). Dashed lines represent upper and lower 95% confidence intervals. Note the logarithmic scales on both axes.

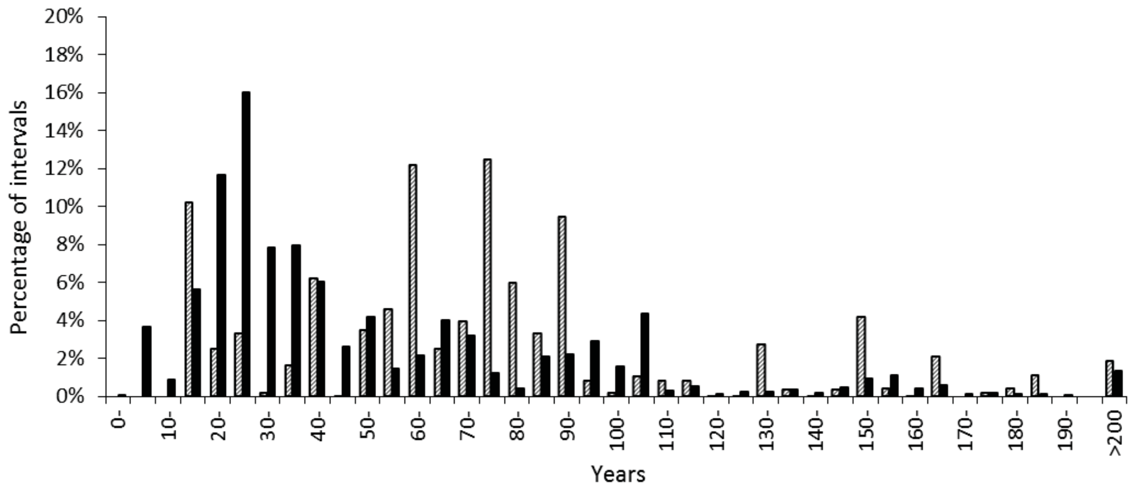


Fig. 10. Frequency distribution of fire return intervals between all recorded fires, pre-1625 (hatched bars) and post-1625 (black bars). Note that no censored data are included.

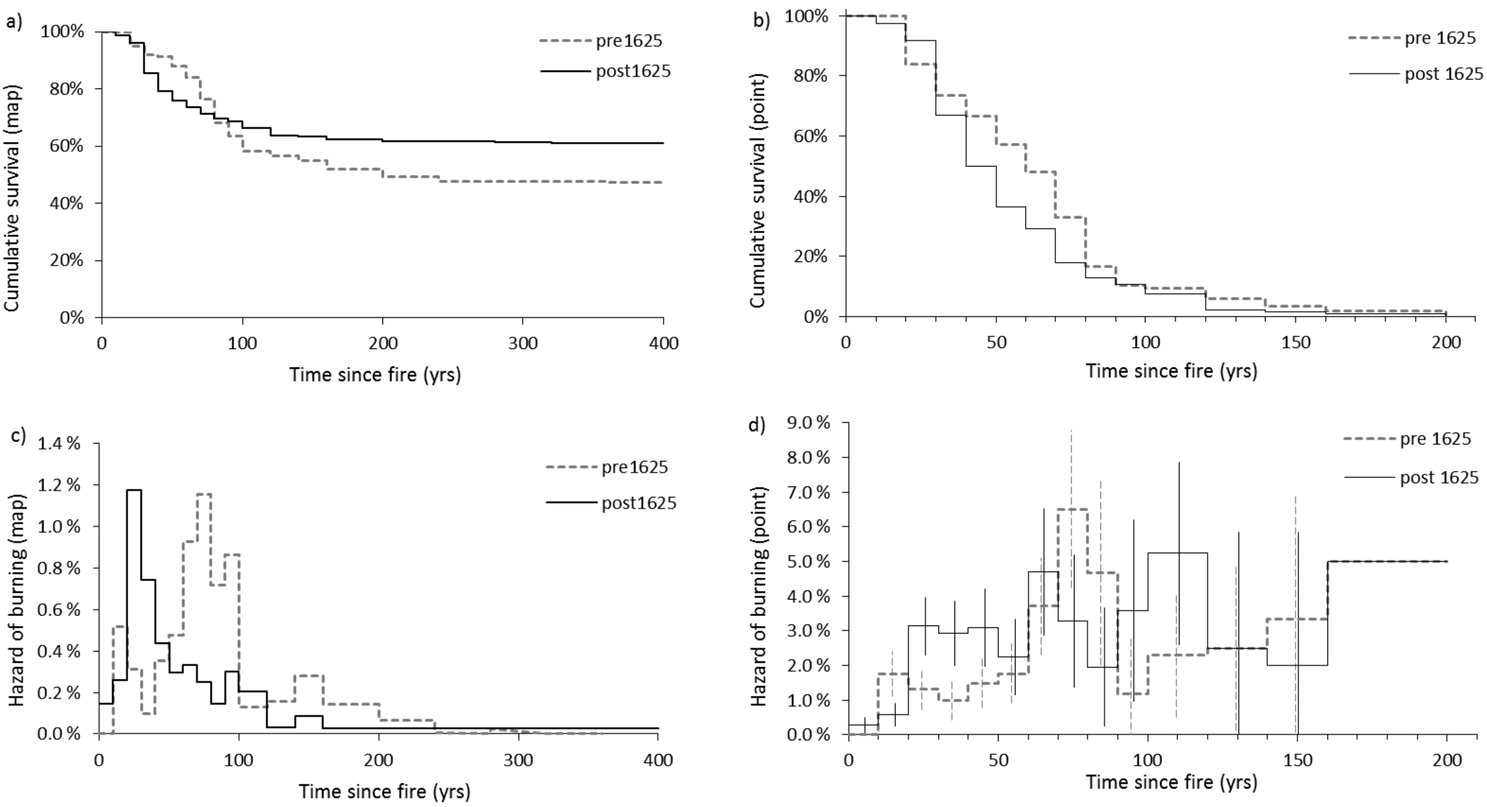


Fig. 11. Estimated cumulative survival function curve (a and b) and estimated hazard of burning (c and d) (i.e., yearly probability of a new fire occurring with increasing time since the last fire), for map-based (a and c) and for scar-based (b and d) data, and drawn separately for pre-1625 (dashed grey) and post-1625 (solid black) time periods. In d) the 95% confidence intervals are shown.

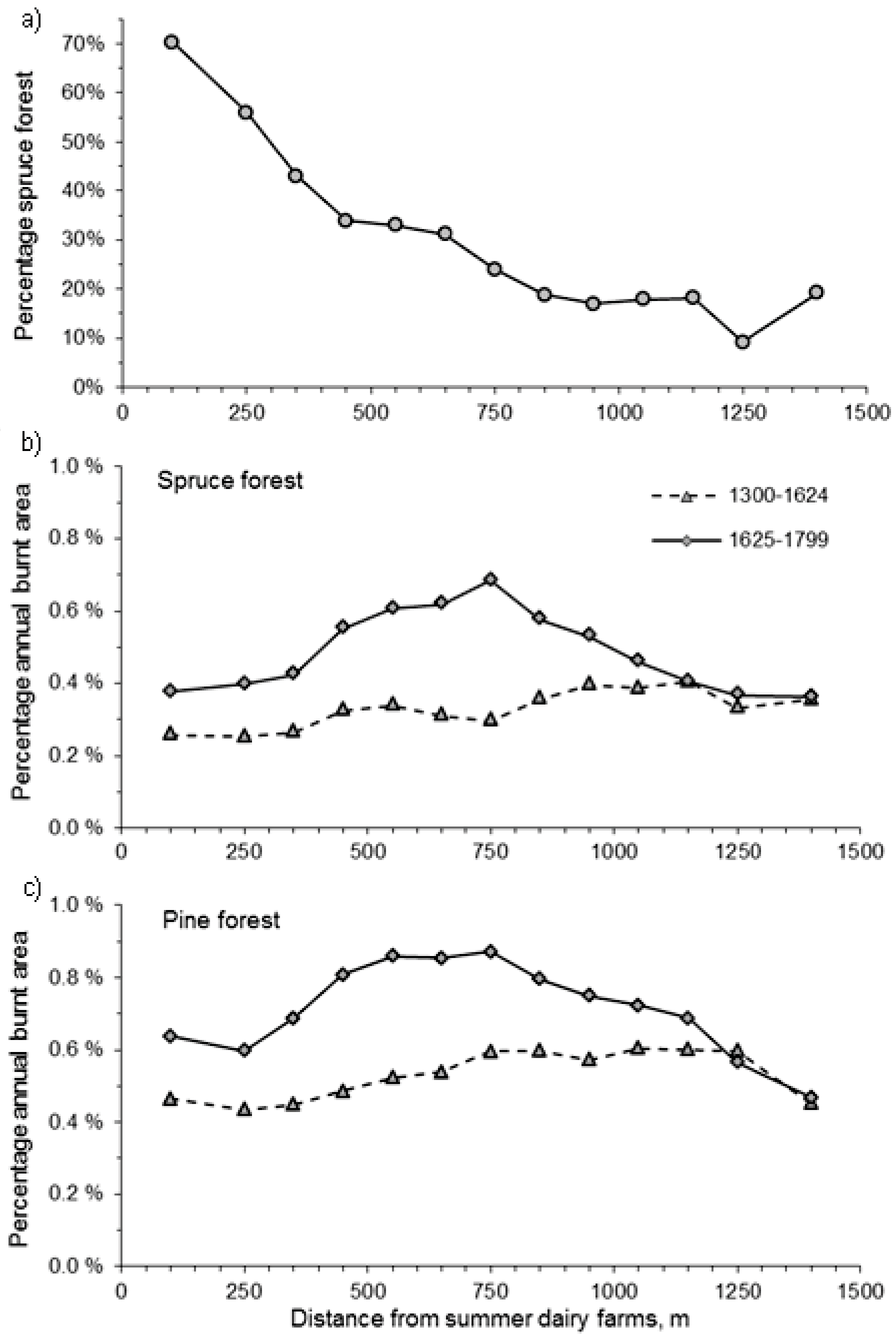


Fig. 12. Percentage of area (≤660 m a.s.l.) dominated by spruce forests (a) and annual percentage burnt area within spruce forest (b) and within pine forest (c) at different distances from the summer dairy farms. In b) and c) the annual percentage burnt area are divided into pre-1625 (1300-1624) (lower, dashed line) and post-1625 (1625-1799) (upper, solid line) time periods.

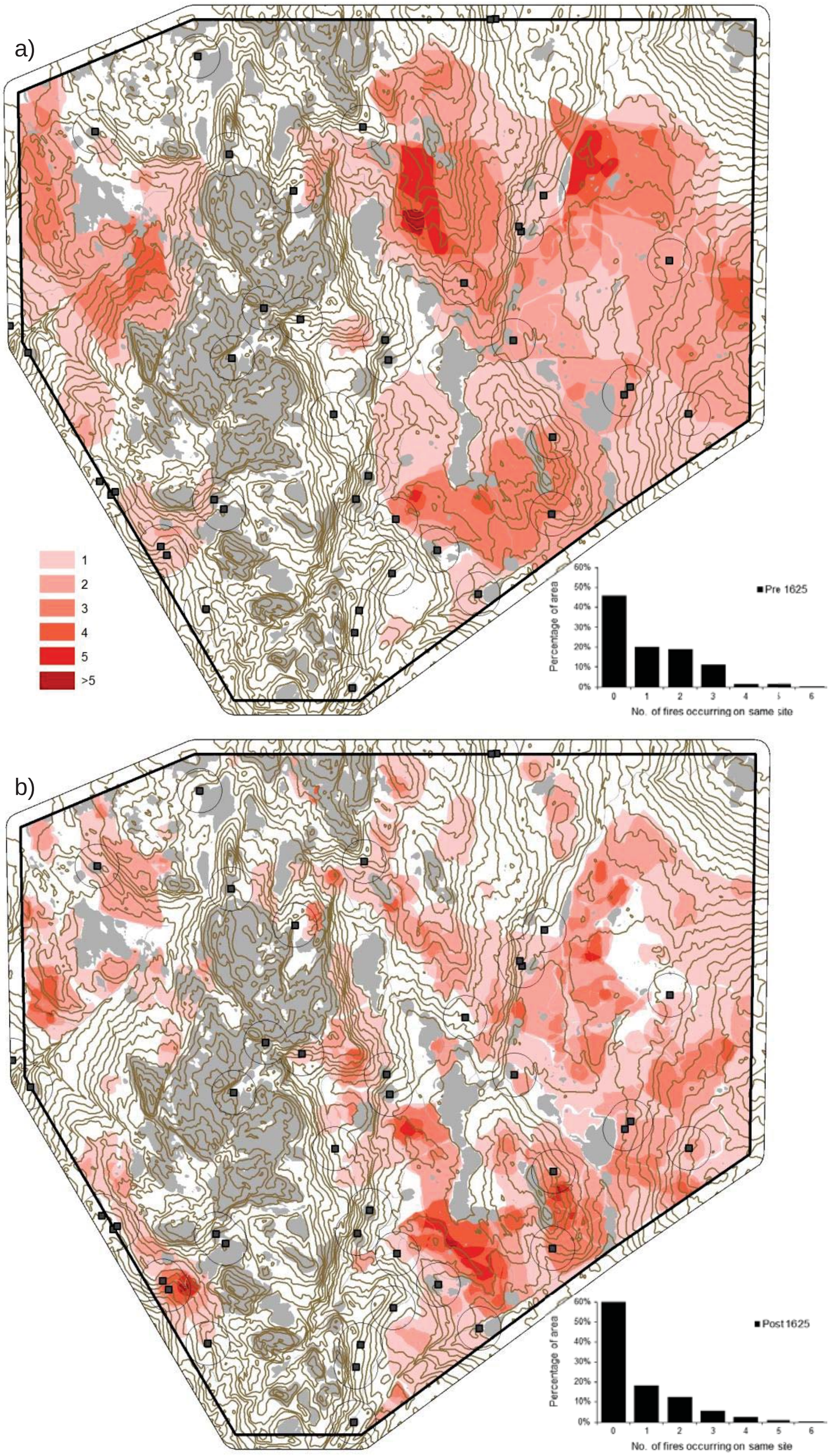


Fig. 13. Spatial distribution of fires (red colour gradient shows increasing number of fires that occurred in an area), during a) 1300-1624, and b) 1625-2009. Squares denote the location of historic summer dairy farms and are encompassed by a 300 m buffer zone. Inserted, lower right: Percentage of the area experiencing different number of fires.

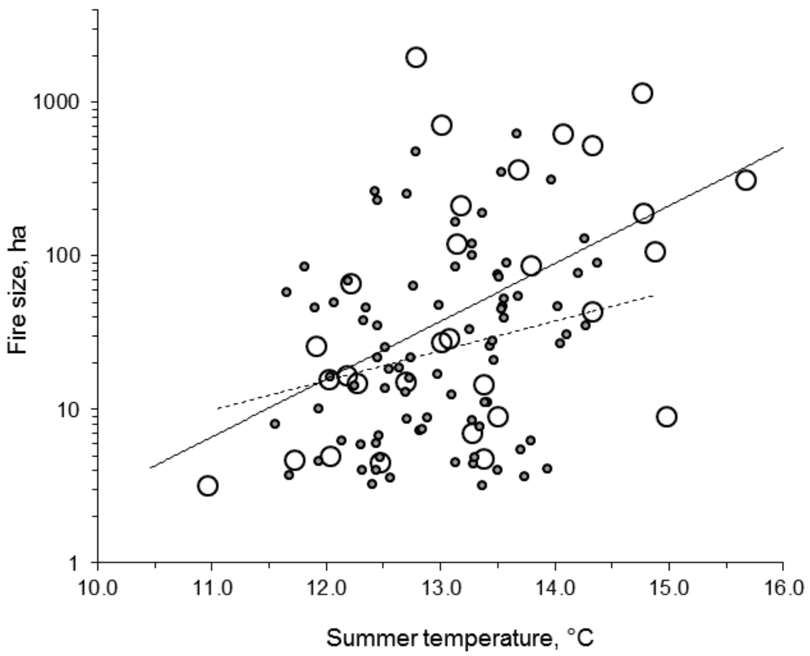


Fig. 14. Fire size (ha) versus summer temperature for pre-1625 (1300-1624) (open circles and solid line) and post-1625 (1625-1799) (filled dots and dashed line). Note the logarithmic scale on the y-axis.

PAPER II

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ARTICLE

Strong anthropogenic signals in historic forest fire regime: a detailed spatiotemporal case study from south-central Norway

Ken Olaf Storaunet, Jørund Rolstad, Målfrid Toeneiet, and Ylva-li Blanck

Abstract: To better understand the historic range of variability in the fire regime of Fennoscandian boreal forests we cross-dated 736 fire scars of remnant Scots pine (*Pinus sylvestris* L.) wood samples in a 3.6 km² section of the Trillemarka-Rollagsfjell Reserve of south-central Norway. Using a kernel range application in GIS we spatially delineated 57 individual forest fires between 1350 and the present. We found a strong anthropogenic signal in the fire regime from 1600 and onwards: (*i*) infrequent variably sized fires prior to 1600 shifted to frequent fires gradually decreasing in size during the 1600s and 1700s, with only a few small fires after 1800; (*ii*) time intervals between fires and the hazard of burning showed substantial differences pre- and post-1600; (*iii*) fire seasonality changed from late- to early-season fires from the 1626 fire and onwards; and (*iv*) fire severity decreased gradually over time. Written sources corroborated our results, narrating a history where anthropogenic forest fires and slash-and-burn cultivation expanded with the increasing population from the late 1500s. Concurrently, timber resources increased in value, gradually forcing slash-and-burn cultivators to abandon fires on forest land. Our results strengthen and expand previous Fennoscandian findings on the anthropogenic influence of historic fire regimes.

Résumé : Pour mieux comprendre l'ampleur de la variabilité du régime des feux dans les forêts boréales de la Fennoscandie, nous avons effectué une datation croisée de 736 cicatrices de feu sur des échantillons de bois de pin sylvestre (*Pinus sylvestris* L.) dans une section de 3,6 km² de la réserve de Trillemarka-Rollagsfjell située dans le centre-sud de la Norvège. À l'aide d'une application fondée sur la méthode du noyau et fonctionnant dans un SIG, nous avons délimité dans l'espace 57 feux de forêt distincts entre 1350 et aujourd'hui. Nous avons trouvé un fort signal anthropique dans le régime des feux à partir de 1600 : (*i*) on est passé de feux peu fréquents dont la taille était variable avant 1600 à des feux plus fréquents dont la taille a graduellement diminué durant les années 1600 et 1700 et à seulement quelques petits feux après 1800; (*ii*) il y avait des différences importantes avant et après 1600 dans l'intervalle de temps entre les feux et le risque d'incendie; (*iii*) la saisonnalité des feux a changé à partir du feu de 1626; les feux qui avaient l'habitude de survenir en fin de saison ont commencé à se produire en début de saison; (*iv*) la sévérité des feux a diminué graduellement avec le temps. Des sources écrites ont corroboré nos résultats, elles rapportent que les feux de forêt d'origine anthropique et la culture sur brûlis ont augmenté avec l'accroissement de la population à partir de la fin des années 1500. Parallèlement, la valeur de la ressource bois a augmenté forçant graduellement les agriculteurs à abandonner la culture sur brûlis en terrain forestier. Nos résultats renforcent et élargissent les connaissances antérieures concernant l'influence anthropique sur les régimes des feux passés en Fennoscandie. [Traduit par la Rédaction]

Introduction

Fire is the most important natural disturbance agent governing boreal forest stand dynamics, by controlling the age, structure, and species composition of these forests (Rowe and Scotter 1973; Bergeron et al. 2002). Studies of fire regimes in North America and Northern Europe have documented striking differences between these continents. Whereas high-severity, stand-replacing fires are common in North America, low- to moderate-severity fires seem to be more prevalent in the Eurasian boreal forests (Johnson 1992; Wooster and Zhang 2004). Historically, forest fires have been frequent throughout Fennoscandia with stands burning at intervals of 50–100 years (Zackrisson 1977; Niklasson and Granström 2000). However, during the last centuries, these forests have been extensively altered through logging and fire suppression (Östlund et al. 1997; Niklasson and Granström 2000). Notably, the almost total cessation of forest fires, combined with subsequent silviculture, has reduced the amount of deciduous forests (Zackrisson 1977; Essen et al. 1997) and promoted dominance of the more shade-tolerant and fire-sensitive Norway spruce (*Picea abies* L. Karst.) (Linder et al. 1997; Niklasson and Drakenberg 2001). Absence of fire, causing tree species compositional changes and increased density of forest stands, has also been reported from North American forests (Parsons and DeBenedetti 1979; Taylor 2000).

Knowledge about past fire regimes illustrates how the forest ecosystem has changed over time, i.e., the historic range of variability (Morgan et al. 1994). This knowledge is important for evaluating the sustainability of forestry today, and may serve as a guideline for managing parks and nature reserves (Swetnam et al. 1999; Bergeron et al. 2002). In North America, many studies have focused on land-use and ecosystem changes following the Euro-American settlement, whereas the earlier impacts of Native Americans have received less attention (Wallin et al. 1996; Veblen et al. 2000; Sherriff and Veblen 2007). In Fennoscandia, studies show strong human impact on fire frequencies and forest structures during several centuries (Östlund et al. 1997; Niklasson and Granström 2000; Wallenius et al. 2004, 2010; Groven and Niklasson 2005). Activities such as logging, pasturing, mountain dairy farming, slash-and-burn agriculture, coal and tar burning, and the mining industry historically impacted the forest landscapes of Northern Europe. Burning of forests for livestock grazing and for growing rye (slash-and-burn cultivation) was probably a common Fennoscandian practice from prehistoric times, although such

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activity is poorly documented in Norway (Asheim 1978; Larsson 1995; Pyne 1996).

Since Fennoscandian forest fires for the most part seem to have been low to moderately severe and only partly stand-replacing, dendrochronological dating of fire scars in remnant trees provide a means to reconstruct past fires (e.g., Niklasson and Granström 2000; Wallenius et al. 2004, 2010). However, a preponderance of Fennoscandian studies have been conducted in the northern regions, with few studies representing the southern parts (Niklasson and Drakenberg 2001; Groven and Niklasson 2005). Notably, most studies based on fire scars are carried out with relatively low sampling density (<15 samples·km^{-2}), which prevents detailed spatial delimitation of the fires.

Fire history studies based on scars typically infer fire frequencies as point estimates from the scarred trees or from local composite fire chronologies. However, more detailed knowledge can be gained if the number of sampled fire scars allows for spatial delineation of individual fire events. In this study, a high sampling density of living trees, snags, logs, and cut stumps of Scots pine (*Pinus sylvestris* L.) allowed us (*i*) to draw detailed maps; (*ii*) to estimate the relative fire size, season, and severity of historical fires; and (*iii*) to estimate fire frequencies, survival curves, and fire hazards with an unprecedented spatial resolution. In particular, we looked for anthropogenic signals in the fire regime that could delineate periods of human activity. In this respect, we examined historical sources for local and regional information that could substantiate the timing, extent, and understanding of the previous human fire activity.

Materials and methods

Study area

Trillemarka-Rollagsfjell Nature Reserve was established in 2002 and enlarged in 2008; today it covers 147 km^2 of forest and mountainous terrain between the valleys of Numedal and Sigdal in Buskerud County of south-central Norway. The reserve is one of the largest forested areas in southern Norway with little influence from modern technical developments and large-scale commercial forestry. However, traces of past anthropogenic activity are abundant, including cut stumps, old tracks, and various legacies of summer dairy farms. This study was confined to a 3.6 km^2 southern section of the reserve, named Heimseteråsen (60°02′N, 09°26′E) (Fig. 1). The area was chosen because of the presence of numerous remnants of fire-scarred Scots pine and because previous studies of forest stand structures and red-listed species have been conducted there (Gjerde et al. 2004; Storaunet et al. 2005). The topography is characterized by north–south extending ridges of Precambrian rocks consisting of acid granites and gneisses. Two east-facing slopes are important landscape elements with deposits of richer glacial materials. A lower area in the eastern part and a central elevated plateau between the slopes consist of mires and forest stands dominated by Scots pine, classified as *Calluna vulgaris – Vaccinium uliginosum* woodland and *Vaccinum* woodland (Moen 1999). Norway spruce predominates the slopes with a field layer characterized by tall herb, low herb, small fern, and *Vaccinum myrtillus* woodland. Deciduous tree species (*Alnus incana* (L.) Moench, *Betula pubescens* Ehrh., *Populus tremula* L., and *Sorbus aucuparia* L.) occur sporadically. The vegetation represents the mid-northern boreal zone and the climate is intermediate continental to oceanic. Altitude ranges 400–650 m a.s.l., annual precipitation averages 800 mm, and snow typically covers the ground from November–December to mid-May. Mean annual temperature is +4 °C, with January and July means of −4 and +15 °C, respectively (Moen 1999).

Although the reserve is little influenced by modern forestry and technical developments, it has a long history of anthropogenic utilization, such as high-grading timber harvesting, summer dairy farming, grazing, and slash-and-burn cultivation (Skatvedt 1914; Mørch 1954). Still, characteristics of old-growth forest, such as very old trees, abundant dead standing and fallen trees, and the presence of rare and threatened species, are present at several localities (Bendiksen 2004; Storaunet et al. 2005; Castagneri et al. 2013).

The National Archives of Norway was searched for documents, diplomas, and old maps covering the reserve and its vicinity. Historic maps give information about locations of summer dairy farms, old roads, tracks, and rivers used for log driving. More general knowledge about the historic use of fire in Norway was gained from old agricultural textbooks and reports with descriptions of forest and land use. The archival documents used and calendar years of historic relevance are listed in the Supplementary data (Tables S1 and S2).[1]

Field sampling

During the summers and falls of 2006 and 2007, we systematically searched through the 3.6 km^2 study area and sampled all fire-scarred material we could find from living trees, snags, logs, and cut stumps of Scots pine. No scars were found in other tree species. Most of the samples were old cut stumps, whereas living trees with visible fire scars were uncommon. A 2–5 cm thick partial cross section was extracted with a chainsaw from the place where the fire record appeared to be most complete. If several sections or heights on the scarred tree appeared to have recorded different fires, multiple cross sections were sampled. In addition to samples with distinct fire scars, we also collected samples from trees with irregular wooden structures indicating possible overgrown scars, from trees that had burned after death, and from trees that appeared very old (for chronology building).

A total of 641 tree samples were successfully cross-dated (see the following), of which 321 were scarred from one or several fire events and 320 had no signs of fire (Table 1 and Fig. 2; Supplementary data Fig. S2).[1] The no-scar samples included 259 living pine trees from a previous study (Storaunet et al. 2005). These were recorded as being the 2–3 oldest living trees in each plot within a 100 m × 100 m grid covering most of the study area. Since these trees had no signs of fires, and we had good estimates of their total age, we included them as "recorder trees" (defined in the following) not recording a fire. Finally, we used samples from 12 fire-scarred trees <200 m outside the study area border, only to facilitate the spatial delineation of individual fires, but these were excluded from all other analyses. The following measurements were taken in the field: tree diameter, tree or stump height, number of fire scars, height of cross-section on the stem, and Universal Transverse Mercator (UTM) coordinates; and we recorded if the tree was living, a snag, a fallen log, or a stump from a cut tree.

Dendrochronology, cross-dating, and assessment of fire season

All cross sections were dried and sanded in the laboratory by an electric belt sander with increasingly finer paper grain until the cell-structure was visible under magnification. The cross sections were measured with an Addo micrometer (accuracy of 0.01 mm), and the ring-width series were cross-dated against three independently developed tree-ring index chronologies using the program COFECHA (Holmes 1983): (1) Flesberg chronology (Eidem 1959; 15–20 km south of the study area), developed from 97 trees with a sample depth of >5 tree-ring series dating back to 1526; (2) Rollag pine chronology (5–10 km NW of the study area, 22 trees, and >5 series from 1560); and (3) the local Sigdal pine chronology

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2012-0462.

Fig. 1. (*a*) Location of the study area (gray circle) within Scandinavia. (*b*) Local topography (contour intervals are 5 m) and location of all successfully cross-dated tree samples within the Heimseteråsen study area. Samples with fire scars (*n* = 321) are indicated by red circles and samples with no fire scars (*n* = 320) are indicated by gray circles. Squares indicate the location of the historic summer dairy farms (1) Naase Seter, (2) two Strand Seter, (3) Lid Seter, and (4) Moslon (there are only indications that Moslon existed as a summer dairy farm). Shaded blue areas indicate open bogs and mires. Blue areas are water bodies, rivers, and brooks.

