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A 700-year record of large fire years in northern Scandinavia shows large variability and increased frequency during the 1800 s

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ABSTRACT: Years with climatically mediated increases in boreal forest fire activity, referred to as large fire years (LFYs), contribute to a disproportionally large portion of the burned area over centuries, and are important drivers of ecosystem processes by affecting forest structure, biodiversity, and carbon balance at regional and continental scales. We analysed changes in LFY return intervals in northern Sweden (the area above 60 °N) over 1273–1960 using a network of 29 sites with dendrochronologically reconstructed fires, complemented by documentary records of fires available from forestry statistics. We observed large variability in return intervals of LFYs, an increase in LFY frequency during the 1800 s, and consistent associations between LFY occurrence and 500-hPa pressure anomalies over the European sub-continent over 1800xps2#1960. An increase in LFY frequency during the 1800 s might be climatically driven, and would thus long precede the period of likely human-induced climatic changes of the 1900 s. Long-term variability in climatically driven LFYs may present a challenge in partitioning the effects of human-related and human-independent components of climatic forcing upon forest fire activity.

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KEYWORDS: boreal forest; climate change; climate forcing; disturbance regimes; fire reconstruction; fire suppression.

Introduction

Forest fire has been a major factor in the development of natural vegetation, and probably the most important natural hazard in the boreal zone over the Holocene (Bradshaw *et al.*, 2010) and over the more recent historical time frames (10^1–$10^{2(3)}$ years, Zackrisson, 1977; Niklasson and Granström, 2000). The impacts of natural fire on forest ecosystems are complex and include both direct and indirect effects, such as changes in forest structure (Johnson, 1992), biodiversity levels (Lindbladh and Nilsson, 1999; Granström, 2001), and release of gases and aerosols into the atmosphere (Conard *et al.*, 2002; Kasischke *et al.*, 2005). Large variability in modern fire activity exists across the boreal zone of the Northern Hemisphere, most of the fires occurring in the Russian and Canadian sectors (Stocks and Lynham, 1996). Satellite-based estimates suggest that in Siberia, for example, more than 13 million ha can burn in a single large-fire year (LFY; Conard *et al.*, 2002). In contrast to these regions, modern fire activity in Scandinavia is relatively low. In Sweden, for example, the fire cycle (the time required to burn the area equal to the study area, *sensu* Van Wagner, 1987) is currently 10^3–10^4 years (Drobyshev *et al.*, 2012). Historically, however, forest fires were an important factor driving ecosystem dynamics of northern European forests before and following the introduction of slash-and-burn practices at around 1600–1700 (Niklasson and Granström, 2000).

Climate is the principal driver of fire activity at large ($> 10^{5-6}$ km^2) geographical scales in the boreal forest. Drought events synchronize forest fuel conditions over the regions where prolonged blocking high-pressure cells develop in the upper atmosphere (Skinner *et al.*, 2002). Until recently, possibilities for large-scale analysis of climate–fire coupling in Scandinavia were limited by insufficient data availability. In Sweden, instrumental data on single large years are available only since the late 1800 s (Högbom, 1934), and detailed, county-specific, fire records only exist for the periods between 1942 and 1975 (Skogsstyrelsen, 1942) and from 1996 to the present (MSB, 2011). Many studies have demonstrated the value of dendrochronological datasets in extending these records back in time (Swetnam, 1993; Falk *et al.*, 2011 and references therein). In Scandinavia, dendrochronological reconstructions of forest fires have accumulated since the 1970 s (Kohh, 1975). With few exceptions (Niklasson and Granström, 2000) reconstructions were limited to parts of single watersheds or even single stands. As a result, earlier attempts in Scandinavia to relate temporally extensive but geographically limited datasets to past climate were not convincing (Niklasson and Granström, 2000). However, newly compiled regional datasets containing dendrochronologically reconstructed fire dates over extensive parts of Sweden (Drobyshev *et al.*, 2014) and recently developed independent climate reconstructions covering this part of northern Europe (e.g. Casty *et al.*, 2007) make such analyses possible. In particular, available long-term atmospheric pressure reconstructions may potentially present a valuable proxy of historical fire-related climate variability at large geographical scales, integrating temperature and precipitation variability.

In the current study we analysed temporal trends in the return intervals of LFYs and their association with reconstructed 500-hPa pressure anomalies over northern Sweden. We specifically focused on LFYs because forest fire activity in Scandinavia has been affected by land-use patterns and practices where fire was deliberately used or suppressed, masking the climatic signal in fire activity (Pyne, 1997;

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Drobyshev *et al.*, 2004b; Granström and Niklasson, 2008). LFYs are a result of synchronicity in fire occurrence at regional scales, and can be considered a sign of climate impact. The degree of synchronicity positively correlates with the degree of climatic forcing upon fire activity (Swetnam, 1993; Falk *et al.*, 2007, 2011). This means that climate drives the occurrence of years when large areas or multiple sites burn. Following this logic, we defined an LFY as a year where (i) dendrochronological evidence showed that fires had occurred at multiple sites, and/or (ii) a large area was burned, according to the documentary fire records. We used dendrochronological data as a spatially non-explicit proxy (i.e. not involving a reconstruction of the areas burned). Instead, documentary fire records provided a direct measure of the annually burned areas. To minimize subjectivity associated with selecting thresholds for LFY definition, we used two alternative LFY definition protocols and relied on the fact that differences in the amount of burned area between LFYs and other years in the boreal zone typically exceed one order of magnitude (Stocks *et al.*, 1998; Drobyshev *et al.*, 2004a 2012). We put forward three specific questions: (i) what was the scale of variability and temporal trends in historic LFY return intervals in northern Sweden, (ii) was occurrence of LFYs associated with 500-hPa pressure anomalies over northern Europe, and if it was so, (iii) what was the geographical pattern of 500-hPa pressure anomalies associated with LFYs?

The study region

The study region covered northern Sweden, i.e. the area north of 60 °N All sites were located within the area limited to 61.67 °N, 14.93°E and 63.89 °N, 17.49°E (Fig. 1). Northern Sweden lies in the temperate climatic zone affected by transfer of air masses from the Atlantic region, especially during the winter season, and occasional intrusions of cold and typically dry air masses from the Arctic. The climate of the region is more maritime in its western part. However, the region as a whole has a rather continental climate, with mean January temperatures varying from −14 to −18 °C, with the mean July temperature varying between 12 and 16 °C. The growing season, defined as the number of days with mean temperature above 5 °C, lasts for 100–160 days (Raab and Vedin, 1995). Over most of the studied area the total annual precipitation is 600–700 mm, althjough in the Scandinavian Mountains precipitation ranges between 500 and 1400 mm. Between 30 and 50% of the precipitation falls as snow. The mean number of days with snow cover is 170–225, while the last day with snow cover typically occurs after 1 May (Raab and Vedin, 1995). Most modern forest fires occur in northern Sweden during May and June, although August fires dominate the total burned area during the fire season (Drobyshev *et al.*, 2012).

