Multi-century reconstruction suggests complex interactions of climate and human controls of forest fire activity in a Karelian boreal landscape, North-West Russia

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Abstract

Spatially explicit reconstructions of fire activity in European boreal forest are rare, which limits our understanding of factors driving vegetation dynamics in this part of the boreal domain. We have developed a spatially explicit dendrochronological reconstruction of a fire regime in a 25 × 50 km^2 area within boreal biome located within the Kalevalsky National Park (Kalevalsky NP), over the 1400–2010 AD period. We dated 184 fire years using 212 fire-scarred living and dead Scots pine (*Pinus sylvestris* L.) trees collected on 38 sites.

The studied period revealed a pronounced century-long variability in forest fire cycles (FC). The early period (1400–1620 AD) had low fire activity (FC = 178 yrs.), which increased during the 1630–1920 period (FC = 46 yrs.) and then decreased over the 1930–2000 period (FC = 283 yrs.). Dendrochronological results did not provide a conclusive answer on the origins of FC dynamics, although several lines of evidence suggest that climate drove the increase in fire activity in the early 1600s, while human-related factors were largely responsible for its decline in the early 1900s. The current FC in the Kalevalsky NP is close to the estimates reported for the pre-industrial colonisation period in Scandinavia, which suggests that the forests of the area currently maintain their close-to-natural fire regime. Fire has been the pivotal factor of forest dynamics in this biome and forest management should acknowledge that fact in developing conservation strategies in Karelia and other areas of European boreal forest. Introduction of prescribed burns of varying severity could be an important element of such strategies.

Key-words: climate variation, natural disturbances, boreal landscape, mixedwoods, fire regime, pine-dominated forests, North-west Russia, natural hazards

Introduction

Forest fires are the main drivers of forest ecosystem dynamics in the boreal biome. Fires are important to maintain the diversity and successional pathways of boreal forests (Melekhov, 1946; Zackrisson, 1977; Payette, 1992; Bergeron et al., 2004). Climate is the major factor controlling regional fire activity (Clark, 1990; Johnson, 1992; Stocks and Lynham, 1996; Flannigan and Wotton, 2001), influencing fuel, moisture conditions and ignition patterns. Topography and the related variation in soil moisture and vegetation affect the fire regime at finer scales (Pitkanen et al., 2003; Hellberg et al., 2004; Girardin et al., 2013; Kuosmanen et al., 2014). Humans has been an important agent of change in boreal fire activity (Wallenius, 2011; Rolstad et al., 2017). They affected fire regimes through slash-and-burn agriculture and associated forest clearcutting (Lehtonen et al., 1996; Lehtonen and Huttunen, 1997; Niklasson and Granström, 2000; Wallenius et al., 2004), changes in fuel abundance and composition through livestock grazing (Savage and Swetnam, 1990; Grissino-Mayer et al., 2004) and more recently - through fire suppression policies (Niklasson and Granström, 2000; Tryterud, 2003; Drobyshev and Niklasson, 2004; Drobyshev *et al.*, 2012).

Fire history studies in northern Europe have reported a decline in forest fire activity since the late 1800s, driven by cessation of land use practices involving fire and the increasing economic value of timber (Tryterud, 2003; Niklasson *et al.*, 2010; Wallenius, 2011; Rolstad *et al.*, 2017). For example, in Sweden, the forest fire cycle is currently (since late 1800s) around 10^4 years (Drobyshev *et al.*, 2012). By contrast, the fire cycle during the pre-industrial era (1300–1650 AD) was around 150–300 years (Niklasson and Granström, 2000), which corresponds to the modern fire cycle in the boreal forest of North-West Russia (Gromtsev, 2002; Drobyshev and Niklasson, 2004).

Despite a number of detailed dendrochronological (Lehtonen and Kolström, 2000; Drobyshev et al., 2004a; Drobyshev et al., 2004b; Wallenius et al., 2004; Aakala et al., 2018) and paleochronological (Pitkanen and Gronlund, 2001; Kuosmanen et al., 2014; Kuosmanen et al., 2016) reconstructions, the long-term fire dynamics in the boreal section of Northern Europe remains poorly understood. A rich land use history of the region and climate variability, in part - synchronized with the changes in forest use, make partitioning the effects of both factors on past fire activity challenging. Geographic variability in the strength of climate and human impacts on boreal fire regimes presents another challenge in partitioning the effects of these two factors. For example, fire activity in the northern boreal forest has been predominantly related to summer drought conditions, whereas in the southern boreal forest, spring drought conditions are more important (Johnson *et al.*, 1998; Drobyshev *et al.*, 2012). Partially as a result of this pattern, the studies have found large differences in sensitivity of fire regimes to climate variability between northern and southern boreal forests (Ali *et al.*, 2012; Drobyshev *et al.*, 2014).

Although the temporal resolution of dendrochronological records generally allows for analyses of many important properties of fire regime, such as fire seasonality, fire cycle and fire return interval, this proxy does not provide information on the origin of fire dynamics, which calls for analyses involving multiple proxies of past variability in climate and land use patterns.

We analyzed the fire history of a northern boreal landscape that is partially included in the Kalevalsky National Park, Republic of Karelia, North-West Russia. The area lies within the northern boreal vegetation zone on the Baltic Shield (Fennoscandia) at the southern spurs of the mountain range Maanselka. The forests of the Kalevalsky NP have been subject to selective cutting (Lehtonen and Kolström, 2000; Raevsky, 2017), though no industrial logging occurred in the area. As a result, large areas of old growth and deadwood-rich forests within and around the national park allow for long-term dendrochronological reconstructions of fire dynamics.

We used fire-scarred living and dead Scots pines to reconstruct the fire history and evaluate climatic and human forcing on fire regime dynamics over a period of 610 years (1400–2010). Our objectives were to (1) develop a spatially explicit fire history reconstruction in North-West Russia, (2) provide long-term and quantitative estimates of fire cycle and seasonal patterns of forest fires over the study period, and (3) evaluate the climatic and human forcing on fire regimes over this period.

Material and methods

The study area

The Kalevalsky NP (744 km2) is located in the Russian Republic of Karelia (64°59′30″ N 30°12′45″ E, Fig. 1). It is considered to be the largest and the most western track of primeval northern boreal forests of European Russia (Gromtsev et al., 2003; Raevsky, 2017). The climate of the area is moderately continental with oceanic features (Alisov, 1936). The mean July temperature is 14.5°C and the mean January temperature is –12.5°C, with the effective temperature sum over the growing season being between 1450 and 1650°C (Anonymous, 1989). Annual total precipitation ranges from 500 mm to 600 mm and accumulation of thick snow cover (50–70 cm) characterizes the winter period, which lasts from 170 to 180 days.