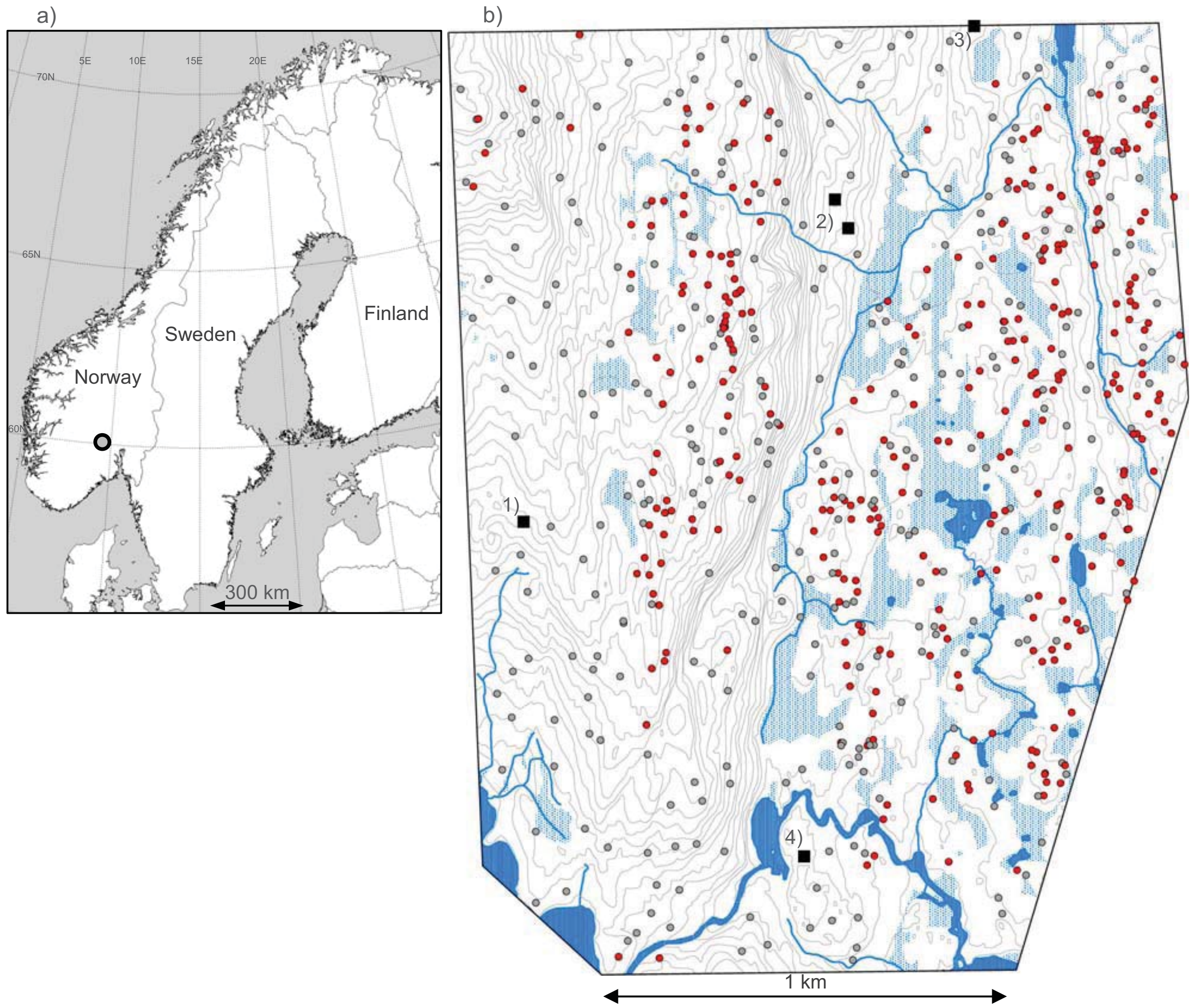


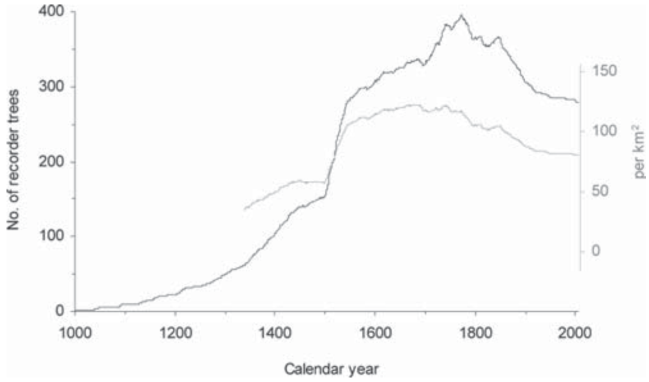
Table 1. Total number of trees sampled.

Description	No.
Successfully cross-dated	641
With fire scars	321*
Collected for other purposes†	61
Living trees without scars‡	259
Undated	62
Total number of trees sampled	703

*A total of 736 fire scars.
†Index chronology; burned after death; or old stumps.
‡Data from Storaunet et al. (2005).

(including data from this study, 117 trees, and >5 series from 1248). The two latter chronologies were developed by the authors. The suggestions from the statistical cross-dating were subsequently confirmed by the pointer-year method (Yamaguchi 1991). The fire scars were identified under magnification and assigned to the correct fire year. A total of 736 fire scars from 321 tree samples were successfully cross-dated (Table 1 and Supplementary data Fig. S2).[1] Unsuccessful datings were mainly due to having fewer

Fig. 2. Total number and density (gray line and right axis) of recorder trees within the study area over time. (See Supplementary data for further details and Fig. S2 for the timelines of all individual tree samples).[1]



tree rings and a complacent ring pattern within the cross section, whereas some of the samples were in poor condition because of decay.

Fire season can be determined by studying the cell structure within the fire-scarred tree ring. When the heat from the fire has killed the outermost row of living cells, the dead cells can be seen under magnification as collapsed or damaged cells. The collapsed cells' relative position within the tree ring reveals the approximate timing of the fire during the growing season. The position of the fire scar within the tree ring was appointed to five seasonal categories: dormant (D), early earlywood (EEW), middle earlywood (MEW), late earlywood (LEW), and latewood (LW) (Baisan and Swetnam 1990). Few of the scars were classified to D (6.9%), and these were assigned to be early fires (instead of late fires occurring after growth season the previous year) because, in most cases, other seasonal datings the same fire year were already classified to EEW or MEW. We calculated a fire-season index for individual fires as the percentage of seasonal datings being classified to D and EEW, resulting in high index values for early season fires and low values for mid- and late-season fires.

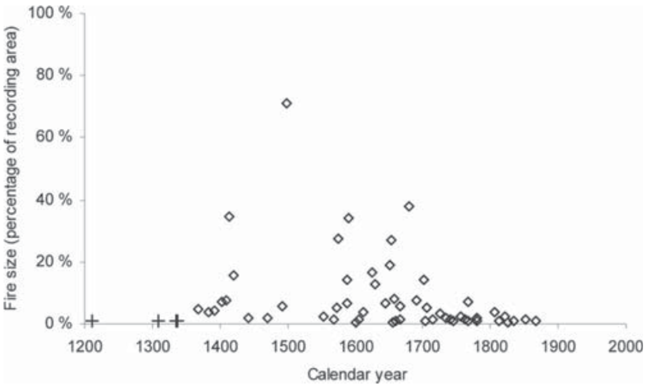
Spatial delineation of individual fires, recording area, and estimate of relative fire size

We delineated individual fires according to the following procedure (for definitions and further details see Supplementary data Fig. S3).[1] First, we identified locations of the recorder trees, including fire-scarred samples, young trees, and trees previously scarred by a fire. Next, we used ArcView GIS 3.3 software (ESRI Inc., Redlands, California) to calculate two contrasting kernel ranges: one for the scarred samples (fire area) and one for the recorder trees without fire scars (no-fire area), respectively. The no-fire area was then subtracted from the fire area to delineate the actual fire perimeter. At the end, minor adjustments of the fire borders were done to make sure that the location of all fire-scarred samples were included in the fire area and to ascertain that fires occurring closely in time were not overlapping. For all fire years we estimated the spatial coverage of the recorder trees, henceforth called the "recording area", using the same GIS kernel procedure. The relative fire size was then calculated as the ratio of the fire area to the recording area of the actual year.

Fire severity, intervals, survival, and hazard of burning

We defined a fire-severity index as the percentage of the number of scarred trees to the number of recorder trees within the perimeter of the fire, a definition deviating from the more established practice of using fire severity to describe the proportion of trees being killed (e.g., Agee 1993). To see if fire severity was related to calendar year and seasonality, we used partial regressions to account for covarying number of scarred trees and fire size. The covariates were log-transformed to achieve normality and homoscedasticity. Time intervals between fires were calculated from 8730 point locations regularly distributed in a 20 m × 20 m grid covering the study area (see the Supplementary data for further details).[1] Intervals were calculated for two separate time periods, 1350–1600 and post-1600, based on the timing of human influence on the fire regime (see Results). The cumulative survival function (i.e., the proportion of newly burnt area remaining unburnt over time) and the corresponding hazard of burning (i.e., yearly probability of a new fire occurring with increasing time since the last fire) (Johnson and Gutsell 1994) were calculated using the Actuarial Analyses (Life Table) routine of the StatView 5.0 software package (SAS Institute Inc., Cary, North Carolina). In the early period, time spans between 1350 and the first occurring fire at a point and between successive fires, were treated as uncensored cases, whereas time intervals between the last fire before 1600 and the year 1600 were treated as censored cases. The same procedure was applied for the latter period (1600–2000). All calculations were done only within the recording area for given periods. The index values of fire season and fire severity pre- and post-1600 were compared using Mann–Whitney *U* tests.

Fig. 3. Relative size (as a percentage of the recording area) of individual fires during 1200–2000. + indicates pre-1350 fires, for which size was not calculated because of a low number of samples.



Results

In total, we recorded 61 separate fire years within the 3.6 km² study area (Figs. 3 and 4). The earliest one occurred ca. 1210, but because the inner portion of the tree was decayed, the exact fire year could not be ascertained. Before 1350 we only recorded a few fire events (1210, 1310, 1335, and 1338), of which none appeared to have been large ones. However, owing to low sampling depth in this early period these fires were excluded from further analyses. From 1350 onwards, the number of recorder trees was numerous enough to estimate spatial coverage of the study area and spatial extent of individual fires (Figs. 2 and 4; Supplementary data Fig. S2).[1] Only one recorded fire (1499) was large enough to cover most of the study area, whereas five (9%) fires (1413, 1575, 1590, 1653, and 1680) covered 25%–40% of the area. About half of the fires (27 of 57) were recorded in only one tree sample, most of them occurring in the 1700s and 1800s. Many of the large fires obviously extended beyond our study area (Fig. 4). However, it was not our intention to estimate the absolute size of fires; hence, we refer to the proportion of the recording area that was burned.

The extent of fires varied considerably during the early period (pre-1600), as illustrated by the 1413, 1499, and 1590 fires, constituting 35%, 72%, and 34% of the recording area, respectively, and the 1442, 1471, and 1568 fires covering less than 2%. The number of fires increased substantially in the 1600s compared with the two preceding centuries, with fire sizes still varying considerably. The 1700s had approximately the same number of fires as the 1600s, but fire sizes decreased dramatically. All fires during this century, except the 1702 fire, covered <10% of the recording area. After 1800, both the number and size of fires decreased, and the last fire was recorded in 1866 (Figs. 3 and 4).

With the whole study area as a reference, the spatial analyses revealed that 25% of the area had no signs of fire, 20% of the area had burned 1–3 times, and 50% had burned ≥5 times during the 650 year period (Fig. 5). However, the recording proportion of the study area increased over time, from approx. 60% in the 1300s, 75% in the 1500s, and to >95% from the 1700s onwards (Fig. 4). The maximum number of fire scars recorded in a single sample was six. Few fire-scarred trees were found in the vicinity of the historic summer dairy farms (Fig. 1). On average, the density of scarred trees was 19 per square kilometre within 250 m of the dairy farms, compared with 106 per square kilometre outside this distance, corresponding to an average of 1.5 fires inside and 4.2 fires outside this area (Fig. 5).

The annual proportional area burned (expressed as a percentage of the recording area) changed markedly over time; 1.0% year^{-1}

Fig. 4. Spatial delineation of individual fires during nine time periods. To enhance readability, different time intervals are being used, and the individual fires are denoted with different colors. Pre-1350 fires are marked as black dots only because the number of recorder trees was low. Light gray shadings illustrate the concurrent recording area (i.e., the spatial cover estimated from all recorder trees). Contour intervals are 20 m.

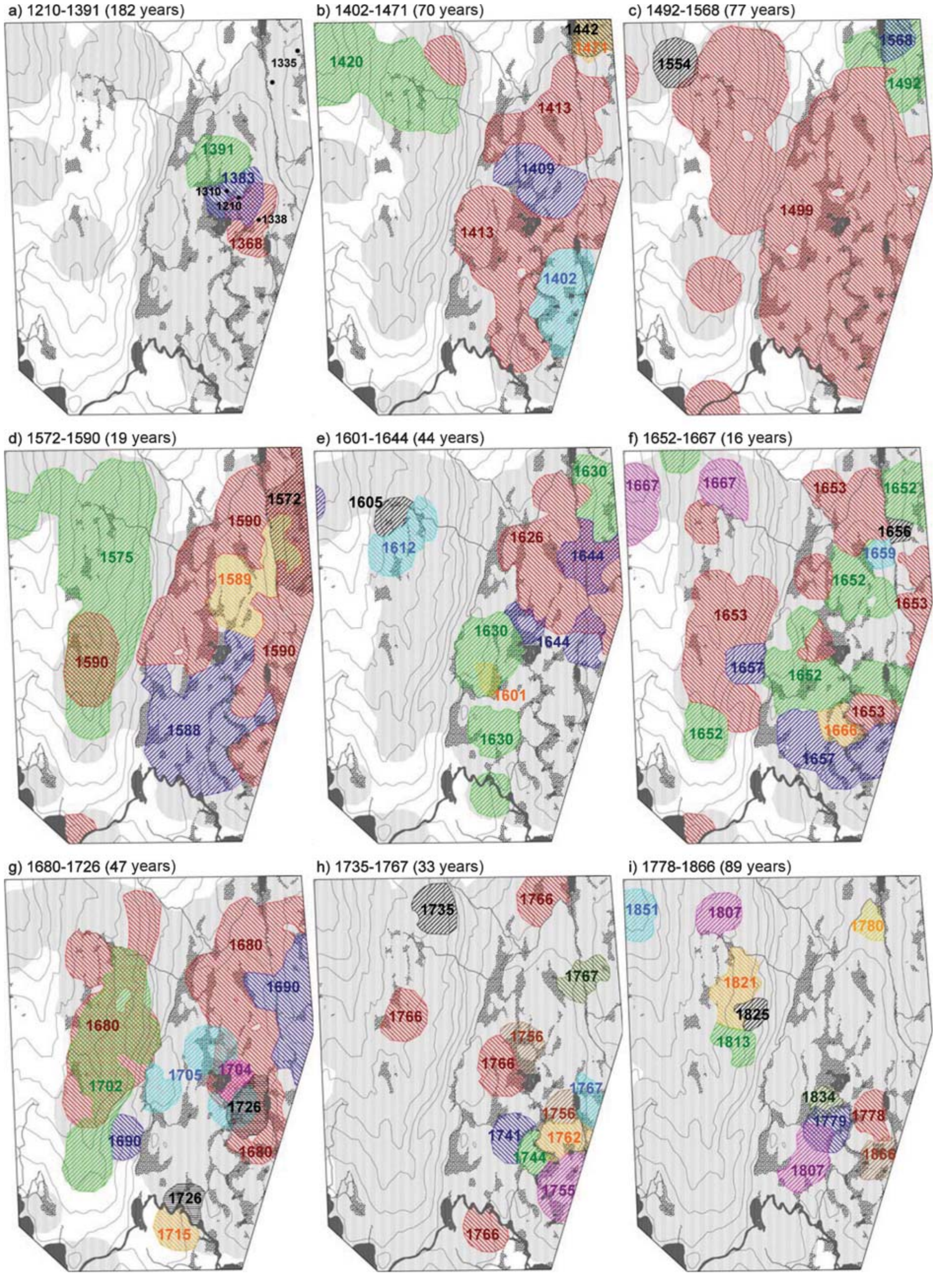
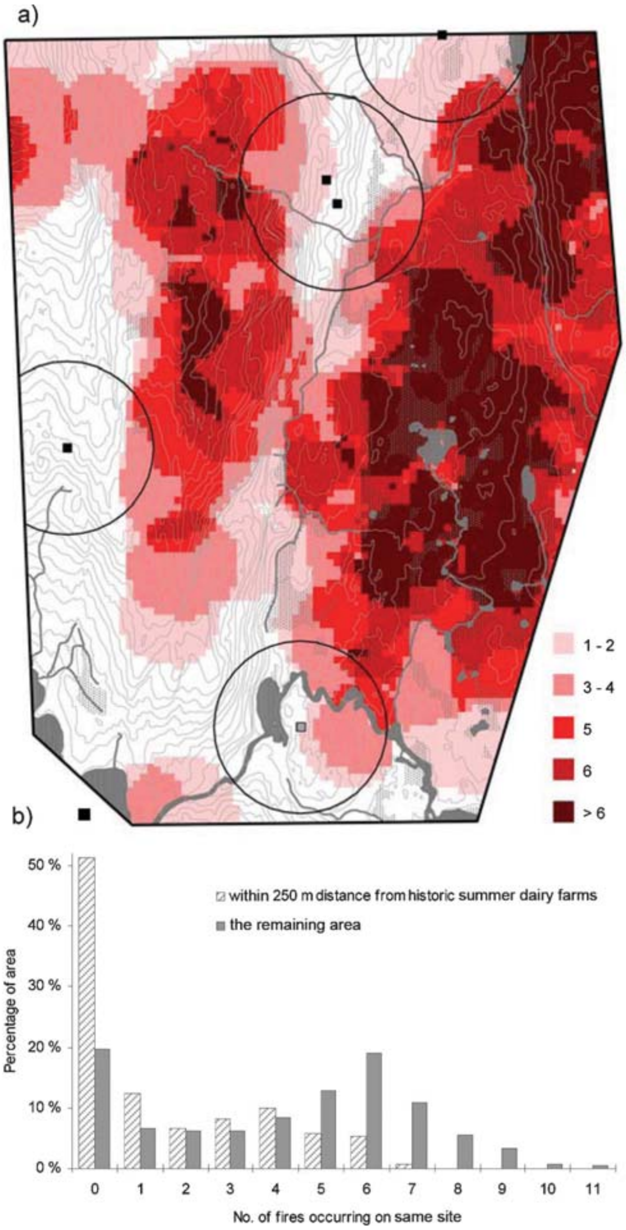


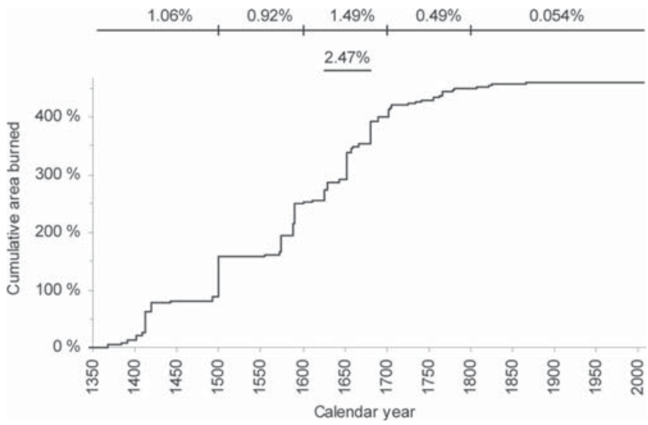
Fig. 5. (*a*) Spatial distribution of fires (red color gradient shows increasing number of fires that occurred in an area) during 1350–2000, within the study area. Black squares denote the location of historic summer dairy farms and are encompassed by a 250 m buffer zone. (*b*) Percentage of area experiencing different numbers of fires within and outside the buffer zone around the historic summer dairy farms.



prior to 1600, 1.5% year^{-1} in the 1600s, 0.5% year^{-1} in the 1700s, and decreasing dramatically to 0.05% year^{-1} after 1800 (Fig. 6). This implies rotation cycles of 100, 67, 204, and 1870 years, respectively. Maximum proportion burnt was recorded during the mid–1600s, when annual percentage burnt area was 2.5% (40 years rotation: 1626–1680).

Consecutive fires at short intervals showed limited spatial overlap, instead they typically displayed a mosaic shaped pattern. In the early period, the 1492 fire was located in the north-eastern corner of the study area, and seven years later the 1499 fire burned most of the remaining areas (Fig. 4*c*). This pattern was even more

Fig. 6. Cumulative percentage burned area (of the recording area) over time (1350–2000). Numbers above the figure show the average annual percentage burned within different time periods.



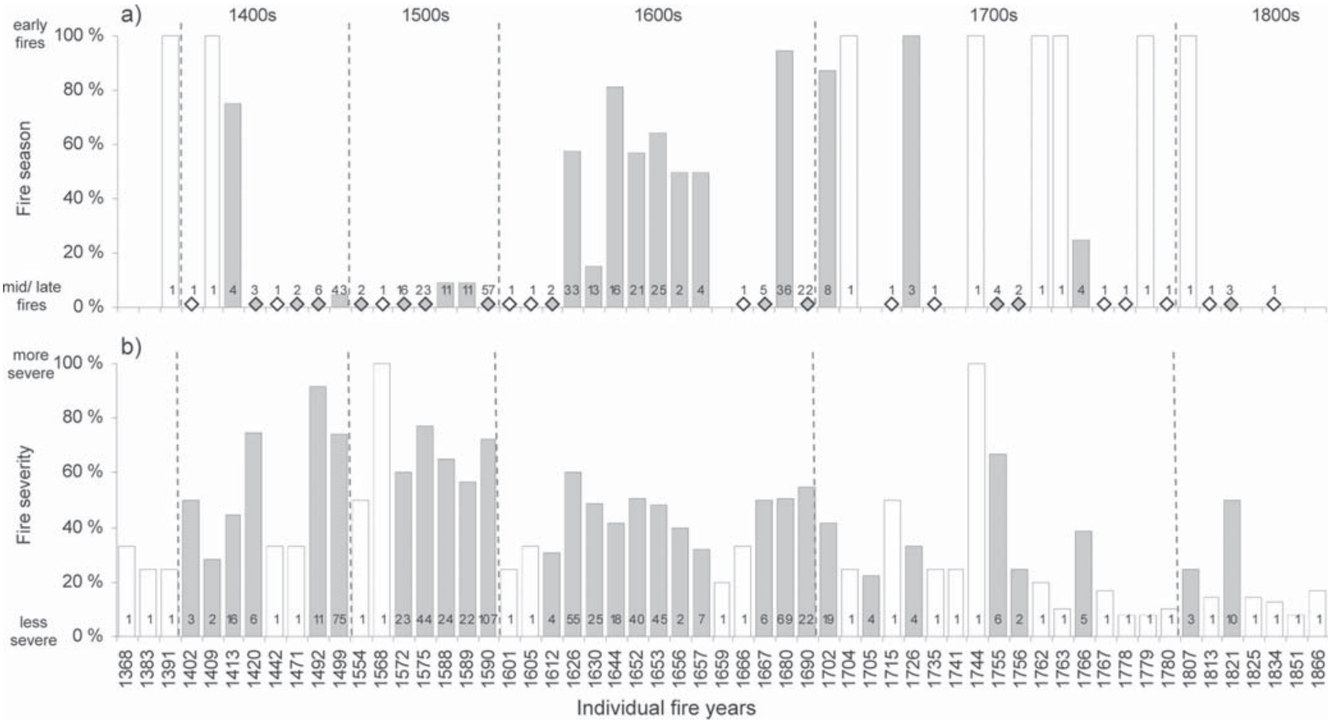
pronounced during 1588–1590, when a fire in the southeastern part occurred in 1588, continuing with a fire in the northeastern part in 1589, being completed with a large fire in 1590 covering most of the remaining areas in the eastern part (Fig. 4*d*). A similar pattern was also apparent in the years 1644, 1652 and 1653 (Figs. 4*e* and 4*f*). Within the study area there were no absolute fire breaks. The creeks are small enough to easily be jumped by a fire. Several fires were recorded on both sides of the mire systems, strongly suggesting that the fires easily ran the mires (e.g., 1413, 1499, 1590, 1652, and 1680).

We were able to determine the fire season for 55% of all dated fire scars. In 28 of the 57 individual fires that occurred after 1350, season was determined from more than one sample (Fig. 7*a*). The fire season changed from mid and late to early season over time. Before 1600 only 1 out of 11 fires (1413) had a fire season index value >50% (i.e., early season), whereas this was the case in 9 out of 17 fires after 1600 (Mann–Whitney $Z = 2.06$, $p = 0.039$, $n = 28$). The shift in fire season appeared rather abruptly, starting with the 1626 fire (Fig. 7*a*).

Fire severity also changed over time, however, decreasing rather gradually (Fig. 7*b*) ($R^2 = 0.21$, $p < 0.001$, $n = 55$, excluding two outliers with only one scarred recorder tree: 1568 and 1744). The fire-severity index was strongly and positively related to the number of fire-scarred trees in the actual fire, the number of recorder trees within the fire perimeter, and also the fire size ($R^2 = 0.58$, $p < 0.001$; $R^2 = 0.24$, $p < 0.001$; and $R^2 = 0.49$, $p < 0.001$, respectively; independent variables were log-transformed). This implies that larger fires scarred a higher proportion of the recorder trees compared with smaller ones. Because fire size decreased over time (Fig. 3), this could explain the decline in fire severity. However, the decreasing trend in fire severity over time was upheld after the size dependency was accounted for ($R_p^2 = 0.23$, $p < 0.001$). Comparing the pre- and post-1600 time periods, the latter period was characterized by significantly lower fire severity (Mann–Whitney $Z = -3.41$, $p < 0.001$). Finally, the fire-severity index was negatively related to the fire season index (after both fire size and calendar year were accounted for: $R_p^2 = 0.37$, $p < 0.001$, $n = 28$), indicating that a higher proportion of the recorder trees were scarred in fires occurring late in the season compared with fires early in the season. Because of these time-related changes in fire pattern (increasing number of fires, decreasing fire sizes, fires earlier in the season, and decreasing fire severity), we split the data set into pre- and post-1600 for further analysis.

The pre- and post-1600 fire interval distributions were strikingly different (see the Supplementary data).[1] Before 1600, the study area was heavily influenced by a few and relatively large fires with 75–95 years intervals (1413/1420, 1499, 1572/1575, and 1590;

Fig. 7. (*a*) Fire-season index values showing the percentage of all seasonal datings being classified to early season (dormant (D) and early earlywood (EEW)) for each fire year (bars). Diamonds on the *x* axis indicate 0%, whereas fire years with no seasonal datings are empty. (*b*) Fire-severity index values showing the percentage of all recorder trees being scarred for all fire years. Numbers above the *x* axes denote (*a*) the number of seasonal datings and (*b*) the number of scarred trees. White bars and diamonds show index values estimated from only one seasonal dating (*a*) or scarred tree (*b*). See Methods for further details.



Figs. 4*b*–4*d*; Supplementary data Fig. S4*b*).[1] After 1600, intervals peaked at 20–30 years with a tail of longer time intervals (Figs. 4*e*–4*i*; Supplementary data Fig. S4*b*).[1] Thus, the cumulative survival function, i.e., the proportion of freshly burnt areas remaining unburnt over time, differed substantially between the two time periods (Fig. 8*a*). Prior to 1600, the corresponding hazard of burning showed three pronounced peaks: at 70–100, 150, and 225 years since fire, peaking at 6%–7% (Fig. 8*b*). These were mainly caused by the same large fires as mentioned above. The post-1600 hazard function peaked at 20–30 and at 50–60 years since fire, with hazard rates of 2%–3%.

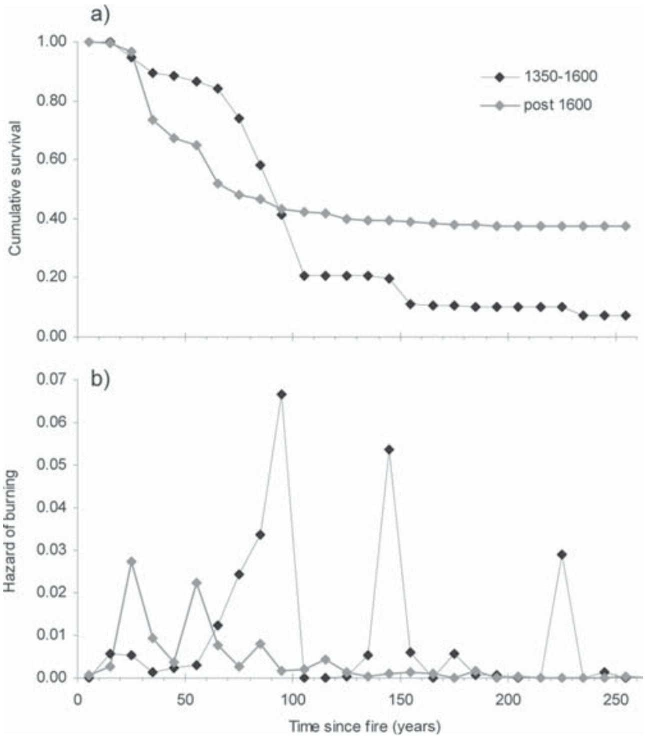
Discussion

In this study, we document the small-scale spatial pattern of forest fires in a Fennoscandian boreal forest landscape over 650 years. The high sampling density allowed for a detailed reconstruction of individual forest fires within the 3.6 km^2 study area. Profound changes in the fire regime occurred over the centuries. We found a general pattern of relatively few fires varying markedly in size up to ca. 1600, followed by two centuries with many fires decreasing in size over time. After 1800, only a few small fires were revealed.