Northern Sweden encloses four bioclimatic domains: the alpine zone, northern boreal forests, and mid- and south boreal forests (Ahti *et al.*, 1968). The main tree species in the boreal zone are Norway spruce (*Picea abies* (L.) H.Karst),

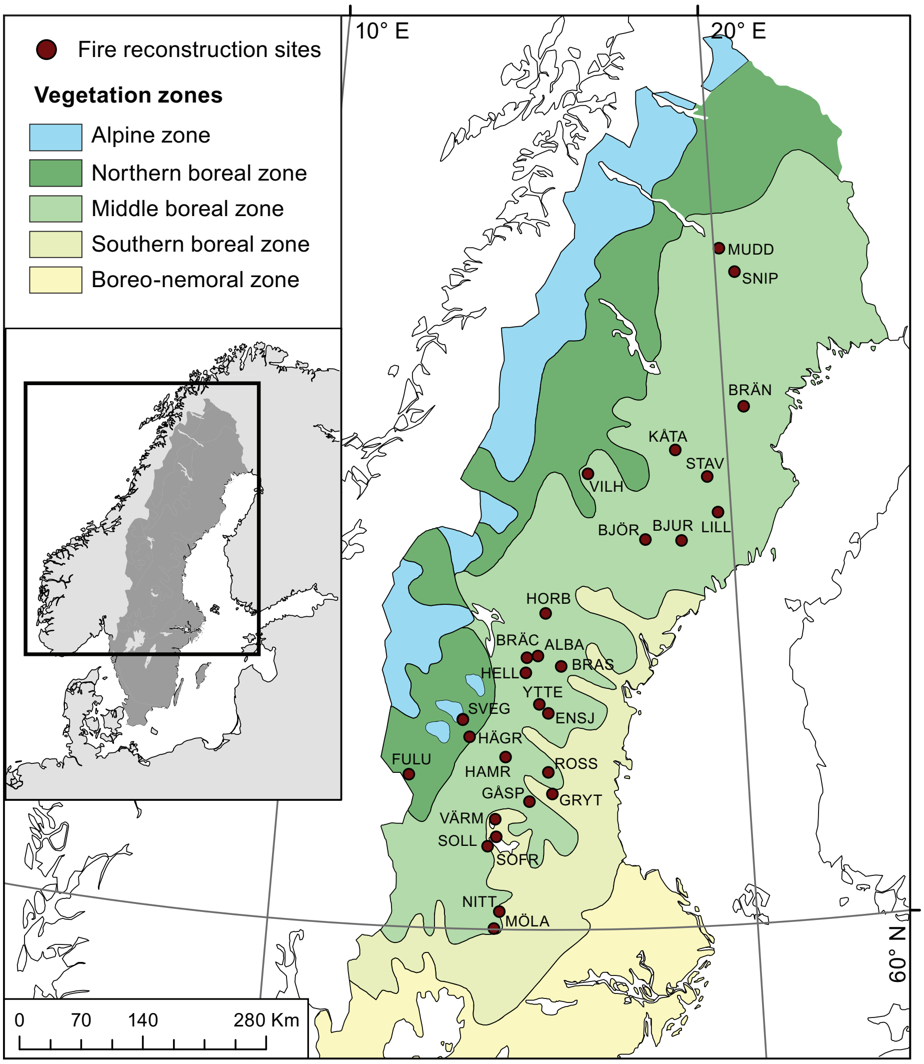

Figure 1. Location of the study sites and vegetation zones in northern Sweden. This figure is available in colour online at wileyonlinelibrary.com.

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Scots pine (*Pinus sylvestris* L.), with birch (*Betula pubescens* Ehrh. and *B. pendula* Roth) representing the deciduous vegetation. Fires have been one of the major disturbance factors across different forest types in Sweden in the past (Niklasson and Granström, 2000; Niklasson *et al.*, 2010). Prior to the fire suppression era before approximately 1850 AD (Granström and Niklasson, 2008), typical fire-return intervals in pine-dominated stands ranged from 20 to 100 years. Currently, the fire cycle in the northern part of Sweden is around 10^3–10^4 years (Drobyshev *et al.*, 2012).

Data sources

The three main data sources for this study included an annually resolved dataset of dendrochronologically reconstructed fires (1273–1914 AD), documentary fire records (1878xps4#1960) and gridded pressure datasets covering the period since 1800.

Dendrochronological data

A dataset of 31 fire history sites and a total of 2101 samples were used in analyses (Fig. 1; Supplementary information Table S1). The dataset represented sites with fire chronologies that were fully or partially published (Table S1). At each site we used a chainsaw to collect between five and 1133 samples (wedges and complete cross-sections) of Scots pine (*Pinus sylvestris* L.), focusing on old trees and dead wood with fire scars. Additionally, coring of trees was done to collect information on stand age structure and was later used as a supporting line of evidence for fire scar dating. No dates were established using exclusively regeneration/cohort age data. We used the classical cross-dating technique (Stokes and Smiley, 1968) and several sub-regional pointer year chronologies to assign calendar years to the fire scars (M. Niklasson *et al.*, unpublished data). The sites varied in size of the sampled territory, temporal period covered and number of dated trees (Table S1). Further details of sampling for fire history reconstructions are available elsewhere (Niklasson and Granström, 2000; Niklasson *et al.*, 2010). We considered site reconstructions as independent datasets, as the distance between sites was generally larger than probable areas of historical fires. The average distance between two nearest sites in the dataset was 51.8 ± 37.6 km (mean ± SD), with a minimum distance of 18.7 km. We limited our analyses to the period from 1270 to 1914, for which each year was represented by at least five sites (Fig. 2Aa).

