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Fire history in a western Fennoscandian boreal forest as influenced by human land use and climate

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Abstract. Knowing the historical variation in fire regimes is instrumental in managing forests today and in predicting what may happen in the future. By cross-dating 745 fire scars in 378 samples of remnant Scots pines, we delineated 254 individual forest fires during the past 700 years in a 74-km^2 section of Trillemarka-Rollagsfjell Nature Reserve in south-central Norway. Fire sizes, numbers, burn rates, and frequencies were compared with historical climate proxies, vegetation maps, and written sources. The results revealed patterns consistent with a predominantly climate-driven fire regime up to 1625, followed by periods of strong anthropogenic influence that increased fire frequency during 1600–1700s and diminished fires during 1800–1900s. This was documented by an abrupt increase in number of small fires from the early 1600s that markedly shortened fire intervals from a median of 73 to 37 yr. This shift in fire frequency coincided with a sudden appearance of early-season fires from 1625 and onward. Whereas late-season burn rate increased with summer temperature, no such relationship was found for early-season fires. These results were corroborated by written sources that describe 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 1700–1800s. Whereas human activity strongly influenced the fire regime at multidecadal to centennial scales, it was the interannual variability in climate that triggered large fire events, especially during the pre-1625 period. Prior to 1625, the percentage of years with fire tripled from 7% during cold summers (10–12°C) to 21% during warm summers (14–16°C). Burn rate increased even more, from 0.01% to 1.3% for the same temperature intervals. Ecologically, the post-1625 period is remarkable in such a way that human activity, first by greatly increasing fire frequency and subsequently almost eradicating fires, possibly influenced the fire regime to such an extent that it may be unprecedented for millennia.

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

Introduction

Fire is a major natural disturbance agent playing a significant role in the carbon dynamics of boreal forests (Heinselman 1973, Zackrisson 1977, Payette 1992, Kasischke and Stocks 2000, Bond-Lamberty et al. 2007). Fires of variable severity create mosaics of burned and unburned areas, affect the species composition and age-class distribution of forest stands, thereby enhancing spatial heterogeneity (Johnstone and Chapin 2006, Kuuluvainen 2009). Fire opens up the forest canopy and releases nutrients, benefits forest regeneration, and creates structural elements such as charcoal and charred and decaying wood that are important for biodiversity both above and below the forest floor (Esseen et al. 1997, Wardle et al. 1998, Granström 2001). Thus, fire is a vital part of forest ecosystems and in many ways important for creating the structural complexity that promotes biodiversity in boreal forests (Wardle et al. 2004, 2012, Peltzer et al. 2010). On the other hand, high-severity fires can be detrimental and possess a major threat to human settlements and forest industry. Each year wildfires destroy millions of hectares of forest, cost society large amounts in firefighting expenses, and cause loss of lives and recreational value (Stephens et al. 2014). In Canada alone, a yearly average of 8600 wildland fires, covering 2.5 million hectares of forest and woodland, have occurred over the past three decades with an annual cost for suppression and fire management exceeding 500 million Canadian dollars (Taylor et al. 2006). Thus, sustainable management of fire-prone ecosystems calls for a trade-off between the ecological benefits and the socioeconomical costs.

Knowing the historical variation in fire regimes is instrumental in managing forests today and in predicting what may happen in the future (Morgan et al. 1994, Perera et al. 2004). Fire regime is used as a collective term to describe the overall spatial pattern, temporal

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frequency, and behavioral characteristics of fires confined to a certain spatiotemporally defined area. As such, fire regimes are dynamic, varying in response to certain drivers like climate, vegetation, and human activity. Early works on fire history sparked a simplified view that boreal forests generally were subject to devastating stand-replacing fires every 100 years or so, thereby legitimating modern clearcutting practice on a similar rotation basis (Mielikäinen and Hynynen 2003, Barker et al. 2014). However, since the classical works of Heinselman (1973) and Zackrisson (1977), knowledge about historical fire regimes of the boreal vegetation zone has increased tremendously (e.g., Lehtonen 1998, Niklasson and Granström 2000, Drobyshev et al. 2004, Wallenius et al. 2010, de Groot et al. 2013), gradually unveiling a more complex picture of the natural forest dynamics (Kuuluvainen 2009). To comprehend the future risk of wildfires we need to disclose the complex interaction between climate, vegetation, and human land use. Understanding how, and how much, the different fire characteristics respond to changes in these driving forces is imperative in predicting future fire regime scenarios.

Spatial variation in fire regime characteristics has been explained by responses to vegetation types or topographic breaks. In northern Sweden, Zackrisson (1977) found dry forests of Scots pine (*Pinus sylvestris* L.) to have burned more frequently (mean fire interval ~50 yr) than mesic forests of Norway spruce (*Picea abies* (L.) Karst.) (80–120 yr). Some spruce-dominated swamp forests seem to have escaped fire for more than 1000 yr (Ohlson and Tryterud 1999). Temporal responses to vegetation changes are not that easily studied, but based on macroscopic charcoal records in peat and humus cores, Ohlson et al. (2011) suggested that the late-Holocene invasion of Norway spruce, a new forest dominant in northern Europe, may have reduced wildfire activity at a subcontinental scale. Similar inferences from charcoal and pollen accumulation in lake sediments have also indicated that vegetation changes may have exerted important control on fire activity during mid- and late-Holocene (e.g., Higuera et al. 2009, Brown and Giesecke 2014). However, a general cause-effect problem that haunts many of these historical studies is whether it is changes in vegetation that induce changes in fire regime, or vice versa.

Fennoscandian dendroecological studies have produced rather strong evidence for anthropogenic influence on fire regime characteristics during more recent time, first by promoting fires by means of slash-and-burn cultivation and forest pasture burning during 1500–1800s, and later by suppressing fires due to increased value of timber resources (Lehtonen and Huttunen 1997, Niklasson and Granström 2000, Niklasson and Drakenberg 2001, Groven and Niklasson 2005, Storaunet et al. 2013). Similar patterns have been indicated for North American and Russian boreal forests, although the human activities responsible for the changes appear less discernable (Drobyshev et al. 2004, 2008, Wallenius 2011, Wallenius et al. 2011).

Several studies across the boreal zone have found a significant climate signal in long-term series of fire statistics, with summer temperature and precipitation being the driving forces (e.g., Gillett et al. 2004, Brown and Giesecke 2014, Drobyshev et al. 2014). This finding has received increasing interest on the background of recent projections of global warming, with increasing temperature predicted to be most pronounced at northern high latitudes (IPCC 2013). Studies from Canada and Alaska have indicated that burn rate (annual area burned) in this region may increase as much as two to three times above current values by the end of the 21th century (Flannigan et al. 2005, Balshi et al. 2009, Bergeron et al. 2010). In western and northern parts of Fennoscandia, this scenario may be less likely due to the strong influence of the North Atlantic Ocean with warmer climate possibly being accompanied by increased precipitation in the future (Hanssen-Bauer et al. 2003, Benestad 2011). Based on recent statistics during 1900s, Drobyshev et al. (2016) found indications that cold climate in northern Fennoscandia seems to be characterized by dry conditions favorable to years of regionally increased fire activity. Thus, increased temperature alone is not necessarily associated with increased burn rates (Lynch et al. 2004, Macias-Fauria and Johnson 2008, Girardin et al. 2009, Drobyshev et al. 2014, 2016).

Good historical estimates of numbers and sizes of fires may assist in separating the effects of climatic vs. human influence (Grissino-Mayer and Swetnam 2000, Niklasson and Granström 2000, Storaunet et al. 2013). However, common for many studies of fire history, especially in North America, is that they report only a few characteristics of the fire regime, most commonly the mean fire interval or its reciprocal, the fire cycle or rotation. This may be because North American fire regimes, as opposed to Eurasian, are more subject to stand-replacing fires (Payette 1992, Wooster and Zhang 2004, de Groot et al. 2013), which eradicate wood legacies of past fires (but see Wallenius et al. 2011). Since Eurasian fire regimes in general, and Fennoscandian regimes in particular, seem to be dominated by low to moderately severe fires, this region appears well suited for dendroecological reconstructions of past fire regimes.

Previously, we have reported a detailed account of historical fires in a small 3.6-km^2 section of the Trillemarka-Rollagsfjell Nature Reserve in south-central Norway, documenting a strong anthropogenic signal in the fire chronology from ca 1600 (Storaunet et al. 2013). However, the small size of this study area prevented unbiased estimates of fire sizes and meaningful assessment of possible influence of climate. In the present study, we expanded the study area 20-fold and intensively sampled fire-scarred material from a 74-km^2 landscape, surrounding the small one, covering an extended period of 700 yr. This allowed us to calculate fire recurrence intervals based on established power-law relationships that facilitates comparison with similar statistics from other study areas and regions (Malamud et al. 2005).

Furthermore, since the study of Niklasson and Granström (2000), seasonally resolved climate proxies, dating back as far as AD 1300, have now become available, thereby enabling us to infer climate relationships on a year-to-year basis for the whole study period.

Specifically, our objectives 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 use these spatiotemporal statistics to estimate fire regime characteristics, such as number and size of fires, burn rates (percentage of area annually burned), fire season, fire intervals, survival functions, and hazard rates, and (3) to relate variation in these characteristics to temporal changes in climate, spatial pattern of vegetation composition, and written history of anthropogenic activity, exploring their relative contributions and possible interactive influence as driving forces.

Material and Methods

Study area

The study area encompasses 74 km^2 of forested and mountainous land between the valleys of Sigdal and Numedal 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 section of the Trillemarka-Rollagsfjell Nature Reserve and 35.3 km^2 of neighboring private land. The reserve that was established in 2002 covers 148 km^2 altogether and it is one of a few large and relatively undisturbed forested areas remaining within the boreal zone of southwestern Fennoscandia. Nonetheless, many remains and traces of past anthropogenic activity exist, including cut stumps, old trails, and historic summer dairy farms (Storaunet et al. 2005). The area was chosen due to the presence of numerous remnants of fire scarred Scots pine, ensuring sufficient samples to be collected for dendrochronological dating and spatial delineation of fires. Today, such areas are hard to find due to extensive industrial harvesting. The boundaries were delineated to cover the whole range of forest types and topographic features between the two main valleys. The landscape is well representative of the mid-boreal forest of southwestern Fennoscandia, and it was judged large enough to encompass forest fires up to a few tens of square kilometers, but still manageable to be adequately sampled during a few field seasons. A detailed small-scale study (Appendix S2: Fig. S1) of the fire history emphasized that anthropogenic forest fires were common during the 1600–1700s (Storaunet et al. 2013). Today, the study area bears no signs of recent large fires, the last recorded fire >0.1 km^2 occurred more than 200 years ago in 1795.

The area belongs to the mid-boreal vegetation zone in the foothills southeast of the Scandes Mountains (Moen 1999). Present-day forests are dominated by two conifers, Scots pine and Norway spruce, and a few deciduous tree species represented by downy birch (*Betula pubescens* Ehrh.), rowan (*Sorbus aucuparia* L.), aspen (*Populus tremula* L.), gray alder (*Alnus incana* (L.) Moench), and goat willow (*Salix caprea* L.). The climate is intermediate oceanic and continental, characterized by rather long winters and short summers with average annual precipitation reaching 800–900 mm, of which one-third comes as rain during summer in June, July, and August (JJA). 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 monthly means varying from −4°C in January to 15°C in July (Norwegian Meteorological Institute; data *available online*).[4] Altitude covers 800 m from 100 m above sea level at the valley bottoms to 900 m above sea level at the mountain tops, but even though the area is below the regional tree line (~1000 m above sea level), most of the terrain above 800 m lacks closed-canopy forest stands and the mountain tops are 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 (Moen 1999) and three altitudinal zones: pine-dominated forest (48%), spruce-dominated forest (27%), mire (10%), and mountain (15%), with forest types and mires about equally distributed among low- (32%), mid- (34%), and high-elevation (35%) zones (Fig. 1; Appendix S1: Plates S1–S4 and Table S1). The pine-dominated forest (>50% Scots pine trees in upper canopy layer) occupies the nutrient-poor and dry sites and areas bordering larger mire systems. It is characterized 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, characterized by bilberry (*V. myrtillus*) but also various grass and herb species. Mires consist of treeless bogs >1 ha, mostly ombrotrophic in nature, and characterized 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 and scattered patches of stunted spruce trees. No larger patches of pure deciduous forest exist in the area.

Information about the historical use of the area by man was searched for in the National Archives of Norway, including juridical documents, diplomas, and old maps covering the reserve and its vicinity. More general knowledge about summer dairy farming and the historical use of fire was extracted from old agricultural textbooks and reports. A summary of this material is presented as supplementary material by Storaunet et al. (2013).