The same general pattern has been reported in a few earlier studies from Fennoscandia, although the spatial resolution and temporal changes in fire size and frequency vary to some degree (Niklasson and Granström 2000; Niklasson and Drakenberg 2001; Wallenius et al. 2004; Wallenius 2011). For example, 45 km SSW of our study area, Groven and Niklasson (2005) found that the increase (ca. 1550) and decrease (ca. 1750) in fire frequency occurred about 50 years earlier compared with our results. In northern Sweden, Niklasson and Granström (2000) found an increased number of fires from the late 1600s and a distinct decrease from the 1870s, changes occurring 50–100 years later than in our study. Both studies relate these general trends to anthropogenic influence on the fire regime, with indications of less human influence in the early period, followed by a period with many man-made fires, whereas the declines are explained by fire suppression. The earlier decrease in fire frequency found by Groven and Niklasson (2005) may be explained by their study area being more strongly influenced by regulations from a regional mining industry, whereas the later decline found in northern Sweden (Niklasson and Granström 2000) presumably was due to a later start of forest timber exploitation in this region (see the following).

A strong mosaic-shaped pattern in forest fires was revealed in our data. In particular, consecutive fires at short time intervals showed limited spatial overlap. The shortest interval found was 9 years, recorded only in two trees. This indicates that recently burnt areas had too little fuel to burn over again. In our data, the pre-1600 hazard of burning was fairly low (<0.01) up to about 50 years since last fire, then it rose steadily up to 0.07 at 100 years, after which it dropped markedly and stayed low, except for two peaks at 150 and 225 years. Post-1600, the hazard of burning peaked (0.03) much earlier, at 20–50 years since last fire, and decreased markedly to low levels (<0.01) above 60 years. Based on experimental fires, Schimmel and Granström (1997) found no or only marginal risk of fire spread up to about 20 years after fire, followed by a progressive rise in fire risk up to 50 years, after which the risk leveled off at a fairly constant rate. This conforms fairly well to our pre-1600 period, although our data showed a later increase and a marked decline in fire risk above 100 years of age. The latter finding may be due to our incorporation of fire-free areas in the analysis, areas that might have burned without leaving fire-scarred legacies. It should also be noted that our results are heavily influenced by a few relatively large fires. Niklasson and Granström (2000) found the hazard of burning post-1650 to peak much earlier (20–30 years) than pre-1650 (about 70 years), similar

Fig. 8. (*a*) Estimated cumulative survival function curves (i.e., the proportion of newly burned area remaining unburned over time) and (*b*) estimated hazard of burning (i.e., yearly probability of a new fire occurring with increasing time since the last fire), drawn separately for pre- (black) and post-1600 (gray) time periods.



to our results. Other Fennoscandian studies from southern regions have also found similar short fire return intervals in anthropogenically influenced areas (Page et al. 1997; Niklasson and Drakenberg 2001; Groven and Niklasson 2005).

Pre- and post-1600, the cumulative survival curve leveled off at 8%–10% and 40%, respectively (cf. Fig. 8*a*), implying that these proportions of the area did not burn during the respective time periods. The differences are partly explained by temporal changes in the recording area. Old fire-scarred samples were clustered within the area (cf. Fig. 1), and many living trees up to 250–300 years without fire scars contributed to the increasing recording area from the 1700s. The historic summer dairy farms were located in areas with none or few fires (cf. Fig. 5), and these areas are also more productive forests, presently having higher proportions of Norway spruce as compared with the other pine-dominated forest (Storaunet et al. 2005).

Anthropogenic signals in the fire regime

Granström and Niklasson (2008) discussed several variables that could indicate an anthropogenic signal in the fire regime: number of fire years, fire size (or percentage annually burned), fire return interval, spatial distribution, seasonality, and fire severity. In our data, all these variables point to a fire regime altered by humans. The number of fire years increased in the early 1600s when it more than doubled (16 per 100 years) compared with the previous 250 years (7 per 100 years). Throughout the 1600s and 1700s, the percentage annually burned decreased substantially, although the number of fire years remained about the same (cf. Figs. 3, 4, and 6). Fire intervals and hazard rates differed substantially between pre- and post-1600, temporal changes that influenced the spatial patterning of the fires (Fig. 4). The fire maps also indicate that many of the individual fires probably were different ignitions in the same year, a pattern that was most prevalent during the 1600s.

From the 1626 fire, most fires occurred early in the cambial growth season, whereas previous fires occurred later in the season. Niklasson and Drakenberg (2001) found a similar change in fire season after 1690 in southern Sweden. Natural forest fires in Fennoscandia are due to lightning strikes, and in southeastern Norway, the main period of lightning is June – August, peaking in July, being more common in August compared with June (Rokseth et al. 2001). This is in accordance with our pre-1600 results, where most fires occurred either in the middle or late in the growing season. Anthropogenic fires from the slash-and-burn cultivation are known to be common in spring or early summer, possibly because early fires were easier to control (Larsson 1995; Niklasson and Drakenberg 2001). Thus, the seasonal shift in our study is most probably due to human ignitions.

Finally, our index of fire severity showed a decreasing trend over time, even after fire size was accounted for. Although the change in fire severity was rather gradual, it indicates that fires after 1600 were less intense (scarred relatively fewer trees) compared with pre-1600. It should be noted, though, that our index of fire severity should be interpreted with caution. Fire severity is commonly categorized into three types (Agee 1993): (1) high-severity stand-replacing fires, which kill most trees; (2) moderate/mixed-severity fires that cause partial removal of the forest stand; and (3) low-severity surface fires, tending to only remove the field layer and debris and leaving most trees alive. Up to a certain point, increasing fire severity is likely to leave more scarred trees behind, whereas above this point an increasing proportion of the living trees will die, leaving no scars. Therefore, the ability to distinguish between low- and high-severity fires, both of which leave few scarred trees, may be difficult when the record of surviving trees is incomplete. In general, studies have indicated that Fennoscandian forest fires, for the most part, seem to have been low to moderately severe, leaving fire-scarred living Scots pines behind within multiaged and multilayered forest stands (Zackrisson 1977; Engelmark et al. 1994; Kuuluvainen 2009; Wallenius et al. 2010). Our study complies with this general picture, as there was a continuous supply of recorder trees throughout the study period. Thus, we strongly believe that most fires, if not all, have been on the low to moderate side of the severity gradient.

Historical sources about the human influence on the fire regime

The historical sources and years of importance are listed in Supplemental data (Tables S1 and S2).[1] Relevant information was scanty on a local level, but increased when expanding the scope to a regional or national level. The fire history was reconstructed back to 1350, coinciding with the Black Death epidemic that hit Europe during 1348–1350. From a total of approx. 4 – 500 000 Norwegian inhabitants, the epidemic extinguished between half and two-thirds of the population. During the following 150 years, the country was struck by several epidemics, resulting in a population minima around 1520 of ca. 200 000 inhabitants. About two thirds of the farms were abandoned during this period. It was not until the mid–1600s that the population had recovered to pre–1350 level (Benedictow 2002). Holmsen (1984) points out that this also applied to the Sigdal valley. Altogether, this implies a wide-ranging decline in the utilization of the abandoned forest land. Summer dairy farming is an old tradition in Norway (Reinton 1961), and Trillemarka was most probably used for summer dairy farming even before the Black Death. Property boundary diplomas from 1540 and 1555 mentioned two summer dairy farms within our study area.

In a legislative decree from 1490, the National Council ordered all farm owners to burn and sow rye on an area of 0.1 ha every year. The authorities invited farmers to recolonize and cultivate the agricultural and forested land that had been abandoned after the Black Death. Tveite (1964) called the period 1520–1620 "the great expansion" due to the introduction of water-driven sawmills and increased timber export. Between 1528 and 1560, timber exports increased sixfold, with a further threefold increase up to 1615 (Fryjordet 1992). From the mid-1600s, a concern rose for the future timber supply due to the extensive logging in southern Norway. In 1667, the land register noted that the farms of Heimseteråsen only had timber for fencing and firewood.

In local sources, the first slash-and-burn cultivation ("braatebrenning") was mentioned in 1632, when a man was allowed to clear land with the use of fire. In an agricultural book from 1721, Juel (1755) describes the slash-and-burn process: "you find a suitable place in the forest as close to the farm as possible, and cut down all the trees in the spring and let them dry up. Next spring the trees are piled and burnt, the ash is spread, and rye is sown." The use of fire on forested land became so common that the first legislation against it came in 1683 to impede damage to timber and forests. This was due to the gradually increasing value of the timber, since there was an increasing demand for timber in Europe (Fryjordet 1992), and locally also because the Kongsberg Silver Mines opened in 1623, 45 km south of our study area. This industry expanded after 1700, and in 1721 a circumference for timber supply was established around the Silver Mines. Within this area a special legislation against burning of forest was approved. Our study area is located just outside the circumference, but several court documents from the area reveal relatively high burning activity. In 1727, seven court cases dealt with burning of forest. The farmers claimed they had no knowledge about the 1721 regulations, and one said he burned his land to improve the quality of the forest and summer grazing land. The protocols confirm that burning of forest was relatively common before the regulations. Our study area was probably treated similarly as these nearby areas. The local circuit judge reported in 1743 that slash-and-burn cultivation was common in the area. With experiences from eastern Norway, Collin (1784) reported on the forest damages by the customary usage of fire in the forests: "when the farmers, to increase or improve their livestock grazing conditions, put fire to the deciduous forest or the poor pine or spruce forest, their carelessness often cause the fire to spread widely, after summer drought and under high winds …". This statement confirms that fire commonly was used for clearing land and growing rye, but also used deliberately to improve grazing conditions in coniferous forests.

Another milestone in the local history was the establishment of Modum Cobalt Mines in 1776, located 25 km southeast of our study area. Timber values probably increased even more after this industry opened up. In 1780, all brooks and rivers that could drive timber logs to the mines were mapped and here the brooks and creeks in the Heimseteråsen area were marked. The account books of the Cobalt Mines reported that the farm owners delivered timber for firewood for many years. For example, in 1841, one farmer delivered about 1440 m^3 of firewood in the Gryde River waterway. On a regional map from 1854 four historic summer dairy farms were shown within our study area (Naase Seter, abandoned 1960s; two Strand Seter, abandoned 1860s; and Lid Seter, abandoned ca. 1850; Mørch 1954). Today, building remnants exist only at Naase Seter, whereas the locations of the others were identified during fieldwork based on remnants of the foundation walls. Additionally, a fifth dairy farm named Moslon was recorded as a summer dairy farm in the Norwegian Central Place-Name Register. Although we could not confirm this in the field, etymological interpretations indicate that this may hold true (O.G. Deli (personal communication, 2012)).

Altogether, the written sources illustrate a history where anthropogenic forest fires and slash-and-burn cultivation gradually increased with the increasing population from the late 1500s and onwards. During the same period, the timber resources gradually increased in value, putting pressure on residents to reduce the application of fire in managing the land. By the late 1700s, slash-and-burn cultivation was basically forbidden and consequently abandoned. This corresponds well with our field results and also with several other Fennoscandian studies of forest fire history (Niklasson and Granström 2000; Niklasson and Drakenberg 2001; Groven and Niklasson 2005; Wallenius 2011).

Could climatic variation have played a role in driving the observed changes in fire regime (e.g., Carcaillet et al. 2007)? Most of the time period of high fire frequency in our study area coincided with the Little Ice Age. Although we did not conduct a detailed correlation analysis between fire frequency and climatic variables, we are not aware of significant changes in the climate that correspond to the marked changes in several variables describing the fire regime. Most importantly, the fact that other Scandinavian studies, e.g., Groven and Niklasson (2005) and Niklasson and Granström (2000), have found similar shifts in fire regimes, but at slightly different time periods, strengthens our conclusion that the changes were due to human activities. Thus, although climate patterns and local weather conditions obviously influence the incidence and behavior of individual fires, we strongly believe that changes in the anthropogenic usage of the forest land were the main driver of the observed trends in the forest fire regime.

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References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Asheim, V. 1978. Kulturlandskapets historie: jord-og skogbruksområdene slik det var og slik det er i flatbygdene på Østlandet. Universitetsforlaget, Oslo, Norway.

Baisan, C.H., and Swetnam, T.W. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. Can. J. For. Res. **20**(10): 1559–1569. doi:10.1139/x90-208.

Bendiksen, E. 2004. Barskogsundersøkelser med hensyn til biologiske verdier i forbindelse med verneplan for Trillemarka - Rollag Østfjell. Norwegian Institute for Nature Research, Oppdragsmelding 830.

Benedictow, O.J. 2002. Svartedauen og senere pestepidemier i Norge. Unipub forlag, Oslo, Norway.

Bergeron, Y., Leduc, A., Harvey, B.D., and Gauthier, S. 2002. Natural fire regime: a guide for sustainable management of the Canadian boreal forest. Silva Fenn. **36**(1): 81–95.

Carcaillet, C., Bergman, I., Delorme, S., Hörnberg, G., and Zackrisson, O. 2007. Long-term fire frequency not linked to prehistoric occupations in northern Swedish boreal forest. Ecology, **88**(2): 465–477. doi:10.1890/0012-9658(2007)88[465:LFFNLT]2.0.CO;2. PMID:17479764.

Castagneri, D., Storaunet, K.O., and Rolstad, J. 2013. Age and growth pattern of old Norway spruce trees in Trillemarka forest, Norway. Scand. J. For. Res. **28**(3): 232–240. doi:10.1080/02827581.2012.724082.

Collin, N. 1784. Forsøg til en Afhandling om de gangbareste Misbruge ved den Norske Skov-huusholdning. Nye Samling af det Kongelige Norske Videnskabers Selskabs Skrifter, **1**: 70–88.

Eidem, P. 1959. En grunnskala til tidfesting av trevirke fra Flesberg i Numedal. Blyttia, **17**(3): 69–85.

Engelmark, O., Kullman, L., and Bergeron, Y. 1994. Fire and age structure of Scots pine and Norway spruce in northern Sweden during the past 700 years. New Phytol. **126**(1): 163–168. doi:10.1111/j.1469-8137.1994.tb07542.x.

Essen, P.-A., Ehnström, B., Ericson, L., and Sjöberg, K. 1997. Boreal forests. Ecol. Bull. **46**: 16–47.

Fryjordet, T. 1992. Skogadministrasjon i Norge gjennom tidene. Bind I. Skogforhold, skogbruk og skogadministrasjon fram til 1850. Norwegian Department of Agriculture and Directorate of State Forests, Oslo, Norway.

Gjerde, I., Sætersdal, M., Rolstad, J., Blom, H.H., and Storaunet, K.O. 2004. Fine-scale diversity and rarity hotspots in northern forests. Conserv. Biol. **18**(4): 1032–1042. doi:10.1111/j.1523-1739.2004.00526.x.

Granström, A., and Niklasson, M. 2008. Potentials and limitations for human control over historic fire regimes in the boreal forest. Philos. Trans. R. Soc. B **363**(1501): 2353–2358. doi:10.1098/rstb.2007.2205.

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

Holmes, R.L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. **43**: 69–78.

Holmsen, A. 1984. Den store manndauen. Universitetsforlaget, Oslo, Norway.

Johnson, E.A. 1992. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University Press, Cambridge, UK.

Johnson, E.A., and Gutsell, S.L. 1994. Fire frequency models, methods and interpretations. Adv. Ecol. Res. **25**: 239–287. doi:10.1016/S0065-2504(08)60216-0.

Juel, P. 1755. En god Bonde, hans Avl og Biæring. H. K. M. prip. Bogtrykkerie, København, Denmark.

Kuuluvainen, T. 2009. Forest management and biodiversity conservation based on natural ecosystem dynamics in northern Europe: the complexity challenge. Ambio, **38**(6): 309–315. doi:10.1579/08-A-490.1. PMID:19860154.

Larsson, B. (*Editor*). 1995. Svedjebruk och röjningsbränning i Norden – terminologi, datering, metoder. Skrifter om skogs-och lantbrukshistoria 7, Nordiska museet.

Linder, P., Elfving, B., and Zackrisson, O. 1997. Stand structure and successional trends in virgin boreal forest reserves in Sweden. For. Ecol. Manage. **98**(1): 17–33. doi:10.1016/S0378-1127(97)00076-5.

Moen, A. 1999. National atlas of Norway: vegetation. Norwegian Mapping Authority, Hønefoss, Norway.

Mørch, A. 1954. Sigdal og Eggedal. Bind III. Gard og slekt. Sigdal og Eggedal historielag, Drammen, Norway.

Morgan, P., Aplet, G.H., Haufler, J.B., Humphries, H.C., Moore, M.M., and Wilson, W.D. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. J. Sustain. For. **2(1**/2): 87–111. doi:10.1300/J091v02n01_04.

Niklasson, M., and Drakenberg, B. 2001. A 600-year tree-ring fire history from Norra Kvills National Park, southern Sweden: implications for conservation strategies in the hemiboreal zone. Biol. Conserv. **101**(1): 63–71. doi:10.1016/S0006-3207(01)00050-7.

Niklasson, M., and Granström, A. 2000. Numbers and sizes of fires: long-term spatially explicit fire history in a Swedish boreal landscape. Ecology, **81**(6): 1484–1499. doi:10.1890/0012-9658(2000)081[1484:NASOFL]2.0.CO;2.

Östlund, L., Zackrisson, O., and Axelsson, A.-L. 1997. The history and transformation of a Scandinavian boreal forest landscape since the 19th century. Can. J. For. Res. **27**(8): 1198–1206. doi:10.1139/x97-070.

Page, H.D., Niklasson, M., Källgren, S., Granström, A., and Goldammer, J.G. 1997. Die Feuergeschichte des Nationalparkes Tiveden in Schweden. Eine kulturhistorische und dendrochronologische Untersuchung. Forstarchiv, **68**(2): 43–50.

Parsons, D.J., and DeBenedetti, S.H. 1979. Impact of fire supression on a mixed-conifer forest. For. Ecol. Manage. **2**: 21–33. doi:10.1016/0378-1127(79)90034-3.

Pyne, S.J. 1996. Wild hearth. Prolegomenon to the cultural fire history of northern Eurasia. *In* Fire in ecosystems of boreal Eurasia. *Edited by* J.G. Goldammer and V.V. Furyaev. Kluwier Academic Publishers, Dordrecht, Netherlands. pp. 21–44.

Reinton, L. 1961. Sæterbruket i Noreg. Bind III. Aschehoug, Oslo, Norway.

Rokseth, O., Pleym, A., and Dahlslett, F. 2001. Sammenstilling av lyndata for perioden 1996–2001. Sintef Energy Research, Tech. Rep. TR A5503.

Rowe, S.J., and Scotter, G.W. 1973. Fire in the boreal forest. Quat. Res. **3**(3): 444–464. doi:10.1016/0033-5894(73)90008-2.

Schimmel, J., and Granström, A. 1997. Fuel succession and fire behavior in the Swedish boreal forest. Can. J. For. Res. **27**(8): 1207–1216. doi:10.1139/x97-072.

Sherriff, R.L., and Veblen, T.T. 2007. A spatially-explicit reconstruction of historical fire occurrence in the ponderosa pine zone of the Colorado Front Range. Ecosystems, **10**(2): 311–323. doi:10.1007/s10021-007-9022-2.

Skatvedt, T. 1914. Sigdal og Eggedal. Historisk beretning. Grøndahl & Søns Boktrykkeri, Kristiania, Norway.

Storaunet, K.O., Rolstad, J., Gjerde, I., and Gundersen, V.S. 2005. Historical logging, productivity, and structural characteristics of boreal coniferous forests in Norway. Silva Fenn. **39**(3): 429–442.

Swetnam, T.W., Allen, C.G., and Betancourt, J.L. 1999. Applied historical ecology: using the past to manage for the future. Ecol. Appl. **9**(4): 1189–1206. doi:10.1890/1051-0761(1999)009[1189:AHEUTP]2.0.CO;2.

Taylor, A.H. 2000. Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, U.S.A. J. Biogeogr. **27**(1): 87–104. doi:10.1046/j.1365-2699.2000.00353.x.

Tveite, S. 1964. Skogbrukshistorie. *In* Skogbruksboka. Bind 3: Skogøkonomi. *Edited by* H.K. Seip. Skogforlaget, Oslo, Norway. pp. 17–75.

Veblen, T.T., Kitzberger, T., and Donnegan, J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecol. Appl. **10**(4): 1178–1195. doi:10.1890/1051-0761(2000)010[1178:CAHIOF]2.0.CO;2.

Wallenius, T. 2011. Major decline in fires in coniferous forests — Reconstructing the phenomenon and seeking for the cause. Silva Fenn. **45**(1): 139–155.

Wallenius, T.H., Kuuluvainen, T., and Vanha-Majamaa, I. 2004. Fire history in relation to site type and vegetation in Vienansalo wilderness in eastern Fennoscandia, Russia. Can. J. For. Res. **34**(7): 1400–1409. doi:10.1139/x04-023.

Wallenius, T.H., Kauhanen, H., Herva, H., and Pennanen, J. 2010. Long fire cycle in northern boreal *Pinus* forests in Finnish Lapland. Can. J. For. Res. **40**(10): 2027–2035. doi:10.1139/X10-144.

Wallin, D.O., Swanson, F.J., Marks, B., Cissel, J.H., and Kertis, J. 1996. Comparison of managed and pre-settlement landscape dynamics in forests of the Pacific Northwest, U.S.A. For. Ecol. Manage. **85**(1–3): 291–309. doi:10.1016/S0378-1127(96)03765-63.

Wooster, M.J., and Zhang, Y.H. 2004. Boreal forest fires burn less intensely in Russia than in North America. Geophys. Res. Lett. **31**: L20505. doi:10.1029/2004GL020805.

Yamaguchi, D.K. 1991. A simple method for cross-dating increment cores from living trees. Can. J. For. Res. **21**(3): 414–416. doi:10.1139/x91-053.

Zackrisson, O. 1977. Influence of forest fires on the north Swedish boreal forest. Oikos, **29**(1): 22–32. doi:10.2307/3543289.

SUPPLEMENTARY DATA:

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STRONG ANTHROPOGENIC SIGNAL IN HISTORIC FOREST FIRE REGIME: A DETAILED SPATIO-TEMPORAL CASE STUDY FROM SOUTH-CENTRAL NORWAY

STORAUNET, K.O., ROLSTAD, J., TOENEIET, M., AND BLANCK, Y.:

Historical archives on forest- and land-use history

The National Archives of Norway was searched for documents, diplomas, and old maps covering Trillemarka-Rollagsfjell Nature Reserve and its vicinity. Historic maps give information about location of summer dairy farms, old roads, tracks, and rivers used for log driving. More general knowledge about the historical use of fire in Norway was gained from old agricultural textbooks and reports with descriptions of forest and land use. The archival documents being used and calendar years of historical relevance are listed in Table S1 and Table S2, respectively. A historic map from 1780 shows all brooks and rivers that could drive timber logs from our study area to the Modum Cobalt Mines (Fig. S1a), whereas a regional map from 1854 shows four historic summer dairy farms located within our study area (Fig. S1b).

Table S1. Archival references to historical diplomas, documents, and maps.

No.	Title/ Content/ Archival reference
1	Legislative decree, published in Diplomatarium Norvegicum. Dated December 4th, 1490. Dipl. Norw. Vol. II, No. 963.
2	National Archives of Norway, Transcriptions and copies of deposited diplomas. Diploma dated February 3rd, 1646. [Transcription from June 23rd, 1859.] 4B.024.13
3	National Archives of Norway. Overbergamtet, Sønnafjellske bergamt, Judgement book 004.1727-cases. 4A.062.56
4	National Archives of Norway, NRA BS II 13. Sogn, Skove og Elvedrag hvorigjennem og hvorfra Fossum Blaae Farve Verk med Træ-Materialier kan forsynes [Map: Parishes, forests, and rivers from where the Cobalt Mines can be supplied with timber and firewood]. 1780. 4B.126.A
5	National Archives of Norway. Modum Blaafarveværk. Tømmerregnskap [Timber accounts]. PA-0157.
6	Kart over Buskerud Amt [Map of Buskerud County], forfattet efter foranstaltning af Den Kongelige Norske Regjerings Departement for det indre, under Bestyrelse af Opmaalings-Directionen efter de ved den geographiske Opmaaling anstillede astronomiske og geodætiske Iagttagelser af S.C. Gjessing, Artillerie Captaine. 1854. STKV/A-1010/002/ T/Tb/0001/0006

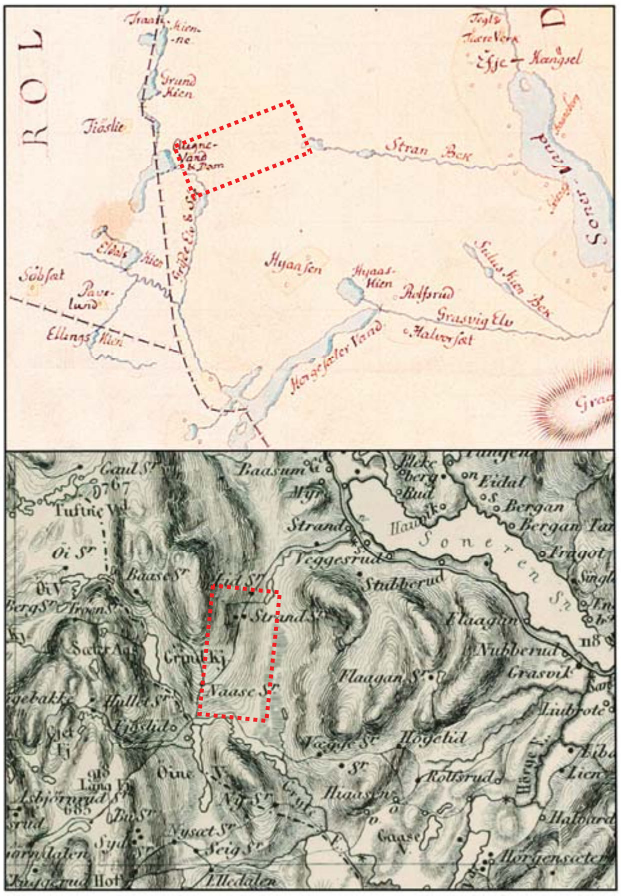
Table S2. Relevant occurrences recorded in the historical sources.

Year	Description	Areal extent	Reference
1349-50	the Black Death	national/ local	Holmsen (1984); Benedictow (2002)
1413	local summer dairy farm mentioned in the historic sources	local	Mørch (1964)
1490	legislative decree ordering all farmers to burn and sow rye every year	national	Table S1: No. 1; Tveite (1964)
1540	two summer dairy farms mentioned in diploma (Naase Seter and Lid Seter)	study area	Table S1: No. 2; Mørch (1954; 1964)
1623	establishment of Kongsberg Silver Mines	regional	Berg (1998; 2001)
1632	1st slash-and-burn mentioned in local historic sources	local	Mørch (1964)
1643	1st legislation regulating forest clearing burns	national	Skogdirektøren (1909)
1667	"*only timber for fencing and firewood available*"	study area/ local	Mørch (1954)
1683	legislation against use of fire in forest to safeguard timber supply	national	Skogdirektøren (1909)
1690	forest fires in Kvisle and other areas of the region	local/ regional	Mørch (1964)
1721	circumference established surrounding Kongsberg Silver Mines, for firewood and timber supply	regional	Berg (1982; 1998)
1723	"*only timber for fencing, firewood, and household available*"	study area/ regional	Skatvedt (1914)
1727	7 court cases about burning of forest within the Silver Mines circumference	regional	Tab. S1: No. 3
1740	legislation against forest clearing burns	national	Fryjordet (1968)
1743	report that burning of forest was common in the area	local	Røgeberg (2005)
1776	establishment of Modum Cobalt Mines	downstream study area	Fryjordet (1992)
1780	map showing rivers and brooks available for floating of timber/firewood to Modum Cobalt Mines	local/ study area	Tab. S1: No. 4
1841	floating of ca. 1 440 m^3 firewood from the Heimseteråsen area to the Cobalt Mines	local/ study area	Tab. S1: No. 5
1854	map showing four summer dairy farms within study area	study area	Tab. S1: No. 6

Fig. S1. Sections of (a) the Modum Cobalt Mines 1780 map of rivers and brooks that could drive logs (Table S1: No. 4), and (b) the 1854 regional map localizing four summer dairy farms within our study area (Naase Seter, two Strand Seter, and Lid Seter) (Table S1: No. 6). The approximate location of our study area is marked with a red rectangle.

a

b



should count as recorders, since these typically have thinner bark offering less resistance to scarring.

Second, we used ArcView GIS 3.3 software (ESRI Inc., Redlands, California) and the ArcView-extension "Animal Movement" (Hooge and Eichenlaub 2000) to outline the contours of individual fires. We calculated the least square cross validation (LSCV) smoothing parameter for kernel home ranges, using all recorder trees as input data. Then we calculated two contrasting kernel ranges for each fire year, one for the trees having fire scars (fire area, Fig. S3a) and one for all recorder trees that did not have scars the actual year (no-fire area, Fig. S3b). To discriminate between these two groups of trees, we divided the smoothing parameter by 1.6 and 3.2 respectively, before calculating the kernel ranges, resulting in polygons closing tighter to the sample points for no-fire areas compared to the fire areas. These smoothing parameters were chosen after several test calculations of the kernel ranges to give the best visual fit to the final delineations of the fires. At the end, the no-fire area was subtracted from the fire area to delineate the actual fire perimeter (Fig. S3c). This procedure resulted in fire borders occurring up to 100-150 m distance from trees with fire scars, depending on the density and distribution of the recorder trees.

