Journal of Ecology

Journal of Ecology 2014, **102**, 738–748 doi: 10.1111/1365-2745.12235

Multi-century reconstruction of fire activity in Northern European boreal forest suggests differences in regional fire regimes and their sensitivity to climate

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Summary

1. Forest fires are one of the main disturbance agents in boreal and temperate ecosystems. To decipher large-scale temporal and spatial patterns of past fire activity in Scandinavia, we analysed the synchronicity of dendrochoronologically reconstructed fire events in a large network of sites (n = 62; 3296 samples, 392 individual fire years) covering a wide geographical gradient (56.5–67.0° N and 9.3–20.5° E) over AD 1400–1900. We identified large fire years (LFY) as years with regionally increased forest fire activity and located the geographical centres of climatic anomalies associated with synchronous LFY occurrence across the region, termed LFY centroids.

2. The spatial pattern of LFY centroids indicated the presence of two regions with climatically mediated synchronicity of fire occurrence, located south and north from 60° N. The return intervals of LFYs in Scandinavia followed a Weibull distribution in both regions. Intervals, however, differed: a period of 40 years would carry a 0.93 probability of LFY occurrence in the southern region, but only a 0.48 probability of LFY occurrence in the northern region.

3. Over 1420–1759, the northern region was characterized by significantly higher temporal variability in LFY occurrence than the southern region. Temporal correlation of LFYs with reconstructed average summer temperature and total precipitation was evident mainly for the northern region. LFYs in this region were associated with positive temperature and negative precipitation anomalies over Scandinavia and with colder and wetter conditions in more southern parts of the European subcontinent.

4. *Synthesis*. Historical patterns of the occurrence of large fire years (LFY) in Scandinavia point towards the presence of two well-defined zones with characteristic fire activity, with the geographical division at approximately 60° N. The northern and mid-boreal forests, although exhibiting lower LFY frequencies, appeared to be more sensitive to past summer climate, as compared to the southern boreal forests. This would imply that fire regimes across Scandinavia may show an asynchronous response to future climate changes.

Key-words: climate variation, dendrochronology, determinants of plant community diversity and structure, drought, fire risk, fire weather, natural disturbances, natural hazards, Scandinavia

Introduction

Forest fire activity has been an integral part of natural disturbance dynamics of the Scandinavian boreal and hemi-boreal forests over large parts of the current post-glacial period (Tryterud 2003; Barnekow *et al.* 2008). Except for (probably uncommon) fire refugia (Segerström, Hornberg & Bradshaw 1996; Ohlson & Tryterud 1999), fires in Scandinavian forests have occurred, on a stand scale, with typical intervals of 20 to 300 years, depending on landscape and site properties (Hellberg, Niklasson & Granström 2004) and the human

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setting of a particular time period (Niklasson & Granström 2000; Granström & Niklasson 2008). Climate has been shown to be strongly linked with the extent of regional forest fire activity in many temperate and boreal biomes (Stocks & Lynham 1996; Veblen *et al.* 1999; Girardin *et al.* 2006). In Scandinavia, the influence of climate on fires has in general been analysed in a long-term (millennial) context using coarse-resolution paleoecological methods (Miller *et al.* 2008; Greisman & Gaillard 2009; Bradshaw, Lindbladh & Hannon 2010). Studies done with higher temporal resolutions (e.g. annual and seasonal) have mostly dealt with non-climatic determinants of forest fire activity, such as interactions between humans and fire (Bleken, Mysterud & Mysterud 1997; Øyen 1998; Groven & Niklasson 2005; Granström & Niklasson 2008), fire suppression activities (Högbom 1934), the effects of landscape structure (Hellberg, Niklasson & Granström 2004) and the role of fuels (Schimmel & Granström 1997). Thus, the lack of annually resolved and long-term historical climate–fire relationships limit our ability to analyse climate–fire coupling in historical, modern, and future contexts.

The level of fire activity in Scandinavia has long since been related to summer drought conditions (Högbom 1934), suggesting a link between climate variability and forest fires. Indeed, a study of recent (20th century) fire activity in Sweden demonstrated a strong, though spatially inhomogeneous, correlation between various drought indices and annually burned forest areas (Drobyshev, Niklasson & Linderholm 2012). In terms of total area burned, forest fire activity in northern Europe has been decreasing since the late 19th century (Tryterud 2003). In Sweden, fire cycles (the time required to burn the area equal to the study area, *sensu* Van Wagner 1987) in different regions are currently on the scale of 10^3–10^4 years (Drobyshev, Niklasson & Linderholm 2012). This decline in forest fire activity has been attributed to efficient fire suppression policies introduced in the second half of the 19th century (Högbom 1934).

Understanding long-term climate–fire relationships in Scandinavia is challenging. It requires a spatially large and temporally long network of sites with fire histories extending over both the period of increased anthropogenic burning (~1600–mid 1800s, Lehtonen & Huttunen 1997; Groven & Niklasson 2005) and the fire suppression period (post 1860). Meeting these requirements is not a trivial task, since the availability of living trees and deadwood bearing fire scars, the principal source of fire history information, is generally poor across the region due to forestry practices eradicating the deadwood and fire-scared trees.