[4] eklima.met.no

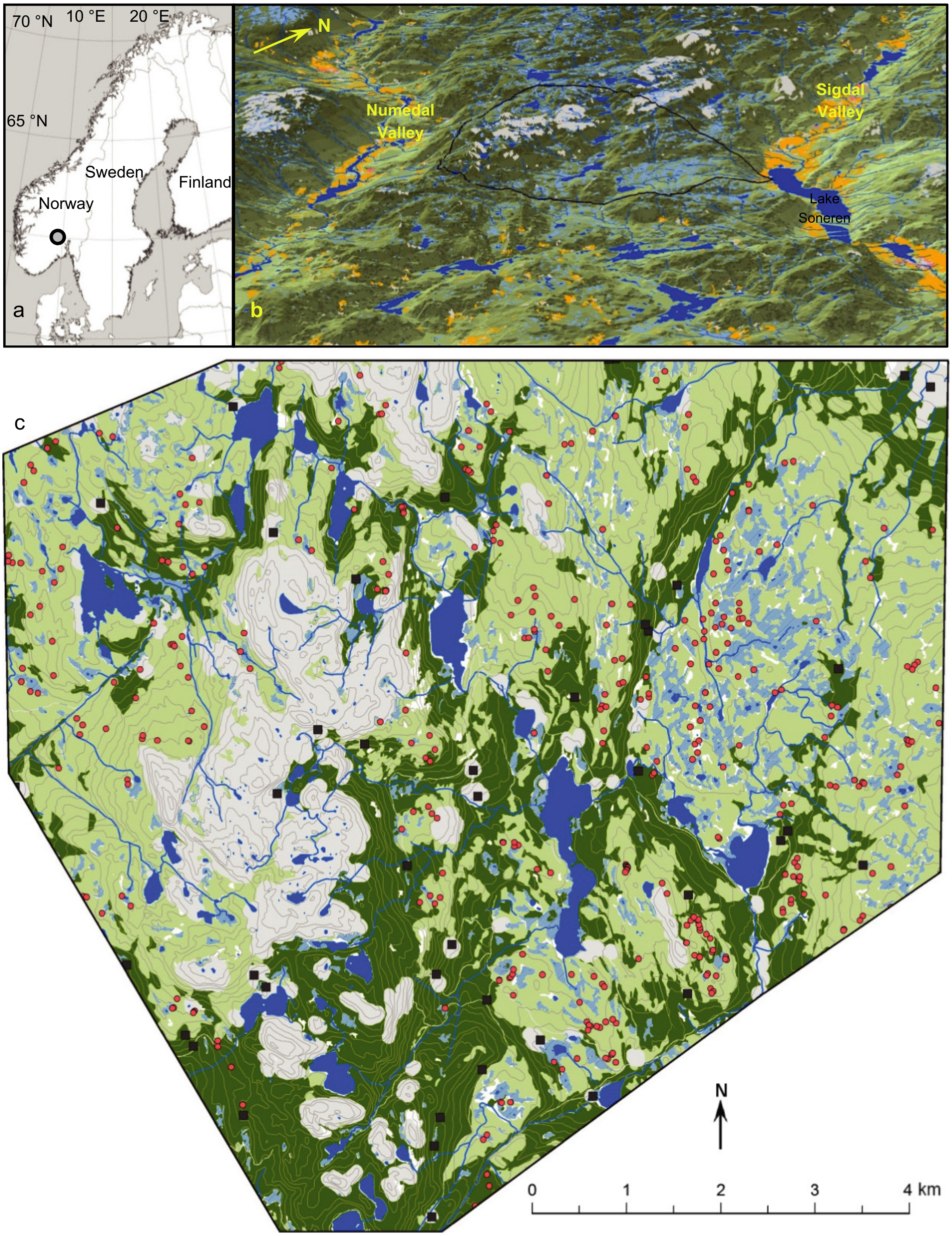

FIG. 1. (a) Location of study area (gray dot) within Fennoscandia. (b) Panoramic view showing the location of the study area (black outline) between the Numedal and Sigdal Valleys. Left-right distances are 22 and 28 km at bottom and top of the view, respectively. (c) Map of the 74 km^2 study area showing mountainous areas (white), open waters and creeks (solid blue), mires (hatched blue), pine-dominated forests (light green), spruce-dominated forests (dark green), successfully cross-dated wood samples (red dots), and summer dairy farms (black squares).

Sampling

Samples were collected during summer and fall of 2009 and 2010. Large areas of the mountains were barren land and rocky outcrops, although at some places, ground vegetation could have supported fires. Mires, on the other hand, had burned at varying frequencies, as documented from charcoal layers in sampled peat columns (Kasin et al. 2013). However, except for a few cases, e.g., 1499 and 1575, burned mires could not be directly connected to individual fires due to uncertainties in the ^{14}C dating of the charcoal layers. For the purpose of this study, we included mires in burned area if they were surrounded by forested land with fire-scarred trees. We excluded treeless mountainous areas and bodies of open water, reducing the area of sampling to 59 km^2.

At the outset, we divided our study area into a 1×1 km grid with a primary aim to collect five to six fire-scarred tree samples per 1-km square. Daily sampling routes were planned in such a way that all 1-km squares were visited at least once and searched for samples. Sampling routes were traversed by one to three persons searching for fire-scarred material. Survey persons walked 20–30 m apart and effectively discovered wood legacies 15 m to each side. To estimate *recording area* we included a survey area on each side of our GPS tracklogs using widths of 30, 50, and 70 m when we were one, two, or three persons, respectively. In total, the recording area covered 38% of the total forest and mire area (Appendix S2: Fig. S1). In 1-km squares with high density of fire-scarred material, samples with numerous visible fire scars were given priority. In other squares, sampling was impeded due to lack of available fire-scarred material, especially in spruce-dominated forests and at higher elevations. Ten of the 1-km squares (~13%) had no samples, of which half were mostly barren mountains. Mean number of samples in the other squares was 7.0 (range 1–22).

Using a chainsaw, samples were collected on average 0.4 m above ground from fire-scarred material of stumps, snags, downed logs and living trees of Scots pine (Arno and Sneck 1977, McBride 1983). 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. A 2–5 cm thick partial cross section was cut 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. Taking advantage of the previously sampled 3.6 km^2 subsection of our study area, we supplemented our material with these already dated fire-scarred samples (Storaunet et al. 2013). To conform with the present sampling effort, this was done by randomly drawing 49 samples from a total of 321, giving a sample density (13–14 per km^2) equaling those parts of the present study area with highest sample density. Altogether, this amounted to 378 successfully cross-dated sampled trees having a total of 745 fire scars and 387 complete fire scar intervals (Appendix S2: Figs. S1, S2).

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 so that tree rings and fire scars could be easily distinguished under a microscope. We used a scalpel and zinc paste when needed to assure better visibility of the ring pattern. The annual ring widths were measured with a micrometer (accuracy of 0.01 mm) and the tree ring series were cross-dated against three different chronologies using the program COFECHA (Holmes 1983): (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 (present study), constructed from 45 trees with ≥5 tree-ring series dating back to 1373, and (3) Sigdal pine chronology (present study), constructed from 117 trees with ≥5 tree-ring series dating back to 1248. The suggestions from the statistical cross-dating were thereafter confirmed by the pointer-year method (Stokes and Smiley 1968, Yamaguchi 1991). 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 neighboring 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 rows of living cells, these dead cells appear as collapsed under magnification. The collapsed cells' relative position within the tree ring reveals the season of the fire. We used five categories to represent the seasonal growth: dormant (D), early early-wood (EE), middle early-wood (ME), late early-wood (LE), 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 approximately same seasonal cambial growth pattern was found in Scots pine in southern Finland (Schmitt et al. 2004). Using this information, we assumed that EE roughly corresponds to first half of June, ME to last half of June, LE to first half of July, and LW to the end of July and beginning of August. This corresponds well to our experience from coring living trees in the study area and subsequently studying the development of the current tree ring. Few scars (2%) were classified to dormant season (D), and these were assumed early-season fires instead of late fires occurring after growth season the previous year. This was done because in most cases other seasonal datings from the same fire year were classified to EE and ME. 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. Fires with mean season index <3 and ≥3 were defined as early and late-season fires, respectively.

Delineation of individual fires and adjusting their number and size

Using ArcView GIS 3.3 software (ESRI, Redlands, California, USA) fires were drawn on the map according to the following procedure. For each fire year, we plotted 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 inspecting available information on the map: (1) number, location, and spatial pattern of the scarred samples the actual year; (2) number, location, and spatial pattern 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 after AD 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 yr) were not spatially overlapping, except when multiple fire scars in single trees indicated otherwise. The 15-yr limit was chosen because <2% of the scar intervals in our samples were of shorter duration.

Number and size of fires were underestimated (1) due to lower density of recorder trees back in time (fading record), and (2) because the recording transects covered only 38% of the forest and mire area (Appendix S2: Figs. S1, S3). We applied a correction procedure to arrive at an adjusted estimate accounting for undetected small fires and underestimated fires sizes (Appendix S2, Niklasson and Granström 2000). Fire size was divided into five classes: <0.03, 0.03–0.05, 0.05–0.1, 0.1–0.3, and ≥0.3 km^2. Fires <0.03 km^2 were excluded from the procedure and subsequent analyses since these were assumed too small to be adequately detected within our recording area. On the other hand, we assume to have recorded practically all fires ≥0.3 km^2. Fires between 0.03 and 0.3 km^2 were adjusted by numbers only, whereas fires ≥0.3 km^2 were adjusted only by size. Number of fires was adjusted within 13 time periods based on the recorded number of fires in each size class (Appendix S2: Table S1). 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 fire frequencies and recurrence intervals

Forest fires typically exhibit robust size-frequency power-law behavior over several orders of magnitude (Malamud et al. 2005, Jiang et al. 2009). Based on the adjusted number and size of fires, we calculated the inverse cumulative size distribution and a normalized size-frequency distribution. To characterize 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 normalized by the period length (yr) and the size (km^2) of the study area. Thus, the normalized 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 study period (km^{-4}/yr).

Time intervals between fires can be either size or site specific. In order to measure how often a fire of a certain size burns in an area, size-class distribution of fires can be used to calculate size-specific *recurrence intervals*. Thus, recurrence interval is the time it takes for a fire above a certain size to occur again within a defined area, regardless of where it recurs. This is opposed to the site-specific *return interval*, which is the number of years between successive fires at a given site irrespective of the fire size. Fire recurrence interval is calculated as the inverse of the annual probability that a given size event will be equaled or exceeded within a defined spatial area. Following Malamud et al. (2005) we fitted least square inverse power-law functions to the normalized size-frequency distributions and used the slope (β) and intercept (log α) parameters to calculate size-specific recurrence intervals (T) and their reciprocal fire densities

$$T(\geq A_F) = \left[\frac{\tau+1}{\tau}\right] \times \left[\frac{\beta-1}{\alpha}\right] \times \left[\frac{A_F^{(\beta-1)}}{A_{SA}}\right] \qquad (2)$$

where A_F and A_{SA} are the size (km^2) of the fire and the study area, respectively, and τ is the length of the study period (yr). Log α is the density of fires at log 1 km^2 fire size. The negative slope (−β) represents the ratio of small to large fires, with β = 2 characterizing a fire size distribution where each size class on a logarithmic scale represents the same total burned area (i.e., fires 0.1–1 km^2 burn the same total area as fires 1–10 km^2). Accordingly, large fire size classes contribute most to burned area at β < 2 and small size classes at β > 2. Excluding fires <0.03 km^2 due to low detectability, 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 SD from the least square fitted power-law functions.

Burn rate (annual percentage of area burned) and fire cycle (fire rotation)

The same area burned can result from either a large number of small fires or a small number of large fires.

Thus, annual area burned incorporates both number and size of fires, typically reported as mean annual *burn rate* (or burning rate), meaning the yearly percentage of certain forest types or the whole study area that has been affected by fire averaged over a defined time period. Importantly, when burn rate is averaged over several years, the same mean burn rate can result from fires burning at different places or fires burning repeatedly in the same area. The reciprocal of burn rate is the *fire cycle* (or fire rotation), which is the time required to burn an area equal to the one that is studied (Grissino-Mayer 1999). Here we report burn rates as the yearly burned fraction of the study or some other specified part of it, averaged over a pre-defined period. When burn rate is calculated relative to the time since previous fire, we use the term *hazard rate* or *hazard of burning*.

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

The site-specific fire *return interval* is the number of years between successive fires at a given point. Whether the fires are small or large is not a matter of interest here, it is a measure of how often a fire returns to a certain point or specific site. Return intervals are usually calculated from multiple scarred trees, using number of fire-scar intervals as sample size. In our study, dated fire scars were used to draw individual fires to the map. Hence, we used the overlapping parts of successive fires to delineate *areas* with similar intervals. We used a non-parametric actuarial life-table survival model to analyze the data (Statview 5.0; SAS Institute, Cary, North Carolina, USA), restricting the analysis to include the overlap area within the recording area only. As this model requires number of intervals as input data, we transformed the vector-based areas of overlap to number of overlapping pixels using a 50 × 50 m resolution that produced a total of 29504 pixels within the study area. This resolution was judged sufficiently high to capture the size and shapes of the overlapping fires adequately.