Third and finally, minor adjustments of the fire area borders were done on the map to ascertain that all fire scars were included in the fire area, and to make sure that fires occurring closely in time (<15 years) were not spatially overlapping (except for a few cases where the fire-scarred trees indicated otherwise) (Fig. S3d). The 15 years limit was chosen because <0.5% of the fire scar intervals in our data were of shorter duration.

For all fire years we also estimated the spatial coverage of the actual recorder trees, defined as the *recording area*, by calculating the kernel range using all recorder trees the actual year as input points. Here, we used the same smoothing parameter value as for the fire area calculation, i.e. the LSCV-value was divided by 1.6. The relative fire size was then calculated as the ratio between the final fire area and the recording area of the actual year.

Single-sample tree lifespan

A total of 641 tree samples were successfully cross-dated, of which 321 were scarred from one or several fire events and 320 had no signs of fire. 259 of the no-scar samples were old, living Scots pine trees from a previous study (Storaunet et al. 2005). These were recorded as being the 2-3 oldest living trees in each plot within a 100 m × 100 m grid covering most of the study area. Since these trees had no signs of fire scars and we had fairly good estimates of their total age, we included them as 'recorder trees' not recording a fire in our data. Estimated lifespan of all individual samples including the dated fire scars are shown in Fig. S2.

Spatial delineation of individual fires and recording area

The spatial delineation of individual fires was performed through three main steps (Fig. S3). First, for each fire year we identified locations of the *recorder trees*, defined using the following criteria: (i) samples having a fire scar the actual year, (ii) trees up to the age of 100 years, and (iii) trees scarred by a fire <150 years ago. The age limits were based on our own data showing that >70% of scarred trees got their first fire scar when <100 years old, and in trees with multiple scars 99% of scar intervals were <150 years. Our definition of recorder trees differ somewhat from that of Grissino-Mayer (2001), however, Baker and Ehle (2003) suggested that also young or small trees

Time intervals between fires

We calculated time intervals between fires using both point-based and map-based methods. For the point-based intervals, we used time periods between successive scars within the same tree sample. The map-based intervals were calculated as the time periods between successive overlapping fires, where the relative contribution of each interval was arrived at by regularly distributing 8 730 point-locations in a 20 m × 20 m grid covering the study area (excluding points located in open water bodies). Map-based intervals were calculated for two separate time periods, 1350-1600 and post-1600, based on the timing of anthropogenic influence on the fire regime.

The point-based fire intervals ranged 9 – 191 years, whereas the map-based intervals ranged 9 – 431 years. The distributions show that the median interval was underestimated by the point-based compared to the map-based method (Mann-Whitney Z = –6.80, p < 0.001) (Fig. S4a), with the map-based method giving a more unbiased estimate. Map-based intervals pre-1600 showed that the study area was heavily influenced by the few and relatively large fires with 75 – 95 years (median 86 yrs) intervals (1413/1420, 1499, 1572/1575, and 1590; Fig. S4b). The post-1600 intervals showed a completely different pattern with most intervals between 20 – 30 years (median 28 yrs) and with a tail of longer time intervals (Fig. S4b).

Fig. S2. Time span of all cross-dated tree samples within the 3.6 km^2 study area in Trillemarka-Rollagsfjell Nature Reserve, Norway. Each horizontal line ranges from estimated germination year to estimated year of death (to 2000 for living trees). (a) Samples with fire scars (vertical ticks marks) (n = 321). (b) Samples without fire scars (n = 320).

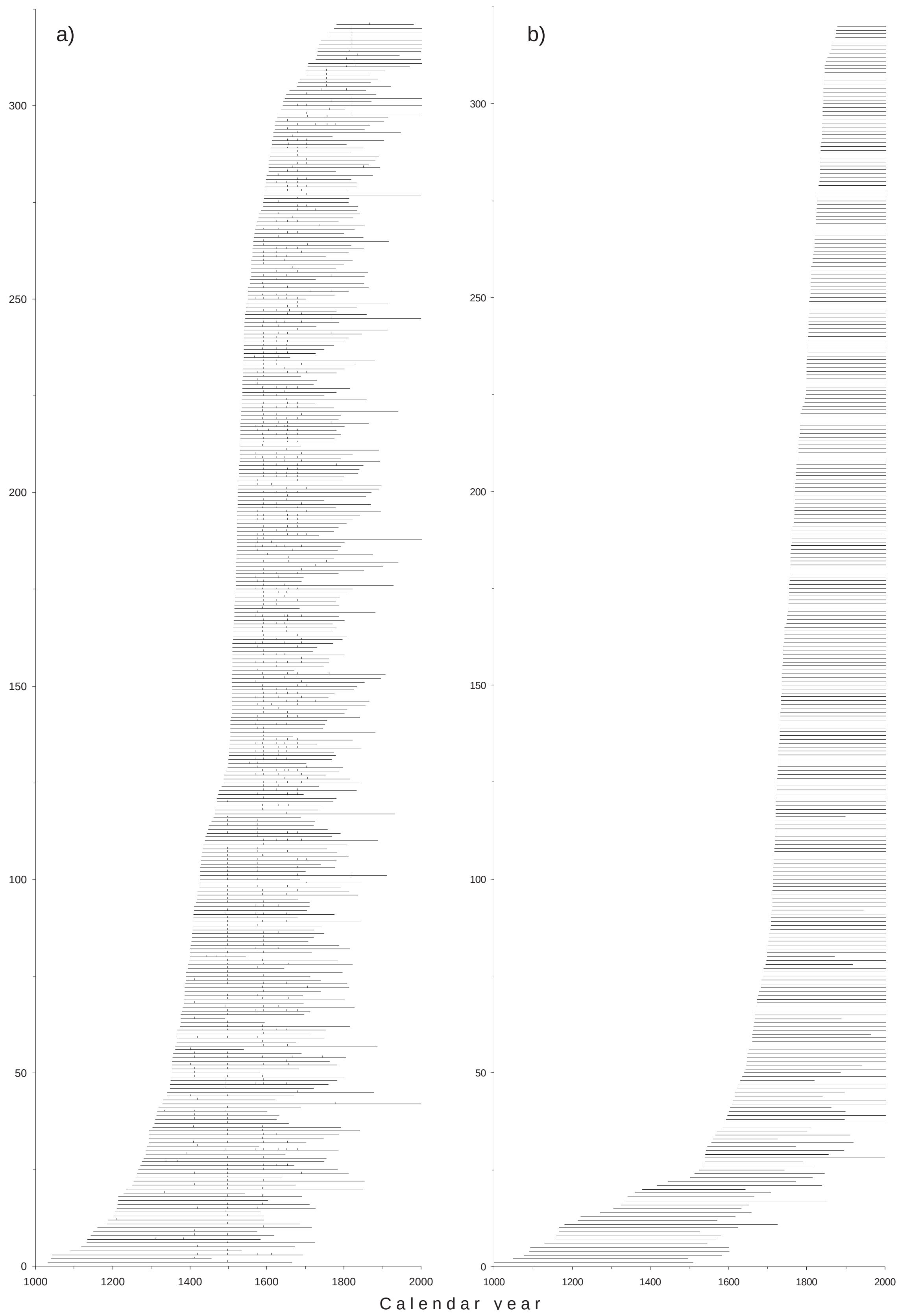


Fig. S3. Illustration of the delineation procedure of the 1588 fire. (a) Trees scarred in the 1588 fire (red dots) and the corresponding kernel range. (b) Recorder trees not scarred in the 1588 fire (blue dots), and their kernel range. (c) The calculated fire area in 1588 (i.e., map a 'minus' map b). (d) The final delineation of the 1588 fire (red), after adjusting the borders against fires occurring closely in time (1589: green, 1590: blue, 1601: yellow).

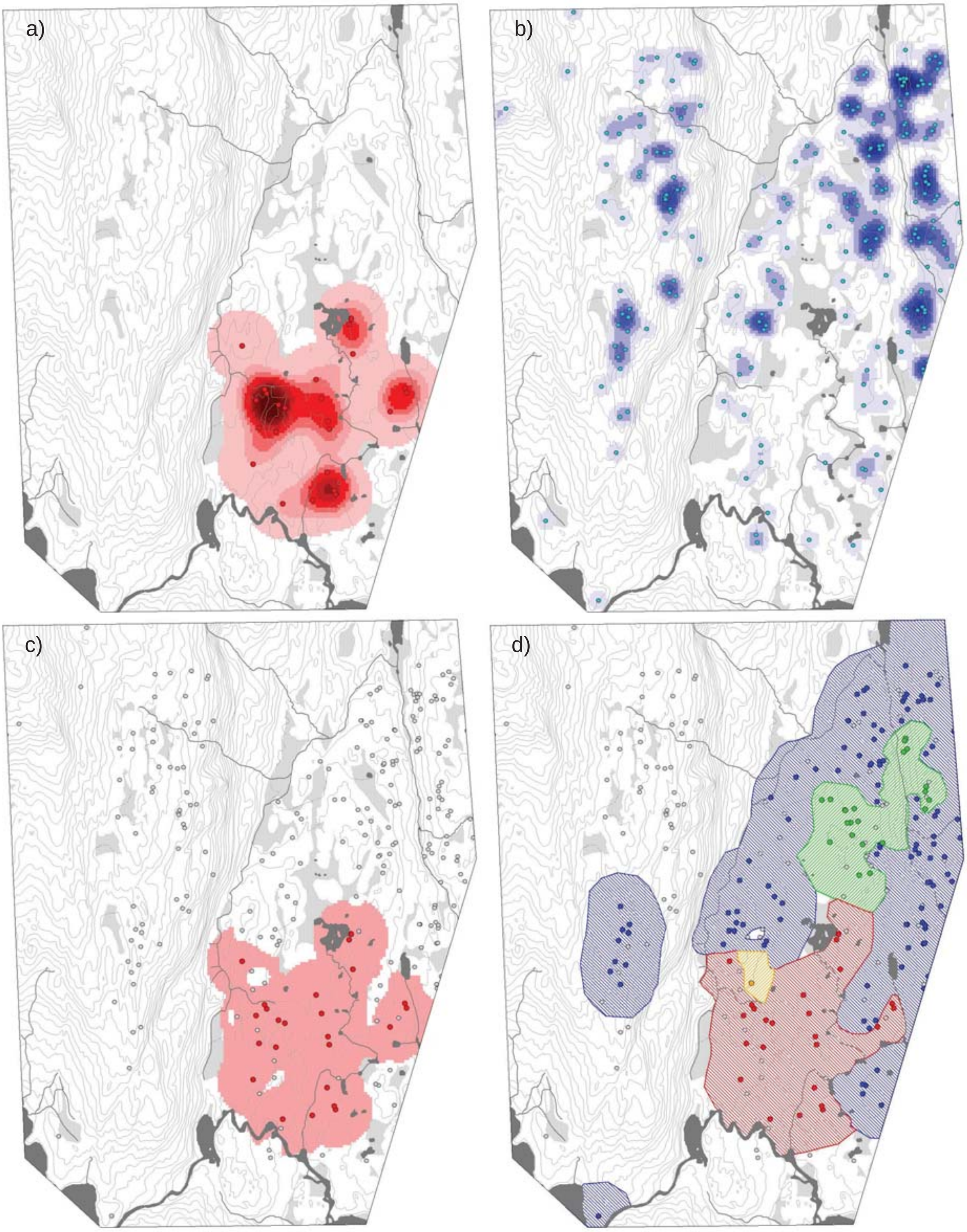
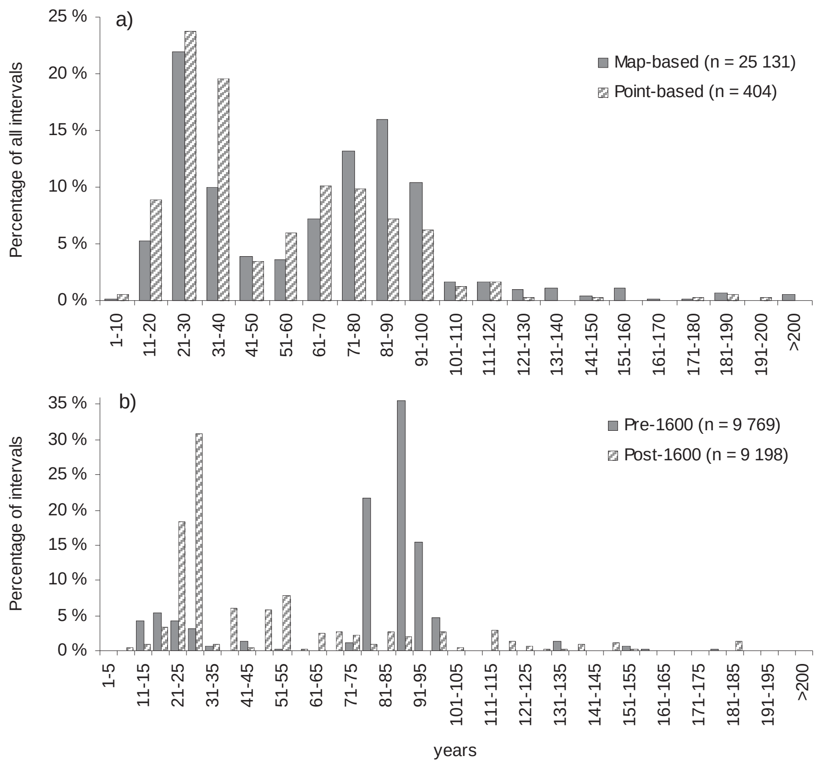


Fig. S4. (a) Frequency distribution of time intervals (10 years intervals) between fires based on the mapped fires (map-based) and based on consecutive fire-scars within trees (point-based), during 1350-2000. (b) Map-based time intervals (5 years intervals) between fires, pre- and post-1600. Note that no censored data are included, meaning that only intervals between mapped fires or between two scars within the same tree are included.



References

Baker, W.L., and Ehle, D.S. 2003. Uncertainty in fire history and restoration of ponderosa pine forests in the Western United States. USDA For. Serv. Res. Proc. RMRS-P-29.

Benedictow, O.J. 2002. Svartedauen og senere pestepidemier i Norge. Unipub forlag, Oslo, Norway.

Berg, B.I. 1982. Riksdaler på sledeføre. Hestekjørsel ved Kongsberg Sølvverk i første halvdel av 1700-tallet. M. Sc. thesis, University of Oslo.

Berg, B.I. 1998. Gruveteknikk ved Kongsberg Sølvverk 1623–1914. STS Report 37. Centre for Technology and Society, Norwegian University of Science and Technology, Trondheim, Norway.

Berg, B.I. 2001. Far from O.K. Corral - Crime and court practice in the eighteenth century - Norwegian mining town of Kongsberg. *In* Book of Proceedings - 5th International Mining History Congress. *Edited by* J.E. Fell, P.D. Nicolaou, and G.D. Xydous. Milos Conference Center, Milos Island, Greece. pp. 422-426.

Fryjordet, T. 1968. Generalforstamtet 1739-1746. Særpublikasjon No. 1. Norsk Skogbruksmuseum, Elverum, Norway.

Grissino-Mayer, H.D. 2001. FHX2 – Software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Research **57**(1): 115-124.

Holmsen, A. 1984. Den store manndauen. Universitetsforlaget, Oslo, Norway.

Hooge, P.N., and Eichenlaub, B. 2000. Animal movement extension to ArcView, ver. 1.1. Alaska Biological Science Center, U.S. Geological Survey, Anchorage, AK.

Mørch, A. 1954. Sigdal og Eggedal. Bind III. Gard og slekt. Sigdal og Eggedal historielag, Drammen, Norway.

Mørch, A. 1964. Sigdal og Eggedal. Bind IV. Bygdehistorie. Sigdal og Eggedal Historielag, Drammen, Norway.

Røgeberg, K.M. 2005. Norge i 1743. Innberetninger som svar på 43 spørsmål fra Danske Kanselli. Bind 3: Akershus stiftamt, Buskerud, Vestfold, Telemark. The National Archives of Norway, Solum forlag, Oslo, Norway.

Skatvedt, T. 1914. Sigdal og Eggedal. Historisk beretning. Grøndahl & Søns Boktrykkeri, Kristiania, Norway.

Skogdirektøren. 1909. Skogvæsenets historie - Utgit i anledning av det offentlige skogvæsens 50-aarige virksomhet 1857-1907. 1. del - Historik. Grøndahl & Søns Boktrykkeri, Kristiania, Norway.

Storaunet, K.O., Rolstad, J., Gjerde, I., and Gundersen, V.S. 2005. Historical logging, productivity, and structural characteristics of boreal coniferous forests in Norway. Silva Fenn. **39**(3): 429-442.

Tveite, S. 1964. Skogbrukshistorie. *In* Skogbruksboka. Bind 3: Skogøkonomi. *Edited by* H.K. Seip. Skogforlaget, Oslo, Norway. pp. 17-75.

PAPER III

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ORIGINAL ARTICLE

Low- to moderate-severity historical fires promoted high tree growth in a boreal Scots pine forest of Norway

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Abstract
Fire is the most important ecological factor governing boreal forest stand dynamics. In low- to moderate-severity fires, the post-fire growth of the surviving trees varies according to fire frequency, intensity and site factors. Little is known about the growth responses of Scots pine (*Pinus sylvestris* L.) following fires in boreal forests. We quantified changes in tree growth in the years following 61 historical forest fires (between 1210 and 1866) in tree-ring series collected from fire-scarred Scots pine trees, snags and stumps in Trillemarka nature reserve in south-central Norway. Basal area increment 10 years pre-, 5 years post-, and 11–20 years post-fire were calculated for 439 fire scars in 225 wood samples. We found a slight temporary growth reduction 5 years post-fire followed by a marked growth increase 11–20 years post-fire. Beyond 20 years post-fire, the long-term tree growth declined steadily up to approximately 120 years. Our results indicate that recurring fires maintained high tree growth in remnant Scots pines, most probably due to a reduction in tree density and thus decreased competition.

Keywords: *Basal area increment, fire severity, historical fires, post-fire tree growth, Scots pine.*

Introduction

Fire is the most important ecological factor governing boreal forest stand dynamics (Rowe & Scotter, 1973), controlling the age, structure and species composition of these forests (Chambers et al., 1986). In terms of intensity and magnitude, forest fires are commonly categorised into three types (Agee, 1993): (1) high-severity stand-replacing fires, which kill most trees, (2) moderate/mixed-severity fires that cause partial removal of the forest stand and (3) low-severity surface fires, tending to only remove the field layer and debris and leaving most trees alive. In low- to moderate-severity fires, the post-fire growth response of the surviving trees varies according to fire frequency, fire intensity, site factors and the pre-fire physiological state of trees (Florence, 1996). Not surprisingly, both increases (Reinhardt & Ryan, 1988; Wyant et al., 1983), decreases (Johansen & Wade, 1987; Wooldridge & Weaver, 1965) or no change (Hunt & Simpson, 1985; Waldrop & Van Lear, 1984) in tree growth following fire have been reported.

The post-fire physiological condition of the surviving trees may be affected both directly and indirectly (Chambers et al., 1986). Low- to moderate-severity fires that reduce tree density may indirectly promote growth of the surviving trees through nutrient release and less competition. However, this may be counterbalanced by direct effects such as crown, stem and fine root damage (Covington & Sackett, 1986, 1992; Reinhardt & Ryan, 1988; Wyant et al., 1983). Pearson et al. (1972) for example, showed an increased radial growth in Ponderosa pine (*Pinus ponderosa* Laws.) following $<60\%$ crown damage, but a decreased growth with $>85\%$ crown damage. On the other hand, in Lodgepole pine (*Pinus contorta* Dougl. Ex Loud.), Peterson et al. (1991) recorded decreased growth above 30% crown injury. Delayed damaging effects may also be seen if the injuries physiologically stress the trees to a point where they are more susceptible to fungal and insect attacks, or unfavourable weather conditions (Botelho & Rigolot, 2000). Furthermore, the foliage may be damaged by the heat from the fire, and the photosynthetic as well as meristematic tissue in buds and twigs may be lost.

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Thus, even if partial defoliation does not result in tree death, it can adversely affect the growth of the tree (Botelho & Rigolot, 2000).

Surface fires may increase the pH of acid soils, increase the availability of phosphorous and cations and remove significant amounts of carbon which may lower the C:N ratio of the soils (Aber & Melillo, 1991). This may lead to increased N mineralisation, although short-term increases in availability may be counterbalanced by longer-term decreases in total soil N content if fire frequency is high or inputs between fires are not high enough to replace the losses (Aber & Melillo, 1991).

Forest fire is regarded as the most important disturbance factor in the boreal forests of Eurasia (Niklasson & Drakenberg, 2001; Zackrisson, 1977) since it maintains mosaic-like and patchy landscape structures. Previous studies from Fennoscandia show strong human impact on fire frequencies and forest structures during several centuries. The general pattern appears to be relative few but large natural fires in the landscape up to approximately 1600, followed by a period of highly increased number of small anthropogenically caused fires until the 1800s. Most notably, there has been an almost total lack of fires during the last 100–200 years (Groven & Niklasson, 2005; Lehtonen & Kolström, 2000; Niklasson & Granström, 2000; Storaunet et al., manuscript in preparation). This has resulted in an increase of the shade-tolerant, late-successional species Norway spruce (*Picea abies* (L.) H. Karst), in areas where fires earlier maintained an open forest dominated by Scots pine (Zackrisson, 1977). Furthermore, species adapted to fires or to the ecological patterns and forest structures created by fires may not find suitable habitats. Re-introduction of fire in the boreal forest has therefore been suggested in future management (Fries et al., 1997; Olsson & Jonsson, 2007; Wallenius et al., 2007).

If prescribed fire is to be implemented, knowledge about both short- and long-term growth and productivity of the residual stand should be pursued. Despite the importance of such information, studies that have investigated long-term tree growth after fire are scarce, and, as a consequence, the effects of fire on post-fire tree growth and forest stand production are still uncertain (Peterson et al., 1994). Due to the paucity of recent fires in Fennoscandia, the only way to get reliable sample sizes of growth responses following different fire frequencies is to study forest fires in the past. Here, we explore a sample of tree-ring series collected from historically fire-scarred Scots pine (*P. sylvestris* L.) trees in Trillemarka nature reserve, south-central Norway. We had two objectives: First, we documented changes in tree growth following 61 historical fire events covering the period 1210–1866. We distinguished between short- (1–5 years), medium long- (11–20 years) and long-term (21–120 years) effects. Second, by using known time since previous fires, we explored how fire return intervals influenced on the post-fire growth response.

At the outset we pinpoint the important difference between growth responses of remnant individual trees after fire as opposed to the total productivity of the new emerging forest stand, i.e. the general site productivity. Our study deals with the first aspect – individual growth responses of fire-scarred trees, as the historic data did not allow us to positively identify non-scarred surviving and new recruiting trees after fire.

Materials and methods

Study area

The study was conducted within a 3.6 km^2 section of the Trillemarka nature reserve (Heimseteråsen) in south central Norway (60°02′N, 09°26′E). The reserve is situated in the middle-northern boreal zone with climate being intermediate oceanic to continental. Snow covers the ground from November–December to mid-May and the average annual precipitation is 800 mm. The mean annual temperature is +4°C, with mean monthly temperature variations from −4°C in January to +15°C in July (Moen, 1999). Altitude ranges from 400 to 650 m a.s.l. The topography is characterised by north–south extending ridges of Precambrian rocks, which consist of acid granites and gneisses. Scots pine dominates on low-productive sites, on ridges and along bogs and mires, with a field layer of the *Calluna vulgaris – Vaccinum uliginosum* type, often with some Norway spruce (*P. abies*) admixed in the understory. Norway spruce dominates on more productive slopes with a field layer of *Vaccinum myrtillus*. Less than 10% of the growing stock consists of deciduous trees, most commonly birches (*Betula* spp.), aspen (*Populus tremula* L.) and rowan (*Sorbus aucuparia* L.), admixed both in the pine and the spruce forests. A central east-facing slope hosts several red-listed and rare lichens and polypore fungi (Gjerde et al., 2004; Rolstad et al., 2004). Some structural characteristics of today's forest stands are presented by Storaunet et al. (2005). Fire frequency within the study area has varied during the centuries, with 0.8% of the area burned yearly before 1450, 1.5% between 1450 and 1700, after which it decreased during the 1700s and 1800s with no fires recorded after 1866. The number of fire events peaked during the 1600s and 1700s, with

15 and 17 different fire years, respectively (Storaunet et al., manuscript in preparation).

Field sampling, cross-dating methods and measurements

We collected wood samples from all visible fire-scarred living trees, snags, logs and stumps of Scots pine within the study area, giving a total of 454 samples. The area was systematically searched during several field seasons (2006–2010). With a chain saw, we took cross sections of stumps and logs, whereas living trees and snags were more carefully sampled by cutting smaller partial sections of the trunk, leaving the trees still standing. Diameter and height at the point of sampling were noted, and for aesthetic reasons, scars were afterwards covered with mosses and lichens.

We only analysed fire-scarred trees, and not the trees that might have been subject to fire without getting scarred. This was due to the following: (1) many of the non-scarred trees are not present today, especially the ones from the oldest historical fires. Since charcoal preserves the wood, burned trees and stumps are preserved to a much higher degree than trees that are not burned. (2) Many of the historical fires presumably were of rather low severity with a highly patchy and mosaic-like spatial distribution. Hence, we cannot be sure whether a non-scarred tree within the perimeter of a fire actually burned or not. Nevertheless, since we found the majority of the scarred trees to increase in growth 11–20 years after fire, we believe that the non-scarred trees would show similar or more pronounced growth increase because they were not damaged during fire.

All fire-scarred samples were dried and sanded with a belt sander (down to grit 400) in the laboratory so that tree rings and fire scars could be readily distinguished under a microscope. Zinc paste and a scalpel were used when needed to assure better visibility of the ring pattern. The annual tree-ring widths were measured with an Addo micrometer (accuracy of 0.01 mm). Using COFECHA (Holmes, 1994) and the "pointer-year" method (Niklasson et al., 1994; Yamaguchi, 1991), we successfully cross-dated 378 samples with 746 different fire scars from 61 different fires ranging from 1210 to 1866. Sixty-six samples could not be cross-dated due to decayed wood or too few tree rings. To avoid influence of callus tissue on the tree-ring widths, we only used tree-ring series that were measured >4 cm from the fire scar. Furthermore, we only included samples with ≥ 5 measured tree rings pre-fire and ≥ 15 tree rings post-fire.

Whereas tree-ring width (RW, one-dimensional) is used in dendrochronology, basal area increment (BAI, two-dimensional) is more useful in growth modelling since it better estimates the three-dimensional mass increment (Biondi & Qeadan, 2008; Motta et al., 2006). Conversion of RW to BAI also reduces age-related variation in radial growth (Leblanc et al., 1992). We calculated BAI (mm^2) using $\pi(r_t^2 - r_{t-1}^2)$, where r is the cumulative ring width increment (mm) up to year t, assuming that stem circumference is circular. This BAI calculation does not take into account the missing part of the circumference due to the scar. However, we considered this error to be negligible.

Analyses and statistics

When testing for possible influence of fire return intervals, we used time since previous fire as an explanatory variable. For samples with multiple fire scars, time since previous fire equalled number of tree rings between two scars. For samples with only one fire scar, and for the oldest scar in samples with multiple scars, time since previous fire was recorded as the number of years since the previous fire event based on maps of detailed spatial delineations of the fires (Storaunet et al., manuscript in preparation). Time since previous fire >100 years were grouped into one class of 120 years. Covariates used in the statistical analyses included diameter and age of the tree when it was scarred, and the total age of the tree (estimated age at tree death or when logged). For cross sections where the inner part was missing due to decay, pith dates were estimated after defining the distance to pith according to Brown (2006). Our data-set included rather few fire events prior to 1600. To increase sample size during this early period, we added 25 dated samples successfully with 55 fire scars from a 70 km^2 large area surrounding the smaller study area. Adjusting our material to the above-mentioned criteria brought our data-set down to a total of 225 wood samples with 439 different fire scars to be used in the analyses.

