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Marginal imprint of human land use upon fire history in a mire-dominated boreal landscape of the Veps Highland, North-West Russia

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ABSTRACT

Dendrochronological reconstructions inform us about historical climate-fire-human interactions, providing a means to calibrate projections of future fire hazard. Most of these reconstructions, however, have been developed in landscapes with a considerable proportion of xeric sites that could potentially inflate our estimates of the historic levels of fire activity. We provide a 420-year long reconstruction of fires in a mire-dominated landscape of the Veps Nature Park, North-West Russia. The area has mostly escaped large-scale forestry operations in the past and is an example of pristine mid-boreal vegetation with a high (approximately 30% for the area studied) proportion of waterlogged areas with ombrotropic mires. The historical fire cycle was 91.4 years (90% confidence intervals, CI 66.2–137.6 years) over the 1580–1720 period, decreasing to 35.9 (CI 28.1–47.6 years) between 1730 and 1770, and then increasing again to 122.7 years (CI 91.0–178.0 years) over the 1780–2000 period. Early season fires dominated over late season fires during the reconstruction period. We documented a higher fire activity period between 1730 and 1780, resulting from the increase in early season fires. This period coincided with one of the largest multi-decadal declines in the reconstructed spring precipitation since 1600 CE, although we found no significant relationship between fire and precipitation over the whole reconstructed period. The nine largest fire years were associated with negative summer precipitation and positive summer temperature anomalies over the study region. Land-use history of the area did not appear to have an effect on historical fire dynamics. Modern (1996–2016) fire records indicate a regional fire cycle of ~ 1300 years, featuring a pronounced pattern with early (April–May) and late (July–September) season fires. The uniform fire cycle in the area since 1780, occurrence of nine largest fire years during years with spring-summer droughts, and low ignition frequencies over the last 420 years (0.005 to 0.037 ignitions per year and km^2) suggest that the fire regime of the Veps Highland remained largely natural until the onset of the 20th century.

1. Introduction

Annually resolved reconstructions of fire histories give us a valuable tool to quantify factors shaping historical fire regimes, specifically – the relative contributions of climate variability and human land use. Availability of such reconstructions, however, varies greatly across the Eurasian boreal zone, with the vast majority in the Fennoscandia (Aakala et al., 2018; Drobyshev et al., 2014). Dendrochronological studies commonly extend in this region to 1500–1400 CE and reveal a strong temporal variability in the properties of fire regimes. Large but infrequent fires dominated the boreal zone prior to the introduction of slash-and-burn agriculture, with the median interval between fires at the point scale being ~ 80 years (Niklasson and Granström, 2000). Colonization of the forest and the use of fire for agriculture (Hamilton, 1997)

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and production of charcoal (Östlund, 1993) resulted in smaller but more frequent fires. The pattern has been broadly similar across Fennoscandia (Rolstad et al., 2017; Storaunet et al., 2013; Wallenius, 2011). Cessation of the land use practices involving fire was associated with widespread decline in the reconstructed fires, suggesting the human activities as the main driver of long-term trends in fire activity (Granström and Niklasson, 2008; Lehtonen and Huttunen, 1997; Niklasson et al., 2010). However, analyses at anuual and seasonal scales have documented the relationship between dynamics of burned areas and climate variability, in particular – dynamics of precipitation (Aakala et al., 2018) and the occurrence of high pressure atmospheric cells developing over the Scandinavian peninsular during the seasons with high fire activity (Drobyshev et al., 2015), the latter likely being conditioned by ocean–atmosphere feedbacks in the Northern Atlantic (Drobyshev et al., 2016). One of the peculiar features of the Fennoscandinavian fire histories is an increase in fire activity in the 1600–1700s, the coldest period of the Little Ice Age (LIA) in the region. It has been hypothesized that LIA featured increased fire activity levels and more frequent conditions of extreme fire hazard (Drobyshev et al., 2016; Ryzhkova et al., 2020).