Fire interval distributions can be presented in a probability density form, $f(t)$, or in a cumulative probability form, $F(t)$. The density distribution represents the probability of burning in a specific time interval, i.e., the frequency distribution of the fire return intervals calculated from the overlapping fires from the map. The cumulative distribution is the probability that a fire has occurred before or at time t, that is, the integral of the probability density function (Johnson and Gutsell 1994, Moritz et al. 2009). From the cumulative density distributions, we derived the corresponding *survival functions*, $1 - F(t)$, which is the proportion of newly burned area that has remained unburned (survived) up until time t. Finally, we calculated the *hazard rate* or *hazard of burning*

$$\lambda(t) = f(t)/1 - F(t) \tag{3}$$

as the probability of burning at time t conditional on the probability that the site had not burned during this time. That is, the yearly frequency of a new fire occurring within a forest age class, given that it has not burned (survived) up to that point (the instantaneous mortality of Johnson and Gutsell 1994). As such, the hazard rate can be interpreted as the age-specific annual burn rate, reported as a percentage (Héon et al. 2014).

Typically, fire-interval distributions and accompanying mean fire intervals are calculated from multiple scarred wood samples with complete intervals bounded in both ends with known dates, i.e., based on those parts of a study area that have burned more than once. However, this precludes the parts of the area that have burned only once, or not at all, i.e., intervals that are open in one or both ends. When the time since last fire or the time to next fire is unknown, a censored observation defines a minimum estimate of the true time since fire (Moritz et al. 2009). All time intervals between successive overlapping fires were uncensored. The analyses were done pre and post AD 1625 based on the timing of the anthropogenic influence on the fire regime (see *Results* and Storaunet et al. 2013). 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 whole period of 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 385 yr pre and post 1625, respectively. Survival distributions and hazard rates were calculated (1) based on uncensored data only and (2) with censored data included. Median fire intervals were calculated from the uncensored data only, due to the bimodality of the frequency distribution that included censored intervals.

Climate

Gridded (0.5° × 0.5° resolution) reconstructed annual spring and summer temperature and precipitation, extending back to AD 1500, were downloaded from the Climate Explorer of the Royal Netherlands Meteorological Institute (KNMI 2014; see also Luterbacher et al. 2004, Pauling et al. 2006). The summer temperature series was extended further back to AD 1300 using a longer time series from The Netherlands (KNMI 2014; see also van Engelen et al. 2001) that correlated well with the Luterbacher series ($R^2 = 0.84$; Appendix S3: Fig. S1). 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 onward (Luterbacher et al. 2004). The gridded reconstructions were calibrated against local instrumental records from nearby meteorological stations downloaded from the Norwegian Meteorological Institute (see footnote 4; Appendix S3: Table S1 and Fig. S2). Although spanning the actual time period, the local tree-ring dating chronologies were not suitable as proxies for local climate. This was mainly because numerous historical fires had influenced the samples included in the chronologies. Also, unburned samples from old trees were rare and rotten, since they were not preserved by repeated fire scarring.

From the annual spring and summer temperature and precipitation series, we derived means and means of sums, respectively, for successive 25-yr periods. Due to significant autocorrelation in the 25-yr time series, possible relationships with fire activity were tested using generalized least squares (GLS) regression with an AR(1) correlation structure. When testing for relationships on annual basis, autocorrelation was accounted for using an exponential spatial correlation structure (corExp) due to unequal periods between fire years (nlme package of R; Pinheiro et al. 2016). However, these data sets exhibited minor temporal autocorrelation, and it did not influence the result outputs significantly. We used multiple regression to separate the contributions of temperature and precipitation. Number of fires and sum of burned areas within the 25-yr periods were $\log(x + 1)$- and $\log(x + 0.1)$-transformed, respectively, and annual burned area was log-transformed to achieve normality. The analyses were based on unadjusted fires ≥0.03 km^2, as this was judged the lower limit to be representatively detected within the recording area. Superposed Epoch Analysis (SEA; Swetnam 1993, Grissino-Mayer and Swetnam 2000) was used to check for multiannual patterns in fire-climate relationships, using a 5-yr window of 3 yr preceding and 1 yr succeeding the fire years. Mean values of the window years were compared to variation in the mean of n randomly selected years of the complete time period pre and post 1625, where n was the number of fire years in the respective periods. Bootstrap 90%, 95%, and 99% confidence intervals of the means were calculated based on 10000 simulations. Whole 5-yr window sequences were resampled simultaneously rather than for individual event years to account for temporal autocorrelation.

Results

Numbers and sizes of fires

In total, we dated and outlined 254 individual fires within 130 separate fire years covering 753 yr (AD 1257–2009). The pith year of the oldest living and dead Scots pine was AD 1515 and AD 1070, respectively. More than one-half of the fires (146) were recorded only in one tree sample, with most of them occurring during the 1600–1700s. Only one fire (AD 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 onward, the observed number of recorder trees was assumed to be numerous enough to estimate the location and extent of individual fires throughout the study area (Figs. 2, 3; Appendix S2: Figs. S2 and S3 and Appendix S4). The largest fire of 23 km^2 (adjusted area) occurred in 1499, covering one-third of the study area and 39% of the forest and mire area (Fig. 3a). Other large fire years occurred in 1572 (14% burned area), 1590 (22%), and 1652 (12%). Eleven out of 23 fires ≥1 km^2 (48%) appeared to have extended outside the study area.

Adjusting the data set for undetected small fires increased the total number of fires from 254 to estimated 422. Compared to the recorded fires, this presumably gives a more unbiased picture of the temporal distribution. The number of fires (adjusted) was rather low from 1300 to the mid-1500s, varying between 5 and 10 fires per quarter-century period (Fig. 4a). Although numbers increased to ~20 fires per quarter during the following three quarters, the most significant increase occurred from AD 1625 when numbers peaked at 50–60 fires per quarter century, an average of more than two fires per year. This number remained high for five quarters until 1750, after which it decreased to ≤5 fires per quarter from 1800 and onward. Although mean fire size varied considerably, especially during the early period, the general trend was a gradual decrease in size throughout the period (Fig. 4c).

Taken together, the counteracting effects of an increasing number of successively smaller fires resulted in annual burn rates increasing only moderately after 1625 (Figs. 4b, 5; Appendix S1: Table S1). Average annual burn rate was 0.43% pre 1625 (adjusted data), increasing to 1.03% during 1625–1699, decreasing to 0.30% during the 1700s, and plummeting to insignificant <0.01% from the 1800s and up until today. This represents fire cycles of 236, 98, 335, and 11000 yr, respectively. During the period of peak fire activity, 1650–1674, 1.76% of the area burned annually (57-yr cycle; Figs. 3b, 5).

Fire season

Except for one fire (AD 1413), all the other 38 seasonally dated fires in the early period occurred in late season (season index 3–5). This changed markedly during the first half of the 1600s, starting with the AD 1625 fire, after which one-third of the dated fires (48 of 148) occurred during early season (season index <3; Fisher's exact test, $P < 0.0001$; Fig. 6). Notably, there were no long-term trends in the season index within the two periods (pre 1625, slope = 0.0008, $R^2 = 0.008$, $t = 0.55$, $P > 0.20$, $n = 39$ fires; post 1625, slope = −0.0008, $R^2 = 0.002$, $t = -0.50$, $P > 0.20$, $n = 148$ fires). Based on the time-related changes in the fire regime (changes in number of fires, fire sizes, and fire season), we split our data into three time periods, one pre-1625 (1300–1624) and two post-1625 periods (1625–1799 and 1800–2009) for further analysis. If not stated in particular, the two post-1625 periods were combined.

Fire size distributions and recurrence intervals

The adjusted number of fires were ranked in inverse cumulative size distributions with 125 fires pre 1625

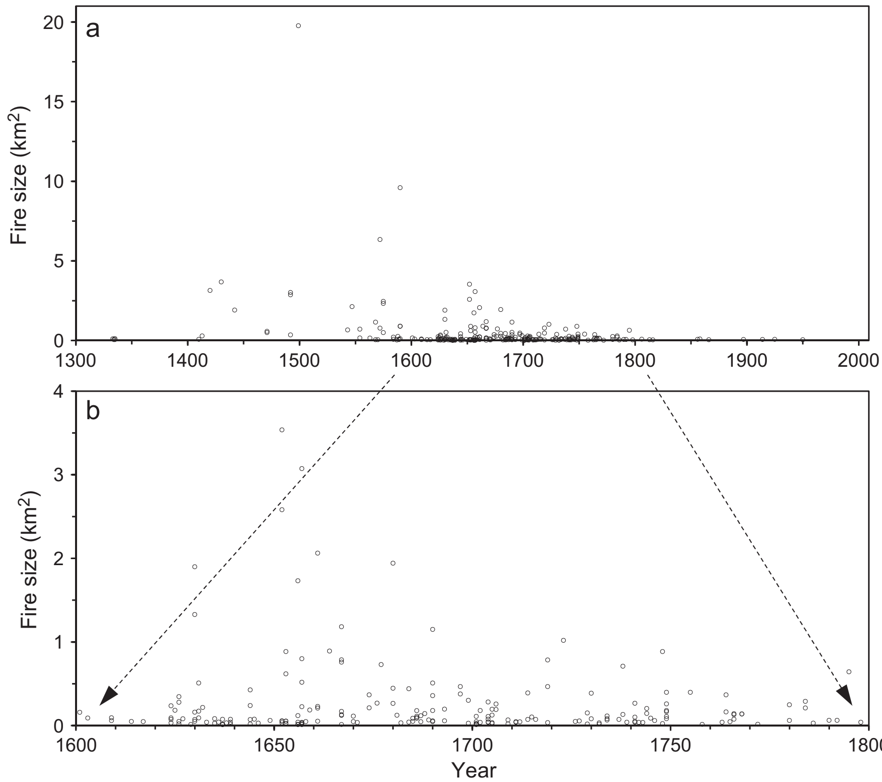

FIG. 2. Size of all recorded fires during (a) 1300–2009, and (b) enlarged for the period 1600–1800.

(1300–1624) and 296 fires post 1625 (1625–2009; Fig. 7a). Excluding 29 fires <0.03 km^2 during 1625–1799 (due to low detectability) and 19 fires during 1800–2009, the inverse cumulative size distributions translated to normalized density plots that closely followed power-law relationships both pre and post 1625, with coefficients of determination (R^2) > 0.98 (Fig. 7b). Log α (intercept), representing the density of fires at 1 km^2 fire size, was significantly higher post-1625 (1625–1799) than pre-1625 (1300–1624), whereas the β values (slopes), i.e., the ratio of small to large fires, were almost identical at 1.7. The latter implies that fires within larger size classes (on a logarithmic scale) burned more area than fires in smaller size classes during both periods (Table 1). However, due to several very large fires pre 1625, the cumulative number of fires ≥1 km^2 contributed 83% of the total burned area, compared to only 39% post 1625. The largest fires in the two periods were 23.1 km^2 in 1499 and 3.6 km^2 in 1652 (Fig. 3).

Density of all fires ≥0.03 km^2 (i.e., the estimated number of fires per unit area and time after correcting for undetected small fires) was 0.65 per 100 km^2 and year pre 1625 and 2.41 during 1625–1799. This implies average recurrence intervals within our 59-km^2 forest and mire area of one fire every second to third year and every 8 months pre and post 1625, respectively. Applying the α and β parameters from the power-law distributed normalized size frequencies, fires ≥0.1 km^2 and ≥1 km^2 were 3–4 times more frequent during the post-1625 (Table 1). Pre 1625, fires ≥10 km^2 occurred on average at 118 yr intervals.

Fire return intervals, survival functions, and hazard of burning

Based on the complete (uncensored) fire intervals derived from the recording area of the map, i.e., comprising only areas that had burned more than once, a pre-1625 median fire interval of 73 yr dropped to half, 37 yr, post 1625 (Fig. 8). The frequency distributions of the intervals were skewed to the right, mostly so for the post-1625 period. Only seven of the individual fire-scar intervals (1.8%) were shorter than 15 yr, with all occurring post 1625 (3, 5, 6, 9, 9, 9, and 13 yr). These fire interval distributions translated to cumulative survival curves dropping off more slowly pre 1625 than post 1625 (Fig. 9a). Consequently, the hazard rate pre 1625 increased gradually, reaching 3–4% at time-since-fire of 60–100 yr, after which it dropped to an average ~2% beyond 100 yr. Post 1625, the hazard rate increased more rapidly to 4% at time-since-fire of 20–40 yr, after which it dropped to the same average of ~2% at longer time spans (Fig. 9b).