The Kalevalsky NP is located in the southeast slope of the Baltic (Fennoscandian) Shield. The underlying bedrock is composed of Pre-Cambrian crystalline rocks – granite or gneiss (Anonymous, 1989). The topography of the study area is generally hilly, characterized by a mean altitude between 104 and 277 m above sea level (Gorkovets and Rayevskaya, 2002). The most common soil type is alluvial-humus-ferrous-sandy podzols. Marshy and marsh-podzol soils dominate the southwestern and northwestern sections of the area. The forests of the Kalevalsky NP cover 71 % of its territory and belong to the northern boreal (northern taiga) subzone (Lavrenko et al., 1947; Yurkovskaya, 1993). It corresponds to the middle boreal zone in the classification of Ahti (1968).

The park's common tree species are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst), silver and downy birch (*Betula pendula* Roth. and *B. pubescens* Ehrh., respectively) and aspen (*Populus tremula* L.). Pine forests of the bilberry (*Vaccinium myrtillus* L.) type dominate the area and are particularly abundant on the rocky outcrops, hill slopes, and edges of various wetlands (Gromtsev, 2009; Ruokolainen and Kotkova, 2014; Raevsky, 2017). Spruce is common in the undergrowth, while pine regeneration is largely absent (Gromtsev *et al.*, 2002). The historical fire regime has been suggested to maintain a dynamic balance between pine and spruce in the past (Gromtsev, 2002; Gromtsev *et al.*, 2002). The area has a rich cultural history, with the first wave of human settlements dating back to 7000 BC (Juvelius, 1889; Zhulnikov, 1993).

Field sampling

We sampled 38 sites within the Kalevalsky NP (Fig. 1). We made an effort to distribute sampling sites in a regular fashion across the studied landscape, by randomly locating points for sampling along the roads within the park and its immediate vicinity. The sites were located from one to four km from each other. Areas of clear-cuts located outside the Kalevalsky NP border and mires were not generally sampled, due to difficulties in locating material for dating. A site represented an area of two–three ha in size and was inventoried over a period of one to two hours. We thoroughly searched each site for the presence of living and dead trees with fire scars. We used chainsaws to extract wedges from living trees and snags and, in the case of stumps, cross-sections to develop a fire chronology. Between four and 10 samples were collected on each site. In total, we acquired 257 samples of 71 living and 186 dead pine trees. Field sampling was carried out in the summers of 2014 and 2015.

Location of most of the sampling points near the forest roads could introduce a bias related to their use by local population in the past. In particular, one could expect an inflation in the estimates of fire activity during the periods when the fire was an agricultural tool and its deflation - during the periods dominated by fire suppression policies. Historical records, however, indicate that the studied area had no forestry roads, which would support horse-drawn transportation, prior to 1908 (Olenev, 1902; Golubtsov *et al.*, 1908). Instead, it was lakes, rivers, and footpaths, which were used for travel at that time. Records indicate that rafting on the lakes was the most convenient way to travel during summers (Golubtsov *et al.*, 1908). The resulting site network covered an area of approximately 25x50 km^2. We considered the size of our study area to be exceeding the size of the largest fires, which might have occurred in the European boreal zone prior to the onset of intensive forest use and its fragmentation (Niklasson and Granström, 2000). The area was, therefore, considered sufficient to represent the dynamics of historical fire cycles in the Kalevalsky NP.

Development of fire chronologies

All of the samples were air dried and sanded with progressively finer sandpapers with up to 400-grit to provide a clear view of the rings and fire scars under a binocular microscope with 40× magnification. We cross-dated samples primarily using the visual pointer year method (Stokes and Smiley, 1968), capitalizing on the point year chronology developed for that area. Examples of useful pointer years heavily used during cross-dating were: 1346 (pale latewood), 1354 (wide ring and dark latewood), 1448 (wide ring and dark latewood), 1453 (pale latewood), 1454 (wide ring and dark latewood), 1466 (narrow ring and pale latewood), 1547 (wide ring and dark latewood), 1567 (pale latewood), 1601 (pale latewood), 1655 (wide ring and dark latewood), 1703 & 07 (wide ring and dark latewood), 1763 (pale latewood), 1801 (wide ring and dark latewood), 1899 (pale latewood) and 1901 (wide ring and dark latewood).

To verify the dating, we correlated sample chronologies with a newly developed regional pine ring-width chronology. Initially, we took advantage of the Scots pine chronology ITRDB RUSS183 (Meriläinen *et al.*, 2014), developed for an area located approximately 50 km away from the Kalevalsky NP. To measure tree rings, we obtained high-resolution (2400–3200 dpi) digital images of the samples with a flatbed scanner and used Cybis AB CooRecorder/CDendro 9.0 to measure the rings (Larsson, 2017). As a proxy of correlation strength, we relied on *t* test calculated in program COFECHA (Holmes, 1983, 1999; Grissino-Mayer, 2001).

Dating of fire scars associated a scar with a particular ring. We also attempted to identify scar position within a dated ring, which provided information on the seasonal occurrence of the fire event. Fire scars with seasonal dating were assigned to one of the following seven categories: early earlywood (EEW), middle earlywood (MEW), late earlywood (LEW), early latewood (ELW), middle latewood (MLW), late latewood (LLW) and dormant (D) (Baisan and Swetnam, 1990).

Reconstruction of historical fire cycles

We developed a spatial reconstruction of fires capitalizing on the fire dates independently identified across our site network. To transfer fire dates obtained at site level into the areal estimate, we assumed that a site represented the fire history of a certain area centered on the site center, later referred to as *unit*. By summing up the areas of these units for the years with dated fire events, we obtained an annual chronology of burned areas. Since some of these units had a portion of their area covered by water (lakes, streams, but not mires nor peatlands), their contribution to the annual amount of burned area was reduced accordingly, using spatial information on the regional hydrology from DIVA-GIS datasets, version 7.5 (Hijmans R.J. *et al.*, 2001). The territory of the Kalevalsky NP is a landscape mosaic pattern that including different type of forests, mires, peatlands, and two types of permanent waterbodies - lakes and streams. Based on our knowledge of the topography of the Kalevalsky NP and the typical size and arrangement of firebreaks (such as lakes and streams), we tested unit radii ranging from 500 to 1500 m, which corresponded to unit sizes of 78.5 to 707 ha. By doing so, we wanted to check for the sensitivity of our results to changes in unit size. We elected to use the unit with the size of 314 ha (1000 m radius), which tend to place the units within one element of the landscape mosaic. The results obtained with other unit sizes are presented in the Supplementary Information section (SI Fig. 1). We converted the reconstructed burned areas into the estimates of fire cycle (FC) (Van Wagner, 1978). The area burned is the inverse of the FC, i.e. the length of time required for the area equal to the total study area to burn. FC was calculated as:

$$FC = \frac{TSA}{TBA * TI}$$

where TI is the length of the time period studied (years) and TSA and TBA are the total studied area and the total burned area over this time period, respectively. We obtained 10% and 90% confidence limits for the FC through the bootstrap method, resampling our pool of sites 1000 times.