We calculated mean BAI (mm^2 $year^{-1}$) 10 years pre-, 5 years post- and 11–20 years post-fire for all fire events (Figure 1), excluding the actual year of fire. After visually inspecting the BAI curves, these intervals were chosen to get an overall estimate of the pre-fire growth pattern (10 years), the short-term growth response (5 years) and the medium-term growth pattern (11–20 years) unaffected by the short-term response. Notably, the 10 years pre-fire period served two purposes: First, it was used as a reference for the growth responses after fire, as we calculated the growth 5 years and 11–20 years post-fire relative to the pre-fire growth by taking ln-values of the ratios. Second, the 10 years pre-fire period also served as a measurement of the long-term

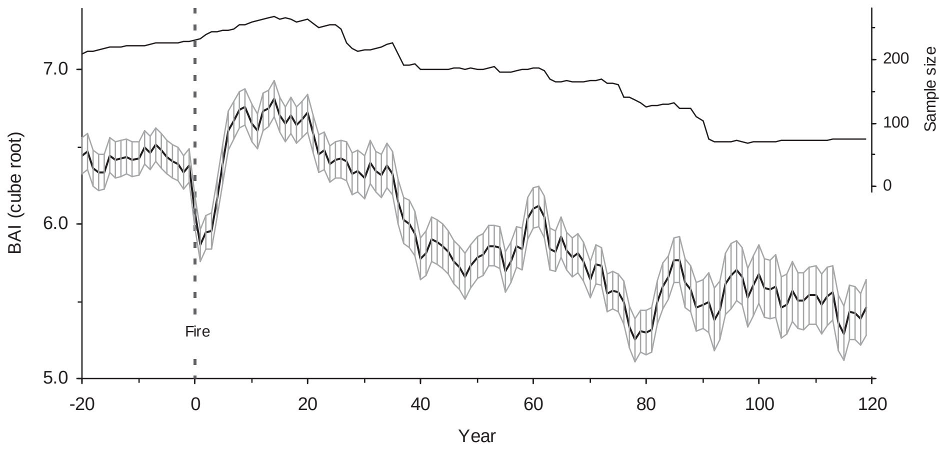

Figure 1. Average BAI growth (mm^2 $year^{-1}$, scaled to cube root) (± 1 SE) related to fire year, of fire-scarred Scots pine trees. BAI-series with ≥ 2 fire events were used, the series were aligned according to the first fire and the series were cut from the next fire event. Sample size (dotted line) shown on right y-axis.

growth pattern (21–120 years) when it was preceded by a previous fire (Figure 1).

Due to the nature of the fire scars, our samples were taken 5–120 cm above ground. This is below breast height (130 cm), which is the most common height of sampling for growth studies. We therefore checked if this biased our measurements by regressing the BAI values against sampling height. No relationships were found ($R^2 < 0.002$, $P > 0.51$, for all comparisons), neither for the absolute nor the relative (ratio) values. Thus, we conclude that our measurements reliably estimate both pre- and post-fire growth patterns.

We explored possible differences between growth 10 years pre-, 5 years post- and 11–20 years post-fire, as influenced by fire return intervals (time since previous fire), using ANOVA, ANCOVA and partial regression. ANCOVA was used to test for homogeneity of slopes in continuous covariates. In case of different slopes, partial regressions were used separately on dependent factors to control for significant covariates. In the same way, we also tested 5 years and 11–20 years post-fire relative response against time since previous fire.

To achieve normality and homoscedasticity, age of trees at fire and total age of trees was $\log_{10}$ transformed, diameter at fire was square root transformed, BAI values were cube root transformed and relative BAI values were ln-transformed (Table I). Analyses of RW data did not deviate much from BAI data, hence results are shown for BAI data only. To visualise the results, we plotted the residual BAI values (adjusted for covariates in ANCOVA and partial regressions) against time since previous fire in bivariate scattergrams and against pre-/post-fire periods in interaction line plots. Statistics were calculated using Statview 5.0 software package (SAS Institute Incorporated Cary, NC, USA) and test outcomes with a two-tailed type-I error rate ≤ 0.05 were considered statistically significant.

Results

BAI-values were positively correlated with diameter and negatively with total age, and also slightly influenced by age at fire, but ANCOVA did not reveal any significant interaction terms with the pre- and post-fire periods (Tables I and II). When BAI values were adjusted for these covariates, there was a minor reduction in growth 5 years post-fire ($P = 0.052$, Bonferroni–Dunn post-hoc test, critical P-value 0.017) and a strongly significant growth increase 11–20 years post-fire ($P < 0.001$) (Figure 2).

When the relative post- versus pre-fire growth values were inspected, covariates somewhat evened out, but due to the rather large sample size there were still statistically significant correlations (Table I). After adjusting for covariates (diameter and age at fire), relative growth 5 years post-fire was significantly below zero (mean ln value: -0.09, 95% CI -0.17, -0.02) and relative growth 11–20 years post-fire substantially above zero (mean ln value: 0.26, 95% CI 0.21, 0.32), confirming the results above that growth decreased 1–5 years and increased 11–20 years after fire.

When time since previous fire was entered in the ANCOVA, a significant interaction term indicated that regression slopes were different among pre- and post-fire periods (Table II). Hence, each period was analysed separately with partial regressions (Table III). BAI 10 years pre-fire was most influenced, and negatively so, i.e. the longer the time since previous fire the lower growth was observed. Because BAI 10 years pre-fire also represented a

Table I. Sample size and mean values (± SE) of variables used in analyses, and correlation coefficients between them (right part of table).

Variable	Transformation method	Sample size (n)	Mean ± SE	Time since previous fire	Diameter at fire	Total age	Age at fire	BAI 10 year pre-fire	BAI 5 year post-fire	BAI 11–20 year post-fire	Relative BAI 5 year post-fire
Time since previous fire	–	368	68.32 ± 1.84								
Diameter at fire	Square root	439	4.61 ± 0.06	−0.10							
Total age	Log_{10}	418	2.49 ± 0.01	0.27***	0.22***						
Age at fire	Log_{10}	438	2.08 ± 0.01	0.04	0.65***	0.66***					
BAI 10 year pre-fire	Cube root	437	6.19 ± 0.07	−0.39***	0.59***	−0.29***	0.05				
BAI 5 year post-fire	Cube root	437	6.03 ± 0.08	−0.27***	0.54***	−0.14**	0.18***	0.62***			
BAI 11–20 year post-fire	Cube root	429	6.73 ± 0.07	−0.20***	0.47***	−0.26***	0.04	0.73***	0.65***		
Relative BAI 5 year post-fire	Ln of ratio	435	−0.03 ± 0.01	0.13*	−0.02	0.15**	0.15**	−0.39***	0.47***	−0.06	
Relative BAI 11–20 year post-fire	Ln of ratio	427	0.09 ± 0.01	0.30***	−0.21***	0.06	−0.02	−0.46***	−0.03	0.25***	0.48***

*, **, and *** denotes correlation significance levels at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively.

measure of the long-term effect of the previous fire, this implies that tree growth declined substantially during a period from 20 to 120 years in the absence of fire (Figures 1 and 3a, Table III). There was also a small, but statistically significant, decline in growth 5 years post-fire, whereas growth 11–21 years post-fire was independent of time since previous fire (Figure 3b,c, Table III).

Similar to the absolute BAI-values, the relative growth values also depended on time since previous fire. Relative growth 11–20 years post-fire increased markedly with increasing time since previous fire, which was mainly due to the decrease in pre-fire growth. A smaller, near-significant increase was also noted in the relative growth 5 years post-fire (Figure 3d, e, Table III). The dependency of growth responses on fire return intervals is visualised for short (< 40 years), moderate (40–80 years) and long (> 80 years) time since previous fire in the interaction line plot of Figure 4.

It should be noted though, that it was a considerable variation in growth of individual trees. The relative BAI 5 years and 11–20 years post-fire ranged from approximately −2 to 2 (ln-ratios), corresponding to a variation in growth changes from approximately 10 to 700% compared to the 100% pre-fire growth levels. In 75% of the samples, relative BAI 11–20 years post-fire exceeded pre-fire values, whereas this was the case in only 47% of the relative BAI 5 years post-fire samples (Figure 3d,e).

Discussion

The goal of this study was to investigate growth responses in Scots pine surviving historical fire events. Our results indicate three key findings: first, we observed a slight temporary growth reduction 1–5 years post-fire compared to 1–10 years pre-fire values. Second, growth 11–20 years post-fire returned to, and often exceeded, pre-fire growth levels, suggesting that the negative effects occurred temporarily. Third, we observed a long-term growth decline 21–120 years post-fire, resulting in relative growth responses (post-/pre-fire ratios) being affected by time since previous fire in the individual trees. In terms of absolute values, growth 5 years post-fire (short-term effects) decreased slightly with increasing time since previous fire, whereas the peak in growth 11–20 years post-fire (medium-term effects) was independent of this. This implies that tree growth slowly declined in the long-term absence of fire (> 20 years), which to a certain degree also seemed to "carry over" and keep the growth low 1–5 years following the next fire. However, 11–20 years post-fire, growth returned to the same relatively high values, independent of the fire return intervals.

Table II. ANCOVA table of BAI 10 years pre-, 5 years post- and 11–20 years post-fire versus covariates and the explanatory variable time since previous fire.

Model	DF	SS	MS	*F*	*P*
Dependent variable:					
BAI 10 years pre, 5 years post, 11–20 years post	2	8.49	4.24	3.05	0.048
Covariates:					
Diameter at fire	1	16.02	16.02	11.51	<0.001
Age at fire	1	6.50	6.50	4.67	0.031
Total age	1	21.08	21.08	15.15	<0.001
Interaction terms:					
BAI $\times$ Diameter	2	6.52	3.26	2.34	0.097
BAI $\times$ Age at fire	2	4.91	2.46	1.76	0.172
BAI $\times$ Total age	2	0.94	0.47	0.34	0.714
Residual	1017	1415.47	1.39		
Adjusted model					
BAI_{adj} 10 years pre, 5 years post, 11–20 years post	2	97.39	48.70	33.86	<0.001
Explanatory variable					
Time since previous fire	1	41.55	41.55	30.45	<0.001
Interaction term					
$BAI_{adj} \times$ Time since previous fire	2	10.90	5.45	3.99	0.019
Residual	1026	1399.99	1.37		

It is important to point out, however, that there was a considerable variation in individual growth responses, especially for BAI values 5 years post-fire. Since this study was based on historical fire data, we were unable to observe fire intensities and degree of crown damage in individual trees. Previous studies have reported reductions (Peterson et al., 1991), increases (Reinhardt & Ryan, 1988), or lack of prolonged growth response (Keyser et al., 2010). The fact that individual trees respond differently to fire events is not surprising, since a fire often creates a mosaic of burned and unburned areas and might not influence all of the trees within the boundary of the fire in the same way (DeBano et al., 1998).

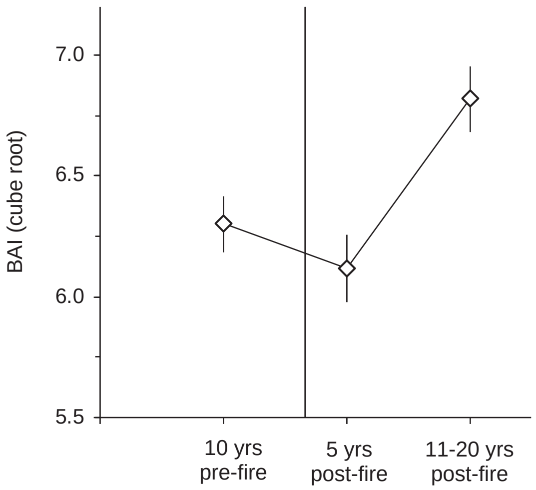

Figure 2. Average BAI growth (mm^2 $year^{-1}$, scaled to cube root and adjusted for significant covariates) of fire-scarred Scots pine trees 10 years pre-, 5 years post- and 11–20 years post-fire. Bars denote 95% CI.

Short-term effects (1–5 years)

The slight temporary growth reduction 5 years post-fire presumably was due to direct injuries such as stem, crown and fine root injury caused by the fire. This may indirectly cause reduced water and nutrient uptake as well as photosynthetic capacity (Botelho & Rigolot, 2000; Landsberg, 1994). Fire may also reduce mycorrhizae and other microorganisms in the rooting zone, decrease the water-holding capacity of the soil or change carbon allocation patterns, which all may influence post-fire tree growth negatively (Landsberg, 1994). In addition to this, increased susceptibility to insect and disease attacks has been suggested as an indirect negative effect of fire on tree growth and mortality (Chambers et al., 1986). Sutherland et al. (1991) similarly reported decreased growth in ponderosa pine the first years after burning, and concluded that fire inhibited nutrient and water uptake in trees where fire caused cambial and root damages. However, the short-term post-fire growth was very variable in individual trees and many trees increased in growth. It is well known that fires may result in increased availability of nutrients both directly from the ashes created and indirectly through increased mineralisation rates. In particular, it has been shown that fires may boost the short-term availability of nitrogen to plants, depending on the severity of the burn (Keyser et al., 2008). Hence, we believe that residual trees, surviving low- to moderate-severity fires with negligible fire damage, may have increased in growth due to enhanced short-term soil fertility, especially of nitrogen.

Medium-term (11–20 years) and long-term effects (21–120 years), and effects of fire-return interval

Growth 11–20 years post-fire increased to pre-fire levels and beyond. This indicates that tree growth recovered relatively short after fire. Presumably, this positive response 11–20 years post-fire was not due to the fertilising effect of fire, since increased availability of soil N from the fire is known to last only up to approximately 5 years (Keyser et al., 2008; Smithwick et al., 2005; Wan et al., 2001). Rather, we believe that the medium-term increased growth in residual trees more likely was a growth release attributed to decreased competition for

Table III. Results from partial regression analyses between different growth parameters and time since previous fire, using diameter, total age and age at fire as covariates.

Variable	Sample size (n)	Slope × 100	R^2	P	Significant covariates
BAI 10 year pre-fire	347	−0.96	0.097	<0.001	Diameter, total age, age at fire
BAI 5 year post-fire	346	−0.56	0.021	0.004	Diameter, total age
BAI 11–20 year post-fire	339	−0.23	0.001	0.245	Diameter, total age, age at fire
Relative BAI 5 year post-fire	365	0.18	0.007	0.060	Diameter, age at fire
Relative BAI 11–20 year post-fire	357	0.40	0.070	<0.001	Diameter, age at fire

nutrients (Riegel et al., 1992) and water (Skov et al., 2004). This is in line with Hoffmann (2002), who concluded that that the short-term direct negative effects of fire on radial growth may be offset by the positive indirect effects resulting from the opening of the vegetation. Increased radial growth after commercial thinning, as well as after fire, is well documented (Feeney et al., 1998; Peltola et al., 2007; Pukkala et al., 1998; Valinger et al., 2000; Schmidt et al., 2004). Furthermore, our results conform with Reinhardt and Ryan (1988) who found a reduced radial growth in the first years, but prolonged growth increases, in Douglas-fir (*Pseudotsuga menziesii*) and Western larch (*Larix occidentalis)* trees 8 years post-fire.

In the longer term, we found growth 21–120 years post-fire to decrease steadily with increasing time since fire, revealed by a negative correlation between growth 10 years pre-fire and time since the previous fire. Absence of fire may result in stagnated nutrient cycles, and thus, decreased nutrient availability and tree growth (Biswell, 1972; Covington & Sackett, 1986). Our results suggest that long periods of fire exclusion slowed down growth due to overstocked stands and, thus, we believe that recurring fires reduced stand density through a "thinning effect" and decreased competition for resources due to fire-related tree mortality.

Evidence for low-to moderate severity fires

Changes in forest structure resulting from low- and moderate-severity fires may not be apparent directly after fire but may be delayed since a certain amount of the mortality does not occur until some years after the fire (Agee, 2003; Keyser et al., 2006). Since we

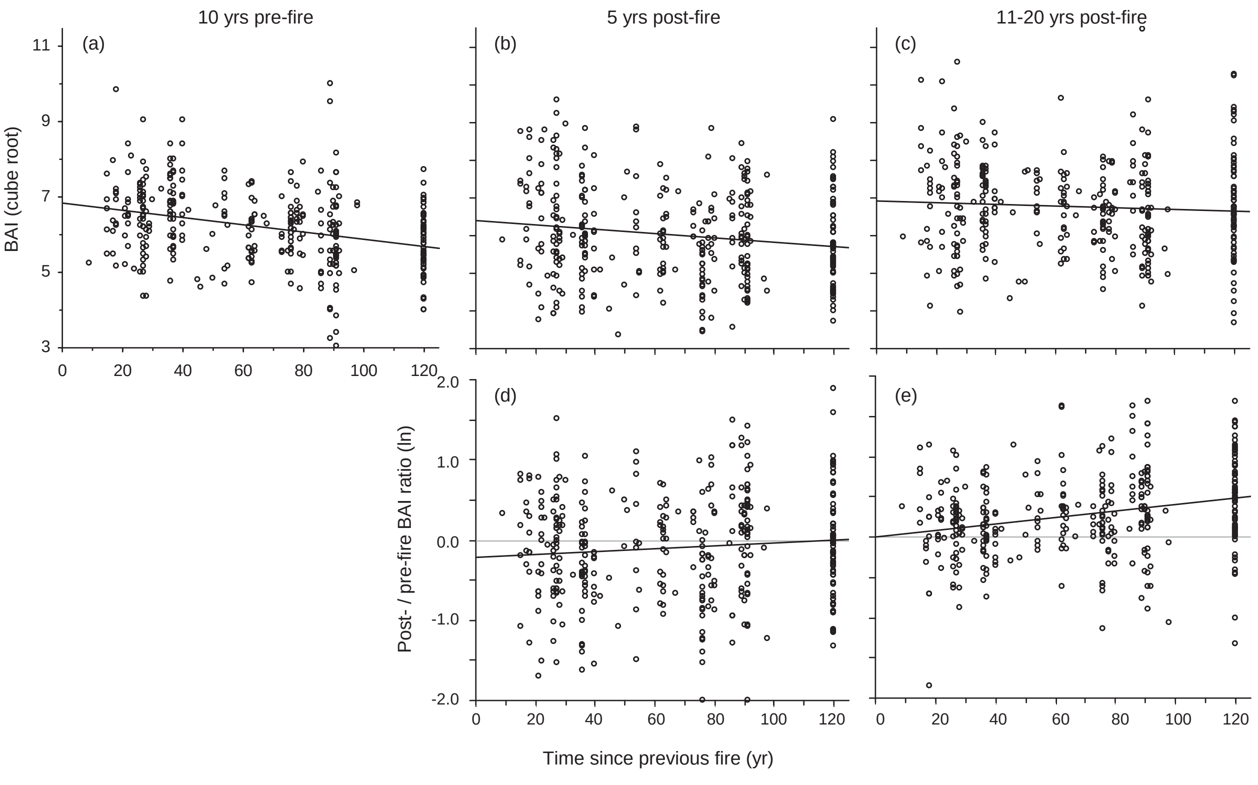

Figure 3. Absolute BAI growth (a, b and c) (mm^2 year^{-1}, scaled to cube root and adjusted for significant covariates) and relative BAI growth (d and e) (ln-ratios of post- vs. pre-fire BAI, adjusted for significant covariates) related to time since previous fire. (a) is 10 years pre-fire, (b) and (d) show 5 years post-fire and (c) and (e) show 11–20 years post-fire growth. See Table III for statistics.

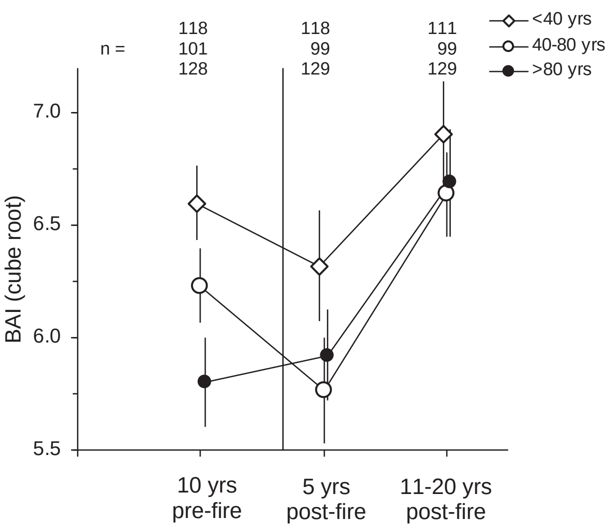

Figure 4. Average BAI growth (mm^2 $year^{-1}$, scaled to cube root and adjusted for significant covariates) 10 years pre-, 5 years post- and 11–20 years post-fire, categorised according to time since previous fire (◇: <40 years, ○: 40–80 years, •: >80 years). Bars denote 95% CI, and sample sizes are shown above.

found numerous fire-scarred trees and stumps in the field, and a growth increase 11–20 years after fire, we believe that the majority of these historical fires have been low to moderately severe. This conforms to previous studies from Fennoscandia indicating that high-severity stand-replacing fires were rare, whereas low-severity surface fires were more frequent (Engelmark et al., 1994; Zackrisson, 1977). Presence of several fire-scarred live trees within multi-aged and multi-layered forest stands illustrates that Scots pine commonly survive fire events in Fennoscandia (Groven & Niklasson, 2005; Hellberg et al., 2004; Wallenius et al., 2002).

Methodological considerations

An important methodological concern in our data and results is the possible influence of the formation of callus tissue close to the fire scar lesion. This could lead us to overestimate post-fire growth responses. However, we assume this type of error to be negligible as we excluded samples that were notably influenced by scar callus tissue.

Time since previous fire influenced both pre- and post-fire growth, with pre-fire growth being most affected (the long-term growth decline). Estimating time since previous fire in historical data may be difficult since fire scars not necessarily persist through time and because not all trees within a burned area get scarred (Dieterich & Swetnam, 1984; Swetnam & Baisan, 1996). However, our historical fires were intensively sampled (>100 samples per km^2), and the single fire events were delineated in detail utilising all samples, both scarred and unscarred. This implies that most fire events probably were recorded, although possible minor fire events may have escaped our attention and thereby contributed to slightly overestimate time since previous fire.

It has been indicated that forest sites are slowly becoming more productive in some regions of central Europe, possibly linked to changes in different growth-limiting factors (Rehfuess et al., 1999). A steady increase in the estimated stand productivity of forest land has also been noticed since the 1920s in Sweden and since the 1950s in Norway (Elfving et al., 1996). In Finland, it has been hypothesised that an increased productivity during the last century may be due to the long fire-free period (H. Lindberg and T. Wallenius personal communication, Nov 27, 2011). Since the fertility of the boreal forest vegetation is linked to total N in the organic layer (Salemaa et al., 2008), it could thus be argued that frequent fires reduce the total N stored in this layer. In Finland, frequent historic fires were associated with slash-and-burn cultivation (Lehtonen & Huttunen, 1997). Conceivably, the biomass loss may have been so high during this traditional cultivation that sites were not given enough time to recover. Along the same line, Squire et al. (1985) concluded that nutrient losses during human-induced slash-and burn practices caused reduced productivity in second rotation plantations of Monterey pine (*Pinus radiata* D. Don) in south-eastern Australia.

To study effects of forest fires on the surviving trees, ideally one would sample all trees affected by the fire. However, since this study is based on historic fires during several centuries, we were not able to positively identify non-scarred surviving and new recruiting trees after fire. Our results are therefore restricted to growth responses of remnant surviving trees as opposed to the general forest stand productivity. In most regions of Fennoscandia, there has been an almost total lack of fires the last two centuries (Groven & Niklasson, 2005; Niklasson & Granström, 2000; Wallenius et al., 2004). Thus, to gain knowledge about long-term effects of fire, a retrospective comparative approach as the one applied, is the only applicable method to use.

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References

Aber, J. D. & Melillo, J. M. (1991). *Terrestial ecosystems*. Philadelphia: Saunders College Publishing.

Agee, J. K. (1993). *Fire ecology of Pacific Northwest forests*. Washington, DC: Island Press.

Agee, J. K. (2003). Monitoring postfire tree mortality in mixed-conifer forests of Crater Lake, Oregon, USA. *Natural Areas Journal*, *23*, 114–120.

Biondi, F. & Qeadan, F. (2008). A theory-driven approach to tree-ring standardization: Defining the biological trend from expected basal area increment. *Tree-Ring Research*, *64*, 81–96.

Biswell, H. H. (1972). Fire ecology in ponderosa pine grassland. *Proceedings in the 12th Annual Tall Timbers Fire Ecology Conference: No. 12 June 8–9*, Lubbock, Tall Timbers Research Station, pp. 69–96.

Botelho, H. & Rigolot, E. (2000). *Fire torch: The effects of prescribed burning on trees*. Report FIRE TORCH Contract no. ENV4-CT98-0715; Deliverable E1. Vila Real: University of Tras-os-Monte and Alto Douro, Forestry Department.

Brown, P. M. (2006). Climate effects on fire regimes and tree recruitment in Black Hills ponderosa pine forests. *Ecology*, *87*, 2500–2510.

Chambers, J. L., Dougherty, P. M. & Hennessey, T. C. (1986). Fire: Its effects on growth and physiological processes in conifer forests. In: T. C. Hennessey, P. M. Dougherty, S. V. Kossuth, & J. D. Johnson (Eds.), *Stress physiology and forest productivity*, pp. 171–189. Dordrecht: Martinus Nihoff Publishers.

Covington, W. W. & Sackett, S. S. (1986). Effect of periodic burning on soil nitrogen concentrations in ponderosa pine. *Soil Science Society of America Journal*, *50*, 452–457.

Covington, W. W. & Sackett, S. S. (1992). Soil mineral nitrogen changes following prescribed burning in ponderosa pine. *Forest Ecology and Management*, *54*, 175–191.

DeBano, L. F., Neary, D. G. & Ffolliott, P. F. (1998). *Fire's effects on ecosystems*. New York: John Wiley & Sons.

Dieterich, J. H. & Swetnam, T. W. (1984). Dendrochronology of a fire scarred ponderosa pine. *Forest Science*, *30*, 238–247.

Elfving, B., Tegnhammar, L. & Tveite, B. (1996). Studies on growth trends of forests in Sweden and Norway. In: H. Spiecker, K. Mielikäinen, M. Köhl, & J. P. Skovsgaard (Eds.), *Growth trends in European forests*, pp. 61–70. Heidelberg: Springer-Verlag.

Engelmark, O., Kullman, L. & Bergeron, Y. (1994). Fire and age structure of Scots pine and Norway spruce in northern Sweden during the past 700 years. *New Phytologist*, *126*, 163–168.

Feeney, S. R., Kolb, T. E., Covington, W. W. & Wagner, M. R. (1998). Influence of thinning and burning restoration treatments on presettlement ponderosa pines at the Gus Pearson Natural Area. *Canadian Journal of Forest Research*, *28*, 1295–1306.

Florence, R. G. (1996). *Ecology and silviculture of eucalypt forests*. Collingwood: CSIRO Publishing.

Fries, C., Johansson, O., Pettersson, B. & Simonsson, P. (1997). Silvicultural models to maintain and restore natural stand structures in Swedish boreal forests. *Forest Ecology and Management*, *94*, 89–103.

Gjerde, I., Sætersdal, M., Rolstad, J., Blom, H. H. & Storaunet, K. O. (2004). Fine-scale diversity and rarity hotspots in northern forests. *Conservation Biology*, *18*, 1032–1042.

Groven, R. & Niklasson, M. (2005). Anthropogenic impact on past and present fire regimes in a boreal forest landscape of southeastern Norway. *Canadian Journal of Forest Research*, *35*, 2719–2726.

Hellberg, E., Niklasson, M. & Granstrom, A. (2004). Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. *Canadian Journal of Forest Research*, *34*, 332–338.

Hoffmann, W. A. (2002). Direct and indirect effects of fire on radial growth of cerrado savanna trees. *Journal of Tropical Ecology*, *18*, 137–142.

Holmes, R. L. (1994). *Dendrochronology program library – User's manual*. Tucson, AZ: University of Arizona, Laboratory of tree Ring Research.

Hunt, S. M. & Simpson, J. A. (1985). Effects of low intensity prescribed fire on the growth and nutrition of a slash pine plantation. *Australian Journal of Forest Research*, *15*, 67–77.

Johansen, R. W. & Wade, D. D. (1987). Effects of crown scorch on survival and diameter growth of slash pines. *Southern Journal of Applied Forestry*, *11*, 180–184.

Keyser, T. L., Lentile, L. B., Smith, F. W. & Shepperd, W. D. (2008). Changes in forest structure after a large, mixed-severity wildfire in ponderosa pine forests of the Black Hills, South Dakota, USA. *Forest Science*, *54*, 328–338.

Keyser, T. L., Smith, F. W., Lentile, L. B. & Shepperd, W. D. (2006). Modeling postfire mortality of ponderosa pine following a mixed-severity wildfire in the Black Hills: The role of tree morphology and direct fire effects. *Forest Science*, *52*, 530–539.

Keyser, T. L., Smith, F. W. & Shepperd, W. D. (2010). Growth response of *Pinus ponderosa* following a mixed-severity wildfire in the Black Hills, South Dakota. *Western Journal of Applied Forestry*, *25*, 49–54.

Landsberg, J. D. (1994). A review of prescribed fire and tree growth response in the genus *Pinus*. *Proceedings of 12th Conference on Fire and Forest Meteorology*, October 26–28, Jekyll Island, Georgia, pp. 326–346.

Leblanc, D. C., Nicholas, N. S. & Zedaker, S. M. (1992). Prevalence of individual-tree growth decline in red spruce populations of the southern Appalachian Mountains. *Canadian Journal of Forest Research*, *22*, 905–914.

Lehtonen, H. & Huttunen, P. (1997). History of forest fires in eastern Finland from the fifteenth century AD – The possible effects of slash-and-burn cultivation. *The Holocene*, *7*, 223–228.

Lehtonen, H. & Kolström, T. (2000). Forest fire history in Viena Karelia, Russia. *Scandinavian Journal of Forest Research*, *15*, 585–590.