The present study attempts to overcome these methodological difficulties and to parameterize the climate–fire linkages by capitalizing on a large and annually resolved data set of fire history reconstructions spread across a large geographical gradient in the northern European boreal forest. The data set represents, to the best of our knowledge, the most extensive network of this kind in northern Eurasia. Extraction of climate signals from the available data set of individual fire dates required two main assumptions. First, we interpreted annually synchronous occurrence of fires across sites as a sign of climatic influence, the degree of synchronicity being positively correlated with the degree of climatic forcing upon annual fire activity (Falk *et al.* 2007, 2011). This association has convincingly been demonstrated in several regional and continent-scale studies (Veblen *et al.* 1999; Brown 2006) and received support in the analysis of 20th century fire activity across Central, eastern and northern Europe (Della-Marta *et al.* 2007) and, specifically, in Sweden (Drobyshev, Niklasson & Linderholm 2012). Secondly, based on results of a previous study (Drobyshev, Niklasson & Linderholm 2012), we assumed that the size of the study area is comparable to the geographical scale of climatic features responsible for patterns of regional fire activity, that is, at a synoptic scale. This assumption is important since it allows the interpretation of synchronicity in fire dates across sites as a geographical 'replica' of the overlying climate anomalies. Aiming at understanding large-scale climatic controls of fire activity in the European boreal zone, we put forward three specific goals: (i) to investigate the presence of large geographical patterns of historical fire occurrences in the northern European boreal forest, (ii) to examine differences in return intervals of large fire years (LFY), defined as years with strong synchronicity in fire occurrence across sites, and assess the scale of temporal changes in the LFY intervals over the studied time frame and (iii) to evaluate the sensitivity of regional fire regimes to climate by analyzing association of LFY with independently reconstructed temperature and precipitation records.

STUDY REGION

The studied sites were located within the geographical boundaries of 56.5–67.0° N and 9.3–20.5° E (Fig. 1a). The sampled area stretched over four bioclimatic domains, including northern boreal forests, mid- and south boreal forests, and boreo-nemoral forests (Ahti, Hämet-Ahti & Jalas 1968). For the purposes of this study, we consider the area of Sweden above 60° N as northern Sweden and below this latitude – as southern Sweden. Large gradients in many climatic variables exist between the southern and northern parts of the study area (Fig. 1b–d). Mean January temperatures vary from −2 °C in the south, to −18 °C in the north. Mean July temperature, however, is more homogenous, with values between 12 and 16 being common across most parts of the study area. The length of growing season, defined as the number of days with the mean temperature above 5 °C, is 170–200 days in the south and 130–170 days in the north (Raab & Vedin 1995). Total annual precipitation ranges from 1000 mm in southwestern part to 600–700 mm in the south-eastern and northern parts of the study area. Number of days with snow cover varies on average between 50 in the south and 170–225 in the north. Last day with snow cover typically occurs in early April in the southern part of the country and only after 1st of May in the north (Raab & Vedin 1995). A 10-fold variation in lightning strike densities is observed in the study area, with southwestern Scandinavia receiving the maximum number of strikes (Fig. 1b).

The sampled forests were dominated by *Pinus sylvestris* L. and *Picea abies* (L.) H. Karst. with a field-layer vegetation