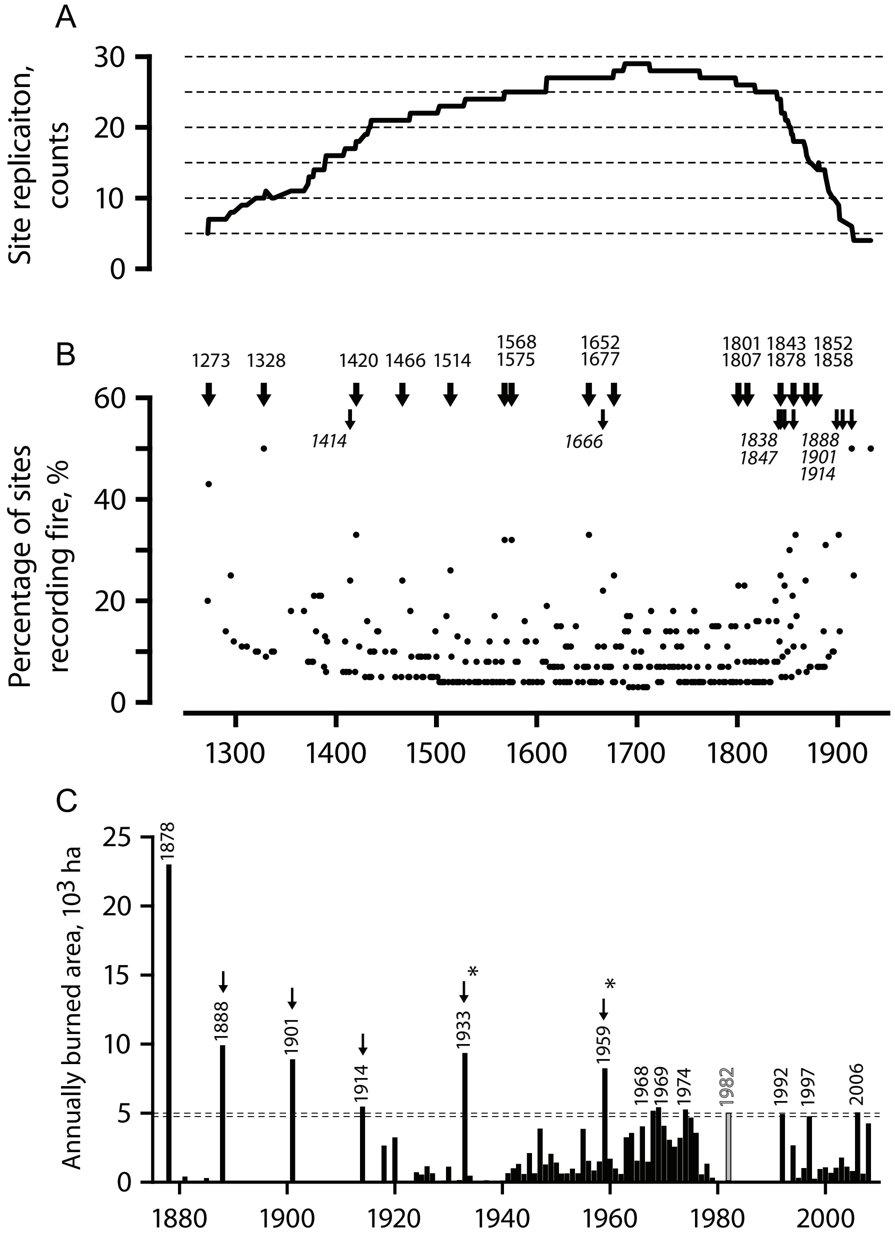

Figure 2. Large fire years (LFY) in northern Sweden between 1270 and 1960, as revealed by dendrochronological (1270–1914) and forestry (1878–1960) data. (A) Replication of dendrochronological dataset. (B) LFY chronology. Arrows indicate LFYs selected with an opportunistic criterion and the years also selected in the conservative version of the analysis are marked with a black circle. Triangles mark the six years with the highest amount of annually burned areas in northern Sweden since 1878, representing the top 10% in the distribution of annually burned areas during that period. (C) Chronology of annually burned area in northern Sweden since 1878, based on compilation from Högbom (1934); Skogsstyrelsen (1945) and MSB (2011). The dashed horizontal lines represents 5000 ha of annually burned area, which was used as a threshold in definition of LFYs. LFYs identified over 1878–1975 are indicated by bold font.

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Documentary fire records

Data on country-wide fire activity are available in Sweden since 1878, but the record is discontinuous (Drobyshev *et al.*, 2012). In this study, we did not consider records after 1975 due to large gaps in data availability and increasingly effective fire suppression leading to a decline in fire activity and difficulties in identifying LFYs. We used an official forest fire record, produced by the Swedish Forestry Board (www.svo.se, Skogsstyrelsen, 1945), for 1942–1960. For years before 1942 data at national scale were available only. For these years, the amount of area burned in forest fires in northern Sweden was estimated from linear regression between Sweden-wide areas burned in and northern Sweden ($R^2 = 0.954$, Fig. S1). For all periods we only selected fires reported on forested land.

Atmospheric pressure data

We used a gridded (2.5° × 2.5°) Europe-wide dataset of reconstructed monthly geopotential 500-hPa pressure heights (Casty *et al.*, 2007) for the period 1800–1960. Preliminary analyses suggested that the average pressure height for July to August exhibited the strongest association with fire years, which was in line with the timing of the modern largest fires (Drobyshev *et al.*, 2012). We therefore used these averages in the analyses.

Methods

Analytical approach

The current analysis focuses on the years with increased fire activity, identified in historical (dendrochronological) and modern (documentary fire records) data. Although the notion of a 'large fire year' assumes a spatially explicit metric of fire activity, we did not use dendrochronological reconstructions to deduce the annually burned areas within each of the study sites nor for the whole study region. Instead, we used synchronicity of fire occurrence across a large network of sites in northern Sweden (Fig. 1) to identify years with increased fire activity. While doing synchronicity analyses, we deliberately did not employ any weighting protocols differentially treating sites on the basis of their size, number of samples supplied and estimates of the area burned during single years, which were available from a subset of sites. We based this approach on our knowledge of the fire history in Scandinavia, suggesting several reasons for avoiding such weighting protocols. In particular, we lacked a solid a priori hypothesis to discriminate sites on the basis of their properties (e.g. site sampled area, number of samples, site temporal coverage) due to temporally large and geographically wide changes in the levels of human impact upon historical forest fire activity (Niklasson and Granström, 2000; Drobyshev *et al.*, 2012). Human impact made it problematic to use spatial estimates and/or the absolute number of trees dating a specific fire year as a temporally consistent measure of historic fire activity. In addition, differentiating study sites on the basis of their size (area studied within each site) would make some landscapes contribute to the overall pattern more than others and lead to the situation where a particular combination of landscape properties (e.g. historical fuel loads, type and density of fire breaks) would provide a disproportionally large contribution to the overall fire pattern. Finally, the very nature of the field sampling for the fire history reconstruction made it problematic to use the number of dated trees as a measure of fire size in most of the sites. We refer readers to our earlier paper (Drobyshev *et al.*, 2014) for a more thorough presentation of this rationale.