The decline in network spatial coverage over time (i.e., in the number of sites contributing to composite fire chronology) biased the results during the oldest portion of the reconstruction, through a reduction in the amount of reconstructed burned area. To address this issue, we adjusted the reconstructed burned areas by (a) calculating the proportion of sites recording fire in the total amount of recording sites for each fire year, and (b) randomly assigning burned/non-burned status to a proportion of the non-recording sites, as identified in step (a).

Identification of fire regime shifts

We used a regime shift detection algorithm (Rodionov, 2004) to identify changes in FC over the period covered by the reconstruction (1400–2010, minimum number of sites = 5). The algorithm is based on sequential t-tests that identify regime change, when the cumulative sum of normalized deviations from the mean value of a new regime is different from the mean of the current regime, as calculated on a pre-defined moving timeframe. The algorithm uses "a cut-off length", i.e. a threshold, in years, below which the ability of the algorithm to detect regime changes is reduced. In the analyses, we set that threshold to 10 years (L parameter). The Hubert weight parameter, controlling for the weights assigned to the outliers, was set to 1 and the significance level t-tests - at 0.05. We opted for the 10 years as the value of the L parameter to increase the sensitivity of the algorithm to short-term changes in the fire cycle. The value of the Hubert parameter was set to 1, which is commonly considered as a default (Rodionov, 2004). We applied the procedure to reconstruct burned areas at the level of the studied landscape.

Analysis of association between fire history and environmental proxies

To test the association of fire events with regional weather states, we studied variability in mean summer geopotential height at 500-hPa (Luterbacher et al., 2002). Previous studies have shown a strong association between variations in the 500-hPa geopotential height level in the midtroposphere and changes in the distribution, frequency and amount of precipitation (Girardin et al., 2006b; Seftigen et al., 2013) and regional fire activity (Le Goff et al., 2008; Drobyshev et al., 2016). Dominance of high-pressure systems, reflected in higher values of 500-hPa heights, could contribute to the development of dry conditions that are more conducive to fire (Potter et al., 2004; Girardin et al., 2006a; Seftigen et al., 2013).

We used the pressure chronology for the grid cell covering the territory of the Kalevalsky NP (63.75–66.25N, 28.75–31.25E), with the record starting in AD 1659. We carried out two analyses focusing on the relationship between pressure variability for the grid cell encompassing the Kalevalsky NP and fire at both high and low frequency domains. To study high frequency variability, we used superposed epoch analysis (SEA) (Swetnam, 1993; Grissino-Mayer and Swetnam, 2000) to evaluate the significance of departures in atmospheric pressure during the large fire years (LFYs) and to quantify the spatial pattern of these departures. We performed the analyses in KNMI Climate Explorer (Trouet and Oldenborgh, 2013).

To study low frequency variability, we used the reconstruction to test for decade-long changes in the mean summer pressure over the whole period for which pressure reconstruction was available (1659–1999). To this end, we used a sequential *t*-test algorithm (see subsection above) (Rodionov, 2004) with the significance level of 0.05, Hubert parameter of 1 and L parameter of 10. Although our fire reconstruction and the pressure reconstruction provided only a partial overlap, the pressure chronology did cover the period with a decline in fire activity in the Kalevalsky NP.

The stream flow reconstruction based on sedimentary cladoceran fossils from the Kuhmo area, 150 km west of the Kalevalsky NP (Luoto and Helama, 2010), were used as a proxy of regional drought conditions during spring period. The stream level changes have been reconstructed using a site-specific cladoceran-based inference model fed with the sediment data from the lake Pieni-Kauro (Luoto and Helama, 2010). The reconstruction reflects historical variability in winter precipitation (Helama et al., 2009; Luoto and Helama, 2010). Although the stream flow reconstruction extended back to AD 500, we included in our analyses, only the period covered by our fire reconstruction, i.e. 1400 to 2010 AD.

Large fire years and climate-fire relationships

LFY were defined as years when the reconstructed annually burned area was above 1000 ha (for the version of analyses with unit size of 314 ha). We used SEA to quantify the relationships between LFYs and environmental variability as represented by ocean temperatures and air pressure patterns in the Northern Europe. We studied the pattern of June-July sea surface temperature (SST) anomalies over the area limited by 40°–80° N and -20°– 45° E during LFYs in the Kalevalsky NP. SST data originated from ERSSTv5 (Huang *et al.*, 2017). We used a subset of the gridded June-July mean temperature anomalies over the area of northern Europe from HadCRUT4 (Morice *et al.*, 2012). In both analyses, we quantified deviations of these variables during the LFYs from the long-term means and evaluated the spatial pattern of such deviations. The temperature record covered the 1850–1930 period and the SST record covered the 1854–1930 period. It contained five LFYs between 1855 and 1919. Significant departures were identified, as those exceeding the 95% confidence interval. SEA analyses were done with the KNMI Climate Explorer tool (Trouet & van Oldenborgh 2013).

Population Data

To evaluate the association of fire activity with human activities, we developed a chronology of population density for the village of Voknavolok, a settlement located 15 km from the Kalevalsky NP. We used the modern census data (Statistics, 2010) and historical estimates dating back to AD 1679 (Kochkurkina, 2000). During the period between 1679 and 1782, the population data was available only for males, excluding women and children. To obtain total population estimates for that period we used a correction factor of 2.5.

Results

The fire chronology spanned the 1400–2010 AD period. We identified 184 fire years, based on the dating of a total of 630 fire scars found on 212 samples. The earliest fire was dated to 1390 AD and the most recent one – to 2007 AD. To ensure the minimum replication of fire events, we limited our analyses to the period from 1400 to 2010, for which each year was represented by at least five sites (Fig. 2a). The majority of the fires (85%) were below 500 ha, or 4% of the study area. Fire seasonality was successfully identified for 69% of the fires. The growing season fires accounted for 95% and 61% of these were early wood fires. Only 21 scars (5%) occurred in the dormant period.

We identified thirteen LFYs for the period 1400–2010 AD. These were AD 1570, 1634, 1640, 1660, 1730, 1750, 1824, 1826, 1855, 1858, 1883, 1914 and 1919 (Fig. 2b). During each of these events, the burned area exceeded 15 km^2 or 12 % of the studied area. Of these years, 1750 was marked as a year with exceptionally high fire activity, when the burned area reached 40 km^2 or 33% of the total study area.

Since 1400 AD, the FC underwent significant changes, resulting in three fire epochs, as identified by regime shift analysis. During the 1400–1630 AD period, the average FC was 178 yrs. (bootstrapped 90% confidence envelop 118 to 300 years). In the following period, 1640–1920 AD, the FC shortened to 46 yrs. (confidence envelop 39 to 53 years). In the most recent period (1930–2000 AD), the FC increased to 283 yrs. (confidence envelop 140 to 1421 years) (Table 1 and Fig. 3a).