Including the censored intervals, i.e., allowing areas that had burned once or not at all to be counted, this influenced the result output markedly. First, the

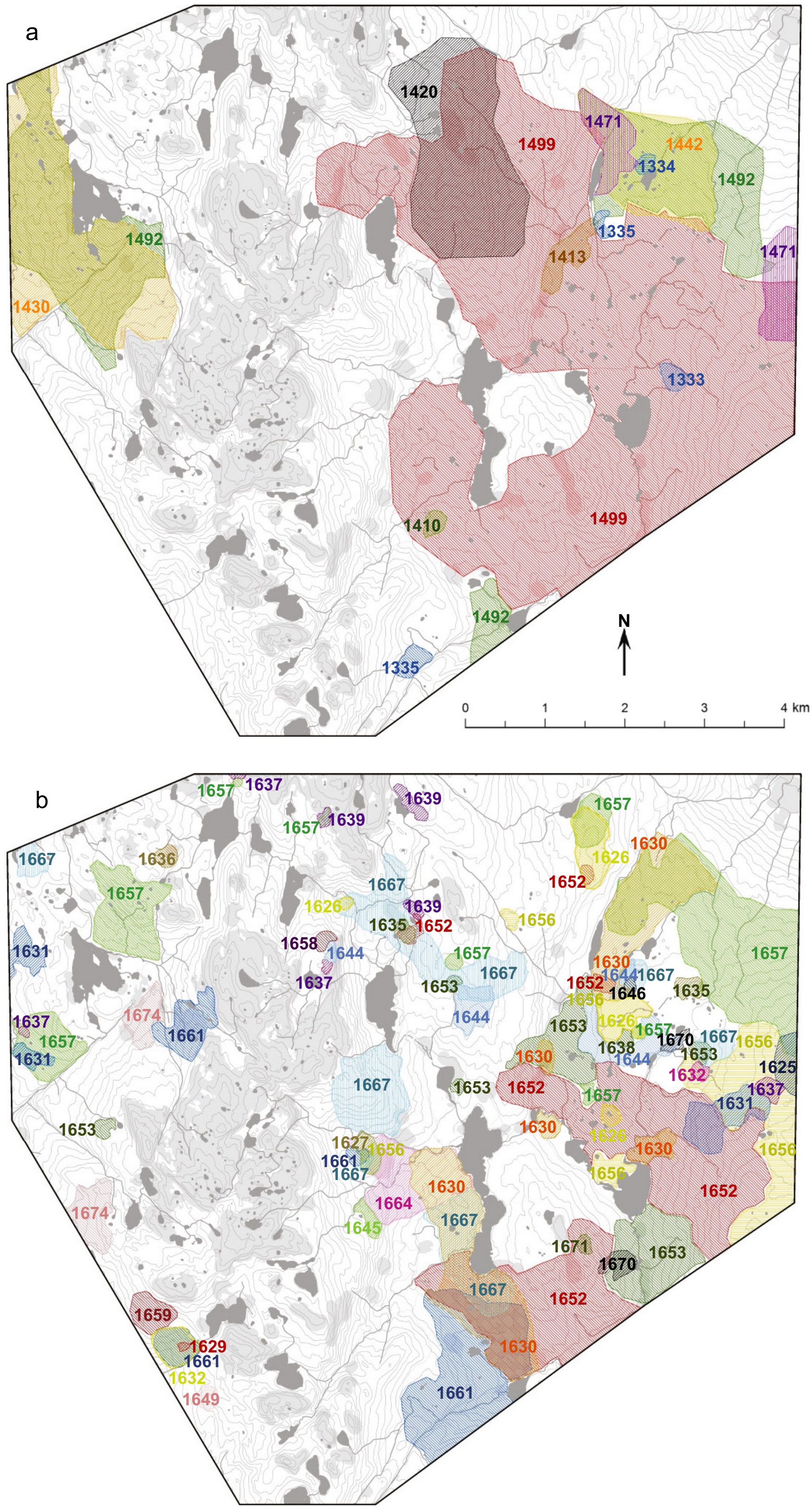

FIG. 3. Delineation of all recorded fires within the study area during two contrasting periods: (a) 1300–1499 (200 yr) and (b) 1625–1674 (50 yr). Maps of all fires during the whole study period are presented in Appendix S4.

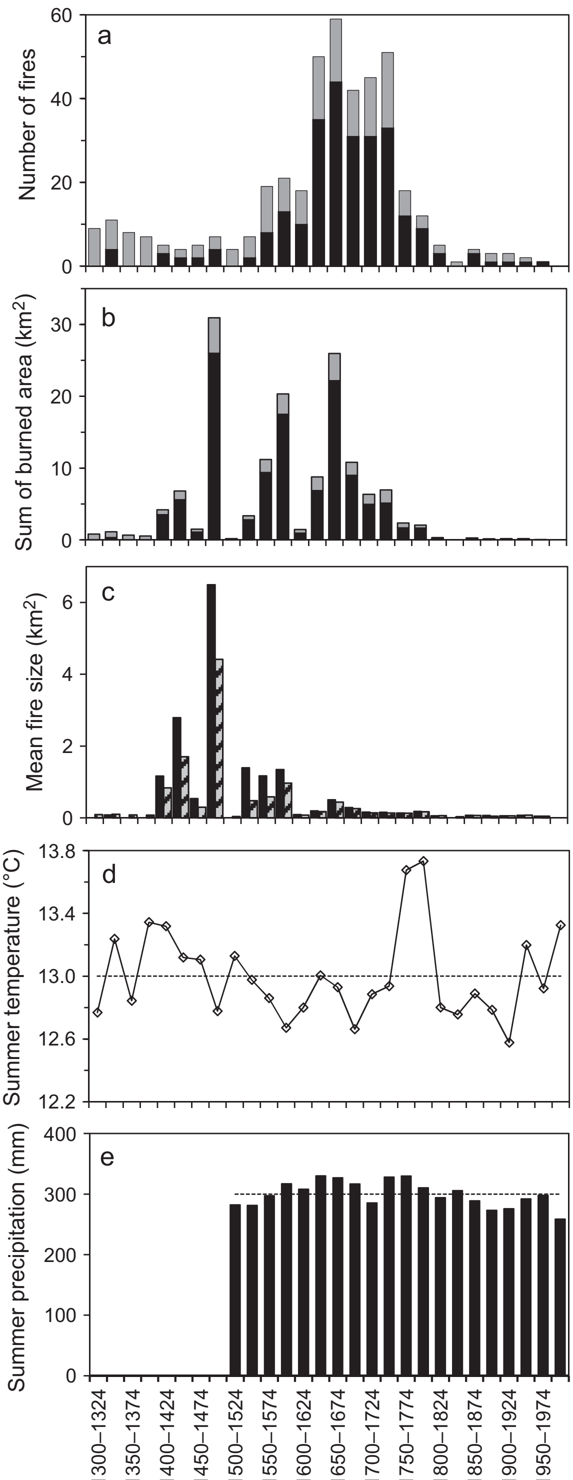

FIG. 4. (a) Total number of fires, (b) sum of total burned area (km^2), (c) mean fire size (km^2), (d) mean summer (June, July, and August [JJA]) temperature (°C), and (e) sum of summer (JJA) precipitation (mm), within 25-year periods. In panels a and b, black and gray bars show recorded fires and added adjusted fires, respectively. The hatched bars in panel c show mean fire size of all fires including both recorded and added ones. Dotted horizontal lines in panels d and e represent overall mean values.

frequency distributions of the fire intervals changed to bimodality, due to the inclusion of many long, censored intervals (Fig. 8). Hence, calculating a central tendency statistic like mean or median fire interval was no longer meaningful. Second, survival curves dropped off more slowly and levelled off at values representing the percentage of the cumulative area of intervals that remained unburned at 50 and 60% pre and post 1625, respectively (Fig. 9c). This was in contrast to the survival curves based on the complete intervals, which both ended up at zero because they included the burned area only. Third, the overall hazard rate was markedly reduced, peaking at ~1% only, and gradually dropping off to zero as time-since-fire approached the full pre- and post-1625 periods. However, the pre vs. post 1625 shift in peak hazard rate, from 60–100 yr to 20–40 yr, remained rather unaffected by the censoring procedure (Fig. 9b, d).

Vegetation, altitude, and spatial distribution of fires

Average annual burn rate and fire return interval of present-day spruce- and pine-dominated forests at different elevations were calculated based on the overlapping fires within the recording area of the map. Fire intervals included only complete (uncensored) intervals, i.e., areas that had burned more than once. Pre 1625, burn rate was almost two times higher in pine than spruce forests, and it was two to three times higher at lower elevations compared to higher elevations (Fig. 11; Appendix S1: Table S1). Overall, the burn rate increased 56% from a pre-1625 rate of 0.43% to 0.67% during 1625–1799, but the relative differences between forest types and elevations were about the same between the two periods (Figs. 10, 11). Post 1800, burn rate was negligibly <0.01%.

The burn rate may increase either due to a higher proportion of burned area or due to fires burning the same area repeatedly, or both. The pre- to post-1625 increase in burn rate was predominantly due to markedly shorter fire intervals (73 vs. 37 yr), as the total proportion of burned area remained about the same. On the other hand, the different burn rates of forest types and elevations were mainly due to different areal proportions burned, as median fire intervals were about the same (Fig. 11). For example, pre 1625, 87% of the area of lowland pine forest burned, compared to only 34% of high-elevation spruce forest. Median fire intervals, however, were rather similar at 73 and 62 yr, respectively. During 1625–1799, 86% of lowland pine forest burned, compared to 40% of high-elevation spruce forest. Here, median fire intervals were 29 and 33 yr, respectively (Appendix S1: Table S1). Thus, the total areal proportion burned was about the same during the two periods but it varied markedly among forest types and elevations (Fig. 10). On the contrary, the fire return interval differed markedly between the two periods, but it was more or less independent of forest type and elevation. As a corollary, the fire hazard rate was also independent of present-day forest types and elevations.

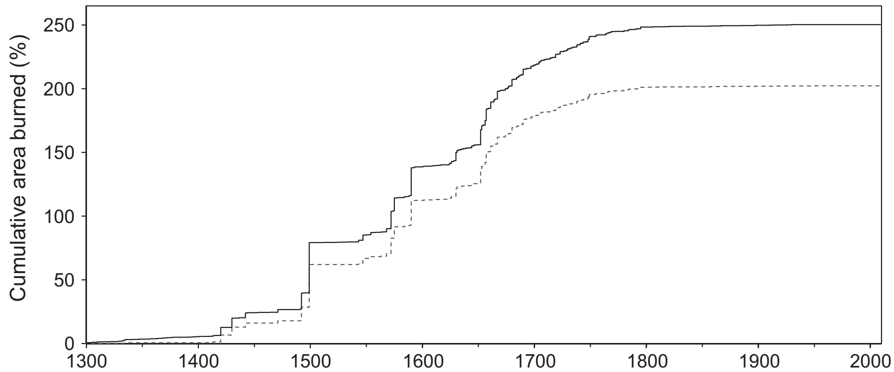

FIG. 5. Cumulative percentage of area burned over time is shown for the recorded fires only (lower hatched line) and for all fires including both recorded and added adjusted fires (upper black line).

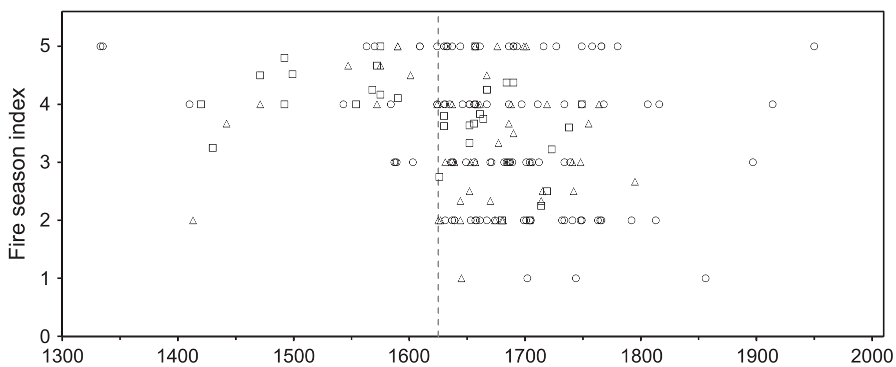

FIG. 6. Fire season index values (1 corresponds to dormant season and 5 corresponds to latewood season) for each individual fire that were dated to season. Symbols indicate number of seasonally dated fire scars per individual fire: 1 scar, circles; 2–3 scars, triangles; and >3 scars, squares. Dashed vertical line represents AD 1625.

The historic summer dairy farms were regularly distributed within the study area, with mean distance to nearest neighbor (DNN) of ~1 km (DNN = 965 m, $R = 1.39$, $Z = 4.3$, $P < 0.001$, $n = 34$). They were also located within the most spruce-dominated parts of the study area (Figs. 1c, 12a). Prior to 1625, the burn rate was rather evenly distributed with respect to distance from the dairy farms. Post 1625 there was a shift toward higher burn rates closer to the summer dairy farms with a peak at 500–800 m (Figs. 10, 12).