The general decline in the burned forest areas in Scandinavia over the 1800 s made our study sites increasingly 'fire free' towards modern times, limiting the use of the dendrochronological data for the analysis of fire activity since the 1900 s. Such decrease was a direct effect of fire suppression, which has been well documented by earlier studies (e.g. Niklasson and Granström, 2000; Niklasson *et al.*, 2010). To account for this effect, we did not consider parts of the time periods when a site was already under fire suppression. By removing portions of site chronologies with no fires we ensured that synchronicity analyses were done on the pool of sites where fires could occur. This filtering decreased the replication (the number of recording sites), which put a limit on how far into the modern time can we extend the analysis of dendrochronological data. We therefore used forestry statistics to extend LFY chronology in northern Sweden over a part of the 1900 s.

Definition of LFY

Dendrochronological record

For the period covered by the dendrochronological data (1270–1914 AD) we defined an LFY on the basis of contingency analyses and the synchronicity threshold. The number of sites burned was required to exceed the expected number, determined by contingency analysis for each century, by a factor of 2. We assumed a binominal distribution of fire occurrence across sites and calculated expected frequencies of years with no, one, and multiple sites burning:

$$p(X) = \frac{N!}{X!(N-X)^{p^{x}q^{N-X}}}$$

where N is the total number of recording sites in the analysis of a specific period; X is the number of burned sites in a single year; p is the the probability of a site burning in any year and q is the inverse of this probability. This criterion was designed to reflect changes in both site replication and centennial fire frequencies affecting probability of simultaneous burning of a certain number of sites. Using this formula resulted in an increase in expected frequencies during the periods with more frequent fires and in a decrease in such frequencies during periods with reduced fire activity. This flexibility in estimating the theoretically expected frequencies of concurrent site burning allowed therefore us to account for human-related changes in ignition frequencies.

Bootstrapping of the contingency analysis output allowed us to assess the statistical stability of the results. At this step we defined two alternative LFY identification protocols to address subjectivity associated with the selection of the threshold used in contingency analysis. An *opportunistic* classification protocol preserved LFYs originally identified in the contingency analysis *and* in 50% of the bootstrap runs ($n = 1000$). A *conservative* classification protocol used only those originally identified LFYs that were also qualified in 90% of the bootstrap runs. Both protocols, although referred to in the text as *opportunistic* and *conservative*, represented a generally conservative approach in selecting LFYs. In both versions of classifications, we defined *site replication* for a year (number of 'recording sites') as the number of sites supplying material for that year and took into account possible hiatuses in fire records, inferred from the analysis of age cohort data and the site-specific onset of fire suppression. A site contributed to the replication for a year if that year was within the period limited by the first and the last fire on that site. In general, the use of contingency analyses in fire studies dates back to the work of Swetnam and co-authors (Swetnam, 1993; Swetnam and Baisan, 2003). In its present form this approach has already been used to avoid effects of fire suppression on the LFY definition protocol in Scandinavia (Drobyshev *et al.*, 2014).

We realized that the selection of a threshold in contingency analysis naturally affected the resulting populations of LFYs. This fact, however, was not viewed as a problem for statistical analyses, as the primary aim of our approach was (i) to select a population of years which represented a significantly higher level of synchronicity than expected under the assumption of a random distribution of fire years across sites and years, and (ii) to maintain the same level of synchronicity in the record over time, taking into account changes in the number of recording sites and in the centennial fire frequencies.

Documentary records

To define LFYs we analysed the long-term distribution of annually burned areas in northern Sweden (Skogsstyrelsen, 1942, 1945) and selected years when burned area exceeded 5000 ha. The selection of this threshold was supported by the observation that before the period of effective fire suppression policies in the second half of the 20th century, there was a clear difference between years with low and high fire hazard, the 5000-ha level effectively differentiating the two groups of years (Fig. 2C). As fire suppression contributed to decreasing peaks in annually burned forest area in the second half of the 20th century, it was difficult to rely on annually burned areas to define LFYs during the second half of the 1900 s. We therefore elected to consider only the period between 1878 and 1960. We also evaluated an alternative LFY identification protocol, which was based on fitting a distribution with a known cumulative distribution function (in our case – a gamma function) and estimating the threshold as the 90th percentile of the respective distribution of annually burned areas. While constructing the distribution of annually burned areas in northern Sweden we omitted the period 1878–1920, as information on ‘average’ and low fire hazard years for this period was largely lacking (Högbom, 1934). For both identification protocols (threshold-based and distribution-based) we obtained an identical list of years.We used the Hollander–Proschan test to evaluate if LFY return intervals followed a Weibull distribution (Dodson, 1994). Conformity of the data to a Weibull distribution allowed us to use scale and shape parameters of this distribution to characterize its mean tendency and variability. Differences in fire return intervals among periods were tested with the Cox–Mantel test, operating on the respective cumulative functions. It has been shown that this test is more powerful than other alternatives for comparison of survivorship functions drawn from populations that follow Weibull or exponential distributions (Lee *et al.*, 1975). Only complete (uncensored) intervals were used in analyses.

Analysis of LFY return intervals and their relationship to pressure patterns

For each grid point within the area limited by 2 °W, 36°N and 72 °N, 57°E we ran a superposed epoch analysis on the monthly 500-hPa pressure fields (Casty *et al.*, 2007) averaged over July and August. The analysis was designed to quantify deviations of the pressure fields during the LFYs from the period-specific means and to evaluate the spatial pattern of such deviations. We studied three periods: 1800–1849, 1850–1899 and 1878–1960. LFYs in the first two periods originated from the dendrochronological dataset, whereas LFYs in the last period originated from the observational records (forestry statistics). To improve the power of the superposed epoch analyses, we used LFY lists from the conservative version of identification protocols. Results were mapped by ESRI ArcMap 10.0, using prediction kriging in the Geospatial Analyst module (ESRI, 2012).