It is unclear to what degree this geographical bias compromises our ability to generalize the findings of these studies over the whole European boreal domain. Indeed, western sections of the European boreal forests are unique in the circumboreal belt of the Northern Hemisphere in terms of the profound impact of human land use exsersized upon their post-glacial development. Similar to other European regions, the climate of Fennoscandia is strongly influenced by Atlantic air and ocean circulation. Insights from existing reconstructions, e.g. concerning the sensitivity of fire regimes in different taiga types to climatic variability (Drobyshev et al., 2014) and the properties of climatically-forced fire regimes (Granström, 2001; Pinto et al., 2020), can, therefore, be representative of these particular historical and climatological settings. Extending reconstructions to eastern sections of the European boreal zone (such as in Ryzhkova et al., 2020) can help document patterns of historical fire activity in regions with considerably less human land use and varying degrees of contitentality in climate conditions.

Two features of the Veps Highland (VH), located on the eastern fringes of the St. Petersburg region in North-Western Russia, set it apart from other eastern European boreal landscapes. First, due to its location on the divide between watersheds of the Baltic and Caspian seas, the area is rich in waterlogged sections, raised bogs and lakes, with their cover reaching 20–30% (Popova et al., 2005). It is reasonable to assume that high density of firebreaks make the area generally less “fire prone” and less sensitive to external drivers of fire activity. Second, the location of the VH at the border between two administrative regions (Leningrandskaya and Vologodskaya oblast’) made the area less exploited commercially over the 20th century, as compared to other sections of North-West Russia. Apart from selective cuttings, which were limited to a minor section of the landscape, and brief of commercial timber harvesting in the 1970s (Fedorchuk et al., 1998), the area has not been affected by intensive forestry operations and is an example of a landscape dominated by natural mid-boreal vegetation. These two VH features made it a valuable area to study climate forcing of historical fire regimes over periods when Scandinavian forest histories were strongly affected by land use policies, including fire suppression (Granström and Niklasson, 2008). Historically, the VH has been sparsely populated, with the main nationality consisting of Veps and Karel indigenous ethnic minorities living in the area. Although there is documented evidence that the Veps people used fire as an agricultural tool (Vinokurova, 2019), a considerable part of their subsistence activities were apparently focused on hunting, fishing, berry picking and, in the winter time, timber harvesting.

In this study, we analyse a 420-year long reconstruction of fire activity, done in a eastern section of the VH, and relate it to (a) reconstructed climate variability and (b) historical records of human land use. In doing so, we tested the hypothesis that (H1) the temporal pattern of fire activity in the VH was similar to the patterns revealed in Fennoscandinavian studies. Specifically, we hypothesized that the area exhibited a period with the peak in fire activity centered on the 1600s, with a decline during the 1700s and 1800s. We further hypothesized that (H2) reconstructed fire activity was synchronized with historic variability in drought conditions, indicating a climate forcing upon the regional fire history. In our analyses, we put a particular focus on understanding the dynamics of ignition frequencies, since it might represent changes in the land use patterns. To support the discussion, we also present analyses of the modern fire records of the area, and relate them to climate variability and estimates of historical fire cycles. Our work extends the network of the spatially explicit dendrochronological reconstruction of fire activity towards the eastern sections of the European boreal zone, filling in the existing gap in annual resolved and multi-century long fire records for that region.

2. Material and Methods

2.1. The area

Veps Highland (VH) lies at the eastern border of St. Petersburg region in North-West Russia (Fig. 1). VH is an extension of the Valdai Highland occupying a more central section of the Russian plain (Isachenko et al., 1965; Petrov et al., 2014). VH marks the divide of the Caspian and Baltic sea watersheds and hosts the upper reaches of several rivers, including Shoksha, Ojat’, Kapsha and Pasha. Geologically, the area belongs to the northern section of the Valdai-Onega ridge. The topography of the area is a fluvio-glacial zander plain featuring gently rolling hills and ridges, covered by quaternary sediments of the glacial origin. The dominating deposits are fluvio-glacial sandy loams underlain by moraine loams (Belyaeva, 2019; Petrov et al., 2014). The ice shield covered the area during the last glacial period, the Valdai (Weichselian) glaciation. The dominating soil types are histosols, retisols, and podzols (FAO, 2014).