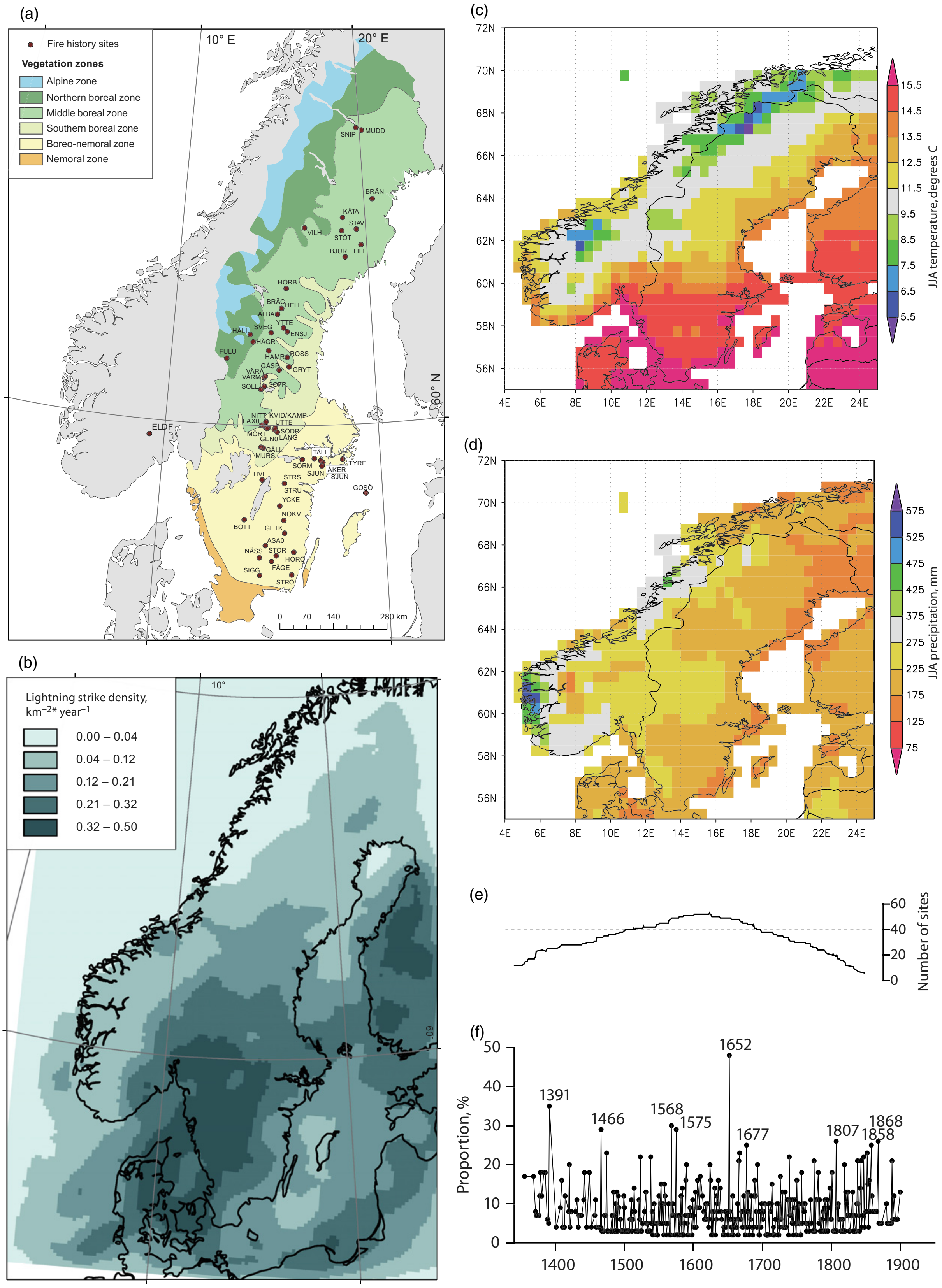

Fig. 1. Geographical location of the study sites (a); pattern of cloud-to-ground lightning strike density, May through September, for 1997–2000, 2002, and 2003 (SMHI 2004) (b); long-term pattern of summer (June through August) average temperature (c) and total precipitation (d) over 1900–2000; data replication represented as number of recording sites covering the study period (e) and frequency of fires years (f). Frequency of fire years is presented as a number of sites recording a particular fire year among all sites, which were 'active', that is recording, in that year. The annual lightning strike density was calculated for the circle with 50 km radius for grid cells with the dimensions of 10 × 10 km^2.

composed mainly of various ericaceous dwarf shrubs and with moss or lichen-covered ground.

Materials and methods

FIRE HISTORY DATA AND ANALYSIS

A data set of 62 fire history sites and 3296 samples were used in the analyses (Fig. 1a, b, Appendix S1). For all sites, fire dates were obtained on cross sections of fire-scarred Scots pine (*Pinus sylvestris* L.), using a classical crossdating technique (Stokes & Smiley 1968) and a number of subregional pointer year chronologies (M. Niklasson *et al.*, unpublished data). Despite the fact that the sites were originally studied within the frame of different projects carried out over a period of about 15 years, the field sampling protocols remained largely the same. Each site was searched for the presence of living or deadwood material of Scots pine, which was sampled with a chainsaw to obtain wedges or cross sections with fire scars. Old trees were routinely sampled in search of completely closed (overhealed) scars. Crossdating of all samples was verified by one of the co-authors (M.N.). During dating, we attempted to recover seasonal information about historical fire events by identifying, when possible, location of the scar with respect to the early- and latewood portions of the ring. The sites varied in terms of size of the sampled territory and temporal period covered (Appendix S1). Further details of sampling for fire history reconstructions are available elsewhere (Niklasson & Granström 2000).

Despite differences in the amounts of data among the sites, we did not employ any weighting or filtering protocols, for example, by assigning higher weights to the sites with larger area covered or single fire years with higher number of samples. The rationale for this was fourfold. First, we lacked a clear *a priori* hypothesis giving reason for discriminating sites on the basis of their properties. Secondly, we considered weighting sites or single fire events as not appropriate given the current knowledge of forest fire history in Scandinavia. Previous studies have convincingly shown that both the average and the maximum fire sizes have been declining (Niklasson & Granström 2000; Drobyshev, Niklasson & Linderholm 2012), starting at different periods. Further, our unpublished data suggest that these changes also had a spatial component, onset of suppression activities occurring at different times across the country. It follows that adjusting the weight of each fire chronology for the sample replication at site scale would be complicated by changing average/maximum number of samples simply due to changing average/maximum fire size. Any adjustment function developed to address this problem will involve multiple assumptions in time-space domains. Since our goal was to minimize the number of assumptions, we rejected this strategy. Thirdly, giving more weight, for example, to larger sites will inevitably increase the influence of properties of particular landscapes (properties such as average fire size, possibilities of fire spread, fuel loads) on the overall picture of fire activity. Finally, we were interested in preserving the maximum number of sites in the data set to ensure reasonable amount of data for the spatial analyses. By avoiding data filtering with respect to the absolute number of fire-scarred samples, we could potentially face two problems: (i) difficulty in translating occurrence of LFYs into absolute estimates of burned area during those years and (ii) difficulties in understanding heterogeneity within the group of indentified LFYs, with respect to the actual area burned. Both issues appeared of little importance for the current study since we did not attempt to reconstruct absolute estimates of the burned areas.

Analysis of age cohort data, temporal coverage of dated samples and timing of the onset of fire suppression on each site were used to keep a proper track of eventual hiatuses in the fire records. Particularly, site replication in a year was understood as the number of sites supplying material for a particular calendar year. Importantly, a site contributed to the replication only up to the year of the last fire on that site. Sites in the fire suppression period, onset of which in Sweden is dated to the period between mid-1700s and mid-1800s, were therefore of little use for our analyses, and by removing them, we ensured that that analyses were done on the pool of sites where fires could occur. Thus, even if dendrochronological material was available for a site, the latter did not contribute to overall replication if it already had entered the fire suppression period.