Results

Over the period covered by the dendrochronological dataset, 1270–1914, replication was at least five sites and in 90% of years it exceeded 10 sites, the peak in replication being between 1433 and 1853, when it was above 20 (Fig. 2A). Contingency analyses run on single 100-year segments (with the exception of the first and the last segments, which did not start–end at the turn of the centuries) revealed 15 (31) LFYs over 1273–1914, following conservative (opportunistic) identification protocols (Fig. 2B). Based on the documentary records we identified six LFYs over the period of 1878xps8#1960. To increase the statistical stability of the results, we aggregated data over several centuries. As no LFYs were detected in both versions of the identification protocol during the 1700 s, we selected two periods, before 1700 and after 1800, for the subsequent analyses.

Over the period covered by dendrochronological data (1270–1914), the average LFY return interval for northern Sweden was 38 (18) years in conservative (opportunistic) schemes. These values, however, incorporated large temporal variability (Table 1) both within and among periods. An apparent feature was a decrease in the interval length since the 1800 s (Fig. 2B), evident in both outcomes of the

Table 1. Distribution parameters for return intervals of LFYs in northern Sweden.

Period and selection protocol	*n*	Mean ± SD	Range	Weibull shape and scale	HP test (statistics, *P*)
Conservative					
1270–1700	7	52.1 ± 38.3	7–102	1.39/57.08	−0.043/0.965
1800–1914	6	9.5 ± 7.6	4–24	1.52/10.67	0.244/0.807
1270–1914	14	37.9 ± 39.5	4–108	0.938/36.72	0.196/0.844
Opportunistic					
1270–1700	17	21.5 ± 18.6	2–54	1.14/22.55	0.133/0.894
1800–1914	12	7.3 ± 7.6	2–30	1.23/7.86	0.295/0.768
1270–1914	30	18.7 ± 23.4	2–108	0.91/17.74	0.407/0.684
Forestry statistics					
1878–1960	5	16.2 ± 6.4	10–26	3.04/18.18	0.171/0.865

n, number of intervals, and mean refers to the mean and the range of LFY return intervals. HP, Hollander–Proschan goodness-of-fit test for conformity of empirical distribution to a Weibull distribution. A 108-year interval covering the fire-free period during the 1700 s was excluded from computations. Only complete (non-censored) intervals were used in these analyses.

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classification protocols. As the distribution of return intervals followed a Weibull distribution (Table 1), we used pair-wise comparisons of respective cumulative survivorship functions to check for significance in the temporal trends in LFY frequencies. Irrespective of the scheme used, the 1270–1700 epoch had significantly longer fire return intervals than the period 1800xps11#1914 (Fig. 3; Table 2). Comparisons involving the observational period (1878xps12#1975) were not significant at the 0.05 level. Cumulative functions exemplified differences in return intervals among the epochs (Fig. 3). For example, in the conservative version of the LFY identification protocol, an interval of 20 years would carry 80–100% probability of an LFY occurrence for the two most recent epochs, and only 20% probability of such an event before 1700.

Table 2. Pair-wise comparisons of three epochs with respect to their LFY return intervals, results of Cox–Mantel test; values are test statistics and respective significance levels.

Epoch	1800–1914	1878–1960
Conservative classification		
1273–1700	2.92/0.003	1.91/0.056
1800–1914		−1.54/0.124
Opportunistic classification		
1273–1700	2.89/0.004	0.54/0.586
1800–1914		−1.85/0.064

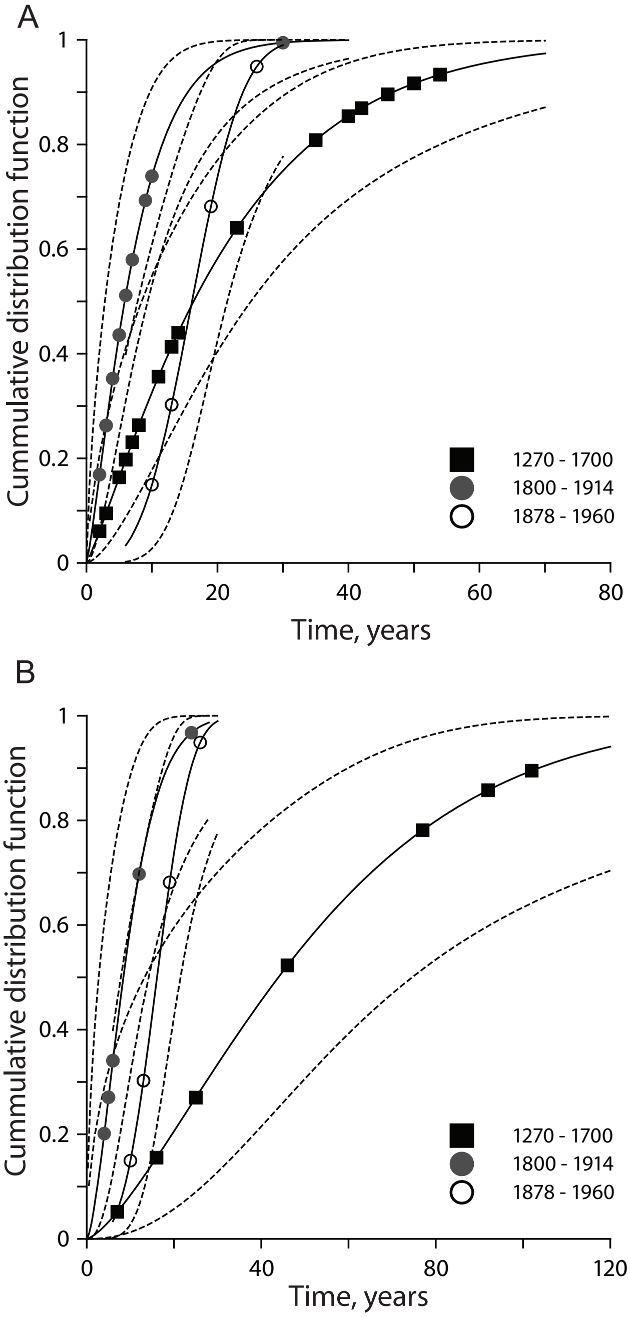

Figure 3. Cumulative survival functions for three time periods and two LFY classification schemes. Dotted lines refer to 95% confidence envelopes for each of the curves. Statistical properties of respective interval distributions are given in Table 1, and the results of the statistical significance of differences among the curves are given in Table 2.