Relationships with climate

On a multicentennial basis, there was a rather warm period during 1300–1550, of which there was only limited proxy data on precipitation (Fig. 4d, e). This period was followed by a rather cold and wet period during 1570–1900 (the Little Ice Age), interrupted by a short warm but still wet incidence during 1750–1800. After 1900, the temperature has been increasing, with precipitation around or below the overall mean. On a 25-yr-period basis, indicating possible multidecadel to centennial patterns, there were no relationships between number of fires and mean summer temperatures, nor between the sum of burned area and mean summer temperatures (Fig. 4a, b, d, Table 2). Unexpectedly, both number of fires and sum of burned area appeared to be positively correlated with precipitation. This was due to the period of high fire activity coinciding with the overall wet period 1600–1799, during which seven of eight 25-yr periods had above average sum of precipitation (Fig. 4e). However, the time series were seriously autocorrelated, and after taking this into account, the explanatory significance of precipitation was no longer present (Table 2).

On a five-year window basis, the SEA (superposed epoch analysis) revealed that large fire years (burned area ≥ 0.3 km^2) were significantly warmer than average pre 1625, whereas small fire years (burned area < 0.3 km^2) tended to be colder than average. Post 1625 (1625–1799), the same pattern applied for years with late-season fires, although the large fire years did not stand out as warm as those pre 1625. In contrast, years with early-season fires, both small and large fire years, tended to be slightly colder than average, although this was not statistically significant (Fig. 13a–f). Prior to 1625, large fire years were dryer and small fire years wetter than average. Post 1625, none of the years within the 5-yr window (except the one prior to early-season small fire years) deviated

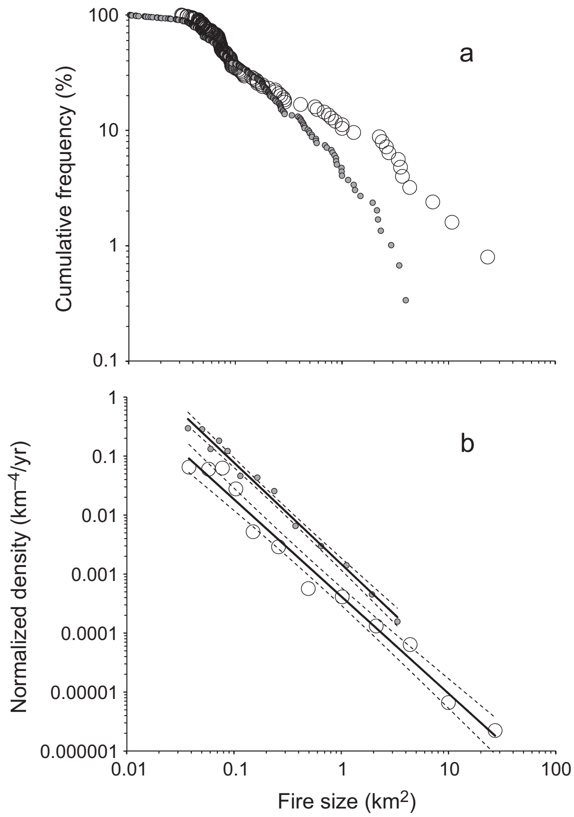

Fig. 7. (a) Inverse cumulative frequency distributions and (b) normalized density plots of fire sizes shown for the pre-1625 (open circles) and post-1625 periods (gray dots). The cumulative distributions show all fires during 1300–1624 (n = 125) and 1625–2009 (n = 296), whereas the density plots were calculated based on fires ≥0.03 km^2 and the post-1625 period restricted to 1625–1799 (n_{pre} = 125, n_{post} = 248). Both panels include the added adjusted fires. Dashed lines represent upper and lower 95% confidence intervals based on fitted power functions. Note logarithmic scales on x- and y-axes.

significantly from average precipitation, although most fire years tended to be drier than average (Fig. 13g–l).

On a year-to-year basis, the data sets were less influenced by temporal autocorrelation. Restricting the analysis to years with fires ≥0.03 km^2, we found a rather strong positive relationship between annual burn rate and mean summer temperature pre 1625 (1300–1624; Fig. 14a), thus confirming the pattern revealed by the SEAs. During this period, all but one fire (AD 1413) occurred in the late season. Likewise, there was a negative relationship between annual burn rate and precipitation (1500–1624; Fig. 14b). In this early period, temperature and precipitation were markedly correlated (R^2 = 0.35), with warmer summers for the most part being dryer and colder summers being wetter. Taking this into account, the multiple regression analysis disclosed that precipitation lost its explanatory significance when inferred in concert with temperature (Table 3).

Post 1625 (1625–1799), temperature and precipitation were markedly less correlated (R^2 = 0.03), presumably due to the gradual inclusion of more accurate instrumental records in the climate reconstructions. Here, we analyzed the data separately for early- and late-season fires, based on the indication that early-season fires may have had an anthropogenic origin as opposed to late-season fires that may have burned more naturally. Expectedly, late-season burn rates increased with increasing summer temperature, but the relationship was notably weaker than pre 1625 and only marginally significant (Fig. 14e). Precipitation had no explanatory significance on late-season burn rates, neither separately nor partially after being added in the multiple regression model (Fig. 14f, Table 3). For early-season fires, summer temperature and precipitation had no bearings on the burn rate (Fig. 14c, d, Table 3). Including spring temperature and precipitation to the model, assuming that these might have had an influence on early-season fires, did not reveal any significant contributions (P = 0.8 and 0.9). Overall, late-season fires burned almost twice as large proportions of the area (burn rate 0.42%; mean of log values) than early-season fires (0.24%; t = 1.96, P = 0.05, n_{early} = 33, n_{late} = 53; Fig. 14c–f).

The inclination of fires to burn more often in warm summers, and the contrast between the pre- and post-1625 periods, also showed up when we inspected the possible effect of summer temperature on the percentage of years that experienced fire and on the average annual burn rate (Table 2). Pre 1625, the percentage of years with

Table 1. 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 forested 59 km^2 of the study area.

Time period	Area (km^2)	Years	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	−3.38 (−3.53, −3.23)	1.65 (1.48, 1.81)	0.981	5.9 (3.6, 9.1)	26.5 (13.8, 46.6)	118.2 (41.8, 301.0)
1625–1799	58.93	175	−2.83 (−2.93, −2.73)	1.72 (1.60, 1.84)	0.990	1.6 (1.1, 2.2)	8.3 (5.5, 12.1)	

Notes: Confidence intervals (95%; in parentheses) are based on the number of "bins" used in the least square fit of the regressions. Includes added fires corrected for detection probability. See *Material and Methods* for details and Fig. 7 for graphic presentation of α and β.

† The parameter log α is the intercept of the fitted power-law function, with α being the normalized density of fires of 1 km^2.

‡ The parameter β is the slope of the fitted power-law function.

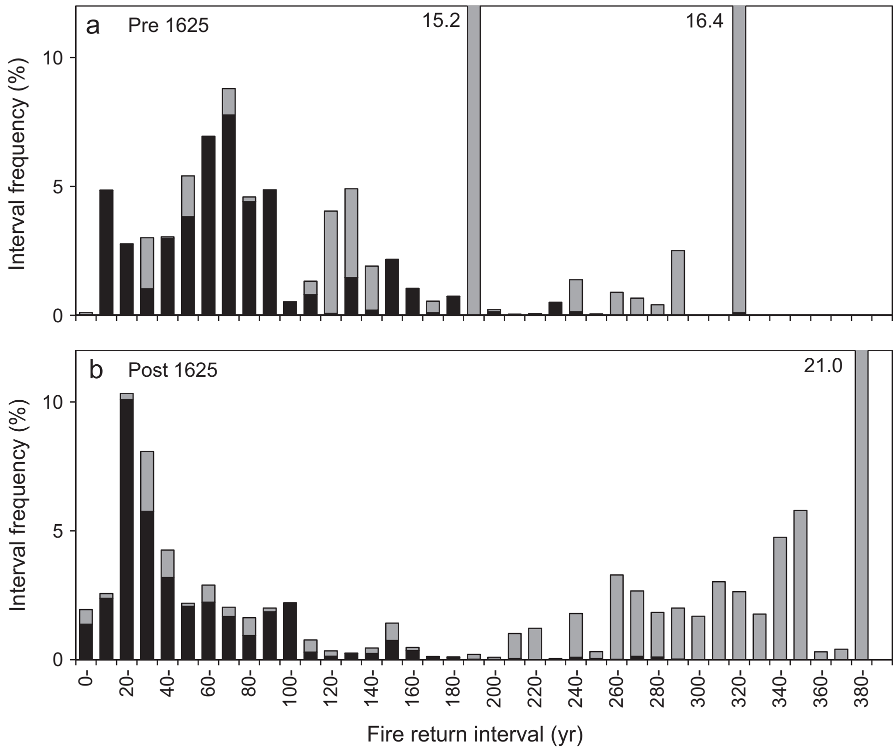

Fig. 8. Frequency distribution of map-based fire return intervals between all recorded fires (a) pre 1625 and (b) post 1625 within the recording area. Complete (uncensored) intervals are shown in black and open (censored) intervals are shown in gray.

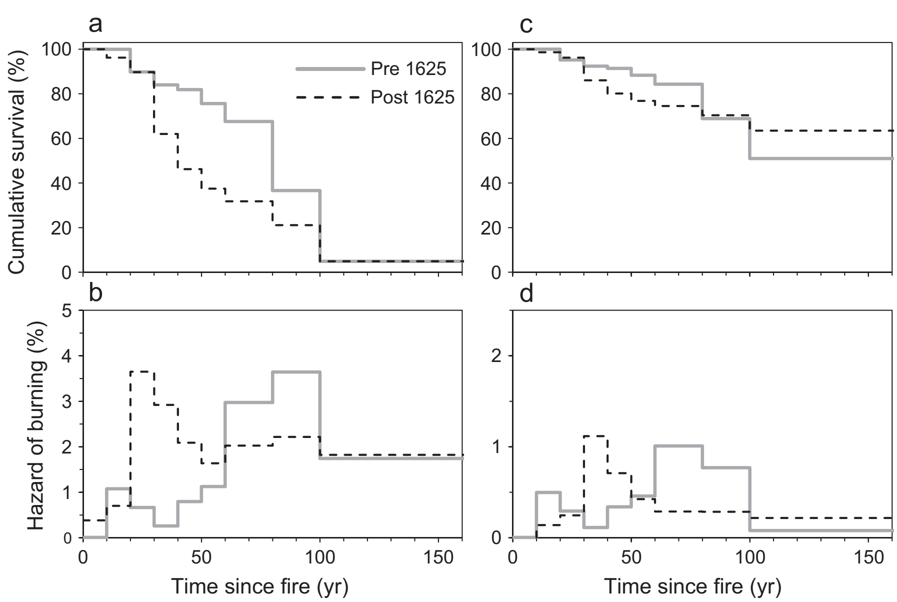

Fig. 9. (a and c) Estimated cumulative survival function curves and (b and d) estimated hazard of burning (i.e., yearly probability of a new fire occurring with increasing time since the last fire) shown for (a and b) complete (uncensored) intervals only and (c and d) including open (censored) intervals. Solid lines denote the pre-1625 period (1300–1624) and dashed lines denote the post-1625 period (1625–2009). Values are annual averages shown for 10-yr periods up to 60 yr, 20-yr periods up to 100 yr, and >100 yr. Note different scales of y-axes for panels b and d.