Moen, A. (1999). *National atlas of Norway: Vegetation*. Hønefoss: Norwegian Mapping Authority.

Motta, R., Morales, M. & Nola, P. (2006). Human land-use, forest dynamics and tree growth at the treeline in the Western Italian Alps. *Annals of Forest Science*, *63*, 739–747.

Niklasson, M. & Drakenberg, B. (2001). A 600-year tree-ring fire history from Norra Kvills National Park, southern Sweden: Implications for conservation strategies in the hemiboreal zone. *Biological Conservation*, *101*, 63–71.

Niklasson, M. & Granström, A. (2000). Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. *Ecology*, *81*, 1484–1499.

Niklasson, M., Zackrisson, O. & Östlund, L. (1994). A dendroecological reconstruction of use by Saami of Scots Pine (*Pinus sylvestris* L.) inner bark over the last 350 years at Sädvajaure, N. Sweden. *Vegetation History and Archaeobotany*, *3*, 183–190.

Olsson, J. & Jonsson, B. G. (2007). Restoration fire and wood-inhabiting fungi in a Swedish *Pinus sylvestris* forest. *Forest Ecology and Management*, *259*, 1971–1980.

Pearson, H. A., Davis, J. R. & Schubert, G. H. (1972). Effects of wildfire on timber and forage production in Arizona. *Journal of Range Management*, *25*, 250–253.

Peltola, H., Kilpeläinen, A., Sauvala, K., Räisänen, T. & Ikonen, V.-P. (2007). Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. *Silva Fennica*, *41*, 489–505.

Peterson, D. L., Arbaugh, M. J., Pollock, G. H. & Robinson, L. J. (1991). Postfire growth of *Pseudotsuga menziesii* and *Pinus contorta* in the Northern Rocky Mountains, USA. *International Journal of Wildland Fire*, *1*, 63–71.

Peterson, D. L., Sackett, S. S., Robinson, L. J. & Haase, S. M. (1994). The effects of repeated prescribed burning on *Pinus ponderosa* growth. *International Journal of Wildland Fire*, *4*, 239–247.

Pukkala, T., Miina, J. & Kellomäki, S. (1998). Response to different thinning intensities in young *Pinus sylvestris*. *Scandinavian Journal of Forest Research*, *13*, 141–150.

Rehfuess, K. E., Ågren, G. I., Andersson, F., Cannell, M. G. R., Friend, A., Hunter, I., et al. (1999). *Relationships between recent changes of growth and nutrition of Norway spruce, Scots pine, and European beech forests in Europe* (EFI Working Paper 19). Joensuu: European Forest Institute.

Reinhardt, E. D. & Ryan, K. C. (1988). *Eight-year tree growth following prescribed underburning in a western Montana Douglas-fir/ Western larch stand* (*Research Note INT-387*). Ogden, UT: USDA Forest Service.

Riegel, G. M., Miller, R. F. & Krueger, W. C. (1992). Competition for resources between understory vegetation and overstory *Pinus ponderosa* in northeastern Oregon. *Ecological Applications*, *2*, 71–85.

Rolstad, J., Sætersdal, M., Gjerde, I. & Storaunet, K. O. (2004). Wood-decaying fungi in boreal forest: Are species richness and abundances influenced by small-scale spatiotemporal distribution of dead wood? *Biological Conservation*, *117*, 539–555.

Rowe, S. J. & Scotter, G. W. (1973). Fire in the boreal forest. *Quaternary Research*, *3*, 444–464.

Salemaa, M., Derome, J. & Nöjd, P. (2008). Response of boreal forest vegetation to the fertility status of the organic layer along a climatic gradient. *Boreal Environment Research*, *13* (Suppl. B), 48–66.

Schmidt, V., Hille, M. & von Gadow, K. (2004) Analyse eines Bodenfeuers – Veränderungen der Bestandesstruktur und des Wachstums. [Change of growth and structure of a pine stand after fire]. *Allgemeine Forst und Jagdzeitung*, *175*, 78–82 (In German).

Skov, K. R., Kolb, T. E. & Wallin, K. F. (2004). Tree size and drought affect ponderosa pine physiological response to thinning and burning treatments. *Forest Science*, *50*, 81–91.

Smithwick, E. A. H., Turner, M. G., Mack, M. C. & Chapin, F. S. III. (2005). Post-fire soil N cycling in northern conifer forests affected by severe, stand-replacing wildfires. *Ecosystems*, *8*, 163–81.

Squire, R., Farrell, P., Flinn, D. & Aeberli, B. (1985). Productivity of first and second rotation stands of radiata pine on sandy soils. *Australian Forestry*, *48*, 127–137.

Storaunet, K. O., Rolstad, J., Gjerde, I. & Gundersen, V. S. (2005). Historical logging, productivity, and structural characteristics of boreal coniferous forests in Norway. *Silva Fennica*, *39*, 429–442.

Storaunet, K. O., Rolstad, J., Toeneiet, M. & Blanck, Y. (manuscript in preparation). A detailed spatial and temporal forest fire history in south-central Norway.

Sutherland, E. A., Covington, W. W. & Andariese, S. (1991). A model of ponderosa pine growth response to prescribed burning. *Forest Ecology and Management*, *44*, 161–173.

Swetnam, T. W. & Baisan, C. H. (1996). Historical fire regime patterns in the southwestern United States since AD 1700. In: C. D. Allen (Ed.), *Proceedings of the 2nd La Mesa Fire Symposium. Fire Effects in Southwestern*, pp. 11–32, Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station, General Technical Report RM-GTR-286.

Valinger, E., Elfving, B. & Mörling, T. (2000). Twelve-year growth response of Scots pine to thinning and nitrogen fertilization. *Forest Ecology and Management*, *134*, 45–53.

Waldrop, T. A. & Van Lear, D. H. (1984). Effect of crown scorch on survival and growth of young loblolly pine. *Southern Journal of Applied Forestry*, *8*, 35–40.

Wallenius, T. H., Kuuluvainen, T., Heikkilä, R. & Lindholm, T. (2002). Spatial tree age structure and fire history in two old-growth forests in eastern Fennoscandia. *Silva Fennica*, *36*, 185–199.

Wallenius, T. H., Kuuluvainen, T. & Vanha-Majamaa, I. (2004). Fire history in relation to site type and vegetation in Vienansalo wilderness in eastern Fennoscandia, Russia. *Canadian Journal of Forest Research*, *34*, 1400–1409.

Wallenius, T. H., Lilja, S. & Kuuluvainen, T. (2007). Fire history and tree species composition in managed *Picea abies* stands in southern Finland: Implications for restoration. *Forest Ecology and Management*, *250*, 89–95.

Wan, S., Hui, D. & Luo, Y. (2001). Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: A meta-analysis. *Ecological Applications*, *11*, 1349–1365.

Wooldridge, D. D. & Weaver, H. (1965). Some effects of thinning a ponderosa pine thicket with a prescribed fire, II. *Journal of Forestry*, *63*, 92–95.

Wyant, J. G., Laven, R. D. & Omi, P. N. (1983). Fire effects on shoot growth characteristics of ponderosa pine in Colorado. *Canadian Journal of Forest Research*, *13*, 620–625.

Yamaguchi, D. K. (1991). A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research*, *21*, 414–416.

Zackrisson, O. (1977). Influence of forest fires on the North Swedish boreal forest. *Oikos*, *29*, 22–32.

PAPER IV

Research paper

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The charcoal record in peat and mineral soil across a boreal landscape and possible linkages to climate change and recent fire history

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Abstract

This study combines tree-ring and charcoal data to explore possible drivers of the charcoal record and its spatial variation in a boreal Norwegian forest landscape. Peat and mineral soil samples were collected in a multiple site sampling approach and the amount of charcoal in the peat is related to fire history, Holocene climate variation, major shifts in the vegetation composition, and fuel availability. Dendrochronologic dating was used to reveal the fire history over the last 600 years with spatial and temporal accuracy, and AMS radiocarbon dating of 20 peat columns and their charcoal records from four peatlands was used to elucidate the fire history over the Holocene. The average amount of charcoal was about 2.5 times higher in the mineral soil than in the peat (270 versus 100 g/m², respectively), and there were considerable between- and within-site variations. There was no relationship between the age of a given peatland and its content of charcoal, nor between the amount of charcoal in a given peatland and in the neighboring mineral soil. Although most of the charcoal mass in the peatlands was found in parts of the peat columns originating from relatively warm climatic periods and from the period before the local establishment of Norway spruce (*Picea abies*), charcoal accumulation rates (per 1000 yr) were higher during cold climatic periods and similar before and after spruce establishment. Recent fires showed up to a low degree in the peat columns. On fine spatial scales (1–10 m), fuel quality and distribution together with fire behaviour throughout millennia are likely to be responsible for variations in the charcoal record. On the landscape scale (100–1000 m), the charcoal records were site-specifically idiosyncratic, presumably due to topography, distribution of fire breaks and fuel types, and human land use, coupled with long-term variations inherent in these factors.

Keywords

boreal forest, charcoal carbon pool, climate change, dendrochronology, fire history, radiocarbon dating, spatial- and temporal scale, variation

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Introduction

The role of fire as a primary disturbance agent in boreal forests is well established (Goldammer and Furyaev, 1996; Johnson, 1992) and a lot of work has been put into understanding its importance in relation to biodiversity, vegetation dynamics, ecosystem management, and the global carbon cycle (Agee, 1993; Apps and Price, 1996; Attiwill, 1994; Carcaillet et al., 2002). As climate change is a major environmental issue of our time, special attention has been paid to drivers, interactions and feedbacks linking carbon emissions from biomass burning and climate change (Carcaillet et al., 2002; Conard and Solomon, 2009; Innes et al., 2000; Kasischke and Stocks, 2000; Kuhlbusch and Crutzen, 1996). Global wildfire emissions vary substantially from year to year and the average annual carbon emission from wildfires amounts to 25–45% of those from fossil fuel combustion (Conard and Solomon, 2009). The boreal forest is the largest terrestrial biome on Earth, and approximately 20% of the global emissions of carbon from wildfires originate from the boreal forest (Conard and Ivanova, 1997).

The majority of organic matter consumed by fires is converted to carbon dioxide and released into the atmosphere. A minor fraction, 1–3% (Preston and Schmidt, 2006), is converted to black carbon, including char, charcoal, soot, and graphite. Black carbon is an ubiquitous component of soils and sediments (Schmidt and Noack, 2000), and charcoal is the quantitatively dominating form of black carbon in boreal forest soils (Ohlson et al., 2009). The size of the charcoal pool in boreal forest soils is known to vary across broad spatial scales that are mainly related to gradients in the regional climate (Ohlson and Tryterud, 2000; Ohlson et al., 2009; Talon et al., 2005; Touflan and Talon, 2009). However, there is a lack of knowledge about size variation at finer spatial scales, e.g. between different vegetation types within a given forest landscape. Lehmann et al. (2008) point out the need for spatially explicit data in order to better understand the size and distribution of the black carbon pool and its role in the global carbon cycle.

Peatlands are an important feature in the boreal forest landscape. They store huge amounts of carbon (Gorham, 1991) and their charcoal records have been frequently used to reconstruct fire histories during the Holocene time period (Innes and Simmons, 2000; Mehringer et al., 1977; Pitkänen et al., 2002, 2003). The controls for production and storage of charcoal are

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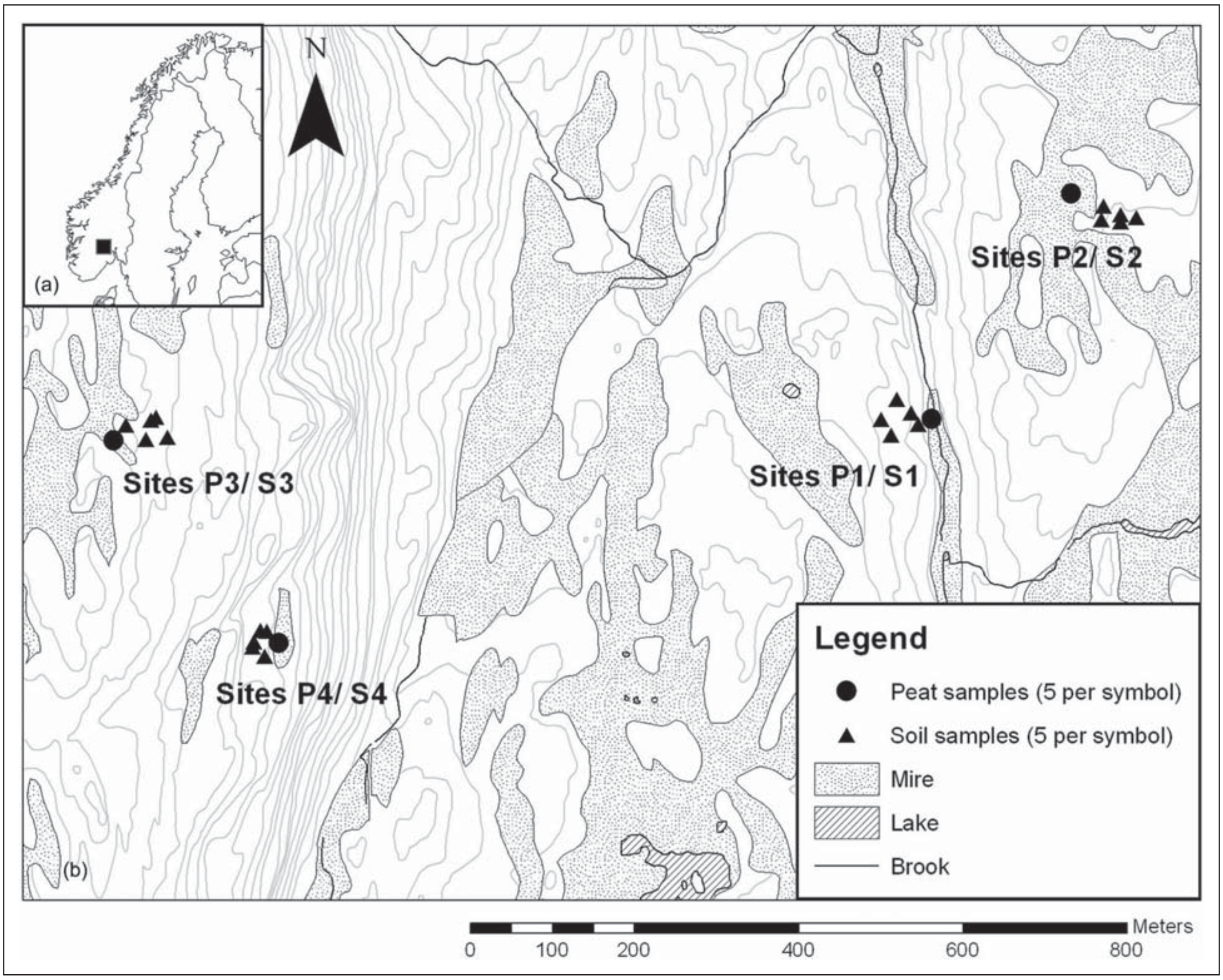

Figure 1. (a) Location of the study area in Norway, (b) location of peat (P) and soil (S) sample sites, see legend for further explanations.

different in peatlands compared with the mineral forest soil. For example, while the charcoal stored in mineral soils may be consumed by recurrent fires (Kane et al., 2010), peatlands typically conserve the charcoal remnants of fire throughout millennia. However, the size (i.e. mass) of the charcoal pool and its spatial variability in boreal peatlands remains poorly understood because palaeoecological studies using the charcoal record generally have focused on charcoal particle numbers, charcoal area, or charcoal banding patterns, but have not estimated the mass of the charcoal per se. The only study we know of that has estimated the mass of the charcoal record in boreal peatlands is Magnan et al. (2012), and to the best of our knowledge, our present study is the first that quantifies the size of charcoal pools in boreal peatlands and examines their variability across different temporal and spatial scales.

The drivers of fire regimes, and thus charcoal production, operate at different spatial and temporal scales (Cyr et al., 2007; Gavin et al., 2003b, 2006; Heyerdahl et al., 2001; Iniguez et al., 2008; Keane et al., 2004; Swetnam, 1993). Only a few studies have tried to describe long-term fire histories in a spatially and temporally explicit manner. This is due to a set of limitations related to availability and quality of historical archives (i.e. tree rings and lake sediments), the time and money needed for analyses, or limitations in spatial and temporal resolution (Gavin et al., 2003a). The spatial scale of our study is the local to landscape scale (1–1000 m). Hence, it allows for a detailed approach with the potential to reveal variation at fine spatial scales. This is especially important since northern European fire regimes are patchy and variable across fine spatial scales (Balshi et al., 2007; Preston, 2009). Here we take advantage of high resolution data on the recent fire history, combined with data on long-term fire activity and a representative number of replicates from the archives in peat- and mineral forest soils. The main objectives of this study are: (1) to estimate the size of the charcoal pool in four boreal forest peatlands and document its variation in size at different spatial and temporal scales; (2) to discuss possible controls on the basis of information derived from local forest fire history, present forest vegetation, and climate change over the Holocene; and (3) to compare the amounts of charcoal in peat and adjacent mineral soil.

Material and methods

Study area

The study area, Heimseteråsen, is located within the Trillemarka–Rollagsfjell Nature Reserve in south central Norway (60°02′N, 09°26′E, Figure 1). It is situated in the mid-boreal vegetation zone (Moen, 1999). The climate is intermediate oceanic and continental with relative warm summers and cold, snow-rich winters. Mean annual temperature (daily average) is +3.5°C with January and July means of −7.5°C and 14.7°C, respectively (Rollag meteorological station, Norwegian Meteorological Institute, 2012). North–south extending ridges of Precambrian rocks, consisting of acid granites and gneisses, and an east-facing slope with deposits of richer moraine material, characterize the landscape. The altitude ranges from 400 to 650 m a.s.l. with the lowest elevation in the gently undulating eastern part of the study area. Mires and rather nutrient-poor Scots pine (*Pinus sylvestris*) forests with dwarf shrubs such as e.g. *Calluna vulgaris* and *Vaccinium uliginosum* dominate the low eastern and higher western area (nomenclature for plant names follows Lid and Lid, 2005). The morainic

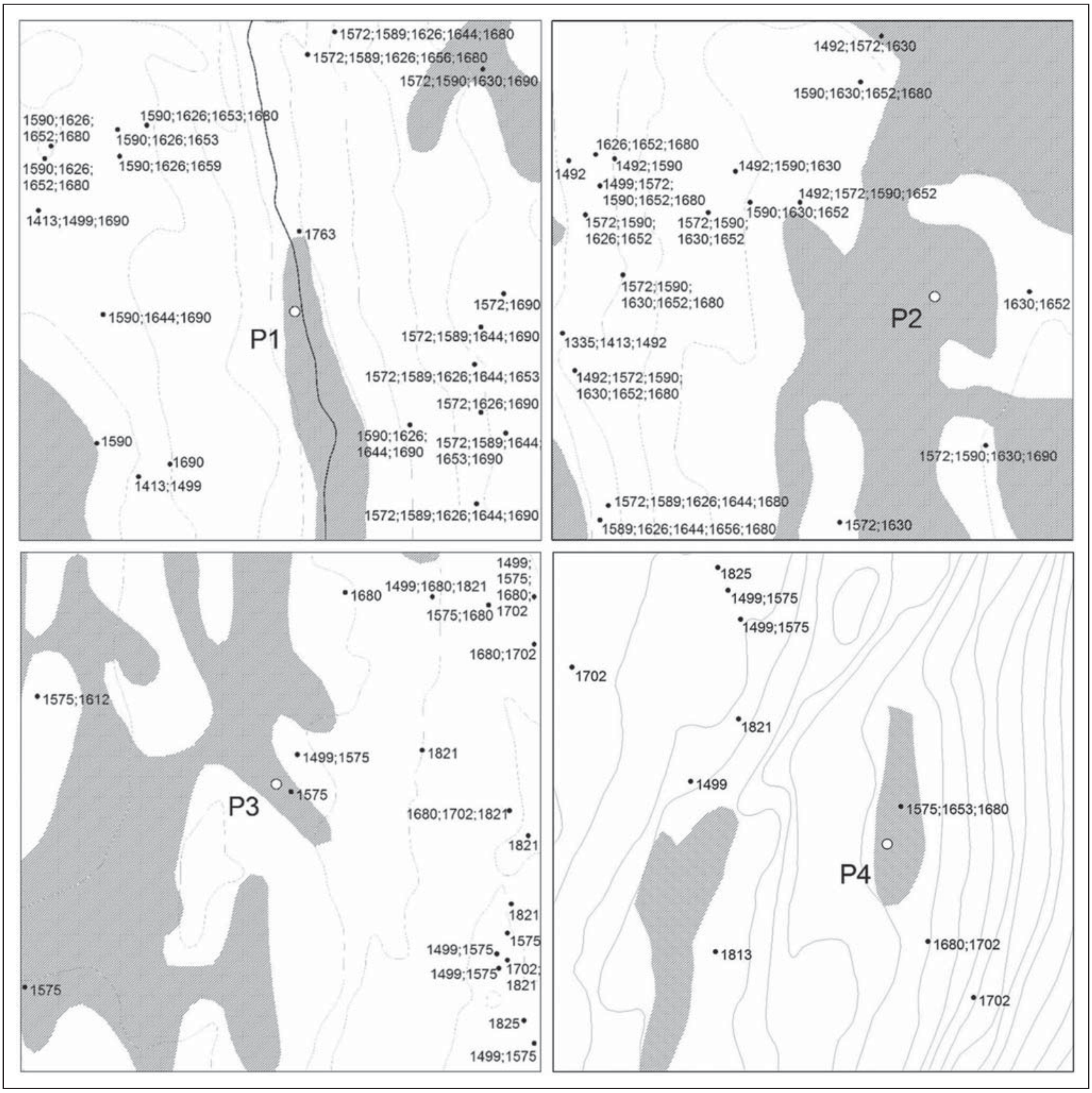

Figure 2. Detailed maps (250 m × 250 m) of the peat sample sites (white circle) and nearby fire-scarred pine stumps (black dots followed by fire years). Hatched areas: mires; black line: brook; gray lines: contours (interval 5 m).

slope is characterized by more nutrient-rich Norway spruce (*Picea abies*) forests in which *Vaccinium myrtillus* and a number of small herbs and ferns are common.

We selected four mires for peat sampling (Figures 1 and 2), two of them surrounded by spruce-dominated forest (sites P1 and P4), and two surrounded by pine forest (sites P2 and P3). Soil samples (S1–S4) were taken in the forests adjacent to the peat-sampling sites. The mire at site P1 stretches *c*. 380 m in a north–south direction along a brook originating in the outflow of lake Litjern. Sample site P1 is situated on the western side of the brook. At this point the mire is *c*. 20 m wide, and the vegetation is dominated by *Sphagnum* mosses, *Vaccinium* dwarf shrubs, and sedges. The adjacent forest in the west where soil samples (S1) were collected is dominated by Norway spruce. Site P4 is situated on a minerotrophic mire (100 m × 25 m) on a terrace on the upper part of an east-facing slope covered with spruce forest. *Sphagnum* spp. and *Carex rostrata* dominate the mire vegetation here. Soil sample site S4 is located in the spruce-dominated forest west of the mire. Peat sample site P2 is situated on the edge of an ombrotrophic mire complex in the eastern part of the study area. *Sphagnum* mosses and *Eriophorum vaginatum* are the most common species here. The adjacent forest east of the mire where soil samples (S2) were collected is dominated by Scots pine. Site P3 is situated in the western part of the study area in the middle of a 15 m wide protrusion of a mire complex surrounded by pine forest. The position was chosen due to its immediate proximity (8 and 18 m, respectively) to two stumps with fire scars which have been analyzed in the study of the tree-ring data. The ombrotrophic vegetation at P3 consists mainly of *Sphagnum* spp. and *Eriophorum vaginatum*. Soil samples S3 were collected in the pine forest east of P3.

Sampling and analysis of tree-ring data

A spatial and temporal fire history reconstruction during the past 600 years based on dendrochronological records has been made in the area (Storaunet et al., 2013). Partial cross-sections from living trees, snags, logs, and stumps of Scots pine with externally visible fire-scars were sampled by using a chain-saw (Arno and Sneck, 1977), and thereafter dried and sanded so that tree-rings could be measured with an Addo micrometer (accuracy of 0.01 mm). These cross-sections were dated against three independently developed tree-ring index chronologies by using the program COFECHA (Holmes, 1983, 1994), and confirmed by the pointer-year method described by Niklasson et al. (1994). In total, 321 samples containing a total number of 736 fire scars were successfully cross-dated. GIS was used to measure distances between peat sample sites on the mires and fire-scarred stumps on the neighboring mineral soil (this was done for all stumps within a range of 100 m from the peat sampling site).

Sampling of peat

Sampling at sites P1–P4 was carried out in August and September 2010. At each site, a sampling block of 5 m × 10 m was placed subjectively in the mire. The distance from a block to the mire margin varied from 2.5 m to 20 m. There is a trade-off between the potentially optimal positions for covering the recent fire history and the long-term history: The chance for more recent fires to be displayed in the peat increases towards the edges (Pitkänen et al., 2001) while it is more likely that the deeper and central parts of the mire contain the oldest peat with the potential to reveal fire activity in a long-term time perspective. Each block was divided into 50 1 × 1 m^2 plots and five of these were randomly selected for sampling of peat columns with a Russian peat corer (Jowsey, 1966; inner diameter 4.8 cm, 50 cm length). This restricted random sampling procedure yielded in total 20 peat columns consisting of 57 individual peat cores including 26.37 m of unique peat sequence after removing overlaps. Prior to sampling, the uppermost 10 cm of vegetation were removed and packed into plastic bags. Immediately after sampling, we took a picture of each peat core in order to preserve the possible banding pattern of charcoal layers against the fresh, un-oxidized peat (Ohlson et al., 2006). The peat cores were wrapped in plastic foil and stored in plastic tubes which had been cut in half lengthwise. This minimized the risk of damaging the stratigraphy during transportation. The peat samples were kept deep-frozen before and between handling at the laboratory.

Charcoal and pollen analysis, ^{14}C dating, age–depth models

The surface peat samples consisting of the uppermost 10 cm of vegetation were searched for macroscopic charcoal under a magnifying lamp (4× magnification). Still half frozen, each peat core was cut into 1 cm slices which were cut in two halves. One set of samples was dedicated to charcoal and the other to pollen analysis. As macroscopic charcoal (longest axis ≥0.5 mm) has been proven to be a reliable proxy for in situ fires (Clark, 1988; Ohlson and Tryterud, 2000; Patterson et al., 1987) and makes up most of the charcoal mass in boreal forest soils (Ohlson et al., 2009), we chose to focus on this fraction. Peat samples for charcoal analysis were gently washed through a sieve (0.28 mm), diluted in water in petri-dishes and searched for macroscopic charcoal under a magnifying lamp, see Hörnberg et al. (1995). This procedure of handling and identifying macroscopic charcoal results in a slight underestimation of the charcoal pool, with the loss from sieving being negligible (Ohlson and Tryterud, 2000). Only black, opaque particles with broken angular ends and often with a silver-shining surface were classified as charcoal. The charcoal fragments were oven-dried at 60°C (Termaks Series TS8000) and weighed (Sartorius ED224S).

In order to capture potentially local low-intensity fires which did not leave behind macroscopic charcoal (Innes et al., 2004; Pitkänen et al., 1999), we also recorded visible charcoal layers in the peat. All evidence of fire in the peat cores was summed up and presented in a centimetre-wise presence or absence record of ‘fire activity’. This evidence included (1) visible charcoal layers on the basis of examination in the field and the photos of the fresh peat cores; (2) macroscopic charcoal ≥0.1 mg per sample, which was used to determine the mass per m^2; and (3) visible charcoal, but <0.1 mg per sample, which was not included in the mass calculation. We adjusted the fire activity record for possible methodological inaccuracy by interpreting visible layers in 1 or 2 cm distance to a charcoal sample from the peat to represent that sample and did not count both. Some of our fire activity records may represent a regional element (i.e. fires which burned at greater distance; Carcaillet et al., 2001; Tinner et al., 1998; Whitlock and Millspaugh, 1996), and they do not necessarily represent single fire events (Clark, 1988; Innes and Simmons, 2000). Uncertainties of this kind have been addressed by authors who focused on particle counts rather than charcoal mass by using numerical techniques for discerning peaks in charcoal accumulation rates (CHAR) (Briles et al., 2008; Higuera et al., 2007). However, macroscopic charcoal still is the most reliable source of information on local fire events and therefore also used in addition to these techniques (Greisman and Gaillard, 2009). AMS radiocarbon dating was used to determine the age of 27 peat samples and site-specific age–depth models were obtained by linear interpolation with the CLAM software (Blaauw, 2010) (Figures 3a–e). The age–depth models are based on the peat column with the highest number of radiocarbon dates and include all dates from a given site except dates that represented age-inversions (Table 1). An additional age–depth model (Figure 3d) was calculated for site P3 because one single date turned out to influence significantly on a result, i.e. the temporal match between fire scars and peat charcoal data. The results for both age–depth models for site P3 are reported concerning that analysis. At sites P2 and P3 the deepest parts of the age–depth relationships (the lowermost 9 and 29 cm, respectively) were calculated by extrapolation. Variation in the age–depth relationship in mires at fine spatial scales is common in boreal peatlands and originates from natural variation in peat accumulation rates (Økland and Ohlson, 1998).