The overlap of the two datasets allowed us to evaluate the correspondence between dendrochronological results and direct estimates of the areas burned, available from documentary fire records. Conservative LFY identification in dendrochronological data resulted in no common years between the two datasets, whereas the opportunistic classification resulted in one common year (1888). We noted that although both versions of contingency analyses appeared overly conservative and did not identify some LFYs known from observational records, our dataset showed an increased percentage of dendrochronological sites burned during such years: 1901, 33% (three out of nine sites); and 1914, 50% (three out of six sites). These percentages were higher than those for the years identified as LFYs in the earlier periods (Table S2).

Analysis of average July–August 500-hPa geopotential pressure heights suggested that LFYs in northern Sweden were associated with positive pressure anomalies (Fig. 4). Their geographical pattern appeared stable over time, the region with positive pressure anomalies covering large parts of Scandinavia. The eastern border of the high-pressure region was consistently located around 20–30°E and its northern border between 65 and 70°N. LFYs in Scandinavia tended to be associated with low-pressure regions in southern Europe.

Discussion

Quantification of the past dynamics of LFYs is crucial for understanding the mechanisms behind, range of variability in and climate sensitivity of boreal fire regimes. In this study we present the longest multi-site annually resolved chronology of fire activity currently available for northern Europe. By focusing the analyses on the frequencies (fire return intervals) of LFYs and capitalizing on a large network of sites (Table S1, Drobyshev *et al.*, 2014), we minimized the effects of changing land use practices and specifically the effects of fire suppression policies introduced in Sweden during the 1800 s. In contrast to other parts of the European boreal zone (Drobyshev *et al.*, 2004a), these effects are considered the main obstacle in extracting climatic signal in fire history reconstructions in Scandinavia (Granström and Niklasson, 2008). Although in the current study we used forestry data to extend our LFY chronology until the second half of the 20th century, we base the following discussion primarily on the results obtained from dendrochronological data, acknowledging difficulties in linking dendrochronological and forestry datasets.

Temporal changes in frequency of LFYs

The temporal patterns of LFY occurrence reveal strong variability with longer LFY return intervals between 1270 and

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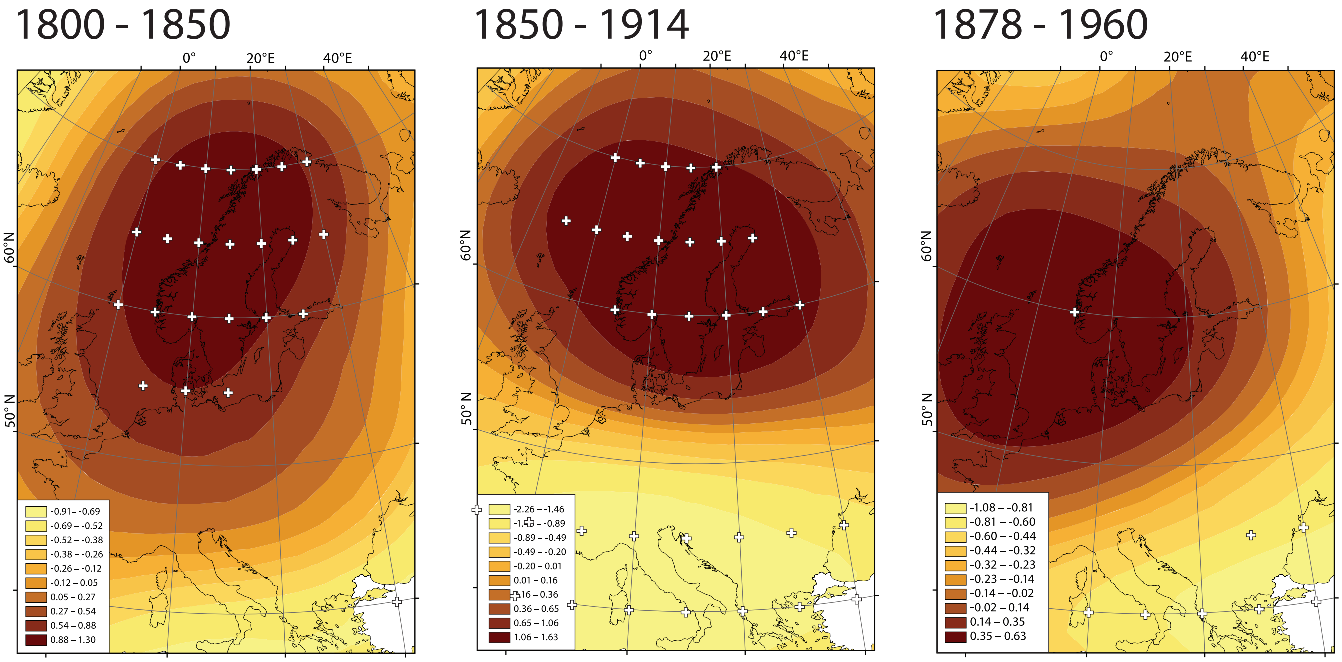

Figure 4. Patterns of July–August 500-hPa pressure anomalies for LFYs in northern Sweden for three periods, expressed as deviation of the pressure anomaly during LFYs from the average over the respective 50-year segment. Fire data for the first two periods originated from dendrochronological reconstructions, and the fire data for the period 1878–1960 are based on observational records (forestry stratistics). Crosses indicate significance at the 0.10 level, estimated through bootstrapping in superposed epoch analysis. This figure is available in colour online at wileyonlinelibrary.com.

1700, their absence during the 1700 s, and shorter return intervals since the early 1800 s. The reason for the observed long-term change in LFY occurrences should be the subject of further research, although it is likely that climate played the main role in its dynamics. We propose changes in the degrees of continentality, already demonstrated for Scandinavia at larger time frames during the Holocene (Giesecke *et al.*, 2008; St Amour *et al.*, 2010), as a potential driver. An example of such a very dry period would be a time around 7000–5000 cal a BP, attributed to an extreme case of a persistent blocking high-pressure centre over Fennoscandia during July–August (Antonsson *et al.*, 2008). Although the differences in scales do not invalidate our hypothesis about the important role of climate continentality, we realize that a proper test of this hypothesis would require equally long and temporally resolved independent reconstructions of fire-related climate variables. Our results suggested climate conditions in the second half of the summer as an important driver of forest fire activity, calling for the use of climate reconstructions with monthly resolution. However, currently available datasets are short (e.g. Casty *et al.*, 2007; Drobyshev *et al.*, 2011), or poorly resolved, providing only seasonal estimates (Pauling *et al.*, 2006).