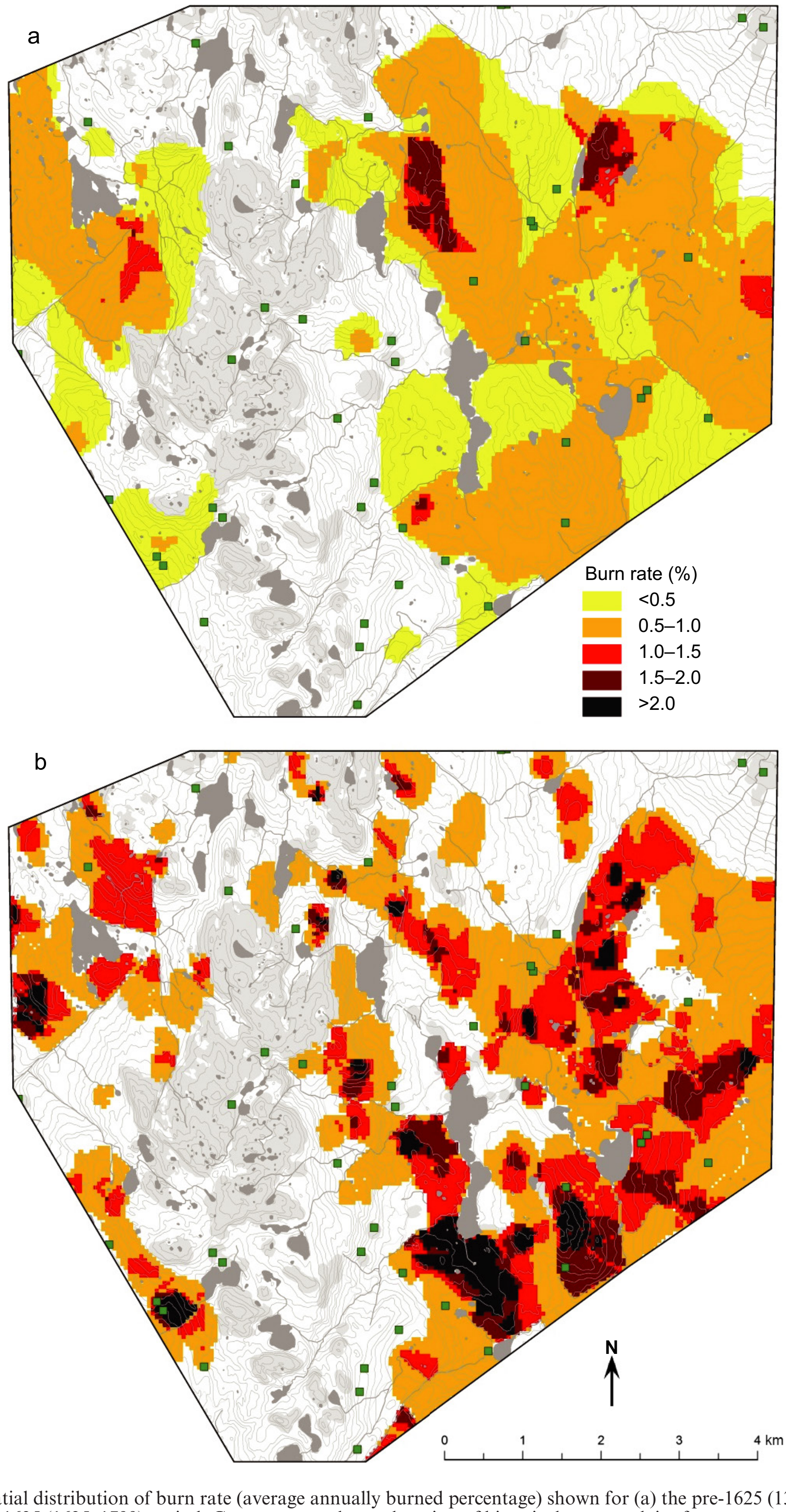

FIG. 10. Spatial distribution of burn rate (average annually burned percentage) shown for (a) the pre-1625 (1300–1624) period and (b) the post-1625 (1625–1799) period. Green squares denote location of historical summer dairy farms.

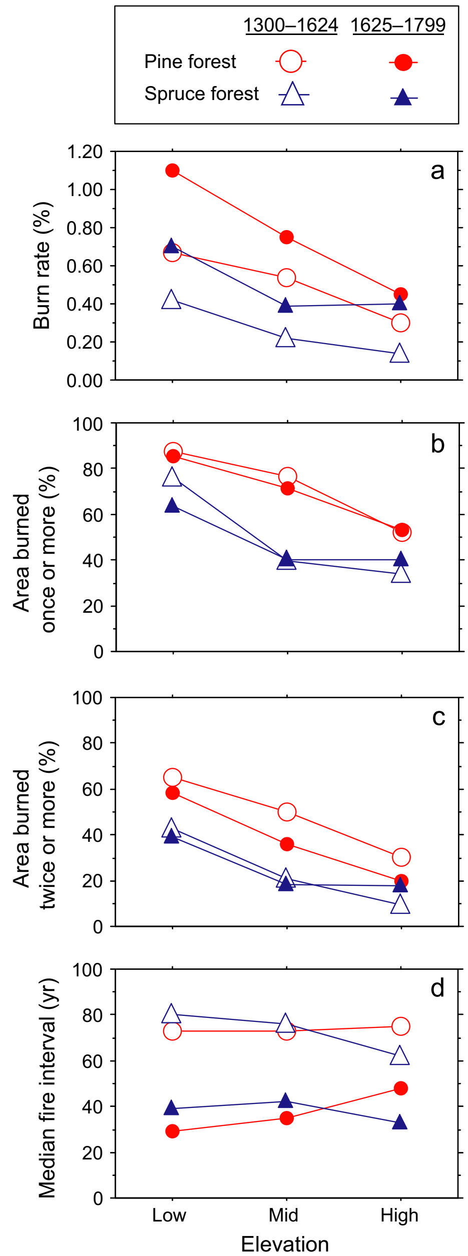

FIG. 11. (a) Burn rate (average annually percent burned), (b) total percentage of area burned once or more, (c) total percentage of area burned twice or more, and (d) median fire return interval of complete (uncensored) intervals. Open symbols, 1300–1624; solid symbols, 1625–1799. Red circles, pine forest; blue triangles, spruce forest. Low, middle, and high elevation correspond to <480 m, 480–660 m, and >660 m above sea level, respectively.

fire tripled from 7% during cold summers (10–12°C) to 21% during warm summers (14–16°C). Burn rate increased even more, from 0.01% to 1.3% for the same temperature intervals. Post 1625 (1625–1799), there was an opposite tendency for early-season fires to be most frequent in colder summers, whereas late-season fires resembled pre-1625 fires, as they tended to occur more often in warmer summers (Table 4).

DISCUSSION

Our study documents that forest fire historically has been a principal disturbance agent influencing the forest landscape of the Trillemarka-Rollagsfjell Nature Reserve. Our data allowed for detailed reconstruction of both numbers and sizes of individual fires, which could be combined with recently available seasonally resolved climate proxies. The results revealed a general pattern of an early, predominantly climate-driven, fire regime prior to 1625, characterized by relatively few, but some very large, fires, presumably only moderately influenced by human activities. Next followed almost two centuries (1625–1800) of

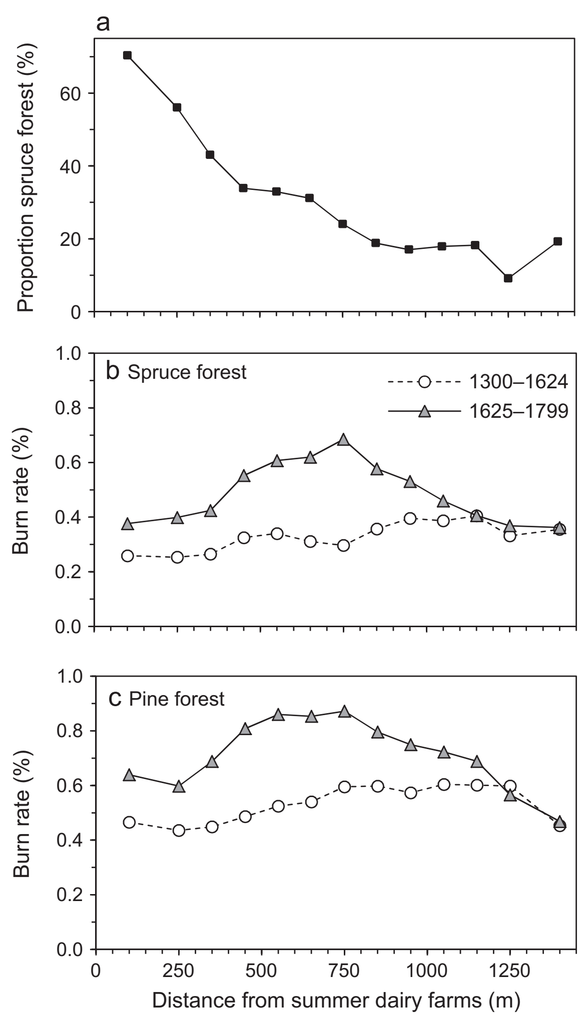

FIG. 12. (a) Percentage of area dominated by spruce forest, and burn rate (average annually burned percentage) within (b) spruce and (c) pine forest at different distances from the summer dairy farms. Burn rates are shown pre 1625 (1300–1624; open symbols and dashed lines) and post 1625 (1625–1799; solid symbols and solid lines).

Table 2. Multiple generalized least squares (GLS) regression coefficients (β) describing number of fires and sum of burned area (km^2) in relation to average temperature and sum of precipitation within subsequent 25-yr periods during 1500–2000 ($n = 20$).

	Number of fires (log[n + 1])				Sum of burned area (log[km^2 +0.1])			
	β	SE	t	P	β	SE	t	P
Intercept	−0.13	2.55	−0.05	0.96	−3.19	4.95	−0.64	0.53
Summer temperature (°C)	−0.03	0.17	−0.15	0.88	0.03	0.35	0.07	0.94
Summer precipitation (mm)	0.0036	0.0031	1.16	0.26	0.0093	0.0062	1.50	0.15

Notes: Based on recorded fires ≥0.03 km^2 in the recording area and corrected for autocorrelation with an AR(1) model. See Fig. 4 for graphic presentation of the periods.

an increased number of fires but with successively decreasing fire sizes, a period coinciding with a sudden appearance of early-season fires and corroborated by written documentation of anthropogenic fire-related activities. Finally, there were only small, scattered fires after 1800 and a total lack of fires the last 50 years, most probably caused by active fire suppression and forest management. Based on several independent data sources, our study provides strong evidence of major human-induced shifts in the fire regime during the last 700 years. Compared with previous studies, the exact timing of the human-influenced periods seems to vary somewhat regionally. In the most comprehensive study, from northern Sweden, Niklasson and Granström (2000) recorded a rapid increase in number of fires from 1750s, and a sudden decrease in fires from the 1860s. In another study, conducted 45 km southwest 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 burned area in the mid-1800s. Most probably, these regional differences were related to when new colonists settled in the respective areas bringing about small-scale agriculture using slash-and-burn techniques and rangeland burning to improve livestock grazing.

Climatic vs. human drivers of the fire regime

In our study, several lines of evidence point to a shift from a predominantly climate-driven regime pre 1625 toward strongly human-influenced regimes afterward. First, there was a rather dramatic increase in number of fires starting in the early-1600s and lasting to the late-1700s. Number of fires increased about 3-fold, a boost in fire frequency happening without any corresponding major shift in climate. As a corollary of the increased number of fires, site-specific fire intervals shortened markedly post 1625, resulting in peak fire hazard rate shifting from older (60–100 yr) to younger (20–40 yr) forest stands.

Second, a sudden appearance of early-season fires from AD 1625 and onward coincided with the increase in number of fires. In southwestern Fennoscandia, the main period of lightning is June–August, peaking in July and being more frequent in August compared with June (Rokseth et al. 2001). Human-caused fires are known to be more common in spring and early summer, probably because dead organic material from the previous year is dry and the new vegetation is not yet lush green (Niklasson and Drakenberg 2001). Third, on a 25-yr-period basis, neither fire frequency (number of fires) nor sum of burned area (burn rate) showed any relationships with mean summer temperature. On a yearly basis, however, there was a rather strong positive relationship between burn rate (annual percentage of burned area) and summer temperature pre 1625, with all but one fire occurring in late season. After 1625, the temperature signal was not present in early-season fires, but tended to be upheld for late-season fires. This pattern, which was supported by the superposed epoch analyses, strongly indicates that the 1625 shift in fire regime was not triggered by climate change. Rather, it suggests that lightning-ignited fires were more prevalent later in the season, and that their occurrence and size were more influenced by the inter-annual variability in climate rather than variations in average climatic conditions over longer periods. This was also concluded in an extensive study of fire history in northern Patagonia (Veblen et al. 1999). The fact that several other studies from Fennoscandia have found similar shifts in the fire regime, but during slightly different times, further strengthens our conclusion that these changes were due to human activities rather than climate (Lehtonen and Kolström 2000, Niklasson and Granström 2000, Wallenius et al. 2004, Groven and Niklasson 2005; see also similar conclusion from southwestern forests of the United States; Swetnam et al. 2016).

Fourth, changes in fire severity over time may indicate human interference on the fire regime. Natural fires may become large since they often burn under conditions of rapid spread and high intensity. Human activity typically shifts this pattern toward smaller fires with lower intensities (Granström and Niklasson 2008). Our sampling protocol did not allow fire severity to be assessed in this study. However, in the small-scale study that was encompassed by the present one, fire severity displayed a decreasing trend over time (Storaunet et al. 2013). Although this change in fire severity was rather gradual, it is consistent with the changes in number and seasonality of fires.