To quantify the contribution of fires of different seasonality to the total fire activity, we run the regime shift detection algorithm separately for early-and late-season fires. For early-season fires, we identified three periods (1400–1610 AD, 1620–1880 AD, and 1890–1940 AD) with FC of 358, 78 and 223 yrs., respectively (Table 1 and Fig. 3a). For late-season fires, the change in fire activity occurred in 1810 with the FC of 873 yrs. prior to the change and of 115 yrs. afterwards (Table 1 and Fig. 3b).

Five LFYs in the Kalevalsky NP occurred in the period covered by SST reconstruction (1855, 1858, 1883, 1914, and 1919 AD). SEA revealed a positive association between LFYs and SST in the Norwegian Sea (Fig. 4a). We observed strong positive June-July temperature anomalies for the area of northern Europe during LFYs (Fig. 4b).

During the 1659–1740 AD period, mean summer 500-hPa geopotential height remained relatively low, which was characteristic of generally cyclonic conditions (Fig. 5). The pressure height increased over the second half of the 1700s towards the first quarter of the 1800s. Reduction in 500-hPa geopotential height occurred between 1820s and 1920s, followed by its increase in the last period (1930s–2000s AD).

Discussion

Human drivers of fire regime

FC changes in the Kalevalsky NP were likely affected by human land use. The area of the Kalevalsky NP has been initial colonized for at least 7000 years (Zhulnikov, 1993). Populations of semi-nomadic Saami (Lopari) people occasionally inhabited the area between ~1000 BC and the late 1300s (Kosmenko, 1978). Saami's primary occupations were fishing, hunting, and reindeer herding (Anonymous, 1957). Their use of fire was minimal (Anonymous, 1957; Klement'ev and Shlygina, 2003; Ivanishcheva and Ershtadt, 2014), since fire killed lichens, the main forage of deer in the winter (Sarvas, 1937). Archeological excavations have suggested that pre-industrial colonization by Karelians originating from the Ladoga Lake coasts intensified in the 1400–1500s (Zherbin *et al.*, 1983), although the population density remained at an estimated 0.2 persons/km^2 (Miuller, 1978). We speculate that differences in typical land use patterns between two nationalities might be at play in promoting changes in FC. The proclivity of Karelians to settle permanently in a pre-industrial colonized area was in contrast to a predominantly nomadic habitation pattern of the Saami population. An increase in the Karelian's population might facilitate transition to fire-intensive slash-and-burn practices. Historical sources have indicated that the land-use patterns of the Karelians compromised those of the Saami people, which resulted in local conflicts (Balagurov, 1959; Klement'ev and Shlygina, 2003) and, possibly, the use of fire by Karelians to secure their land rights. During the 1500–1600s period, the Kalevalsky NP was a territory of cross-border wars between Sweden and Russia that contributed to economic recession (Anonymous, 1957; Miuller, 1978). The wars likely hindered the expansion of land use practices involving fire. Historical records report low soil fertility and a harsh climate (Olenev, 1902), further limiting the area involved in farming (Golubtsov *et al.*, 1908).

An increase in fire activity around the 1630s coincided with the signature of the Treaty of Stolbovo between Russia and Sweden (1617 AD) and the onset of economic recovery in the region (Anonymous, 1957). Industrial colonization of the area by Swedes and Finns (from the west) and by Novgorod Russians (from the east), contributed to a population increase during the 1600s (Pöllä, 1995). The mining and processing of iron ore drove economic development at that time (Chubinskii, 1866; Vasilevskii, 1949) and commercial deer hunting, tar extraction, charcoal burning and small-scale agriculture were popular occupations among the local population until the 1800s (Vasilevskii, 1949; Anonymous, 1957). All these activities likely contributed to fire ignitions and the amount of burned areas. Previous studies of fire activity in Scandinavia have consistently associated human land use with the increase in fire activity during 1600s (Niklasson and Granström, 2000; Wallenius *et al.*, 2004; Wallenius, 2011), although not necessarily with the increase in the amount of burned area. In particular, the study of Wallenius et al (2004) related the increase in fire occurrence to the political urge from Stockholm for the people of Sweden to industrial colonize eastern fringes of the kingdom in 1673 (Veijola, 1998). In our study, however, the increase took place about 40 years earlier, which questions the role of policy changes in fire dynamics. Variation in both the sampled areas and the analyzed metrics of fire regime was a likely source of differences in studies' results. In our study, the area investigated totaled 119000 ha whereas in Wallenius et al (2004) it was 419 ha. Difference in fire metrics could further contribute to differences in the results between two studies: our study operated with an areal estimate of fire regime whereas the one of Wallenius et al. (2004) focused on the fire return intervals.

The observed decline in fire activity that occurred around 1920s might be a result of socio-economic changes, although the timing of this decline does not conclusively point to a particular event as a trigger of these dynamics. Since the early 1800s, the processing of iron ore has been losing its economic importance, due to the high duty on firewood imposed by the Russian state at that time (Chubinskii, 1866). Forest burnings have been criminalized since the 1870s

(Chubinskii, 1866) and were largely replaced by a three-field system (Kochkurkina, 2000). The coup-d'état of 1917 and the political split among inhabitants of the Karelian countryside resulted in their mass immigration to Finland, followed by a deep economic recession in the region (Nygerd, 1980). Not until the end of 1923 (Kochkurkina, 2000), did most refugees return to Russian Karelia from Finland. However, the population of Voknavolok, a village located ~5 km away from the Kalevalsky NP, never reached the level observed prior to the coup-d'état (Fig. 5).

The dramatic shift from high to low fire activity appeared to coincide with changes in the economy of Karelian villages, which took place early during the Soviet period. Following the increase economic value of timber, the government organized state forest units during the 1920s and tasked them with fire prevention (Anonymous, 1918; Ulianov and Fotieva, 1920). The border protection zone was established on the Russian side of the Russian-Finnish border in the Soviet period (Gromtsev *et al.*, 2003). This prevented most of the traditional activities in the area.

Climate forcing upon fire regime

A low-frequency (centurial) synchrony between climate proxies and fire activity varied over the studied period. Overall, pressure pattern did not show a consistent association with the dynamics of fire cycle (Fig. 5). The periods with both higher and lower 500-hPa levels overlapped with the fire-prone epoch in the fire cycle reconstruction. We speculate that the result may reflect not the actual lack of a mechanistic link between two records, but the fact that the data extracted from the Luterbacher et al. (2002) represented the area located at the fringes of the region covered by this reconstruction product. It is also possible that the reconstruction recond for the area had a limited ability to reflect water balance of forest fuels.

Instead, the reconstruction of the stream flow in an area about 150 km away from the Kalevalsky NP (Luoto and Helama, 2010) indicated a general trend towards drier conditions during the Little Ice Age (LIA). The onset of the period with shorter fire cycle in the Kalevalsky NP coincided with decline in stream flow (Fig. 5). The large fire year of 1570 AD occurred during the driest period observed between 1500 and 1600 AD, was possibly conditioned by lower amounts of winter precipitation (Fig. 5) (Luoto and Helama, 2010; Nevalainen et al., 2013). Four other LFYs in the Kalevalsky NP occurred during the period of more than a century long decrease of stream flow, between the years 1600-1720s, which was likely associated with dryer forest fuels during spring. The dominance of early season fires prior to 1800s is consistent with dryer conditions at the starts of the fire seasons, indicating the principal role of climate in controlling fire cycle at that time. Instead, a decrease in fire activity was not consistent with a decline in stream flow around 1900s, suggesting a decline in climate forcing upon fire activity (Fig. 5).