Over 1270–1700, LFYs occurred in northern Sweden with an average interval of 40–50 years. Even within this period large variations in the intervals are evident (Table 1). In particular, the second part of the 1600 s, suggested as one of the coldest periods of the Little Ice Age in Scandinavia (Gouirand *et al.*, 2008), coincided with increased fire activity (Fig. 2B). Indeed, a recent reconstruction of cloud cover over Fennoscandia with the help of stable carbon ratios in rings of Scots pine has suggested that summers during that period were sunny and dry (Gagen *et al.*, 2011). In line with our results, reconstruction of glacier mass balance in Scandinavia during the Little Ice Age indicated that summers were not necessarily colder during that period: it was an increase in winter precipitation, and not a decrease in summer temperature, that caused glacial expansion in western Scandinavia (Nesje *et al.*, 2008). In general, the century-long dynamics of LFYs did not reveal a clear positive association with temperature variability at centennial scales. For example, an increase in the summer temperature in Scandinavia over the second half of the 1700 s (Gouirand *et al.*, 2008) coincided with the absence of LFYs for that period. The lack of a positive relationship between temperature and fire activity is supported by empirical data (Hansson *et al.*, 2011), and climate models (Champion *et al.*, 2011) suggest that warmer climates may accompany an increased amount of precipitation, which would translate into lower fire hazard. Direct comparisons of historical LFY frequencies with other boreal regions are complicated due to the lack of similar studies, operating with truly annually resolved data.

The absence of LFYs, as defined in this study, during the 1700 s is an intriguing finding which clearly requires additional data and analyses. It is important to realize that forest fires did occur during that period, and several fire years (e.g. 1709, 1739, 1757, 1775 and 1778) were recorded at four sites. However, the level of annual synchronicity of fire activity was lower than in preceding and following periods, which precluded the identification of LFYs according to the protocols used. A review of available reconstructions of summer drought conditions (Fig. S2) revealed periods of both high and low aridity, but no consistent trend that would indicate a generally lower fire hazard during that period. Realizing that monthly and seasonal resolution of these reconstructions might be sub-optimal in capturing dynamic changes in fire hazard during a fire season, we could not exclude the possibility of a non-climatic explanation of the observed pattern. Although our study was designed to exclude non-climatic effects, a rich cultural history of Scandinavia may nevertheless have an effect on the occurrence of LFYs. Earlier studies on the most thoroughly studied sites (Niklasson and Granström, 2000) revealed a decline in forest fire during the early 1700 s and associated this observation with the general economic recession after the Great Northern War (1700–1721). This decline, however, only extended into the mid 1700 s, the second half of this century exhibiting a dramatic increase in the number of fires, which, according to Niklasson and Granström (2000) reflected post-war re-colonization of northern Europe and an increase in agricultural activities. Our results revealed only a limited correspondence with cultural history of the studied region.

Increase in LFY frequency during the 1800 s

The increased LFY frequency during the 1800 s (Figs 2 and 3) suggested an increased frequency of upper-level ridges in northern Sweden that apparently led to an increased frequency of summer and particularly late summer droughts. Available drought reconstructions (Fig. S2; Drobyshev *et al.*, 2011) suggest several drought-prone periods during the 1800 s, including the decades centred on the 1820 s and 1850 s (Linderholm and Chen, 2005). This is in line with our reconstruction suggesting that the increase in LFY frequency was mostly associated with the first half of that century (Fig. 2B). By contrast, the standardized precipitation index for June–July for the city of Stockholm clearly indicated the whole 1800 s as a dry period (fig. 4 in Seftigen *et al.*, 2013).

During the 1900 s, drought frequency in Europe generally appears to have increased (Worrall *et al.*, 2006; Pärn and Mander, 2012), although the temporal scale of this dynamic remains unclear. For example, an earlier onset of spring warming has already been noted during the 19th century in the southern part of the Baltic sea (Tarand and Nordli, 2001), implying better conditions for the development of water deficit in forest fuels during the fire season. Reconstructions typically indicate increases in European and global temperatures only since the 20th century (Luterbacher *et al.*, 2004; Mann *et al.*, 2008), i.e. much later than the observed increase in LFY frequency in our study. Twentieth-century increases in LFY frequency have also been reported for the Canadian (Kasischke and Turetsky, 2006) and Siberian boreal forests (Soja *et al.*, 2007). However, such a pattern is apparently not truly circumboreal and may also be a direct result of changes in fire data quality over time. A number of studies from eastern North American boreal and mixed forests, especially of eastern Canada, and Scandinavia have demonstrated an opposite trend – i.e. longer fire return intervals and longer fire cycles since the end of the Little Ice Age, implying a less fire-prone climate during the 1900 s (Bergeron and Archambault, 1993; Engelmark *et al.*, 1994; Weir *et al.*, 2000; Bergeron *et al.*, 2004; Girardin *et al.*, 2006).

Geographical patterns of 500-hPa geopotential pressure heights

Since 1800, LFYs in northern Sweden are associated with positive pressure anomalies, predominantly covering northern Europe and the British Isles, and negative pressure anomalies in southern Europe (Fig. 4). The position of the high-pressure fields appears rather stable over time, suggesting that the same climate system may be responsible for the establishment of fire-prone weather in northern Sweden. The observed pattern of pressure anomalies also supports the notion that LFYs in northern Sweden were predominately a result of regional climatic variability. The most recent example of this is perhaps the year 2003, which was not an LFY in northern Sweden, but has been estimated to be the warmest summer in Europe since 1500 (Luterbacher *et al.*, 2004), resulting in clearly increased fire activity over the sub-continent. Similarly, the year 1998 was not an LFY in the studied region, but was a major fire year in many parts of the temperate zone of the Northern Hemisphere (Conard *et al.*, 2002). In turn, some LFYs apparently represented climate anomalies of much larger geographical scale, examples being the years 1652 (Drobyshev *et al.*, 2014) and 1969 (Fig. 2C and Girardin *et al.*, 2009).

As pressure anomalies associated with LFYs covered a larger part of Scandinavia one would suggest that the synchronicity in fire activity would be region-wide. However, an earlier study has demonstrated clear differences in historical fire activity between the northern and southern parts of this region and a more geographically fine-scale pattern of temperature and precipitation anomalies (Drobyshev *et al.*, 2014). The effect of this spatial patterning is apparently further enhanced by differences in the timing of the fire season onset (Drobyshev *et al.*, 2012).