Finally, the increase in number of fires during the early 1600s corresponds well with the written history of the

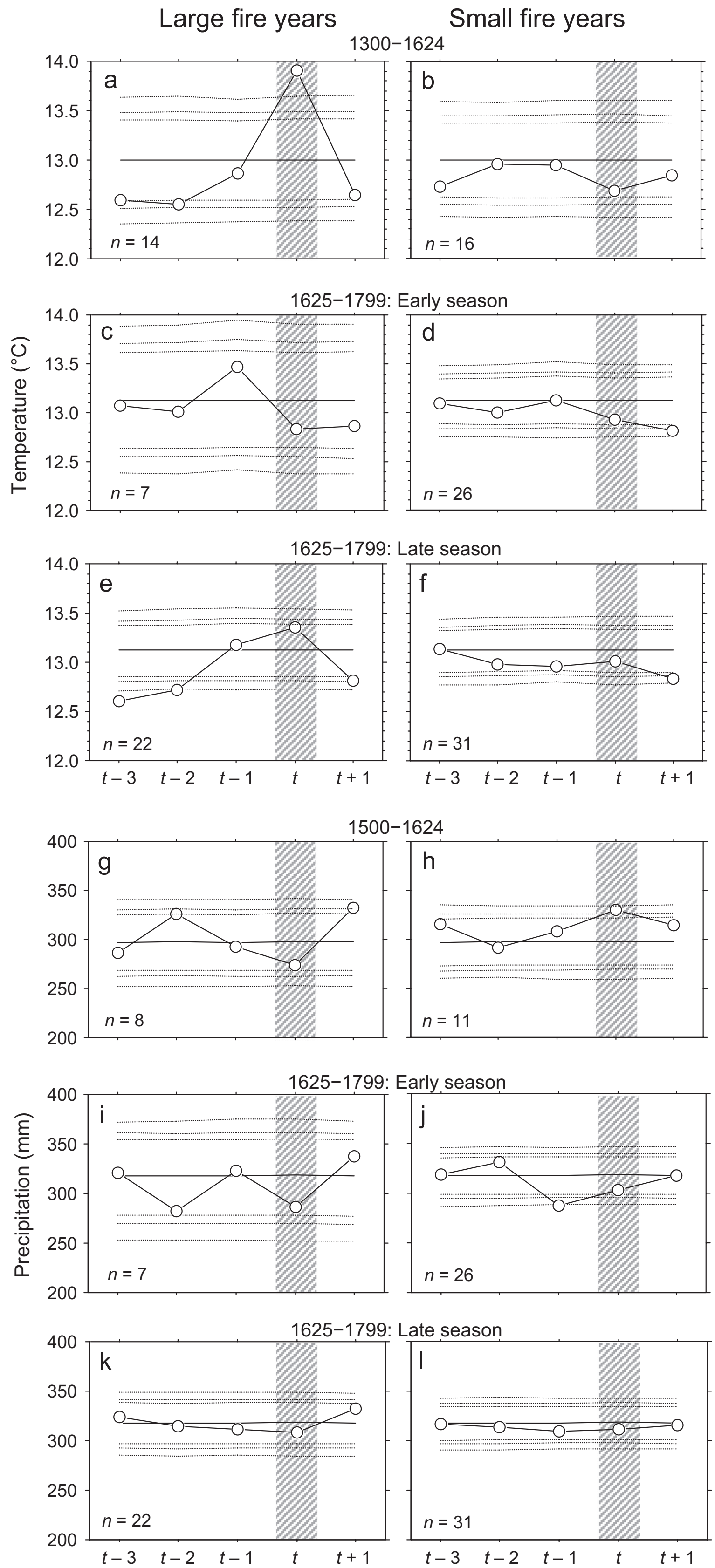
Large fire years
Small fire years
1300−1624
1625−1799: Early season
1625−1799: Late season
1500−1624
1625−1799: Early season
1625−1799: Late season
Temperature (°C)
Precipitation (mm)
a
b
c
d
e
f
g
h
i
j
k
l
n = 14
n = 16
n = 7
n = 26
n = 22
n = 31
n = 8
n = 11
n = 7
n = 26
n = 22
n = 31
t − 3
t − 2
t − 1
t
t + 1

FIG. 13. Superposed Epoch Analysis (SEA) of mean summer (JJA) (a–f) temperature and (g–l) precipitation of five-year windows centered on the fire years (*t*; hatched areas) compared to the overall mean values (horizontal solid lines) of the pre- and post-1625 periods. The post-1625 period is shown separately for years with early-season fires and late-season fires. Large (≥0.3 km^2 burned area) and small fire years (<0.3 km^2 burned area) are shown in left and right panels, respectively. Dashed lines indicate 90%, 95%, and 99% confidence intervals of the overall means based on bootstrap samples equaling the number of fire years (*n*) in each category.

area, indicating that the anthropogenic fires were due to various activities such as burning for improved livestock grazing conditions and slash-and-burn cultivation (Storaunet et al. 2013). The Black Death epidemic spread to Norway in 1349–50, subsequently reducing the population to between one-half and one-third of previous numbers. The country was thereafter struck by several epidemics that kept the population low, resulting in an estimated minimum of ~200000 around 1520. It was not until the mid-1600s that the population had recovered to the pre-1350 level. Circumstantial evidence suggests that most of the forest and mountain areas became desolate after 1350. From the late 1500s and onward, the population increased and people started recolonizing the previously abandoned summer dairy farms, as indicated in local historical sources. Our finding that the burned areas shifted from being independent of distance from the dairy farms pre 1625, toward a higher burn rate within a 1-km radius of the farms post 1625, supports this view. 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 gradually was abandoned during the 1700s (see Storaunet et al. [2013] for details and references).

What caused the decline in fires?

In our study, number of fires decreased from the mid-1700s, and after 1800, only scattered small fires occurred. This has been documented in other parts of Fennoscandia (Zackrisson 1977, Engelmark 1984, Lehtonen 1998, Niklasson and Granström 2000) as well as in boreal forests of North America (Heinselman 1973, Bergeron et al. 2001), although the timing of the decrease in fire frequency in most of these cases occurred almost a century later than in our study area. This general trend of decreasing fire activity has been explained by a gradual

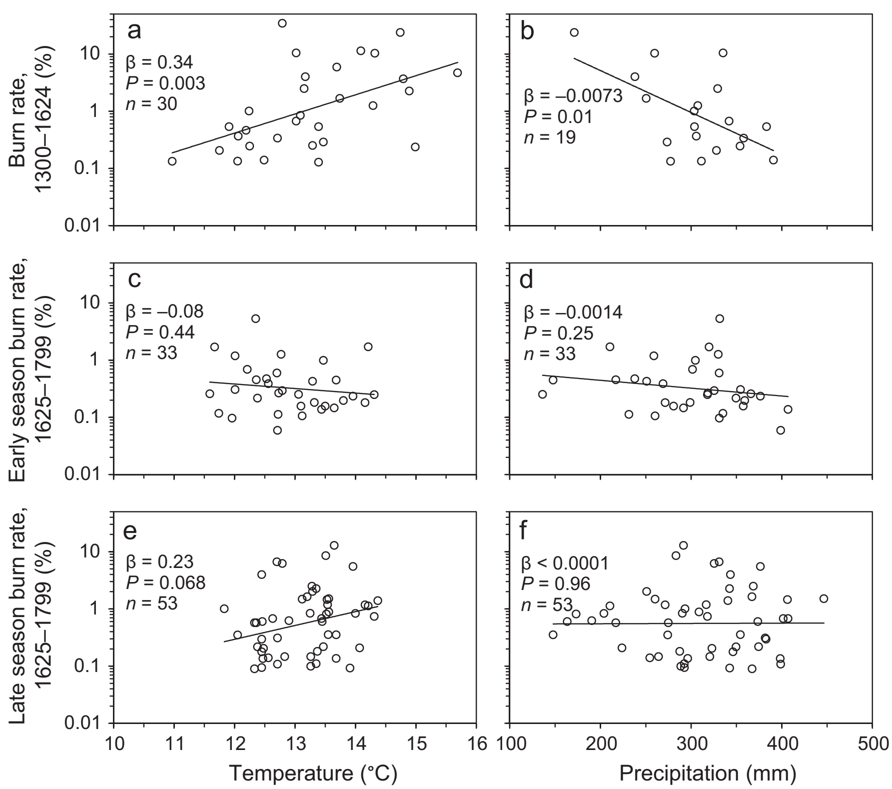

FIG. 14. Relationships between burn rate (annual percentage of area burned) and (a, c, e) mean summer (JJA) temperature and (b, d, f) sum of summer precipitation for the pre-1625 period (a, 1300–1624; b, 1500–1624) and the post-1625 (1625–1799) period (panel c–f). The post-1625 period is divided into fires occurring in early season (c and d) and in late season (e and f). β values are coefficients from simple generalized least squares (GLS) regressions with AR(1) autocorrelation form. Based on recorded (unadjusted) fire sizes ≥0.03 km^2 within recording area at logarithmic scale.

TABLE 3. Multiple generalized least squares (GLS) GLS-regression coefficients (β) describing the relationships between burn rate (annual percentage burned area) and climate variables during the early (1500–1625) and late periods (1625–1799).

	Period 1500–1624 (n = 19 fires)				Period 1625–1799: Early-season fires (n = 33)				Period 1625–1799: Late-season fires (n = 53)			
	β	SE	t	P	β	SE	t	P	β	SE	t	P
Intercept	−4.52	2.22	−2.04	0.058	1.30	1.40	0.93	0.36	−3.23	1.82	−1.78	0.082
Summer temperature (°C)	0.42	0.13	3.16	0.006	−0.10	0.10	−1.02	0.32	0.23	0.13	1.78	0.081
Summer precipitation (mm)	−0.0032	0.0024	−1.29	0.21	−0.0016	0.0012	−1.33	0.20	−0.0001	0.0012	−0.08	0.93

Notes: Based on recorded fires ≥0.03 km^2 in the recording area and corrected for autocorrelation with an exponential model (corExp). The late period is shown separately for early-season and late-season fires. See Fig. 14 for simple regression coefficients.

TABLE 4. Percentage of years with fire and average annual burn rates (%) in relation to summer temperature. Based on recorded fires in recording area.

	Period 1300–1624					Period 1625–1799: Early-season fires					Period 1625–1799: Late-season fires			
Temp °C	No. years	No. years with fires	Sum burned area (km^2)	Years with fire (%)	Burn rate (%)	No. years	No. years with fires	Sum burned area (km^2)	Years with fire (%)	Burn rate (%)	No. years with fires	Sum burned area (km^2)	Years with fire (%)	Burn rate (%)
10–12	42	3	0.33	7.1	0.01	10	4	0.74	40.0	0.13	1	0.42	10.0	0.06
12–13	136	8	21.15	5.9	0.26	73	15	5.25	20.5	0.12	21	12.19	28.8	0.26
13–14	108	11	15.90	10.2	0.25	68	15	1.70	22.1	0.04	28	24.06	41.2	0.55
14–16	39	8	29.65	20.5	1.29	24	4	0.97	16.7	0.07	7	2.86	29.2	0.19

abandonment of the slash-and-burn cultivation practice (Storaunet et al. 2013), 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. This legislation was due to the gradually increasing timber value, caused by increasing demands of timber in Europe, and regionally also from the Kongsberg Silver Mines, which opened in 1623 (located only 50 km south of the study area). The mining industry expanded after 1700, and in 1723 a management zone for timber supply was established around the silver mines. This designated area was subject to special legislation against the burning of forest, and by the mid-1700s slash-and-burn cultivation basically was forbidden and consequently abandoned (for further details and references, see Storaunet et al. 2013). This supports the view that a decrease in anthropogenic burning was a major reason for the decline in forest fires after 1800. Furthermore, the increased logging activity, by itself, most likely reduced the amount of dead woody debris and possibly created a more mosaic-shaped forest landscape that reduced the fire risk during the 1800s. The fact that most of our wood samples were collected from cut stumps shows that the logging activity was very high during this period. The increased demand for timber presumably generated more extensive efforts to suppress fires. However, it is doubtful how effective firefighting was during the 1800s in remote locations without access to roads and motorized equipment (Engelmark et al. 1994, Wallenius 2011). Finally, although deliberate burning to improve free-grazing conditions ceased during the 1800s, extensive livestock grazing continued up until about 1950. In addition to the timber harvesting, this may have contributed to reduce the fine fuel load that otherwise could have supported surface fires (Swetnam et al. 2016). Whatever reason being the most important, the combined effect of banning slash-and-burn cultivation, increasing logging, continued livestock grazing, and increasing fire suppression, strongly indicates that humans played a major role in reducing the fire frequency throughout the 1800–1900s.

In western Fennoscandia, the summer climate between 1570 and 1900 was rather cool and wet (the Little Ice Age; Grove 2004, Matthews and Briffa 2005, Nesje 2009), except for a warm (but still wet) intermittent period during 1750–1800. Notably, this warm climatic incidence, which is rather distinct and well documented (Luterbacher et al. 2004), happened to occur exactly during the main decline in fire frequency (see Fig. 4; Appendix S3: Fig. S3). This coincidence advocates strongly against climate being the cause of decline in fire activity.