DEFINING SYNCHRONICITY IN FIRE OCCURRENCE

We used a composite definition of LFY, utilizing both the percentage of sites burned in a year and theoretical probabilities of observing a particular number of sites burned in a year. In particular, we first evaluated the relationship between absolute number of sites recording a fire year and corresponding proportion of these sites in the total number of recording sites during that year (Appendix S2) and selected years with ≥20% of sites burned. Secondly, we evaluated the theoretically expected frequencies of years with fire recorded at different number of sites and calculated joint probabilities of fire occurrence for years with up to eight sites burning in the same year (Swetnam 1993). We limited our analysis by eight sites since in our data set, the theoretically expected number of years with eight sites burned was zero (assuming random occurrence of fire across sites, Appendix S3). We calculated expected frequencies of years with no, one and multiple sites burning, assuming the binominal distribution of the events:

$$P(X) = \frac{N!}{X!(N-X)} P^x q^{N-X} \qquad \text{eqn 1}$$

where N was the total number of recording sites in the analysis of a specific period; X – number of burned sites in a single year; P – the probability of a site burning in any year; and q – inverse of this probability. The differences between expected and observed frequencies were estimated with the chi-square test (Sokal & Rolf 1995). The selection of threshold was based on the analysis of expected and observed frequencies of years with different numbers of burned sites. The threshold was selected as a minimum number of burning sites, corresponding to at least a twofold difference between observed and expected frequencies within any of the 100-year periods within the studied time frame (AD 1400–1900). This was done to address the fact that fire frequencies varied over time and to verify that our selected threshold was not compromised on shorter intervals.

Years qualifying both criteria were considered as climatically driven LFY. Following this protocol, we effectively avoided problems with non-climatic variability in average fire sizes over the different parts of the study period (Niklasson & Granström 2000), enhancing the climatic signal in the resulting LFY record.

SPATIAL ANALYSES

The spatial analysis was used to classify the study area into subregions, based on the synchronicity of fire years among sites. Our rationale was that synchronicity in fire occurrence is a manifestation of atmospheric circulation anomalies with a defined spatial extent and a geographical centre. To estimate its centre position, termed *LFY centroid*, we averaged coordinates of all sites burned during a LFY. Geometrically, a LFY centroid corresponded to the centroid of points, which in this case were burned sites (Appendix S4, a). Clearly, the position of the LFY centroids was not 'absolute' in a sense that it was dependent on configuration of the study area, the number and location of actual recording sites. LFY centroid might therefore be biased in relation to the actual climate anomaly (Appendix S4). We, however, did not consider that as a problem for this study since the aim of the whole spatial exercise was to establish the zonation *within* the study area. Another potential difficulty with this method would arise if different weather systems caused fire activity, for example, in two separate parts of the study area. In this case, coordinates of the centroid would point to the area away from the centres of the respective climate anomalies. The resulting effect, if present, would decrease the power of the spatial classification algorithm. We used *K*-means clustering (Hartigan & Wong 1979; Sokal & Rolf 1995) on latitude–longitude coordinates of established LFY centroid to objectively identify the geographical affinity of each LFY.

To estimate the optimal number of clusters, that is the classification minimizing the loss of information, we bootstrapped 1000 times the value of the Jaccard index, a measure of similarity among *a priori* established clusters, for classifications with up to seven clusters and selected classification with the lowest Jaccard index values (Hennig 2007). To do that, we selected randomly and with replacement LFYs from the complete pool of LFYs and recalculated LFY centroids and respective Jaccard values for each bootstrap run. To assess the statistical robustness of the obtained classification, we compared the obtained two-cluster classification and a set of 1000 bootstrapped classifications utilizing the same set of LFY centroids but with randomly chosen cluster identities. To verify if sizes of study areas differed among subregions, we compared distributions of site areas by Student's *t*-test.

ANALYSIS OF RETURN INTERVALS FOR LFYs

The distribution of fire return intervals, that is the average number of years between successive fires for a single stand, can often be well represented by the Weibull probability distribution (Grissino-Mayer 1999). We tested whether the distribution of LFY return intervals could be approximated by a Weibull distribution using the Hollander-Proschan test, utilizing only complete (uncensored) observations (Dodson 1994). In the context of our analyses, uncensored intervals were those between two LFY recorded within a geographical region. Cumulative functions were compared using the Cox-Mantel test, a powerful test for comparison of survivorship functions drawn from populations that follow Weibull or exponential distributions (Lee, Desu & Gehan 1975). Differences in spreading of return intervals, represented by the scale parameter, were tested by a permutation test. It consisted of random resampling without replacement of the original distributions and recording the number of cases when empirical difference in scale parameters exceeded the value obtained during resampling.

CONNECTION OF LFYs TO INDEPENDENTLY RECONSTRUCTED CLIMATE

We used Europe-wide gridded (0.5° × 0.5°) seasonal temperature (Luterbacher *et al.* 2004) and precipitation (Pauling *et al.* 2006) reconstructions to relate subregional LFY records to reconstructed summer precipitation. Since the precipitation reconstructions extended back to only 1500, we did not consider LFY chronologies prior to that year. For the southern region, the LFY chronology covered the period 1523–1759 and contained 16 LFYs. For the northern region, the chronology covered the period 1514–1858 and contained 11 LFYs. For each region-specific LFY and grid point, we obtained average summer (JJA) climate anomaly, calculated as difference between the focal (LFY) and long-term values. Prior to the analysis, we transferred climate data for each grid point by calculating difference between each value and ten previous years. This was done to reduce the effect of low-frequency variability in reconstructed climate variables on results of the comparisons. The statistical significance of precipitation and temperature anomalies during LFYs in each region was tested assuming normal distribution of data values using 0.1 significance level in Climate Explorer (http://climexp.knmi.nl/, van Oldenborgh & Burgers 2005).