At the annual time scale, the fire regime of the Kalevalsky NP synchronized with summer SST dynamics in the Norwegian Sea and summer temperature anomalies over northern Europe (Fig. 4a, b). The positive correlation between the occurrence of large fire years (LFYs) and two temperature variables suggested that the establishment of a high-pressure cell over northern Europe, warming up both the ocean and forest fuels, is likely behind the observed relationships. LFY identified in this study were not associated with the colder sea surface temperatures in the western North Atlantic, earlier shown to predict periods of regionally increased fire hazard in Northern Sweden (Drobyshev et al., 2016). It was therefore likely that the occurrence of LFY was driven primarily by the regional climate dynamics rather than by large-scale transatlantic teleconnections. Both mechanisms likely rely on the inflow of dry-cold arctic air masses in the summer, preconditioning increased regional fire hazard (Drobyshev et al., 2016).

Temporal changes in forest FC dynamics in Fennoscandia

The earliest period in our reconstruction (1400–1620 AD) had a FC of 178 years. Although the period partially coincided with the wave of pre-industrial colonisation of the area by Karelians in the 1400s, the population density apparently remained low during that period (Table 1 and Fig. 5). Prior to the wave of human colonization of the Northern Fennoscandia during the 1600s, the average FC in European boreal forests ranged ~ 40 to 300 years (Lehtonen, 1997; Lehtonen and Huttunen, 1997; Niklasson and Granström, 2000; Niklasson and Drakenberg, 2001; Rolstad et al., 2017). Our FC (178 years) was shorter than the length of FC reconstructed in Northern Sweden, estimated at 304 years (Niklasson and Granström, 2000; Drobyshev et al., 2016), but longer than in eastern Finland and south-central Norway, estimated at 107 and 73 years respectively (Lehtonen and Kolström, 2000; Rolstad et al., 2017). The similarity in FCs estimates suggested that a FC of about 200 years as a characteristic level of fire activity in Fennoscandia boreal forests, prior to the expansion of intensive forest use practices (Table 1).

The period of increased fire activity started in ~ the 1630s and was characterized by a three-fold increase in the amount of burned areas (Fig. 3a). The synthesis of boreal biome fire histories has proposed the 1600s as the most fire prone period in boreal forest, due to the dry and unstable climate of the Little Ice Age (Bergeron and Flannigan, 1995; Gavin *et al.*, 2003; Wallenius *et al.*, 2007; Drobyshev *et al.*, 2016). In the Kalevalsky NP, this climate-driven pattern might be further enhanced by human population dynamics (see the discussion on that point above). Around the 1920s, the FC declined back to the levels that are only marginally higher than the ones reconstructed for the earliest period. Similar changes in fire activity have been shown for northern Fennoscandia (Niklasson and Granström, 2000; Wallenius et al., 2007; Drobyshev et al., 2016; Rolstad et al., 2017; Aakala et al., 2018) and for boreal forests of North America (Weir et al., 2000; Bergeron et al., 2001). A large variability in the timing of the decline in fire activity, reported across European and North American sectors of boreal forest supports the view on this dynamics as driven primarily by cessation of land use practices involving fire, and not by active prevention or suppression policies. Indeed, efficient application of such policies would require the level of technological development, which was largely missing during 1700s and 1800s.

In Russian Karelia, the differences among the period-specific FCs were considerably more pronounced than in the middle and northern Sweden, the only region of the European boreal forest with available analyses of FC regime shifts. Shifts in FC among periods in Karelia reached almost 150 years (Table 1), while in northern Sweden FC changes from one period to another did not exceed 100 years (Niklasson and Granström, 2000; Drobyshev et al., 2016). An even lower level of differences in FC has been reported for southern boreal forests in Sweden (Niklasson and Drakenberg, 2001; Drobyshev et al., 2016). The differences in the regional climate between Sweden and Karelia is a possible reason for the observed difference in the FC variability. The climate of the Kalevalsky NP is more continental (Alisov, 1936), which creates more fire-prone conditions, compared to Swedish sites. Karelia is a region with strong alternation between periods of cyclonic and anti-cyclonic activity, a pattern that likely promotes fires during drier periods (Anonymous, 1989).

At the interannual scale, the list of LFYs identified here differed markedly from LFYs obtained in the landscapes located only 50-170 km west of our study area (Lehtonen and Huttunen, 1997; Lehtonen and Kolström, 2000; Wallenius et al., 2004). Over 1400-2007, only two (1570 AD, 1634 AD) out of 13 identified LFYs were common between the North Karelia and the eastern Finland (Lehtonen and Huttunen, 1997). We speculate that such moderate level of synchrony is caused by the differences in the data collection protocols, rather than differences in climate or landscape properties among the locations. Lack of synchrony might be due to the limited size of the areas sampled in the earlier studies, which might act towards increasing the stochastic behavior of the fire records.

Seasonality fires in Kalevalsky NP

Seasonal patterns of fire occurrence may provide an insight into the relative contributions of natural vs. human-mediated ignitions upon fire activity. The large proportion (61 %) of early season fires in the Kalevalsky NP might point to the natural origin of fire ignitions, despite the view on the dominance of spring and early summer fires as an indicator of human activities in northern European forests (Niklasson and Drakenberg, 2001; Groven and Niklasson, 2005). Observations have documented that lightning-ignited fires in the European part of the Russian boreal zone predominantly occur early in the fire season, due to frequent high pressure cells established over that region immediately after the snowmelt (Kurbatsky, 1976; Stolyarchyuk and Belaya, 1982). Kalevalsky NP is located in the part of the European boreal forest north of 59°N, which has been designated as a "May-June forest fire belt" (Melekhov, 1946) due to the dominance of such early season fires.

The origin of an increase in late season fires (Fig. 3c) from the early 1800s until the mid-1900s remains unclear. However, we speculate that the pattern was likely of a human population. We observed a strong association between the onset of a period with increased late season fires ~1810 and the time of peaking population density in the area (Fig. 5). Late-season fires can be potentially of higher severity and are more difficult to control (Ferrenberg *et al.*, 2006), which make them a type of event not commonly used in the past as an agricultural tool. However, an increase in population density early in that period might have contributed to additional, not necessarily "agricultural" ignitions, which were spread over the whole fire season. The increase in the amount of area burned late in the fire season was relatively minor, since it did not appear to affect the overall FC dynamics (Fig. 3a).