Another possible reason for the decreasing fire activity is the expansion of Norway spruce. Local peat stratigraphies show that spruce pollen was only present in very low numbers in parts of the study area until about 500 yr BP (Kasin et al. 2013). Today, a few forest stands hold individual spruce trees with total ages in the range of 400–530 yr (Castagneri et al. 2013), but as these stands have few snags and downed woods, they may be the first generation of spruce in the area. To our surprise, we found that present-day spruce and pine forests, and forests at different elevations, experienced more or less the same fire return intervals, a pattern that also has been noted by Engelmark (1987) from Muddus in northern Sweden. These findings are consistent with a view that the forest landscape was more pine dominated at the time of the historical fires. Norway spruce makes the forest denser, darker, cooler, and thus locally more humid with moister soil conditions, all reducing flammability and fire activity. The question is whether an expanding spruce forest lessened the risk of fire, or whether a decreasing fire activity caused the spruce forest to expand. Most likely, an expansion of Norway spruce was promoted by the lower fire frequency, a successional pathway documented in more eastern Fennoscandian forest landscapes (Bradshaw and Hannon 1992, Bradshaw 1993, Wallenius et al. 2007).

In our view, abandonment of active anthropogenic burning, combined with reduced fuel loads due to increased logging and continued free-range grazing, were the principle reasons for the decline in forest fires. Subsequently, active fire suppression and a negative feedback from an increasing spruce dominance may have been contributing factors.

Density of fires

In our study, the density of fires ≥0.03 km^2 (based on adjusted number of fires) averaged 0.65 fires per 100 km^2 per year in the early period of 1300–1624, which we assume was moderately influenced by humans. In the following human-influenced period of 1625–1799, density of fires rose to an average of 2.41, with a maximum of 3.46 fires per 100 km^2 per year during 1650–1675. In northern Sweden, the only other study with comparable details, Niklasson and Granström (2000) estimated an average density of 0.10 fires per 100 km^2 per year in their early period of 1350–1650 (also based on adjusted number of fires). However, due to lower density of sampling points, and thereby lower detectability of smaller fires, their estimate applies to fires approximately ≥0.3 km^2 only. Restricting our estimate to the same lower cut-off point gives 0.11 fires per 100 km^2 per year, corresponding to the estimate from northern Sweden. A comparison for the post-1600 human-influenced period also reveals rather similar estimates of 0.58 and 0.39 fires (≥0.3 km^2) per 100 km^2 per year in Sweden and Norway, respectively. This overall conformity indicates that human activity boosted fire frequency four to six times compared to the earlier less-influenced period.

Lightning is the only natural cause of fire ignition in Fennoscandian forests (Granström 1993). Lightning density in the mid-boreal zone ranges about 30–50 cloud-to-ground lightning flashes per 100 km^2 per year (Rokseth et al. 2001, Larjavaara 2005, Anderson and Klugmann 2014). Average density of lightning-caused fires (the *ignition rate*, sensu Baker [2003]) have been reported to 0.08 fires per 100 km^2 per year in south-central Norway (Øyen 1998), 0.03–0.10 in central Sweden (Granström 1993), and 0.06–0.20 in southwestern Finland (Larjavaara 2005), indicating that the present *ignition ratio* (the number of lightning strikes needed to start one fire, Baker (2003)) varies in the range of 300–500. If all of our pre-1625 fires were caused by lightning, and applying the present lightning density, this gives an *ignition ratio* for the Trillemarka Reserve of 50–80, figures that are markedly lower than those reported today. Moreover, whereas we used a cut-off point at fires size 0.03 km^2 due to low detectability of smaller ones, present-day statistics report fires down to about 0.001 km^2. How can this mismatch be explained?

First, although fire surveillance has become more efficient during the last century, many small fires are not detected or reported in modern fire statistics. Using a simple probability model, Larjavaara et al. (2005) estimated that as much as 63–70% of the actual number of lightning-ignited fires might remain unreported. In addition, the ignition source is not known for 17–25% of the reported fires, many of which may have been started by lightning (Øyen 1998, Larjavaara 2005). Second, we may have added too many fires in the procedure to correct for low detection probability. We also may have drawn multiple fires in cases where there was only one. On the other hand, this will be counteracted by larger fires initially being started by multiple ignitions that later merged, of which the Yellowstone 1988 fire season is a good example (Rothermel et al. 1994). In our view, the statistical procedure behind the correction method seems well justified, and we see no obvious reasons that it should seriously have inflated the density estimates. Third, thunderstorms and lightning may have been more frequent historically. In general, lightning frequency increases with increasing temperature, but the retrospective temperature and precipitation proxies for the region do not indicate that the pre-1625 climate was very different from the present. Higher fuel loads may also have promoted the risk of fire. Intensive logging during later centuries efficiently has reduced the amount of old and dead trees, snags, and coarse woody debris (Granström 1993).

Finally, there may actually have been more fire-related human activity during the early period than we have inferred. Although we presently do not have firm evidence that this actually was the case, some summer dairy farms are mentioned in historical sources from AD 1413 and 1540. A national legislative decree from 1490 encouraged farmers to burn forests and sow rye every year (see Storaunet et al. 2013). Although the local population was greatly reduced after the Black Death epidemic in 1350, the main valleys were still subject to farming (Fig. 1b). With no parts of the study area being situated more than 7 km from the main valleys, people most likely used the outback country for fishing and hunting, activities that accidentally may have started fires. Thus, although the pre-1625 fire regime displayed a clear climate signal, the human influence may not have been negligible. Similar underestimation of early human activities has also been acknowledged by Niklasson and Granström (2000) and Wallenius et al. (2010) from northern parts of Fennoscandia. Altogether, the accumulating evidence indicates that the early pre-1600 fire regimes in Fennoscandia were affected by human activities in varying degrees, although to a much less extent than later.

Normalized size-frequency statistics

For the first time in Eurasian boreal forests, we present power-law fitted, normalized fire size distributions. Although the power-law related self-similarity model (Malamud et al. 1998) has been questioned as a universal relationship (Lehsten et al. 2014), it seems to be valid over more than five orders of magnitude for relevant fire sizes in boreal forests (coefficients of determination: $R^2 > 0.95$, Malamud et al. 2005, Jiang et al. 2009). Notably, the fitted power-law coefficients (log α and β) allow for estimation of densities and recurrence intervals of fires above a certain size. 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 ecoregions in Canada and the northern United States, log α values for lightning-caused fires range from −4.66 to −4.60 and β values from 1.33 to 1.60 during the last three to four decades (Boreal Shield, Boreal Plains, Temperate Steppe Mountains). Both our log α at −3.38 and β at 1.65 for the pre-1625 period are higher than the North American counterparts. Based on the cumulative size distribution of the pre-1650 fires in boreal Sweden (Niklasson and Granström 2000), the power-law parameters in that study area are rather similar to ours. Thus, in western Fennoscandia, smaller fires historically seem to have outnumbered the larger ones to a greater extent than what presently has been seen in wildfire regions of North America.

Although our statistics are based on a large number of fires during a long period, the spatial extent of our study area is small compared to the North American ecoregions. This must be taken into account when comparing the normalized fire size distributions. As acknowledged by Malamud et al. (2005) and Jiang et al. (2009), many small fires may go undetected or unreported. This may be more common in North America due to the remoteness of many of the regions. In addition, the process of initially smaller fires growing into single larger ones presumably occurs more often in ecoregions of North American due to more large-scale topography. This process of fire amalgamation will tip the slope of the power-law function toward lower β values.

Comparable data for European Russia and Siberian boreal forests are less accessible. A size distribution of fires ≥2 km^2 compiled for Central Siberia during 2001–2007 (de Groot et al. 2013) translates to a normalized frequency function with log α at −2.47 and β at 2.08, indicating higher fire frequency and smaller fires to outnumber larger ones compared to Fennoscandia. However, the Russian account includes human-caused fires, which according to Shvidenko and Nilsson (2000) amount to as much as 86% of the fires. Interestingly, the Central Siberian distribution coefficients come close to our post-1625 estimates of log α at −2.83 and β at 1.72.

Burn rates, fire return intervals, and hazard of burning

When delineating fires on the map, we excluded overlap areas <15 yr unless there was unequivocal evidence of shorter intervals in multiple scarred trees. This was done because in our data <2% of the individual scar-intervals were <15 yr, all of which occurred after 1625. This presumably was due to recently burned areas having too little fuel to burn over again, a pattern that 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). Niklasson et al. (2010), in a study of historical fires in lowland Poland, found many scar-based intervals <10 yr in Scots pine. Such short intervals are also commonly found in other pine species, e.g., *Pinus ponderosa* Douglas ex C. Lawson (e.g., 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.

Our fire intervals, survival curves, and corresponding hazard rates differed substantially pre- and post-1625, with complete-interval, map-based hazard of burning initially increasing and peaking at 60–100 yr pre 1625 and at 20–40 yr post 1625. These results corroborate those of Niklasson and Granström (2000), although their rates were based on composite scar intervals. In northern Sweden, Schimmel and Granström (1997) found no or only marginal risk of fire spread up to about 20 yr after fire, followed by a progressive rise in fire risk up to ~50 yr, after which the risk leveled off at a fairly constant rate.

Historical range of variability (HRV): reference and predictions

The historical range of variability (HRV) has been proposed as a useful guide for ecosystem management and a reference for predicting future conditions (Morgan et al. 1994, Perera et al. 2004). The idea is that if we keep present ecosystems within the past range of variability it might work as a "coarse filter" to maintain biodiversity (Seymour and Hunter 1999). Past responses of ecosystems to variation in climate and human impact may also warn us about possible undesired changes in the future. By dendrochronologically cross-dating fire scars in remnant woods of Scots pine, we provided unequivocal evidence that (1) fire has been a major natural disturbance agent and (2) that the forest ecosystem of the Trillemarka reserve has undergone major shifts in the fire regime during the last 700 years. The general conformity with earlier studies in Norway, Sweden, and Finland makes it increasingly clear that the human influence on the fire regime of Fennoscandian boreal forests has been spatially extensive and long lasting, first by increasing fire frequency through active slash-and-burn cultivation and pasture burning, later by almost eradicating fire by prohibiting active burning and actively suppressing wildfires.

Previous attempts to correlate climate variables with fire activity have produced ambiguous results for western Fennoscandia. Niklasson and Granström (2000) were unable to find significant correlation between historical number of fires and temperature. Based on improved climate proxies dating back to AD 1500, Drobyshev et al. (2014) found historical "large fire years" to be significantly warmer and dryer for northern parts of Sweden, but significantly wetter in southern Sweden. In another analysis, including last century fire and climate statistics, Drobyshev et al. (2016) suggested that cold and dry conditions promoted fires in northern Sweden, a phenomenon they linked to lower North Atlantic sea surface temperatures pushing low-pressure climate systems southward. In our study, located at the western fringe of the Eurasian boreal region, warmer summers consistently increased burn rates, both pre 1600 and late season post 1600, with only marginally additional contribution from precipitation. However, because temperature and precipitation were strongly negatively correlated, especially during the early period, their independent predictive significance should be interpreted with caution.

The dual role of forest fire, both constructive in terms of sustaining biodiversity and destructive in terms of loss to society, is well recognized. First, there is a certain segment of the boreal biodiversity that is closely associated and possibly dependent on recent burns, mostly species among beetles and fungi (Johansson et al. 2011, Kouki et al. 2012, Penttilä et al. 2013). Natural disturbance emulation by mimicking forest fire regimes is currently gaining acceptance as a management strategy both in North American and Fennoscandian boreal forests (e.g., Gauthier et al. 2004, Kuuluvainen and Grenfell 2012). In Sweden and Finland, prescribed burning for nature conservation is increasingly being applied countrywide (e.g., Rydkvist and Kraus 2010), but this management practice has yet to be implemented in forest reserves of Norway.

On the other hand, and perhaps more important, is the long-term buildup of organic matter, after two centuries of almost no fires. During the latter part of this period, Norwegian forests have experienced a 2.5-fold increase in standing volume and a 4-fold increase in dead wood (Storaunet et al. 2011). With global climate expected to become warmer, and fuel loads and human populations to continue increasing, wildfires are expected to become more frequent, larger, and more severe in the future (Gillett et al. 2004, Westerling et al. 2006, Kelly et al. 2013, Stephens et al. 2013). According to Marlon et al. (2012), the trend in fire activity has strongly diverged from the trend predicted by climate alone, thereby creating a "fire deficit" that is unsustainable given the current trajectory of climate change. Increased incidence of "mega-fires" (>100 km^2) will threaten timber resources, human settlements and infrastructure, and release large amounts of stored carbon to the atmosphere (Stephens et al. 2014). Summer of 2014, Sweden experienced the largest and most devastating forest fire in more than 100 yr. In the course of 2 weeks, the Västmanland fire burned 140 km^2 of productive forest, amounting to 100 mill. US dollars in direct loss and rescue operations (Earth Observatory 2014).

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Supporting Information

Additional supporting information may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/ecm.1244/full

Data Availability

Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.56p6q