In order to get an indirect date for a given level in each of our peat columns, we determined the level at which spruce pollen percentages exceeded 2% of the sum of tree pollen. Above this threshold we considered spruce to be locally established (Hafsten, 1992). Pollen analysis followed standard methods (Berglund and Ralska-Jasiewiczowa, 1986) and at least 300 tree pollen were counted in each sample.

Sampling and analysis of soil

In October 2010, we collected 100 soil samples in the forests most adjacent to the peat coring sites. Soil sampling locations were determined by a restricted random procedure, i.e. first we selected an area of 100 m × 100 m in each of the adjacent forests, starting at 2 m off the edge of the mire, then we subjectively placed five blocks (5 m × 10 m) in each of the forests to cover variation in vegetation and topography, and finally five soil samples were collected at random positions in each block with a steel cylinder (50 cm long, inner diameter 5.8 cm). Locations on naked bedrock and peat-filled depression were discarded. The depth varied with the thickness of the organic layer (2–50 cm), and we made sure that all samples contained a few centimetres of the underlying mineral soil. The samples were packed into plastic bags, transported to the laboratory and stored in the freezer. With 25 samples collected at each site, this yielded a total number of 100 soil samples. At the laboratory, samples were oven dried at 80–105°C (Termaks series TS 8000) and searched for macroscopic charcoal using a magnifying lamp (4× magnification). We used the same criteria as for the peat samples for defining macroscopic charcoal. The dry

Table 1. AMS radiocarbon datings of peat samples.

Lab. ref.	Site	Peat column no.	Depth (cm)	Cal. age
TRa-2741	P1	13	21	Younger than cal. AD 1710
TRa-2746	P1	15	125	cal. 5385–5285 BC
TRa-2747	P1	13	142	cal. 5985–5895 BC
TRa2748	P1	13	150	cal. 7040–6740 BC
TRa-2737	P1	11	230	cal. 7080–6785 BC
TRa-2742	P2	54	60	cal. 1405–1300 BC
TRa-2750	P2	53	79	cal. 1170–1040* BC
TRa-2749	P2	52	84	cal. 1945–1870* BC
TRa-2751	P2	54	97	cal. 1915–1775 BC
TRa-2752	P2	54	106	cal. 3640–3510 BC
TRa-2753	P2	55	122	cal. 4000–3960 BC
TRa-2754	P2	55	141	cal. 4255–4095 BC
TRa-2738	P2	51	150	cal. 3955–3800* BC
TRa-2743	P3	32	41	cal. AD 1245–1275(*)
TRa-2755	P3	35	64	cal. AD 1395–1420
TRa-2756	P3	35	111	cal. 930–845 BC
TRa-2757	P3	35	115	'active'*
TRa-2739	P3	35	140	cal. AD 450–565*
TRa-2745	P4	44	65	Younger than cal. AD 1955
TRa-2744	P4	42	85	'active'*
TRa-2758	P4	41	93	'active'*
TRa-2759	P4	42	99	Younger than cal. AD 1955*
TRa-2760	P4	43	104	cal. AD 1305–1375
TRa-2761	P4	44	105	cal. AD 1065–1180*
TRa-2762	P4	44	108	cal. AD 1220–1290
TRa-2764	P4	42	114	'active'*
TRa-2740	P4	44	125	cal. BC 380–225

Notes:
*Excluded from age–depth models because of inverse ages.
(*) Excluded from the age–depth model used throughout the study, Figure 3(c), and used instead of TRa-2755 in the additional age–depth model (Figure 3d).
All samples were bulk samples (particles > 0.28 mm). AMS radiocarbon datings prepared at the National Laboratory for ^{14}C dating, Norwegian University of Science and Technology, Trondheim and measured at Tandem Laboratory, Uppsala University. Cal. age determined with CALIB (Stuiver and Reimer, 1993), calibrated age ranges at 1 SD.

weight of macroscopic charcoal per sample was determined with an analytical scale (Sartorius ED224S).

Vegetation, forest density and Holocene climate variation

At all the sample sites we recorded vegetation composition and determined the basal area of the surrounding forest to indicate site productivity and relative differences in the amounts of tree biomass. We used an angle gauge to measure the basal area in each site (mires) and block (mineral soil), divided into the major tree species present (i.e. *P. sylvestris, P. abies* and *Betula pubescens*). Information on major trends in climatic variation between warm and dry versus wet and cold periods over the Holocene was derived from Seppä et al. (2009), who summarized current knowledge from key proxy records for northern Europe. Variation inherent in single proxies and consequences for climate reconstruction has been described by e.g. Nesje et al. (2008), Nesje (2009), and Seppä et al. (2010).

Statistics – variation in the amount of charcoal

The peat columns have been sampled in a nested block design (samples within sites within forest types), and mixed model variance components analysis was performed in order to determine on which level of the spatial hierarchy there was important variation. We used the R software for statistical computing (Pinheiro et al., 2011; R Development Core Team, 2011) for this analysis. Prior to the analysis, the amounts of macroscopic charcoal derived from the individual peat columns (expressed in g/m²) were log-transformed in order to achieve approximation to normality. The analysis was then carried out with site nested in forest type (both as random factors). We also carried out an ANOVA and a subsequent post hoc test (Tukey's HSD) to elucidate whether the average amounts of charcoal at the different sites were significantly different from each other. For this analysis we used the R software (R Development Core Team, 2011) and the same log-transformed values as above. The assumption of homogeneity of variances was met by the data (Fligner-Killeen test, p=0.5163).

Results

Fire history 600 BP to present from tree-ring analysis

The oldest evidence of forest fire at the peat and soil sample sites based on dendrochronological analysis dated back to AD 1335, when a fire occurred in the northeast of the study area at sites P2/S2. During the following centuries, periods with longer (about 80 years) or shorter (about 20–40 years) fire return intervals could be documented at the sample sites (Table 2 and Figure 2). Up to seven and ten fires are likely to have touched the peat- and mineral soil sampling sites, respectively (see Storaunet et al., 2013, for a detailed description of the recent fire history).

Long-term fire history from peat samples

The oldest peat column dated back to *c*. 9000 cal. yr BP, and the time span covered on all sites was the period from about 2250 cal. yr BP to present. Information on the peat samples is gathered in

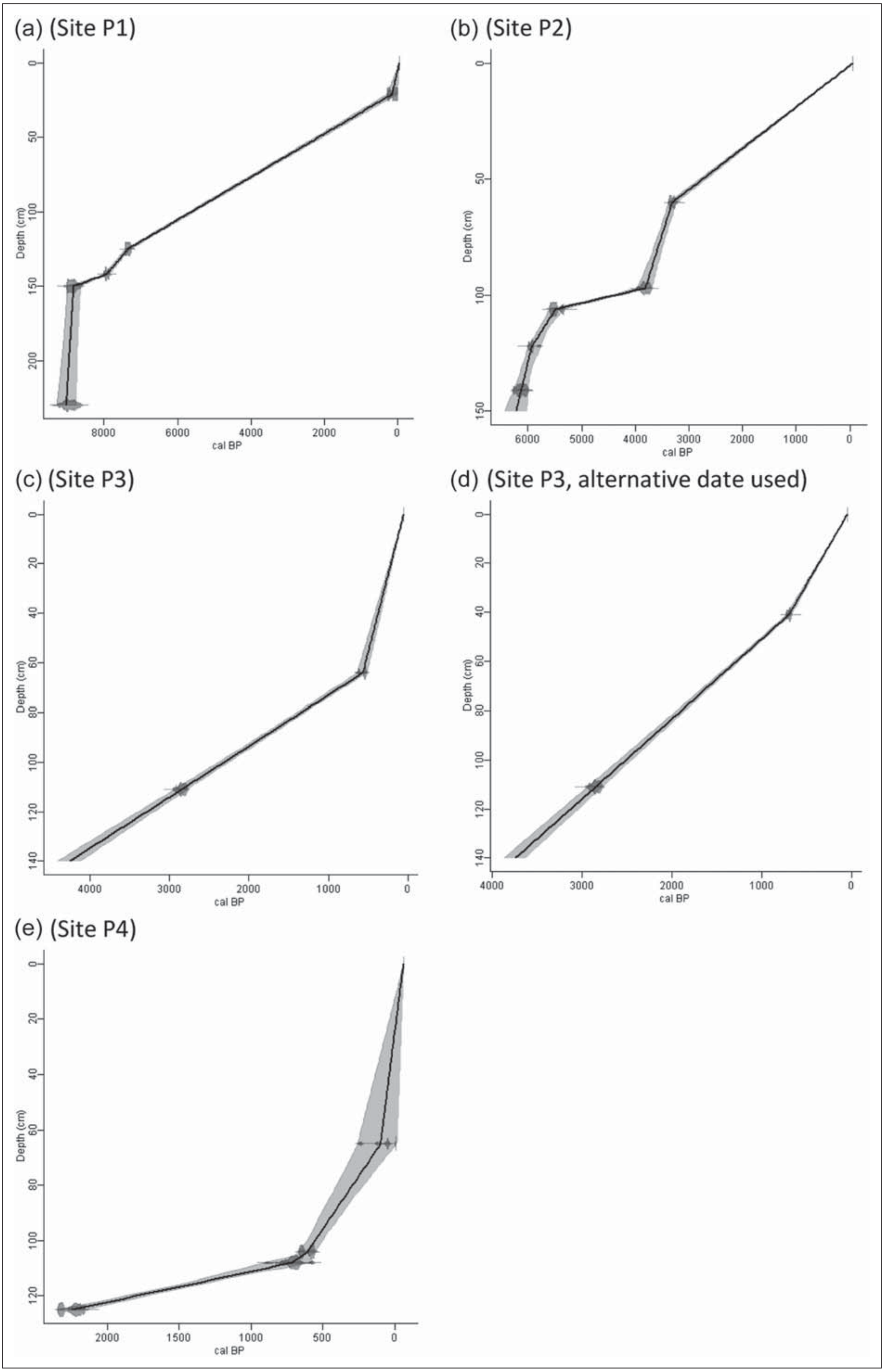

Figure 3. Age–depth models for the different sites. Calibrated age ranges at 2 SD.

Table 2. Local fires at peat and soil sample sites documented through fire scars and tree-ring analysis (see Figure 2). Fire-scarred samples closer than 50 m in boldface, and samples 50–100 m in italic. Sums in parentheses: sum of fires documented through fire scarred samples within 100 m from peat sample sites.

Sites		Fires						Sum fires
		AD 1300– 1399	AD 1400– 1499	AD 1500–1599	AD 1600–1699	AD 1700–1799	AD 1800–1900	
1	P1, *peat*			*1572* *1589/90*	*1626* *1644* *1653* *1690*	**1763**		1 (7)
	S1, *soil*		*1413* *1499*	**1590**	*1626* **1644** *1652/53* *1659* *1680* **1690**	**1763**		3 (10)
2	P2, *peat*		*1492*	*1572* *1590*	1630 1652			2 (5)
	S2, *soil*			*1563* **1572** **1590**	**1630** *1644* **1652** **1690**			5 (7)
3	P3, *peat*		**1499**	**1575**	*1680*		*1821*	2 (4)
	S3, *soil*		**1499**	**1575**	**1680**	**1702**	1821	5 (5)
4	P4, *peat*		*1499*	**1575**	**1653** **1680**	*1702*	*1813* *1821*	3 (7)
	S4, *soil*		*1499*	**1575**	**1653** **1680**	**1702**	*1813* *1821*	4 (7)

Table 3, and Figure 4 displays every peat sequence and the charcoal record in detail. Distances between the peat sampling blocks and the mire margins varied between 2.5 and 20 m, and even though site P1 was located closest to the mire margin (2.5 m), the deepest (2.3 m) and oldest peat column was sampled here. At site P4, peat consistence changed abruptly at a depth of 0.9–1 m (corresponding to *c*. 425–550 cal. yr BP) from very low humified material (roots of sedges, mosses) where charcoal was almost absent, to highly humified peat containing large amounts of charcoal. Four radiocarbon dates from site P4 from depths below 0.84 m were dated to be modern and were excluded from the analysis because of age inversion. The downward transport of younger carbon by plant roots, downward water flow, or both can lead to erroneous radiocarbon ages (Charman et al., 1992; Tolonen et al., 1992). *Carex rostrata* has been mentioned to cause such problems because of the species' distribution of biomass (Pitkänen et al., 2002; Saarinen, 1996), and it is one of the dominating species in the mire.

According to the age–depth models for the different sites, there was a marked difference between the time period for spruce establishment at the two eastern sites at lower elevation (site P1: 1274 ± SD 160 cal. yr BP, and P2: 1950 ± SD 384 cal. yr BP) and the two western sites on top of the slope (P3: 524 ± SD 165 cal. yr BP, and P4: 601 ± SD 136 cal. yr BP) (Table 3).

None of the samples from the uppermost 10 cm of vegetation contained macroscopic charcoal. All peat columns contained traces of fire measured as fire activity. The mean number of fire activity recordings per peat column varied from 8.2 to 13 among the sites (expressed as rates per 1000 yr: 1.3–6.5), and there was a considerable amount of within-site variation (Table 4). The average number of samples per peat column containing macroscopic charcoal was twice as high at site P4 (10.4 ± SD 4.2) as at the other sites (4 ± SD 5.4, 4.6 ± SD 1.5, 4.8 ± SD 4.2), and also here within-site variation was considerable. Also when expressed as rate per 1000 yr, site P4 stands out with the highest value among the sites (Table 4).

At all sites, most of the fire activity recordings were found in peat sequences which temporally coincided with the period before the local establishment of spruce and warm climatic periods (Table 4, Figure 5). Pre- and post-spruce fire activity rates were 3.7 ± SD 3.2 and 2.2 ± SD 2.7, respectively (Figure 5), and fire activity rates in warm and cold climatic periods were 3.3 ± SD 2.8 and 2.2 ± SD 3.0 (rates per 1000 yr, averages over all sites). Owing to many zero values among a limited number of samples we did not test whether these differences (pre- versus post-spruce, warm versus cold climatic periods) were statistically significant.

Correspondence between the tree-ring and charcoal fire record

The fire years determined through the dendrochronological analysis are marked in the peat sequences in Figure 4. At sites P1, P3, and P4 there were charcoal layers at depths that corresponded in time to fires described by the tree ring data. However, a charcoal banding pattern clearly matching all fire events in the tree ring data could not be found at any site. At two sites (P1 and P2), the cm wise resolution of the samples was too coarse to distinguish between recent fire events from the tree-ring analysis. At site P1, fire activity recorded in two of the peat columns may correspond to the fires that occurred between AD 1499 and AD 1763. At site P3, three peat columns show fire activity that may correspond to the fires in AD 1499 and AD 1575, and at site P4, both the fire in AD 1499 and AD 1575 may be represented in the fire activity record in two peat columns. However, one of the charcoal layers at site P3 which may correspond to the fire in AD 1575 according to the age–depth model used had been dated to cal. AD 1245–1275. When used in an alternative age–depth model (Figure 3d), this date led to much older dates for the fire activity in the other peat columns discussed here.

Amount of macroscopic charcoal in peat samples

The average amount of charcoal in the peat was 102 ± SD 113 g/m², and between-site variation was considerable (Table 5). For example, there was nearly eight times as much charcoal in the peat at site P4 (200 ± SD 100 g/m²) compared with site P1 (26 ±

Table 3. General information about peat samples and spruce (*Picea abies*) establishment. Ages in parentheses obtained by extrapolation.

Site	Altitude (m a.s.l.)	Maximum depth sampled (m)	Average depth of samples (m)	Total length of unique peat sequence sampled at the site (m)	No. of peat columns sampled to mineral soil	Distance to mineral soil (m)	Age at maximum depth (cal. yr BP)	Spruce pollen > 2%, average depth (cm)	Spruce establishment, average age (cal. yr BP)
1	410	2.3	1.66 ± SD 0.4	8.32	0	2.5	9027	37.4 ± SD 2.3	1274 ± SD 159.8
2	428	1.5	1.23 ± SD 0.23	6.15	5	20	(6218)	35.8 ± SD 6.8	1950 ± SD 383.7
3	548	1.4	1.17 ± SD 0.29	5.85	4	3	(4256)	54 ± SD 10.3	524 ± SD 164.8
4	504	1.25	1.21 ± SD 0.07	6.05	5	6	2246	101.2 ± SD 6.8	601 ± SD 136.4

SD 29 g/m²), which was unexpected because the peat sequences at site P4 cover the shortest time period of all sites used in this study. The difference between the average amounts of charcoal at the two sites was significant at the 0.05 level (ANOVA: n=20, F=4.623, p=0.0164; Tukey's HSD: p=0.024). There was no correspondence between the amount of charcoal in the peat and the dominant forest type adjacent to the site. This was supported by the variance component analysis according to which variation between sites accounted for 42.01% of the overall variance, and the contribution of forest type (pine versus spruce dominated) was negligible (<1%, p=1). The residual variation was 57.99%, and considering the standard deviations for the mean amounts of macroscopic charcoal per site, a major part of it was within-site variation. Within-site variation in the amount of charcoal was especially high at site P3 (average weight 81 ± SD 155 g/m²), because of a single peat column (P35) which contained 17 to over 350 times as much charcoal as the other columns from that site (359 g/m², the highest value measured in a peat column in this study), see Figure 6. The amounts of charcoal which accumulated during the periods covered by the dendrochronological analysis at each site (since 1350, Storaunet et al., 2013; Table 2) showed a different pattern than the total amounts. At the two sites adjacent to pine forest (P2 and P3), there was no macroscopic charcoal at all or too little (< 0.1 mg per sample) to be weighed. At P1 and P4 adjacent to spruce forest, the average amounts were 0.8 ± SD 1.2 g/m² and 3 ± SD 7 g/m², respectively. There was no clear pattern in the present density of the surrounding forest and the average amounts of charcoal in the peat, but both parameters reached high values at site P4. The major part of the charcoal mass at all sites was found in peat sequences corresponding to the time before the local establishment of spruce, but pre- and post-spruce accumulation rates (per 1000 yr, averages over all sites) were similar (49 ± SD 91 g/m² and 43 ± SD 90 g/m², respectively, Table 5 and Figure 6). At all sites most of the mass of macroscopic charcoal was found in peat sequences temporally corresponding to warm climatic periods, but the accumulation rate for macroscopic charcoal per 1000 yr was higher during cold climatic periods than during warm (170 ± SD 238 g/m² and 47 ± SD 60 g/m², respectively, averages over all sites, Table 5).

Amount of macroscopic charcoal in mineral soil samples

On average, there was about 269 ± SD 402 g/m² charcoal in the mineral forest soil, which is 2.5 times more than in the peat. The lowest average amount measured (P4, 131 ± SD 244 g/m²) and the highest (P3, 411 ± SD 555 g/m²) differed by a factor of about 3 (n=100, 25 per site). Interestingly, at sites where there was a lot of charcoal in the peat, there was comparatively little charcoal in the soil, and vice versa (Table 5 and Figure 7). The factors by which the amounts in peat and soil differed from each other ranged from 2 to 13 among the sites.

Generally, basal area values were higher at the sample sites in the spruce forest (15 and 19 m²/ha) than in the pine forest (*c*. 10 m²/ha), but there was no positive relationship between the present density of the forest and the average amount of charcoal in the mineral soil. Actually, the sample site in the spruce forest with the highest density (P4) contained the smallest average amount of charcoal among all sites. On the contrary, the value measured at the other spruce forest location (P1) was the second highest. The highest average amount of charcoal in the mineral forest soil was measured in the pine forest at P3, while the amount at the other pine forest location (P2) was the second lowest (Table 5).

Discussion

High degree of spatial variation in peat charcoal pool

The magnitude of spatial variation in the mass of charcoal in the peat was considerable, both at the local (metre) and landscape (100–1000 m) scale. We found that a given site in a peatland can store up to 350 times as much charcoal as a neighbouring site located only metres away in the same peatland. This finding underpins that charcoal records in boreal peatlands are highly variable across fine spatial scales, which has been indicated previously by identification of charcoal banding patterns (see e.g. Ohlson et al., 2006; Talon et al., 2005). Experimental burns have demonstrated that macroscopic charcoal produced in one single fire event is distributed very unevenly within the burn area and that single sample points even may lack macroscopic charcoal completely (Ohlson and Tryterud, 2000). Even though these results originate from forest fires, the factors responsible for creating this pattern can probably be transferred to peatland fires. The production of charred particles depends on the availability of fuel and the degree to which it is consumed (Clark et al., 1998). The presence and distribution of macroscopic charcoal in the peat will thus depend on the presence and distribution of woody vegetation on the peatland that can be converted to macroscopic charcoal, and to which degree the woody material is consumed by a fire. Moreover, this will be the case throughout the entire period of peat accumulation, stacking the different patterns of charcoal abundance on top of each other. In our study, all peat columns (n=20) contained traces of fire (measured as fire activity), but not all of them contained macroscopic charcoal. Ohlson et al. (2006) report that 16% of the peat columns in their study (n=247) lacked macroscopic charcoal and any visible traces of fire.

The fine scale variation in the amount of macroscopic charcoal discovered here demonstrates the necessity of studying multiple cores in order to obtain representative results per peat basin. In their study of vegetation dynamics in three peatlands in northwestern Québec, Canada, Magnan et al. (2012) recorded the amount of macroscopic charcoal per cm³ in only one peat column per peatland. The peak amounts measured in that study were higher than ours (442 g/m² in a single sample compared with 177 g/m² in our study (P43, at 1.04 m depth)). A rough estimate on the basis of their graphs indicates that two of their peat columns contained about two to three times more charcoal than our peat column with the highest total amount (359 g/m², P35). Magnan

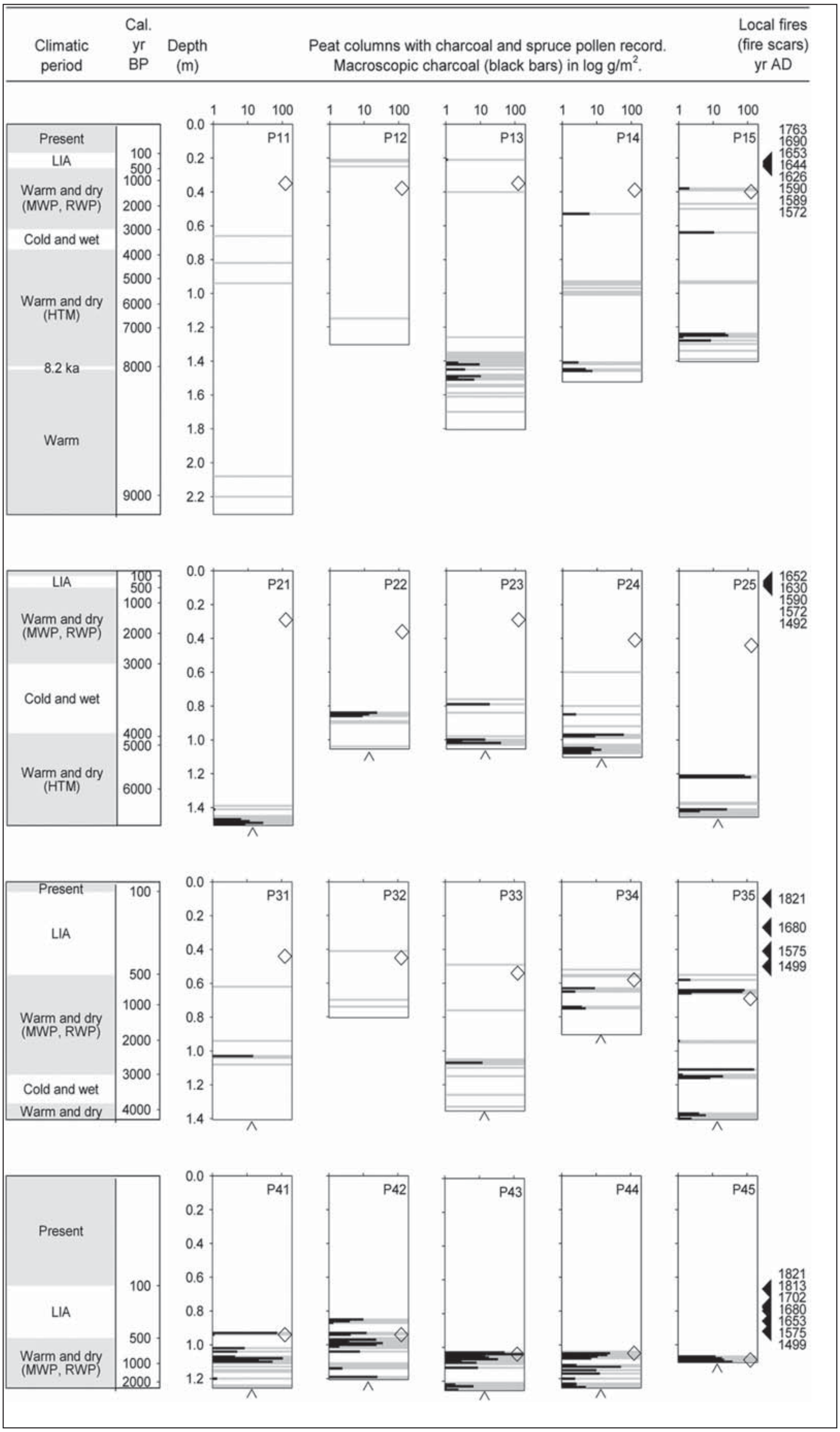

Figure 4. Peat charcoal record, local fire history (fire scars) and establishment of Norway spruce (*Picea abies*). The four panels represent the four sites with five peat columns each. Black bars: amount (mass) of macroscopic charcoal (note the log scale). Grey lines: fire activity, (for definition see section 'Material and methods'). The local establishment of spruce is indicated by the open diamond (position at P22 estimated from average for the site). Arrowheads at the bottom of peat columns mark that samples reached mineral soil. Cal. yr BP has been obtained through the age–depth models for the different sites. Local fires documented through the analysis of fire scars are indicated at the right hand side (yr AD). Climatic variation according to Seppä et al. (2009), LIA: 'Little Ice Age'; MWP: 'Medieval Warm Period'; RWP: 'Roman Warm Period'; HTM: 'Holocene Thermal Maximum'; '8.2 ka: 8.2 kiloyear cooling event'.

Table 4. Fire activity (see section 'Material and methods'), presence of macroscopic charcoal and fire activity in relation to climatic periods and spruce (*Picea abies*) establishment.

Site	Fire activity		Samples with macroscopic charcoal[a]		Spruce establishment				Climatic periods			
					Period before		Period after		Warm[c]		Cold[c]	
	Average	Average per 1000 yr	Average no.	Average no. per 1000 yr	Average part of total time span[b]	Average fire activity	Average fire activity per 1000 yr		Average part of total time span[b]	Average fire activity	Average fire activity	Average fire activity per 1000 yr
1	11.4 ± SD 7.3	1.3 ± SD 0.8	4.8 ± SD 4.2	0.6 ± SD 0.5	84%	10.2 (89%)	1.4 ± SD 1.0	0.9 ± SD 0.9	84%	10.2 (89%)	1.4 ± SD 1.1	0.9 ± SD 0.9
2	8.8 ± SD 2.6	1.5 ± SD 0.5	4.6 ± SD 1.5	0.8 ± SD 0.3	65%	8.8 (100%)	2.4 ± SD 0.9	0.0 ± SD 0.0	79%	6.4 (73%)	1.4 ± SD 0.7	2.0 ± SD 1.9
3	8.2 ± SD 4.7	2.8 ± SD 1.3	4.0 ± SD 5.4	1.3 ± SD 1.5	82%	6.2 (76%)	2.5 ± SD 0.9	3.6 ± SD 2.8	72%	6.4 (78%)	3.0 ± SD 1.2	2.5 ± SD 1.8
4	13.0 ± SD 5.5	6.5 ± SD 2.3	10.4 ± SD 4.2	5.3 ± SD 1.7	60%	10.2 (78%)	8.6 ± SD 2.0	4.5 ± SD 2.7	77%	11.6 (89%)	7.6 ± SD 1.2	3.5 ± SD 5.5
Sum							3.7 ± SD 3.2	2.2 ± SD 2.7			3.3 ± SD 2.8	2.2 ± SD 3.0

Notes:
[a]Macroscopic charcoal ≥ 0.1 mg per sample, samples with less were recorded as fire activity only.
[b]Part of the total time span covered by peat column which corresponds to the given period.Average per site.
[c]Definition of warm and cold climatic periods: see section 'Material and methods'.