The climate of the VH is moderately continental and is classified as Dfc-Dfb in the Köppen-Geiger climate classification (Rubel et al., 2017). The month with the coldest temperature is January (mean −8.6C, with the 95% distribution range is between −19.5 and −2.1C) (Dee et al., 2011). July is the warmest month with a mean of 17.4C (14.8–22.0C). Annual precipitation is, on average, 810 mm (95% distribution range is 286 to 1337 mm) (Dee et al., 2011). The period from April to September is commonly snow-free, overlaps with a fire season in the area, and accounts for half of the annual precipitation of 454.4 mm (168–763 mm).

Ombrotrophic and mesotrophic wetlands cover the lower portions of the landscape, gradually replacing post-glacial lakes. The forests of VH are predominantly spruce (*Picea abies*) and spruce-pine (*P. abies - Pinus sylvestris*) types and the discussion on successional climax of these communities has been a vivid theme in Russian phytosociological literature (Dyrenkov, 1984; Fedorchuk et al., 1998). The area has enjoyed formal protection as the Veps Forest Nature Park since 1999 (Anonymous, 1999).

2.2. Human population of the area

Archeological excavations indicate the presence of human population of the area since the onset of the second millennium AD (Kochkurkina and Linevsky, 1985). A portage linking the Ojat’ (Baltic Sea basin) and Koloshma rivers (the White Sea and Volga river watersheds) likely contributed to the colonization of the area. During the 900s-1100s, human activities in the area were further influenced by nearby Lake Ladoga, which provided a major transportation route for goods at that time. In the 1100s, the region became a part of the Novgorod State and since the end of the 1400s, the territory has been a part of the Moscow, and later – Russian state (Adrijashev, 1930). The establishment of churchyards at the river banks was a major way to colonize the VH during the 1500–1600s (Kurilov, 2016). Over this period, the local population lived in one-family farms located several kilometers from