Part of the observed variability of LFYs in northern Sweden is probably related to the summer atmospheric circulation. It has been shown that the summer North Atlantic Oscillation (SNAO, *sensu* Folland *et al.*, 2009) is of significant importance for the summer climate of Northern Europe, e.g. by influencing the position of the storm tracks in the region. Storm tracks, the paths of mobile extratropical cyclones, play a significant role in mid- to high-latitude climate by influencing precipitation, cloudiness and radiation and their variation in time and space (Bengtsson *et al.*, 2006). In its negative phase, the SNAO corresponds to a shift of the storm tracks to lower latitudes, yielding warmer and drier conditions in northern Sweden, but wet and mild conditions in southern Sweden (Linderholm *et al.*, 2010; Fig. 2). The increase in LFYs during the 1800 s corresponds to a period of predominantly negative SNAO (fig. 10 in Folland *et al.*, 2009). This storm track boundary between northern and southern Sweden may explain why modern fire activity in parts of the country differs from southern Scandinavia (Drobyshev *et al.*, 2012) and probably the rest of Europe.

Methodological challenges in building LFY chronology

A challenge we faced in this study was bridging dendrochronological (based on the dates of fire scars) reconstructions and records available from documentary fire records. Essentially, this exercise assumed that a certain level in synchronicity of fire occurrence across a network of sites would reflect the amount of annually burned areas over the whole of northern Sweden. LFY hazard rates obtained by partially overlapping dendrochronological and forestry datasets were similar, supporting our assumption. However, a comparison of specific fire years yielded only one common LFY (1888), contingency analysis failing to identify three other LFYs (1875, 1901 and 1914), despite these years exhibiting clearly increased proportions of sites burning (Table S2). The results suggested that the used contingency analysis protocol was generally overly conservative compared with LFYs recorded by observations.

Analysis of overlapping periods may also point to potential problems with representativeness of dendrochronological data. The year 1878 appeared in the historical statistic as the all-time largest fire year, with an estimated 23 000 ha of forest burned in northern Sweden (Fig. 2C). This year was also noted as a year with large fires in other studies based on old forestry records (Kohh, 1975). However, it was completely absent in the dendrochronological dataset with no single site recording fire during that year. The nature of this discrepancy remains unclear, especially given that even less fire-prone LFYs identified in forestry datasets were well visible in the

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dendrochronological dataset, which progressively declined in replication. We do not exclude the possibility that the problem may lie with the quality of the earliest documented fire records.

The total annually burned areas decreased in Sweden over the course of the centuries (Drobyshev *et al.*, 2012), although shorter LFY return intervals indicated that actual fire hazard and climate forcing upon fire activity might have been high during the 1800 s. It is important to mention that the change in fire regime was detected within the time frame covered by the single dataset (in this case, dendrochronological reconstructions) and not at the transition between dendrochronological and forestry datasets. In today's northern Scandinavia, climatic forcing of fire activity is largely hidden by efficient fire suppression – the maximum amount of annually burned forest areas during the 20th century has been several orders of magnitude below the levels before 1900 (Drobyshev *et al.*, 2012).

The onset of fire suppression in northern Sweden occurred during the second half of the 1800 s and 1900 s (M. Niklasson *et al.*, unpublished data), which generally coincides with the onset of the period with increased LFY frequency. Although the protocol used for the identification of LFYs accounted for the temporal variation in the number of recording sites and fire frequency at the site level, it is possible that fire suppression may have affected the relative representation of climatic versus non-climatic fires. In particular, fire suppression acted towards (i) elimination of the human ignition sources, and (ii) reducing the fire sizes, especially during climatically non-extreme seasons. Both effects apparently led to a decline in the number of fire scars formed during years with average or below-average fire hazard, which may ultimately lead to a higher proportion of climatically driven fires in the fire scar dataset during the 1800 s and early 1900 s. However, even if present, it seemed unlikely that this effect affected our selection of LFYs. Indeed, consistent patterns of pressure anomalies during identified LFYs (Fig. 4) suggested that these were climatically controlled.

What was the actual forest area burned during 'large fire years' in the past? The current study does not provide a direct answer to this question. The earliest documented fire records suggest that 10 000 ha of burned forests during single years was common in northern Sweden, with the earliest available estimate (year 1878) approaching 25 000 ha. The second part of the 1800 s was a period when the policy of fire suppression and a level of technological development were both in place to limit natural fire activity. It is therefore likely that earlier LFYs might well have exceeded these estimates. Although estimating the distribution of burned areas during LFYs is beyond the scope of this study, we note that the main difficulty for such estimation is scale-related: large historical fires typically exceed the size of the single study areas, while the density of available study areas in the region is too low to capture the spatial extent of single fire events. However, it is evident that even within the group of LFYs there was large variability in the level of fire activity and the total area of annually burned forest. Forestry data and differences in the level of synchronicity of fire years within the dendrochronological dataset exemplify this variability.

Conclusions

Quantification of the past dynamics of LFYs is crucial for understanding the sensitivity of boreal fire regimes to climate. In this context, LFY return intervals may present an important proxy of climate forcing upon annual fire activity at low (centennial) frequencies. Using the example of northern Scandinavia, we suggest that the large temporal variability in fire hazard might be independent of human-mediated climate changes. Support for this conclusion comes from a large network of dendrochronological reconstructions across northern Sweden extending until the late 1800 s. Given the different nature of the datasets prior to and after 1900 and that fire suppression policies dominated in Sweden over the 20th century, comparison of LFY frequencies between these two periods should be interpreted with caution. Our study has presented undocumented low-frequency variability in climate forcing upon forest fire activity in Northern Europe. Such variability may pose a challenge in partitioning the effects of human-related and human-independent components of climatic variability on forest fire activity during the 20th and 21st centuries. Large-scale atmospheric circulation patterns probably exert strong controls over long-term variability in LFY frequencies and, more generally, boreal fire regimes, which exemplify feedbacks between atmospheric and ecosystem processes.

Supporting Information

Additional supporting information can be found in the online version of this article:

Table S1. Characteristics of the study sites. Site codes correspond to those in Fig. 1 of the main text.

Table S2. List of LFYs obtained with conservative and opportunistic classification protocols, shown with the corresponding percentage of sites burned.

Figure S1. Relationship between areas annually burned by forest fires in the whole of Sweden and in northern Sweden (1942–1975 and 1996–2008).

Figure S2. Two reconstructed aridity indexes (drought index and a simple aridity index).

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Abbreviations. LFY, large fire year; SNAO, summer North Atlantic Oscillation.

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