Results

TEMPORAL AND SPATIAL PATTERNS IN FIRE ACTIVITY

The site fire history chronologies contained 392 individual fire years over the 500-year period 1400–1900. Site replication stayed above 20 sites from 1400 to 1880 and dropped down to 10 for the last 20 years of the 19th century (Fig. 1b). Considering the whole data set, general synchronicity of fire occurrence was considerable: we found nine fire years (1391, 1446, 1568, 1575, 1652, 1677, 1807, 1858, and 1868) with occurrences at ≥25% of the sites (Fig. 1c). The year 1652 was clearly exceptional in the analysed data set, with 48% of the sites burned.

K-means clustering resulted in two clusters with significantly different positions ($P < 0.01$). Bootstrapping with up to seven *a priori* selected clusters showed that two-cluster classification yielded the lowest Jaccard index value (mean and SD for 1000 runs: two clusters 0.449 ± 0.422, three clusters 0.815 ± 0.235, four clusters 0.721 ± 0.232, five to seven clusters >0.681 ± 0.226). This indicated that the chosen two-cluster classification was optimal in minimizing loss of information.

Visual examination of LFY centroid positions revealed that geographically they were separated by the latitude of 60° N (Fig. 2a). To verify that the average coordinates of active sites during LFY did not have an impact on the classification results, we also plotted the results as differences between LFY centroid coordinates and average latitude and longitudes for respective year (Appendix S7). The original classification yielded the highest ratio between-cluster/total sum of squares (55.00), as compared to 1000 bootstrapped runs with geographical locations assigned randomly chosen LFY centroid identities (maximum values in all runs 34.0), indicating that it was superior over any bootstrapped classification.

Sites below 100 ha dominated the whole data set and both regions (Appendix S5). *t*-tests for interdependent samples showed no difference between the two regions with respect to the size distribution of the sites ($P = 0.957$).

A moderate proportion of fires were dated with seasonal resolution in each subregion: 10 and 19% in north and south subregions, respectively. Dormant-season fires and fires timed at the start of the earlywood development dominated in the southern region, whereas this group of fires was the smallest one in the northern region (Appendix S8).

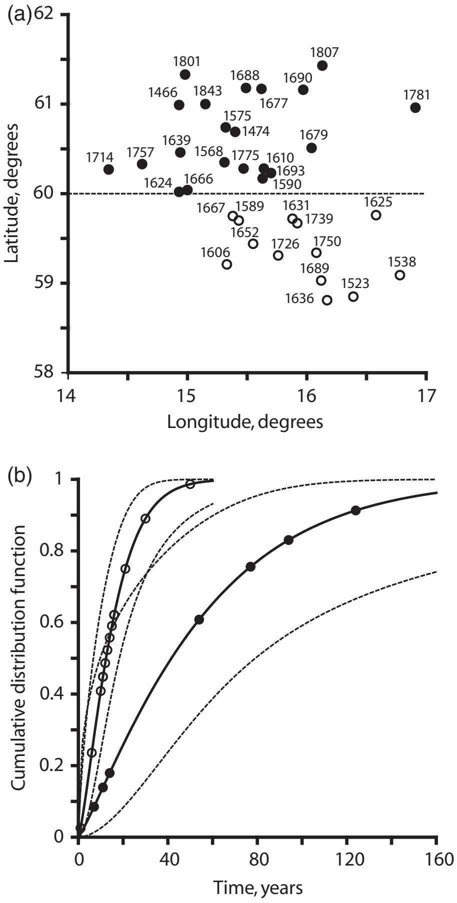

Fig. 2. Geographical location of LFY centroids over 1450–1850 and its classification into two geographical clusters (a), and cumulative distribution functions for northern (filled circles) and southern (empty circles) subregions (b). Dotted lines refer to 95% confidence envelop for each curve. The common period analysed was 1420–1759. LFY, Large fire year.

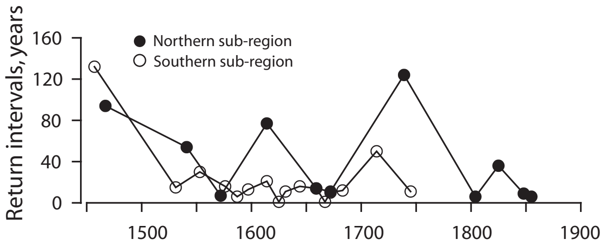

Fig. 3. Temporal dynamics of return intervals of LFYs for northern (filled circles) and southern (empty circles) subregions. Points represent middles of respective intervals. The average percentages of sites burned during LFY were 28.1% and 31.2% in the northern and southern subregions, respectively. LFY, Large fire year.

RETURN INTERVALS FOR LFY WITHIN NORTHERN AND SOUTHERN SUBREGIONS

At the subregional level, the classification protocol used thresholds of six sites for both the northern and southern subregions. We used the Hollander-Proschan test to confirm that the resulting distributions of LFY return intervals could be approximated by Weibull distributions (Table 1), negative exponential distributions being inadequate for both subregions. The fire return intervals were longer in the northern than in the southern region (Fig. 2b). Cox-Mantel test statistics was 2.35 and significant at $P = 0.019$. Over the 1400–1900 period, LFY return intervals in the northern region showed large variability (Fig. 3). Long-term pattern of LFY intervals suggested a decline in interval lengths in the second half of the 1600s and their subsequent increase over the 1700s, observed mostly in the northern subregion. A trend towards shorter intervals could also be noted in the 1800s.

Generally, the temporal dynamics of LFY return intervals was more pronounced in the northern than in the southern subregion. Indeed, permutation test with the scale parameter of Weibull distributions for northern and southern subregions showed that the empirical difference between scale parameters (39.75) was equal or smaller than a resampled value only eight times in 1000 permutations (with average difference 7.62), giving 0.008 probability of this difference being a random event.