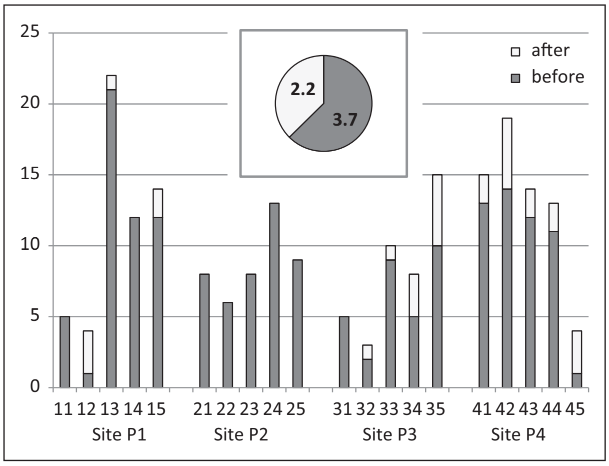

Figure 5. Fire activity (for definition see section 'Material and methods') pre- and post-spruce (*Picea abies*) establishment. Columns show the number of fire activity records per peat column. Pie chart shows fire activity rates (per 1000 yr).

et al. (2012) mention that higher abundances of trees and greater proximity to forested mineral soils caused higher values and thus were important factors responsible for variation in their data.

In our study, too, the placement of the blocks of samples in the mires may have played a role. The rates (g/m² and 1000 yr) were calculated in order to account for this problem when describing variation. The range of distances between the sample sites and the mineral soil in our study was only a few tens of metres, and on that scale the distance to the mineral soil and the amounts of charcoal was not positively related, i.e. sites with the shorter distance to the mineral soil did not contain higher amounts of charcoal. Moreover, the onset of peat genesis is a site-specific feature (Weckström et al., 2010), and as the comparison of sites P1 and P4 shows, the oldest mire did not necessarily contain most charcoal. Here, it should also be noted that those sites are minerotrophic fens, in which an inflow of water-transported organic matter and relative high decomposition rates may have impacted on the radiocarbon age of the peat as well as the preservation of pollen and charcoal in the peat. However, the present inflow of minerogenic water in both sites is small.

No correspondence between the amounts of charcoal in peat and mineral soil

We expected to find more soil charcoal in fertile sites with presence of spruce and dense forests, but this was not the case. Forest density was higher at the spru+ce-forest locations, but the amounts of charcoal in peat and mineral soil varied independently of that. Neither our data on fire activity nor the number of fires during the period covered by the tree-ring analysis corresponded with the variation in the amounts of charcoal. Only at site P4, the high amount of charcoal in the peat corresponded with higher fire activity and high forest density (both peat and soil). However, the average amount of charcoal in the mineral soil at that site was the lowest measured in this study. Clearly, other factors not covered by our investigations are responsible for creating the observed variation. These may include loss through oxidative degradation (Ascough et al., 2011; Hockaday et al., 2006), consumption by fire (Kane et al., 2010; Ohlson, 2012), the shifting amounts and quality of fuel (composition and flammability of the vegetation) over time, as well as hydrology in case of the mires. Peatlands have often been considered as fuel breaks (Hellberg et al., 2004; Hörnberg et al., 1995; Magnan et al., 2012; Tolonen, 1983), which means that a fire in the adjacent forest not necessarily extends into the mire or burns over

Table 5. Amounts of macroscopic charcoal (≥ 0.1 mg per sample) in peat and mineral soil.

Site	Peat			Average amount of macroscopic charcoal (g/m^2) accumulated in certain periods							Soil	
	Average amount of macroscopic charcoal (g/m^2)	Average amount of macroscopic charcoal (g/m^2) per 1000 yr	Basal area (m^2/ha)	Before spruce establish-ment	Average amount per 1000 yr: *Before spruce establishment*	Average amount per 1000 yr: *After spruce establishment*	During warm climatic periods	Average amount per 1000 yr: *During warm climatic periods*	Average amount per 1000 yr: *During cold climatic periods*	*During period covered by tree ring analysis*	Average amount of macroscopic charcoal (g/m^2)	Average basal area (m^2/ha)
1	26 ± SD 29	3 ± SD 4	5	25 (96%)	4 ± SD 4	0.8 ± SD 0.8	23 (89%)	4 ± SD 4	20 ± SD 24	0.8 ± SD 1.2	329 ± SD 427	15 ± SD 4
2	100 ± SD 74	17 ± SD 12	2	100 (100%)	27 ± SD 20	0 ± SD 0	87 (87%)	21 ± SD 14	84 ± SD 62	0	204 ± SD 263	10 ± SD 0.8
3	81 ± SD 155	21 ± SD 36	1	49 (60%)	16 ± SD 24	43 ± SD 94	76 (93%)	29 ± SD 51	75 ± SD 127	0	411 ± SD 555	10 ± SD 4
4	200 ± SD 100	101 ± SD 31	16	118 (59%)	151 ± SD 145	127 ± SD 128	179 (89%)	132 ± SD 39	501 ± SD 249	3 ± SD 7	131 ± SD 244	19 ± SD 6
Sum	102 ± SD 113				49 ± SD 91	43 ± SD 90		47 ± SD 60	170 ± SD 238		269 ± SD 402	

Notes:
Values in parentheses: percentage of the avarage amount of macroscopic charcoal on the respective site. Site indicates the number of peat sample site (P1–4) for peat samples and the corresponding soil sample sites (S1–4) on the adjacent mineral soils.

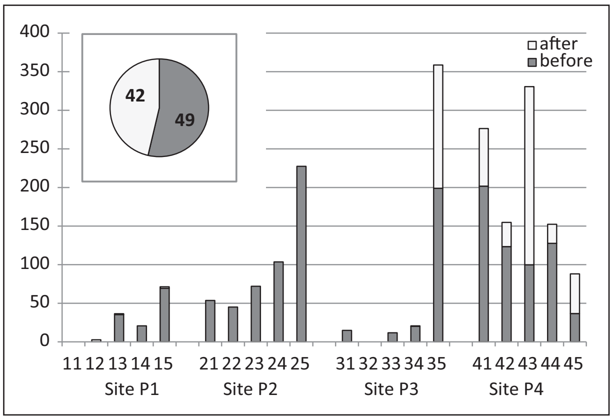

Figure 6. Macroscopic charcoal per peat column, pre- and post-spruce (*Picea abies*) establishment. Columns show the amount of macroscopic charcoal (g/m^2) per peat column. Pie chart shows charcoal accumulation rates (g/m^2 and 1000 yr).

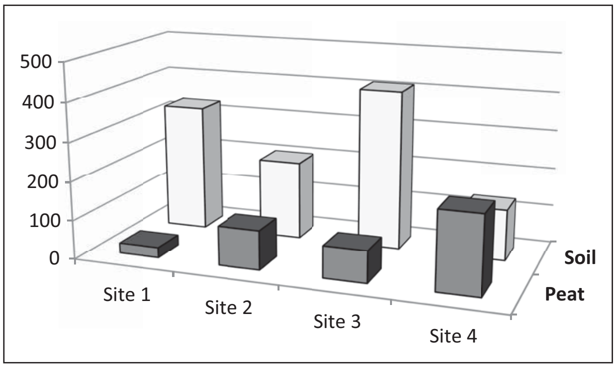

Figure 7. Macroscopic charcoal (g/m^2), average per site in peat and mineral soil.

the entire peat surface. On the other hand, Bradshaw et al. (1997) present indications for considerable amounts of peat being lost in recurrent fires in Finland. It is possible that hiatuses in the age–depth curves in this study represent such events. Charcoal preservation in peat soil may be higher under cold and wet conditions, but on the other hand it seems less likely that fires affect peatbogs under such conditions and produce charcoal. It has also to be mentioned that the difference in the total area sampled between peat and mineral soil (20 × 4.5 cm^2 and 100 × 26.4 cm^2, respectively) may have influenced our results. The much smaller area that is represented by the peat samples opens for variation in the results. However, our multiple sample design in the peat soil ensures a reasonable reliability for capturing variation, but the precision of the estimated amount of charcoal is higher for the mineral soil samples than for the peat samples in this study.

Data from tree ring and peat analysis complement each other

The correspondence between the charcoal record in the peat and in the tree ring data for the time span where they overlap was rather vague. The fires in 1499 and 1575 were most likely documented in the peat (at site P3 and P4), and only at site P1 there might be traces of later fires. One possible explanation for this can be found in the historic data on human land use in the area. In 1490, the national council ordered every farmer to burn and sow rye on an area of 0.1 ha every year (Tveite, 1964). This was a period with low population, and the forest was encroaching the crop land. In 1667 the population had increased, and the land register recorded that the farm owners only had timber for fencing and firewood (Mørck, 1954). Hence, there might not have been enough fuel to produce large enough amounts of macroscopic charcoal to be detected. Furthermore, distances to the mire edges at the time of fire may have played a role, and different peat accumulation rates at the sites may have influenced the results. Higuera et al. (2005) compared the charcoal record from small-hollow sediments with the tree-ring record of fire, and concluded that the detection of a fire in the sediment may depend strongly on fine-scale spatial patterns of burning, and that many moderate- and low-severity fires may be missed. Even though their study was based on a single sediment core per site, they found that high-severity fires were accurately displayed by the charcoal record in the soil sediments. However, high-severity fires are not common in Fennoscandia (Zackrisson, 1977; Zackrisson and Östlund, 1991), and a possible reason for why the fire records in the peat and the tree ring data did not show the same pattern in our study may be that the macroscopic charcoal record in the peat samples does not reveal low-severity fires. Here it should also be noted that a lack of macroscopic charcoal in a soil or peat sample is not a solid evidence for local absence of fire as Ohlson and Tryterud (2000) showed that the probability that a charcoal-trap in a burnt forest would lack charcoal ≥ 0.5 mm is about 14% (see also Ohlson et al., 2006). It is nonetheless likely that the match between charcoal and tree ring data would have been better if we had included smaller fractions of the macroscopic charcoal record, i.e. sizes down to 0.15 mm wide, in our analysis (Higuera et al., 2005).

Niklasson et al. (1998) found two matching absence-presence records of fire in tree ring data and a single 63 cm core from a peat hollow in N Sweden. The authors concluded that this combination of methods has great potential for high resolution studies in fire and vegetation history. Although there were discrepancies between the peat and tree ring data in our study, it is obvious that the two methods complement each other. Only the tree ring analysis provides proof of recent fires, but the archive in the peat provides information about the fire history at a scale of millennia.

Variation at different temporal scales

The importance of looking at variation not only at different scales in space but also in time became clear when we involved information about major shifts in vegetation composition (i.e. the establishment of spruce) and climate throughout the Holocene. Although most of the macroscopic charcoal was found in peat sequences temporally coinciding with the period before the establishment of spruce, as has been shown to be a general pattern in the NW European boreal forests (Ohlson et al., 2011), the difference in accumulation rates (per 1000 years) between pre- and post-spruce establishment periods in our data was negligible and the rates varied across sites. This emphasizes the need for stand-scale data on vegetation history and a regional-study scale if these relationships are to be studied in detail. It must also be mentioned that the successively greater distances between the sampling points and the mire edges throughout time may lead to a slight underestimation of the amounts of charcoal produced in the more recent post-spruce period.

The spread in our data for the timing of the local establishment of spruce express pollen-analytical challenges such as discussed by Hafsten (1992). He pointed out that not only the distance to the nearest spruce forest, but also factors such as forest density and composition prior to spruce establishment, play an important role for when a given site displays a marked rise in the spruce-pollen percentage. In our case, topography might also be part of the reason why spruce establishment was documented later at the western sites upslope (on average 524 and 601 cal. yr BP) than at the eastern sites (on average 1274 and 1950 cal. yr BP). Our dates for spruce establishment corresponded with those of Hafsten (1992), who dated the establishment of spruce in the district to 1315–750 yr BP (three sites located about 15–25 km from our study area).

Fire activity rates in this study were similar in warm and cold climatic periods, although most of the fire activity recordings were found in peat sequences corresponding to warm climatic periods. This corroborates the findings of Greisman and Gaillard (2009) who documented higher fire activity during these periods in southern Sweden. However, Pitkänen et al. (2002) reported a decrease in fire frequency during the warmer period between 9000 cal. yr BP and 6300 cal. yr BP. in their study of a mire in eastern Finland. In our study the average charcoal mass accumulation rate was lower during warm climatic periods than during cold, even though the average fire activity rate during these periods was similar. This suggests that high fire activity (and possibly more frequent fires) is not necessarily coupled with the deposition of large amounts of charcoal (larger amounts of charcoal may be produced during possibly fewer fire events), or possibly that cold climatic periods improve charcoal preservation in the peat. Causal explanations will remain open to speculation.

Authors which included the regional spatial scale in their studies have pointed out that changes in vegetation composition can override the effect of climate change at local and regional scales (Campbell and Campbell, 2000; Campbell and Flannigan, 2000; Ohlson et al., 2011). Moreover, the relative importance of climatic and local controls over fire occurrence may shift over time (Gavin et al., 2006). This may lead to different fire histories at neighboring sites that are similar in modern vegetation, climate and fire regime. It was not the objective of the present study to analyse relationships and interactions between these drivers in detail. Among others, more specific data on Holocene climate variability for the region would be needed. Holocene climate variability is still subject for discussion (see e.g. Helama et al., 2012), and the use of delimited climatic periods in this study implies approximations.

While there was no correspondence between the present types and densities of surrounding forest and the total amounts of charcoal in the peat (covering time spans of millennia), there was an indicative correspondence with the amounts of charcoal accumulated in the peat during the period covered by the dendrochronological analysis, i.e. the last 650 years. Forest density was high at the two spruce forest sites compared with the pine forest sites, and only at the spruce forest sites we found measurable amounts of macroscopic charcoal in the peat from this period.

Conclusion

This study documents a high degree of variation in the fire and charcoal record in a boreal landscape across peat and mineral soils at different temporal and spatial scales. The charcoal pools in peat and soil have to be seen as the result of the concert of controls operating at different temporal and spatial scales throughout millennia. Our results stress the variable nature of the charcoal record in boreal forests and show that multiple sampling is essential to estimate the amount of charcoal or to reveal the fire history of a given peatland or forest landscape. Different drivers influence the charcoal pools in peat and mineral soil and cause variation across the two types of archives at spatial scales of 10–100 m. When estimating the amount of charcoal (and carbon stored in it) in a forest landscape, we cannot conclude about the size of the charcoal pool in one archive through knowledge about the other. The comparison of methods used to reconstruct fire history from the different archives further supports this finding. For this purpose, dendrochronological and charcoal-based approaches complement each other, and cannot substitute one for another.

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References

Agee JK (1993) *Fire Ecology of Pacific Northwest Forests*. Washington DC: Island Press.

Apps MJ and Price DT (1996) *Forest Ecosystems, Forest Management and the Global Carbon Cycle*. Berlin: Springer-Verlag, 452 pp.

Arno SF and Sneck KM (1977) A method for determining fire history in coniferous forests of the mountain west. In: USDA Forest Service (ed.) *General Technical Report*. Ogden UT: Intermountain Forest and Range Experiment Station, 35 pp.

Ascough PL, Bird MI, Francis SM et al. (2011) Variability in oxidative degradation of charcoal: Influence of production conditions and environmental exposure. *Geochimica et Cosmochimica Acta* 75: 2361–2378.

Attiwill PM (1994) The disturbance of forest ecosystems: The ecological basis for conservative management. *Forest Ecology and Management* 63: 247–300.

Balshi MS, McGuire AD, Zhuang Q et al. (2007) The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: A process-based analysis. *Journal of Geophysical Research* 112: G02029.

Berglund BE and Ralska-Jasiewiczowa M (1986) Pollen analysis and pollen diagrams. In: Berglund BE (ed.) *Handbook of Holocene Palaeoecology and Palaehydrology*. Chichester: John Wiley & Sons Ltd, pp. 455–484.

Blaauw M (2010) Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology* 5: 512–518.

Bradshaw R, Tolonen K and Tolonen M (1997) Holocene records of fire from the boreal and temperate zones of Europe. In: Clark J, Cachier H, Goldammer JG and et al. (eds) *Sediment Records of Biomass Burning and Global Change*. Berlin, Heidelberg: Springer, pp. 347–365.

Briles CE, Whitlock C, Bartlein PJ et al. (2008) Regional and local controls on postglacial vegetation and fire in the Siskiyou Mountains, northern California, USA. *Palaeogeography, Palaeoclimatology, Palaeoecology* 265: 159–169.

Campbell ID and Campbell C (2000) Late Holocene vegetation and fire history at the southern boreal forest margin in Alberta, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164: 263–280.

Campbell ID and Flannigan MD (2000) Long-term perspectives on fire–climate–vegetation relationships in the north American boreal forest. In: Kasischke E and Stocks BJ (eds) *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*. New York: Springer-Verlag, pp. 151–172.

Carcaillet C, Almquist H, Asnong H et al. (2002) Holocene biomass burning and global dynamics of the carbon cycle. *Chemosphere* 49: 845–863.

Carcaillet C, Bouvier M, Fréchette B et al. (2001) Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. *The Holocene* 11: 467–476.

Charman DJ, Aravena R and Warner B (1992) Isotope geochemistry of gas and water samples from deep peats in Boreal Canada. *Suo Mires Peat* 43: 199–201.

Clark JS (1988) Particle motion and the theory of charcoal analysis – Source area, transport, deposition, and sampling. *Quaternary Research* 30: 67–80.

Clark JS, Lynch J, Stocks BJ et al. (1998) Relationships between charcoal particles in air and sediments in west-central Siberia. *The Holocene* 8: 19–29.

Conard SG and Ivanova GA (1997) Wildfire in Russian boreal forests – Potential impacts of fire regime characteristics on emissions and global carbon balance estimates. *Environmental Pollution* 98: 303–313.

Conard SG and Solomon AM (2009) Effects of wildland fire on regional and global carbon stocks in a changing environment. In: Bytnerowicz A, Arbaugh MJ, Riebau AR and et al. (eds) *Wild Land Fires and Air Pollution*. Amsterdam: Elsevier, pp. 109–138.

Cyr D, Gauthier S and Bergeron Y (2007) Scale-dependent determinants of heterogeneity in fire frequency in a coniferous boreal forest of eastern Canada. *Landscape Ecology* 22: 1325–1339.

Gavin DG, Brubaker LB and Lertzman KP (2003a) An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. *Canadian Journal of Forest Research* 33: 573–586.

Gavin DG, Brubaker LB and Lertzman KP (2003b) Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. *Ecology* 84: 186–201.

Gavin DG, Hu FS, Lertzman K et al. (2006) Weak climatic control of stand-scale fire history during the late Holocene. *Ecology* 87: 1722–1732.

Goldammer JG and Furyaev VV (1996) Fire in ecosystems of boreal Eurasia: Ecological impacts and links to the global system. In: Goldammer JG and Furyaev VV (eds) *Fire in Ecosystems of Boreal Eurasia*. Dordrecht: Kluwer, pp. 1–20.

Gorham E (1991) Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications* 1: 182–195.

Greisman A and Gaillard M-J (2009) The role of climate variability and fire in early and mid Holocene forest dynamics of southern Sweden. *Journal of Quaternary Science* 24: 593–611.

Hafsten U (1992) The immigration and spread of Norway spruce (*Picea abies* (L.) Karst.) in Norway. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography* 46: 121–158.

Helama S, Seppä H, Bjune A et al. (2012) Fusing pollen-stratigraphic and dendroclimatic proxy data to reconstruct summer temperature variability during the past 7.5 ka in subarctic Fennoscandia. *Journal of Paleolimnology* 48: 275–286.

Hellberg E, Niklasson M and Granström A (2004) Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. *Canadian Journal of Forest Research* 34: 332–338.

Heyerdahl EK, Brubaker LB and Agee JK (2001) Spatial controls of historical fire regimes: A multiscale example from the interior West, USA. *Ecology* 82: 660–678.

Higuera PE, Peters ME, Brubaker LB et al. (2007) Understanding the origin and analysis of sediment-charcoal records with a simulation model. *Quaternary Science Reviews* 26: 1790–1809.

Higuera PE, Sprugel DG and Brubaker LB (2005) Reconstructing fire regimes with charcoal from small-hollow sediments: A calibration with tree-ring records of fire. *The Holocene* 15: 238–251.

Hockaday WC, Grannas AM, Kim S et al. (2006) Direct molecular evidence for the degradation and mobility of black carbon in soils from ultrahigh-resolution mass spectral analysis of dissolved organic matter from a fire-impacted forest soil. *Organic Geochemistry* 37: 501–510.

Holmes RL (1983) Computer-assisted quality control in tree-ring dating and mesurement. *Tree-ring Bulletin* 43: 69–78.

Holmes RL (1994) *Dendrochronology Program Library. Users Manual*. Tucson AZ: Laboratory of Tree-Ring Research, University of Arizona.

Hörnberg G, Ohlson M and Zackrisson O (1995) Stand dynamics, regeneration patterns and long-term continuity in boreal old-growth *Picea abies* swamp-forests. *Journal of Vegetation Science* 6: 291–298.

Iniguez JM, Swetnam TW and Yool SR (2008) Topography affected landscape fire history patterns in southern Arizona, USA. *Forest Ecology and Management* 256: 295–303.

Innes JB and Simmons IG (2000) Mid-Holocene charcoal stratigraphy, fire history and palaeoecology at North Gill, North York Moors, UK. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164: 151–165.

Innes JL, Beniston M and Verstraete MM (2000) *Biomass Burning and its Inter-relationships with the Climate System*. Dordrecht: Kluwer Academic Publishers.

Innes JB, Blackford JJ and Simmons IG (2004) Testing the integrity of fine spatial resolution palaeoecological records: Microcharcoal data from near-duplicate peat profiles from the North York Moors, UK. *Palaeogeography, Palaeoclimatology, Palaeoecology* 214: 295–307.

Johnson EA (1992) *Fire and Vegetation Dynamics: Studies from the North American Boreal Forest*. Cambridge: Cambridge University Press.

Jowsey PC (1966) An improved peat sampler. *New Phytologist* 65: 245–248.

Kane E, Hockaday W, Turetsky M et al. (2010) Topographic controls on black carbon accumulation in Alaskan black spruce forest soils: Implications for organic matter dynamics. *Biogeochemistry* 100: 39–56.

Kasischke ES and Stocks BJ (2000) *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*. New York: Springer, 461 pp.

Keane RE, Parsons R and Rollins MG (2004) Predicting fire regimes across multiple scales. In: Perera AH, Buse LJ and Weber MG (eds) *Emulating Forest Landscape Natural Disturbances: Concepts and Applications*. Cambridge: Cambridge University Press, pp. 55–68.

Kuhlbusch TAJ and Crutzen PJ (1996) Black carbon, the global carbon cycle, and atmospheric carbon dioxide. In: Levine JS (ed.) *Biomass Burning and Global Change*. Cambridge MA: MIT Press, pp. 160–169.

Lehmann J, Skjemstad J, Sohi S et al. (2008) Australian climate–carbon cycle feedback reduced by soil black carbon. *Nature Geoscience* 1: 832–835.

Lid J and Lid DT (2005) *Norsk Flora*. Oslo: Samlaget.

Magnan G, Lavoie M and Payette S (2012) Impact of fire on long-term vegetation dynamics of ombrotrophic peatlands in northwestern Québec, Canada. *Quaternary Research* 77: 110–121.

Mehringer PJ Jr, Arno SF and Petersen KL (1977) Postglacial history of Lost Trail Pass Bog, Bitterroot Mountains, Montana. *Arctic and Alpine Research* 9: 345–368.

Moen A (1999) *National Atlas of Norway – Vegetation*. Hønefoss: Norwegian Mapping Authority.

Mørck A (1954) *Sigdal og Eggedal. Bind III. Gård og slekt*. Drammen: Sigdal og Eggedal historielag.

Nesje A (2009) Latest Pleistocene and Holocene alpine glacier fluctuations in Scandinavia. *Quaternary Science Reviews* 28: 2119–2136.

Nesje A, Bakke J, Dahl SO et al. (2008) Norwegian mountain glaciers in the past, present and future. *Global and Planetary Change* 60: 10–27.

Niklasson M, Hörnberg G and Zackrisson O (1998) *Age structure and disturbance history in a boreal* Pinus-Picea *forest, N. Sweden*. Silvestria 52, Doctoral thesis. Umeå: Swedish University of Agricultural Sciences, 14.

Niklasson M, Zackrisson O and Östlund L (1994) A dendroecological reconstruction of use by Saami of Scots Pine (*Pinus sylvestris* L.) inner bark over the last 350 years at Sädvajaure, N. Sweden. *Vegetation History and Archaeobotany* 3: 183–190.

Norwegian Meteorological Institute (2012) *Daily and Monthly Normal Values, Normal Period 1961–1990, Mean Temperature, Rollag Meteorological Station*. Available at: www.met.no.

Ohlson M (2012) Soil charcoal stability over the Holocene – Comment to the paper published by de Lafontaine and Asselin, Quaternary Research, v. 76, 2011, pp. 196–200. *Quaternary Research* 76: 196–200.

Ohlson M and Tryterud E (2000) Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10: 519–525.

Ohlson M, Brown KJ, Birks HJB et al. (2011) Invasion of Norway spruce diversifies the fire regime in boreal European forests. *Journal of Ecology* 99: 395–403.

Ohlson M, Dahlberg B, Okland T et al. (2009) The charcoal carbon pool in boreal forest soils. *Nature Geoscience* 2: 692–695.

Ohlson M, Korbøl A and Økland RH (2006) The macroscopic charcoal record in forested boreal peatlands in southeast Norway. *The Holocene* 16: 731–741.

Økland RH and Ohlson M (1998) Age–depth relationships in Scandinavian surface peat: A quantitative analysis. *Oikos* 82: 29–36.

Patterson WA, Edwards KJ and Maguire DJ (1987) Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6: 3–23.

Pinheiro J, Bates D, DebRoy S et al. (2011) *nlme: Linear and Nonlinear Mixed Effects Models*. R package version 3.1–98 ed.

Pitkänen A, Huttunen P, Jungner H et al. (2003) Holocene fire history of middle boreal pine forest sites in eastern Finland. *Annales Botanici Fennici* 40: 15–33.

Pitkänen A, Huttunen P, Jungner H et al. (2002) A 10 000 year local forest fire history in a dry heath forest site in eastern Finland, reconstructed from charcoal layer records of a small mire. *Canadian Journal of Forest Research* 32: 1875–1880.

Pitkänen A, Lehtonen H and Huttunen P (1999) Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: Evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. *The Holocene* 9: 559–567.

Pitkänen A, Tolonen K and Jungner H (2001) A basin-based approach to the long-term history of forest fires as determined from peat strata. *The Holocene* 11: 599–605.

Preston CM (2009) Fire's black legacy. *Nature Geoscience* 2: 674–675.

Preston CM and Schmidt MWI (2006) Black (pyrogenic) carbon: A synthesis of current knowledge and uncertainties with special consideration of boreal regions. *Biogeosciences* 3: 397–420.

R Development Core Team (2011) *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Saarinen T (1996) Biomass and production of two vascular plants in a boreal mesotrophic fen. *Canadian Journal of Botany* 74: 934–938.

Schmidt MWI and Noack AG (2000) Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Global Biogeochemical Cycles* 14: 777–793.

Seppä H, Birks HJB, Bjune AE et al. (2010) Current continental palaeoclimatic research in the Nordic region (100 years since Gunnar Andersson 1909) – Introduction. *Boreas* 39: 649–654.

Seppä H, Bjune AE, Telford RJ et al. (2009) Last nine-thousand years of temperature variability in Northern Europe. *Climate of the Past* 5: 523–535.

Storaunet KO, Rolstad J, Toeneiet M et al. (2013) Strong anthropogenic signal in historic forest fire regime: A detailed spatio-temporal case study from south-central Norway. *Canadian Journal of Forest Research* in press.

Stuiver M and Reimer PJ (1993) Extended ^{14}C data base and revised CALIB 3.0 14C age calibration program. *Radiocarbon* 35: 215–230.

Swetnam TW (1993) Fire history and climate change in Giant Sequoia Groves. *Science* 262: 885–889.

Talon B, Payette S, Fillon L et al. (2005) Reconstruction of the long-term fire history of an old-growth deciduous forest in Southern Quebec, Canada, from charred wood in mineral soils. *Quaternary Research* 64: 36–43.

Tinner W, Conedera M, Ammann B et al. (1998) Pollen and charcoal in lake sediments compared with historically documented forest fires in southern Switzerland since AD 1920. *The Holocene* 8: 31–42.

Tolonen K (1983) The post-glacial fire record. In: Wein RW and McLean DA (eds) *The Role of Fire in Northern Circumpolar Ecosystems*. Chichester: John Wiley and Sons, pp. 21–44.

Tolonen K, Possnert G, Jungner H et al. (1992) High resolution ^{14}C dating of surface peat using the AMS technique. *Suo Mires Peat* 43: 271–275.

Touflan P and Talon B (2009) Spatial reliability of soil charcoal analysis: The case of subalpine forest soils. *Ecoscience* 16: 23–27.

Tveite S (1964) Skogbrukshistorie. In: Seip HK (ed.) *Skogbruksboka 3*. Oslo: Skogforlaget, pp. 17–76.

Weckström J, Seppä H and Korhola A (2010) Climatic influence on peatland formation and lateral expansion in sub-arctic Fennoscandia. *Boreas* 39: 761–769.

Whitlock C and Millspaugh SH (1996) Testing the assumptions of fire history studies: An examination of modern charcoal accumulation in Yellowstone National Park, USA. *The Holocene* 6: 7–15.

Zackrisson O (1977) Influence of forest fires on the north Swedish boreal forest. *Oikos* 29: 22–32.

Zackrisson O and Östlund L (1991) Branden formade skogslandskapets mosaik. *Skog & Forskning* 4/1991: 13–21.

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