Conclusion

We reconstructed dynamics of forest fire cycle in a northern boreal landscape of Eastern Fennoscandia, dating back to 1400 AD. The majority of earlier analyses of fire history in Fennoscandia are based fire-interval data (Haapanen and Siitonen, 1978; Lehtonen et al., 1996; Lehtonen and Kolström, 2000) and estimates of fire cycle are rare, especially in the middle boreal zone (Wallenius et al., 2007; Wallenius et al., 2010; Lankia et al., 2012). The general picture emerging is of a pronounced variability in forest fire cycles. An earlier period (1400–1620 AD) had low fire activity (FC = 178 yrs.), which increased during the 1630-1920 period (FC = 46 yrs.) and then decreased over the 1930-2000 period (FC = 283 yrs.).
Dendrochronological results did not provide a conclusive answer on the origins of FC dynamics, although several lines of evidence suggest that climate drove the increase in fire activity in the early 1600s, while human-related factors were of importance in causing its decline in the early 1900s. First, the increase in fire activity in the early 1600s coincided with decline in reconstructed spring stream flow, which pointed to the drier conditions during the LIA, a pattern already suggested by earlier studies (Bergeron and Flannigan, 1995; Gagen et al., 2011; Drobyshev et al., 2016). Second, the dominance of early season fires since 1620 AD (Fig. 3a, b) further suggested climate as a dominant factor in this dynamics (see the previous sub-section). Third, SEA revealed a significant signature of LFYs in the dynamics of Norwegian Sea SSTs and summer temperature anomalies over northern Europe (Fig. 4a, b). These patterns suggested that periods with increased fire activity in the Kalevalsky NP were contingent upon development of the regional high-pressure cells during the summer time, contributing to the drying of the

forest fuels (Seftigen et al., 2013; Drobyshev et al., 2016). Finally, a dramatic increase in fire activity in early 1600s, with the FC declining from 178 to 46 years, occurred in the period when the population densities within the Kalevalsky NP remained low (Kochkurkina, 2000; Statistics, 2010) (Fig. 5), which argued against the role of climate factors in controlling fire regime at that time. In contrast, the decrease in fire activity in the early 1900s was likely associated with shift of forest use practices towards the use of the forested lands as a source of timber (Kochkurkina, 2000).

The current fire cycle in the Kalevalsky NP is close to the estimates reported for the pre-colonization period in Scandinavia (Niklasson and Granström, 2000; Niklasson and Drakenberg, 2001; Drobyshev et al., 2016), which suggests that the forests of the area currently maintain its close-to-natural fire regime.

A challenge to partition climate and human factors is common in dendrochronological fire history reconstruction in boreal landscapes. The availability of well-resolved and independently developed records of environmental variability is critical to provide a sound interpretation of changes in fire regimes. Upscaling the analysis beyond the single landscapes and feeding them with the data collected in networks of sites, spreading across environmental and land use gradients, is another sound approach to decipher the drivers of historical fire activity. The current work will contribute towards the establishment of such a network covering the boreal Eurasia.

Management implications

The forests of the Eastern Fennoscandia are dominated by pine, whose cohort dynamics is driven by a combination of repeated surface and stand replacing fires (Zackrisson, 1977; Niklasson and Granström, 2000; Wallenius *et al.*, 2004). Quickly decreasing with time, the number of trees representing older cohorts make reconstruction of fire severity in these forests difficult.

However, the common presence of trees and deadwood with multiple fire scars and the large amount of dead wood in the studied stands, indicate that low-severity surface fires prevailed across the landscape of Kalevalsky NP in the past. Even the most pronounced fire years, such as 1640 and 1750, left behind a large number of scarred trees, many of which had earlier fire scars, pointing to a largely non-stand replacing type of these events.

Our findings demonstrate that fires were an important factor affecting the forests of the Kalevalsky NP over the past 600 years. Conservation management of this area and similar protected areas of Eastern Fennoscandia should, therefore, acknowledge the role of this disturbance agent. We argue that a balance is needed between fire suppression activities dictated by the economic value of the forest and fire risks to human lives and infrastructure, on one hand, and the preservation of fire as a driver of vegetation dynamics, on another. The value of this nature-based approach has been convincingly demonstrated across a wide range of ecosystems, where fire acts as the primary disturbance factor (Peterson and Reich, 2001; Conedera *et al.*, 2009; Clear *et al.*, 2013).

A prolonged absence of fire prevents the natural regeneration of pine and promotes its replacement by shade-tolerant trees. The pattern has been documented in the pine-dominant forests of the Kalevalsky NP (Gromtsev *et al.*, 2003), in other parts of Fennoscandinavia (Niklasson and Drakenberg, 2001; Kuuluvainen *et al.*, 2002; Wallenius *et al.*, 2004) and in European Russia (Gromtsev *et al.*, 2002; Kuosmanen *et al.*, 2014; Kuosmanen *et al.*, 2016). Prescribed surface fires can be instrumental in maintaining habitats for pine regeneration (Kuuluvainen and Rouvinen, 2000). These fires may also minimize the risks of large stand-replacing fires, by reducing the amount and continuity of fuels (Angelstam and Kuuluvainen, 2004; Drobyshev *et al.*, 2008).

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Table 1. Reconstructed FC with corresponding confidence intervals in the Kalevala NP for the periods identified by the regime shift analysis. FC estimates of two locations in Sweden are based on published reconstructions (Niklasson and Granström, 2000; Niklasson and Drakenberg, 2001) and the results of respective regime shift analyses (Drobyshev *et al.*, 2016).

Epoch, years AD	Mean FC	95 % CI lower bound	95 % CI upper bound
All fires			
1400–1630	178	118.67	300.98
1640–1920	46	39.07	53.82
1930–2000	283	140.96	1421.89
Early season fires			
1400–1610	358	210.05	768.37
1620–1880	78	66.61	93.84
1890–1940	223	133.55	520.25
Late season fires			
1570–1810	873	408.25	6720.29
1820–1940	115	86.86	161.07
Tiveden (middle Sweden)			
~1500–1600	75	–	–
~1600–1700	63	–	–
~1700–1800	88	–	–
Bjuvholm (northern Sweden)			
~1500–1600	304	–	–
~1600–1700	217	–	–
~1700–1800	320	–	–
~1800–1900	233	–	–

Fig. 1. Location of the study area and the sampled sites within or in the vicinity of the Kalevalsky NP. The insert shows the location of the area on the map of biomes (Olson *et al.*, 2001): 1, Kola Peninsula tundra; 2, Northwest Russian-Novaya Zemlya tundra; 3, Sarmatic mixed forests; 4, Scandinavian and Russian taiga; 5, Scandinavian coastal conifer forests; 6, Scandinavian Mountain Birch forest and grasslands.