COMPARING LFY RECORDS WITH CLIMATE RECONSTRUCTION

The LFYs, identified separately for both regions, were compared with summer (JJA) temperature and precipitation reconstructions to evaluate association of LFY with climate anomalies (Fig. 4). LFYs in the northern subregion were associated with positive temperature anomalies covering northern and a larger part of Central Europe, areas below 50° N showing cooler than normal conditions. With regard to precipitation, these years exhibited negative anomalies located approximately above 60° N, and wetter conditions below 60° N, including a larger part of the continental western Europe and British Isles.

Large fire year in the southern subregion were not associated with any temperature anomalies which were significant at 0.1. However, a tendency for warmer summers in southern

Table 1. Distribution parameters for return intervals of large fire years (LFY) in two regions for the common period 1420–1759 (see statistics for the whole study period in Appendix S6)

Geographical subregions	*n*	Mean ± SD	Range	Weibull shape, scale	Covariance, shape/scale	HP test (statistics, *P*)
Northern	7	54.4 ± 46.0	7–124	1.15/57.2	2.25	-1.36×10^{-2}/0.989
Southern	15	15.1 ± 12.0	1–50	1.31/16.5	0.269	-1.07×10^{-2}/0.915

n – Number of intervals, HP – Hollander-Proschan goodness-of-fit test for conformity of empirical distribution to a Weibull distribution. Only complete intervals were used in analyses.

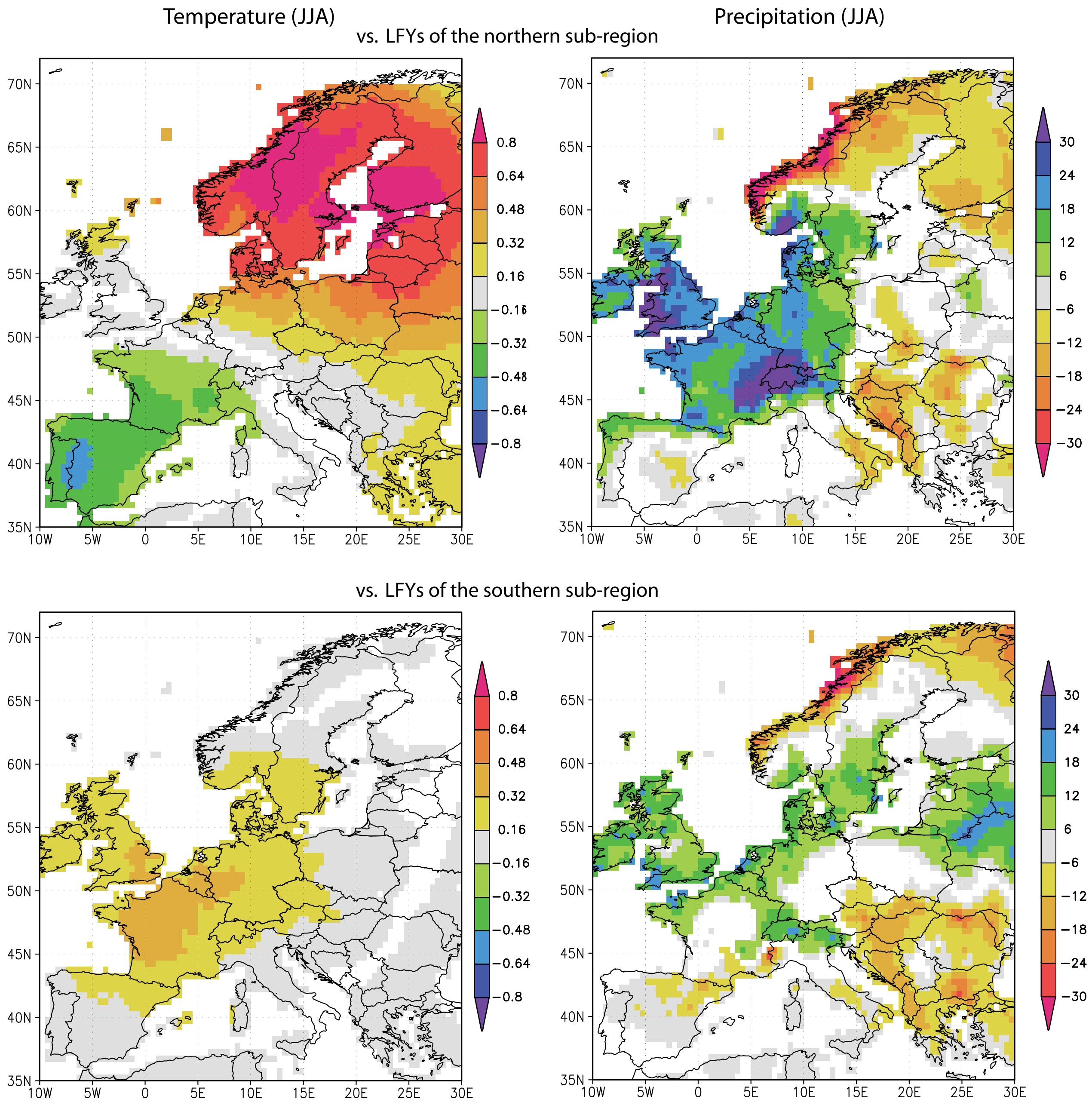

Fig. 4. Relationship between LFYs and temperature (Luterbacher *et al.* 2004) and precipitation reconstructions (Pauling *et al.* 2006) in two subregions over 1500–1860. Colour codes represent departures significant at 0.1 for all graphs except for the graph with LFYs and temperature comparison for the southern subregion, where no departures were significant at 0.1 and results are shown without filtering. LFYs, Large fire years.