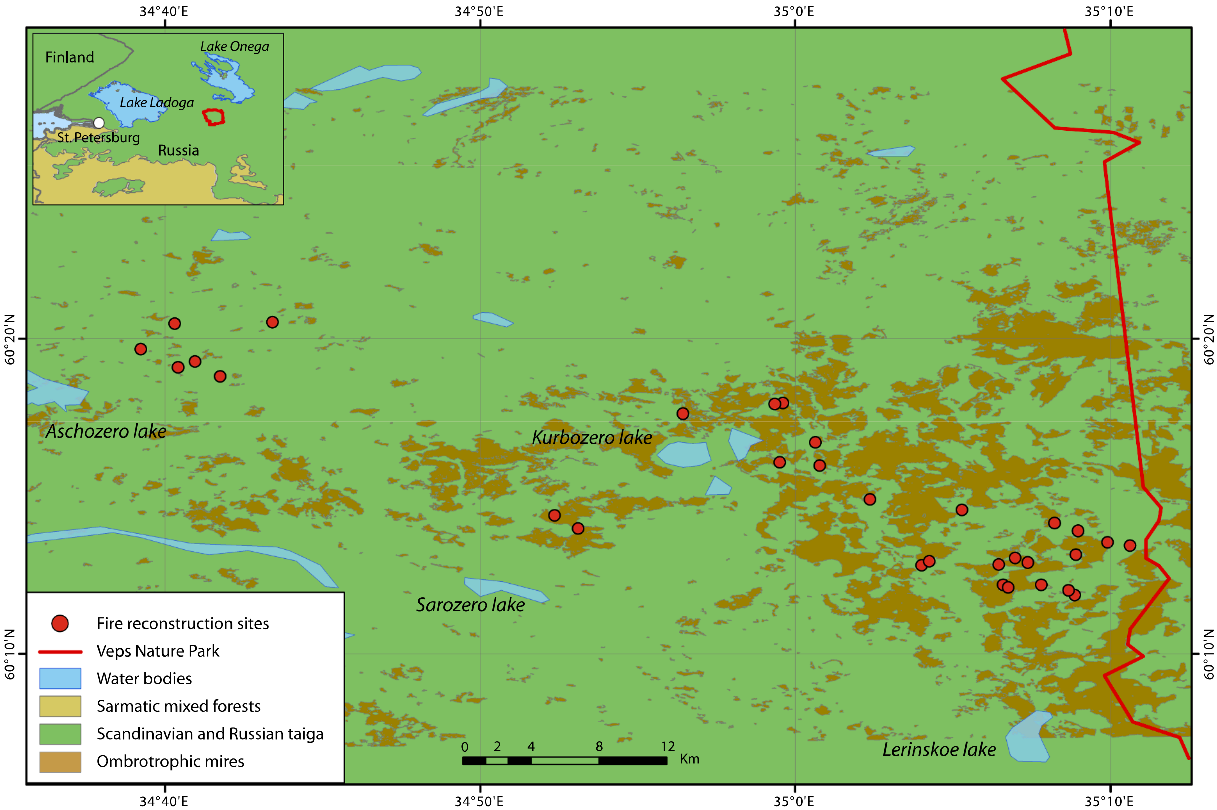

Fig. 1. Location of the study area and the sampled sites (red dots) within the Veps Nature Park, with its eastern border indicated by the red line. The map insert shows the location of the park territory (red line) in North-West Russia on the map of biomes (Olson et al., 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

each other, occupying areas suitable for agricultural production.

The Veps population was around 15 000 in the middle of the 1800s and reached 25 000 towards the end of the 1800s (Egorov, 2014). The original type of Veps social organization was a network of farms, similar to the neighboring region of Karelia and other western fringes of north-western Russia, that helped maintain low population density. Most of the land occupied by the Veps people featured soils of the fluvio-glacial zander plain, which offers generally inferior conditions for agricultural production. During 1970s and 1980s, as a part of the federal program to reduce the number of smaller settlements in the countryside, inhabitants of many villages in the area were forced to relocate towards neighboring towns making the area even less populated (Egorov, 2014).

2.3. Field sampling

The sampled sites located inside Veps Nature Park, within 60.19–60.34 N and 34.65–35.18 E (Fig. 1). Using the existing forest road network, we placed sites by randomly locating points for sampling along the roads. To ensure sufficient site density for estimating the size of individual fires, we kept the distance between neighboring sites within one to three km. We sampled forested areas and areas covered by mires, since both provided material for dendrochronological dating. Although we aimed at an even distribution of our sampling effort within the park, we did not succeed in providing a truly homogenous coverage of its territory by our sampling sites (Fig. 1) due to challenging topography and a limited number of access routes into the area.

We sampled 31 sites, each one to two ha, during 1999, 2001 and 2004. Each fire reconstruction site represented an area of one to two hectares. To ensure an equal distribution of the sampling effort among sites, we inventoried each site for 1.5 h, by thoroughly searching the area 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, we extracted cross-sections. We collected between five and 12 samples at each site, acquiring a total of 164 samples of Scots pine (*Pinus sylvestris* L.) via 69 living and 95 dead trees. All of our sites were located at least six km away from nearest villages.

2.4. Development of fire and axe scar chronologies

We air dried and sanded the samples with progressively finer sand-papers to secure a clear view of the rings and fire scars under a binocular microscope. We cross-dated samples using the visual pointer year method (Stokes and Smiley, 1968) and using the pine pointer year chronology developed for the VH area. The following rings were particularly instrumental in dating: 1965 (narrow latewood), 1925 (dark latewood), 1965 (narrow latewood), 1906 (a wide ring with dark latewood), 1899 (narrow latewood), 1867 (pale latewood), 1750, 1735, 1727 and 1712 (all with narrow latewood), 1652 (a narrow ring with pale latewood), 1601 (pale latewood) and 1588 (a wide ring with dark latewood). To verify the dating, we correlated sample chronologies with a newly developed Scots pine ring-width chronology. 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 and CDendro 9.0 software bundle to measure and crossdate the rings, using *t*-test as a proxy of crossdating success (Larsson, 2018).