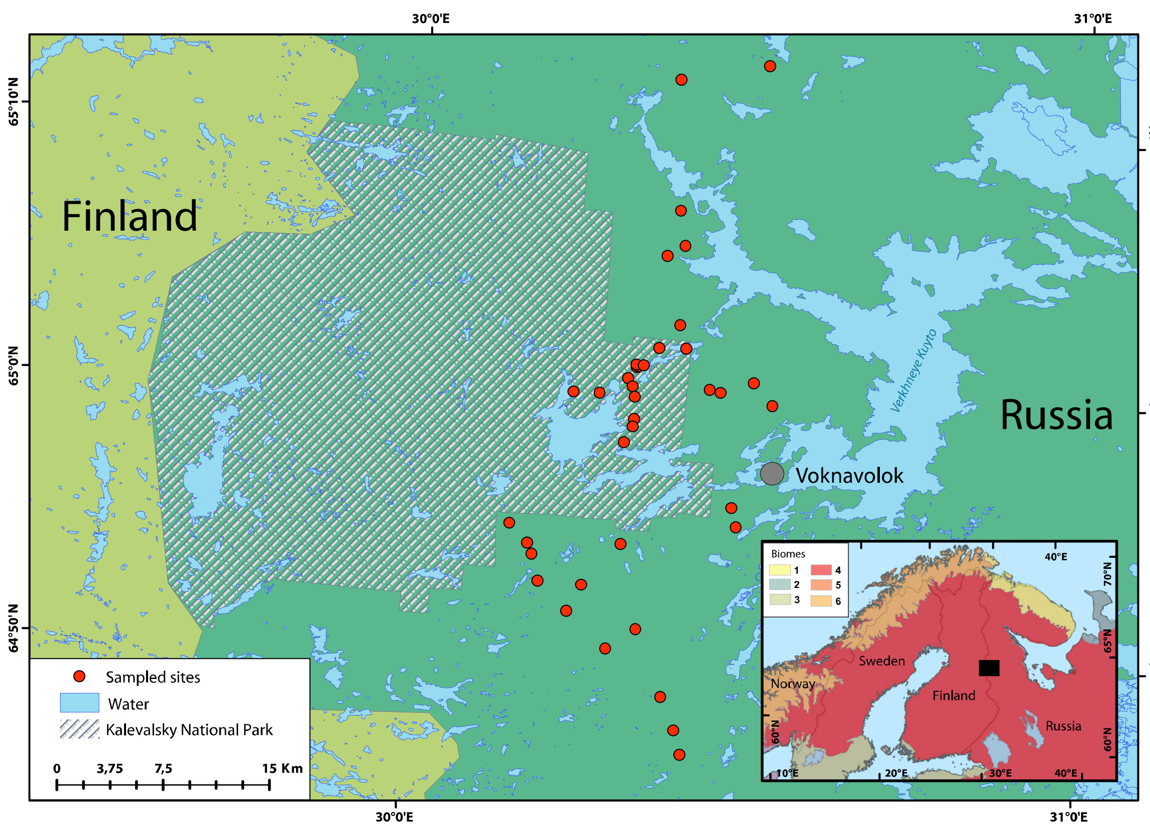


Fig. 2. Dendrochronologically reconstructed fire history of the Kalevalsky NP over the 1400–2010 period. (A) Summary of fire scar dating with a single straight line representing a site and a dark circle representing a fire event. (B) Reconstructed chronology of annually burned areas with large fire years marked with dark circles.

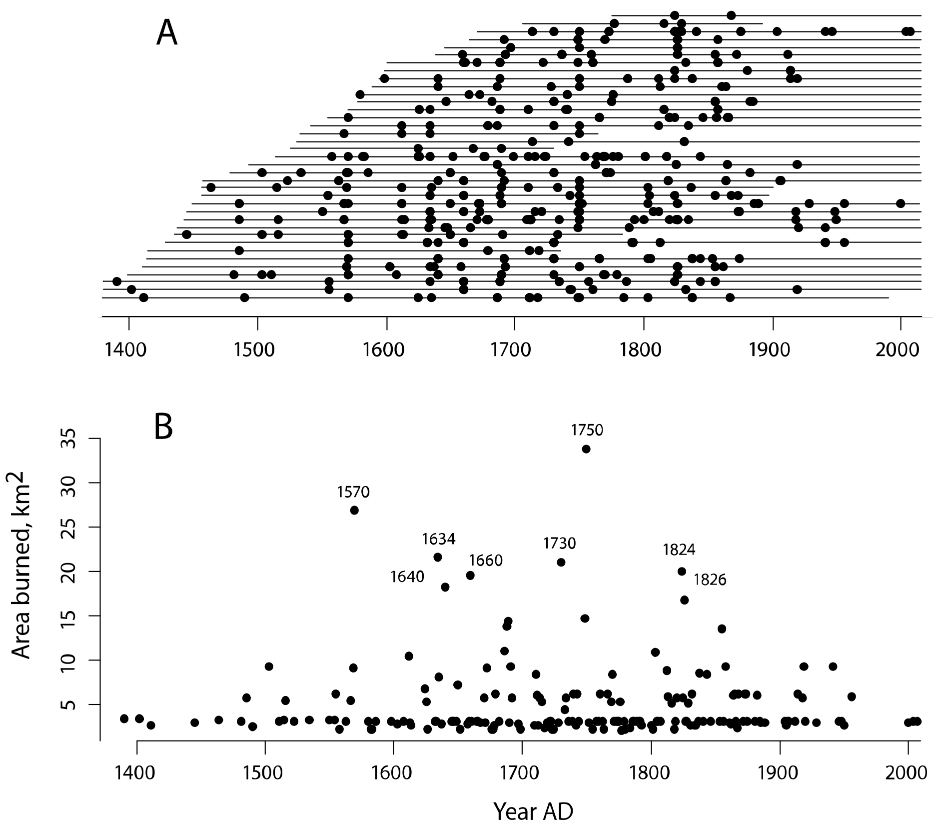


Fig. 3. Changes in the FC of (A) all fires, (B) early season fires, and (C) late season fires in the Kalevalsky NP between 1400–2010 AD. Dashed lines represent decadal burned area, in km^2. The red line shows periods with similar fire cycles, as identified by the regime shift analysis (Rodionov, 2004) using a 10-year window. The solid black line indicates sample depth.