Scandinavia and western Europe was visible in the data (Fig. 4). Analysis of precipitation suggested that these years were wetter in southern Scandinavia (~below 65° N), along the Atlantic coast of Europe and in the British Isles.

Discussion

GEOGRAPHICAL PATTERN OF HISTORICAL FIRE ACTIVITY

Years with increased forest fire activity are crucial drivers of ecological processes in temperate regions, making profound impacts on the atmospheric properties, landscapes and population dynamics of species. Long-term ecological effects of fire disturbances occurring during such years have previously been acknowledged (Meyn *et al.* 2007), although in many parts of the temperate and boreal regions, we lack detailed information on the frequency and spatial patterns of these events. In this paper, we provide the first large-scale analysis of historical fire occurrence in northern European boreal forest, suggesting the presence of well-defined temporal and spatial patterns during years with increased fire activity. Spatial analysis of LFY centroids suggested that over the studied area, the geographical division between two regions with characteristic fire activity could be found around 60° N. Although a N–S division of the defined clusters was not surprising, given the large N–S extent of the study area and differences in general length of the fire season along this axis (Raab & Vedin 1995), the position of the actual division line is of interest. It revealed the same geographical pattern as shown in studies of modern fire records, historical drought indices and distribution pattern of fire-adapted species. Specifically, an analysis of 20th century county-scale forest fire activity in Sweden suggested two zones with largely independent fire activity located approximately above and below 60° N (Drobyshev, Niklasson & Linderholm 2012). Moreover, a reconstruction of the Drought Index (DI), a ratio of actual to equilibrium evapotranspiration (AET/EET) over the growing season, indicated that the separation of zones with different DI dynamics occurs around 57–60°N (Drobyshev *et al.* 2011). The biological meaningfulness of this geographical limit is also implied by the fact that the division line roughly coincides with Limes Norrlandicus, a major biogeographical division between the northern and southern boreal forests, dividing the Central Plain and the Fennoscandian shield in Sweden (Dahl 1998). Interestingly, a number of fire-associated species have their northern distribution limits close to the above-mentioned latitudes. For example, a fire-adapted herb species *Geranium bohemicum*, whose germination is triggered by heat, extends its northern distribution limit to approximately 63° N (Granström 1993).

We envision two non-exclusive explanations of the observed geographical pattern. First, different atmospheric circulation systems could be responsible for establishment of two zones with mostly independent fire activity. In the North, years with strong anti-cyclonic activity are associated with increased temperature and decreased precipitation (Antonsson, Chen & Seppä 2008). Anticyclonic activity apparently decouples the weather pattern of this subregion from the rest of Scandinavia and likely enhances the role of local convection processes, delivering lightning ignitions. Secondly, differences in fire seasonality might play a role in shaping the observed pattern. The limited number of LFY fires dated with seasonal resolution demonstrated a small but significant difference in fire seasonality between the two subregions (Appendix S8). Further, analysis of modern fire activity (Drobyshev, Niklasson & Linderholm 2012) suggests that the majority of the burned area in southern Sweden is recorded earlier than in the north, perhaps related to earlier snow-free conditions at a time of year when precipitation typically is at its lowest (Raab & Vedin 1995).

DYNAMICS OF LFY RETURN INTERVALS

The probability of LFY was significantly higher for the southern region where a period of 40 years would carry 0.93 probability of LFY occurrence, compared to only 0.48 probability of LFY occurrence in the northern region. Shorter return intervals in the southern region might reflect (i) higher synchronization in the frequency of effective lightning ignitions and (ii) a generally longer fire season in the south, increasing the frequency of regional fire-prone episodes. The geographical differences in lightning strikes (Fig. 1b) and lightning ignition densities could contribute to the short return interval of LFY in the southern subregion. A study of modern lightning ignition data across Sweden has showed a fivefold gradient of lightning-caused fires with its highest frequency observed in the southern–eastern part of the country (Granström 1993).

In both regions, a prominent feature of the temporal dynamics of LFY return intervals was a sharp increase in interval length during the 1700s. The timing of this period coincided with the coldest period of the Little Ice Age in Scandinavia (Fig. 10 in Gouirand *et al.* 2008). Although the temperature reconstructions suggest that the 1700s in Scandinavia were not much different (difference within 0.5 °C) from the conditions at the turn of 20th century, the summer precipitation appeared to stay generally above the long-term average (Appendix S9, Luterbacher *et al.* 2004), suggesting lower water deficits in forest fuels.

Cold weather might not necessarily translate into longer LFY return intervals in the past. The generally cold period known as Maunder solar minimum (second half of 1600s) coincided with shorter LFY intervals, the effect being mostly visible in the northern subregion. Decline in solar activity translated into colder weather recorded across the temperate zone of the northern hemisphere (Luterbacher *et al.* 2001; Xoplaki *et al.* 2005) and was also associated with more negative values of spring NAO, implying reduced precipitation amounts reaching Scandinavia, particularly during the spring period. This, in turn, would suggest higher levels of water deficit developing in forest fuels over the summer and a higher frequency of years with increased fire hazard. Association between colder weather and lower air humidity has earlier been suggested for the area of Quebec, where lower temperatures reconstructed for the period of the Little Ice Age coincided with increased fire frequency and shortening of the regional fire cycles (Bergeron & Archambault 1993; Girardin *et al.* 2013). We speculate that a similar mechanism might have been in action also in Scandinavia, the colder conditions being primarily related to a reduced transport of moist air from the Atlantic during spring months. Indeed, in the seasonal precipitation reconstructions of Pauling *et al.* (2006), several periods with clearly reduced summer precipitation are visible for both regions during the Maunder minimum (Appendix S9). We should note here that the mentioned climate reconstructions represent 'mean' climate, whereas LFY dynamics generally reflect more extreme conditions at shorter, often subseasonal temporal scales, which may not be well captured by such reconstructions. Although this limits the meaningfulness of comparing climate- and fire reconstructions, they may nevertheless point to important links between these processes at different temporal domains.