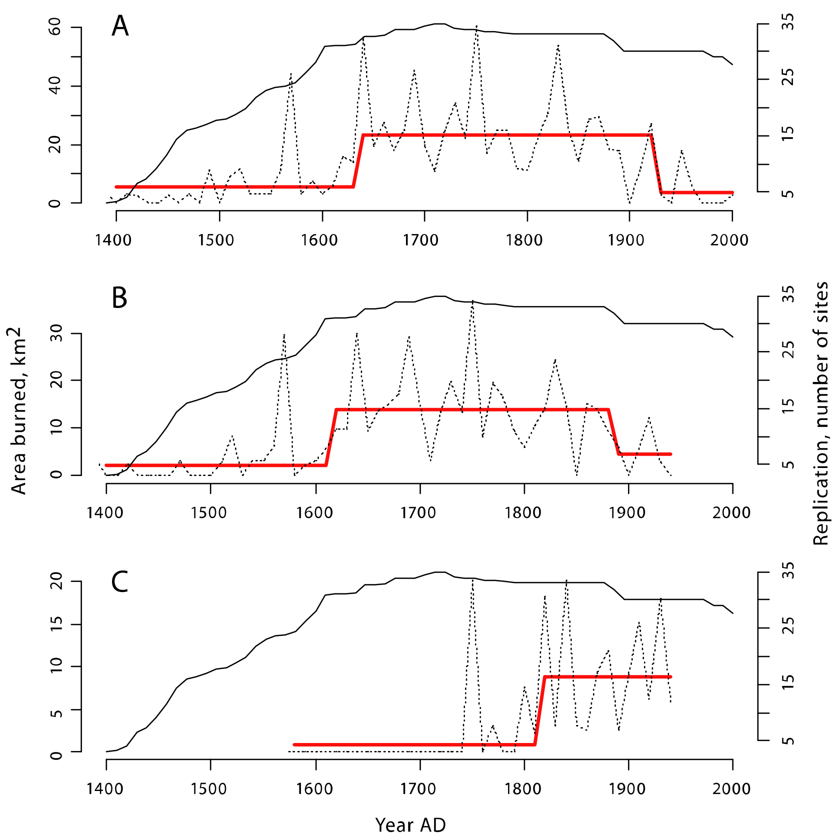


Fig. 4. Relationship between LFYs in the Kalevala NP and (A) June–July sea-surface temperatures (Huang *et al.*, 2017) over the 1854–1930 period, and (B) June–July temperature anomalies (Morice *et al.*, 2012) over the 1850–1930 period. The location of the study area is marked with a dark circle. Colored areas indicate temperature anomalies, which were significant at $p < 0.10$.

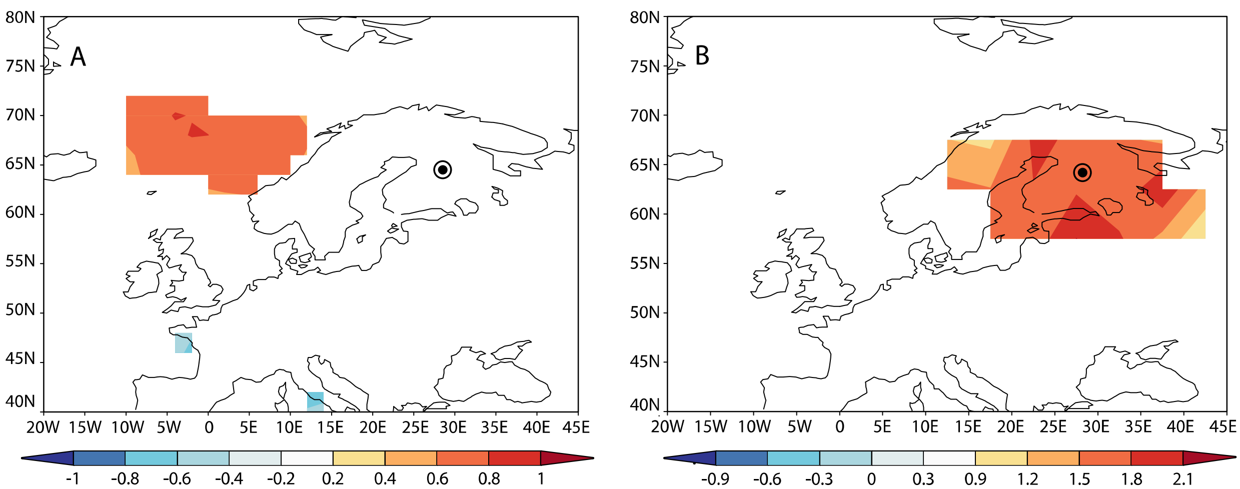
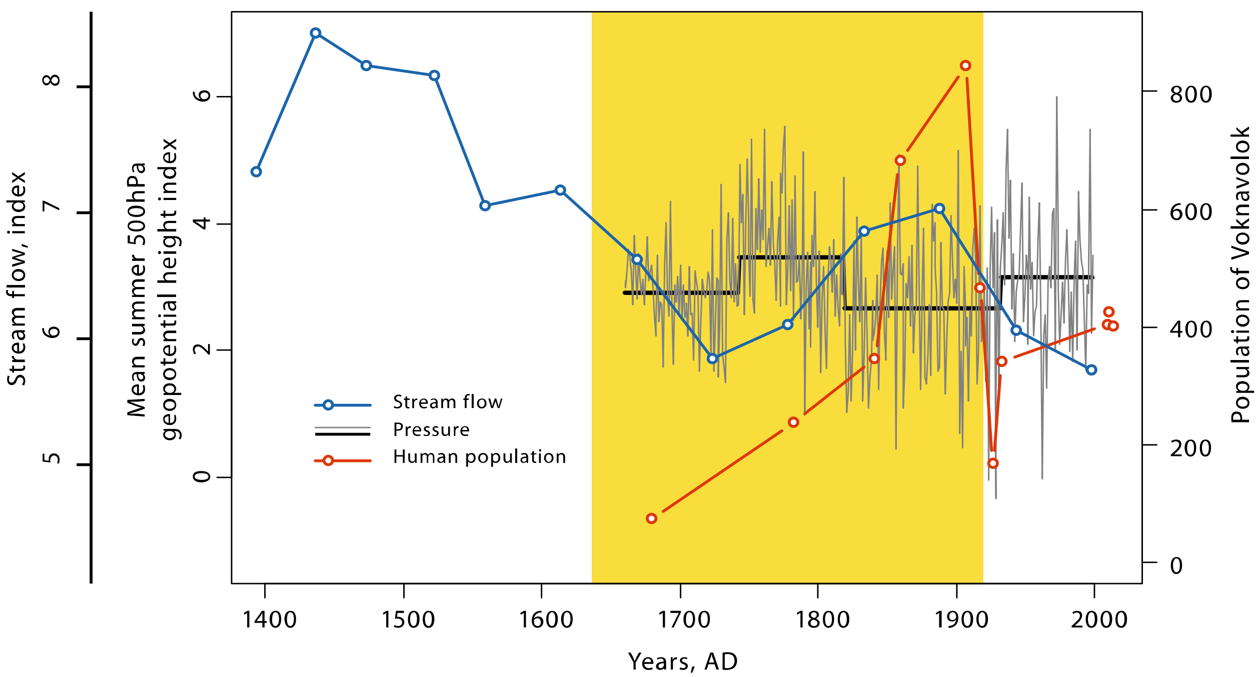


Fig. 5. Chronologies of population density of Voknavolok (Kochkurkina, 2000), reconstructed summer 500-hPa pressure for the territory of the Kalevalsky NP (Luterbacher et al., 2002), and stream flow reconstruction based on the sedimentary cladoceran fossils of the Lake Pieni-Kauro in Eastern Finland (Luoto and Helama, 2010). The yellow bar indicates the period with increased fire activity as revealed by dendrochronological reconstructions (see Fig. 3a).



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