Considering a temporal perspective, longer fire return intervals in the North would translate into longer periods of fuel accumulation, higher quantities and continuity of fuels, and, possibly, stronger fire synchronicity within that region. However, our analyses showed the opposite pattern (higher synchronicity in the South as compared to the North), indicating that this feedback was of little importance at large regional scales in Scandinavia.

SENSITIVITY OF NORTHERN EUROPEAN BOREAL FOREST TO CLIMATIC VARIABILITY

Association between LFYs and anomalies in summer temperature and precipitation (Fig. 4) suggested an important role of climate in controlling regional forest fire activity in Scandinavia. Both temperature and precipitation patterns during LFYs in the northern subregion pointed to continental-scale changes in atmospheric circulation during such years. We speculate that southward shifts of westerly storm tracks, leading to warmer and drier conditions in northern Scandinavia (Bengtsson *et al.* 2006; Linderholm, Folland & Hurrell 2007), was the primary driver of LFYs in that subregion. As for the southern subregion, association of LFYs with increased summer precipitation is counter-intuitive but could possibly arise if the fires during LFYs are separated in time from the bulk of precipitation. This warrants further analyses. In two out of four comparisons between LFY lists and climatic data sets (namely, precipitation analyses for both regions, Fig. 4) geographical borders of significant climate anomalies were located close to 60° N. This observation supported the results of the spatial analyses of the fire record, suggesting a division of the study area into two subregions with the border between them located at that latitude. Differences in fire seasonality might be behind both the larger temporal variability in fire activity and its better link to climate in the northern subregion.

The larger variability in historical frequency of LFYs and a stronger association between LFYs in the northern subregion and continental-scale climate variability suggested that northern and mid-boreal forests might be more sensitive to past changes in summer climate, compared to vegetation in more southern parts of Scandinavia. In the context of future projections, this would imply that fire regimes across Scandinavia may show an asynchronous response to future climate changes. Particularly, the fire regime of the northern boreal forests is expected to follow changes in future temperature and precipitation regimes more closely than other parts of the North European temperate region. A higher sensitivity of northern forests coupled with projections from global climate models (GCM) indicating more severe climate changes at high latitudes (Meehl *et al.* 2007) would point to much more dynamic and uncertain future of this vegetation. Specifically, changes in summer aridity affected by projected increases in temperature (Büentgen *et al.* 2011) and precipitation (IPCC 2007) will define trends in LFY return intervals and regional fire cycles.

Eventual higher sensitivity of northern forests coincides with generally higher percentage of forest cover in the North, lesser fragmentation of the forest cover and forest fuels, as compared to forests in the south of Scandinavia. This may amplify the climatic forcing upon fire regimes in the northern subregion, representing a general trend of increasing ecosystem sensitivity to climatic changes with increasing latitude (Serreze & Barry 2011). In contrast to North America (Bergeron, Leduc & Li 1997), even large changes in regional fire regimes in Scandinavia, characterized by generally low diversity of tree strata and wide-spread dominance of very few boreal trees, are unlikely to have an effect on the distribution of main tree species.

Acknowledgements

The project was done within the frameworks of the Nordic-Canadian network on forest growth research, supported by the Nordic Council of Ministers (grant # 12262 to I.D.), the Swedish-Canadian network on dynamics of the boreal biome, supported by the Swedish Foundation for International Cooperation in Research and Higher Education STINT (grant # IB2013-5420 to I.D.), and was also supported by the Swedish Research Council FORMAS (grant # 2007-1048-8700-51 to H.L.). We thank Swedish Meteorological and Hydrological Institute for giving us access to lightning strike data. M. N. thanks FIREMAN project (Fire Management to Maintain Biodiversity and Mitigate Economic Loss) for financial support. We thank Narek Pahlevanyan, Gyumri State Pedagogic Institute, and Sandrine Picq, UQAT, for programming help, Mélanie Desrochers (UQAM) for help with cartography, Geert Jan van Oldenborgh (KNMI) for advice on the use of Climate Explorer, and anonymous referees for constructive comments on earlier versions of the MS.

Data accessibility

Data used in this paper are available in the Supporting Information section and online at www.dendrochronology.se/fdbase (from 2015-03-01).

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Received 8 May 2013; accepted 18 February 2014
Handling Editor: Matt McGlone

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Characteristics of the study sites. Site codes correspond to the codes on Fig. 1.

Appendix S2. Relationship between absolute number of sites recording a fire year and corresponding proportions of the total number of recording sites during fire years.

Appendix S3. Contingency analysis of the synchronous occurrence of fire events in northern and southern regions.

Appendix S4. Identification of the LFY centroid (A) and the bias associated with this protocol (B).

Appendix S5. Site size distribution in two subregions.

Appendix S6. Distribution parameters for return intervals of large fire years (LFY) in two regions for the whole studied period. For abbreviations see Table 1.

Appendix S7. Geographical location of LFY centroids for large fire years over 1450–1850.

Appendix S8. Seasonal pattern of LFY for two subregions.

Appendix S9. Dynamics of reconstructed summer precipitation (Pauling *et al.* 2006) in the southern and northern regions over 1500–1900.