Dating of scars allowed us to associate the calendar years with fire scars and date the oldest and the youngest rings on each sample. We also attempted to identify intra-annual scar position within a dated ring, which provided information on the seasonal occurrence of fire. We assigned to fire scars one of the following categories: no seasonal dating, early season scar (a scar located in early and middle earlywood), mid-season scar (a scar located in late earlywood and early latewood), late season scar (scar located in the middle or late latewood), and dormant scar. Dormant scars were located on the interface between two rings. In this case, we assigned the year and season, based on the seasonal dating of scars dated at the same site and to the years in question.

To develop a proxy for human use of VH forests, covering the same period as fire reconstruction and resolved at the annual scale, we sampled and dated trees with axe scars. In contrast to fire scars, axe scars on the cross-sections appear as straight lines and are followed by a very local (if any) post-disturbance growth response. Since the majority of these scars occurred in the dormant season, we did not provide a precise seasonal resolution for this axe scar chronology and assigned the earliest calendar year to the scar. For example, if scar was dated to the dormant season of 1841/1842, it was assigned year 1841.

2.5. Historical fire cycles and identification of regime shifts

To test whether the temporal pattern of fire activity in the VH was similar to the patterns revealed in Fennoscandinavian studies (H1), we converted the point data (i.e. fire dates from a population of sites) into the area estimates. We assumed that a site fire chronology represented the fire history of a certain area centered on that site, 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. We excluded the proportions of the units containing river and lake surface from calculations. We tested unit radii ranging from 200 to 600 m, which corresponded to unit sizes of 12.7 to 113.0 ha, for the sensitivity of our fire cycle (FC) reconstruction to changes in unit size. We selected units of 78.5 ha (500 m radius), which best placed units within one element of the landscape mosaic.

We converted the reconstructed burned areas into the estimates of FC (Van Wagner, 1978), which is the length of time required for the area equal to the total study area to burn:

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

where *TI* is the length of the time period studied (in years) and *TSA* and *TBA* are the total studied area and the total burned area over this time period (in ha), respectively.

Although the concept of the FC as defined above has been criticized for its lack of correspondence to the fire return interval at the landscape level (Reed, 2006), the current study did not extend its discussion to the concept of fire return interval. Furthermore, our calculation of the areas burned operated on a much more constrained spatial "universe" (sensu Johnson and Van Wagner, 1985) that supports the adopted definition. To adjust for the decline in the number of sites representing the oldest sections of the area-wide chronology, we adjusted the estimates of the area burned using the protocol of (Ryzhkova et al., 2020).

We used a regime shift detection algorithm based on sequential *t*-tests (Rodionov, 2004) to identify changes in FC and fire occurrence over the period covered by the reconstruction (1580–2000, minimum number of sites = 9). Specifically, a new regime was identified when the cumulative sum of normalized deviations from the mean value of a new regime was different from the mean of the current regime, calculated on a pre-defined moving timeframe. See details of the algorithm used in the context of FC analyses in Ryzhkova et al. (2020). The algorithm was run with the L parameter set to 10, the Hubert weight parameter set to 1 and with the significance level of 0.05. The Rodionov algorithm represented, therefore, the dynamics of fire activity at the whole studied area. To assess sensitivity of the results to a particular combination of sites, we used bootstrapping to obtain 5% and 95% confidence limits of FC estimates, resampling sites 1000 times.

2.6. Estimation of the ignition rates

Quantifying historical ignition rates, i.e. time and area-weighted estimates of fire occurrence, is instrumental for the evaluation of a possible human contribution to natural ignitions through lightning strikes:

Ignition rate = number of fires / (period_considered * area_studied).

The determination of the "studied area" and of a spatial extend of single fires, i.e. the actual number of fires that occurred within a particular year, are two major sources of uncertainty in the estimation of the ignition rate. Concerning the study area, two alternative calculation pathways are possible: (a) the area is estimated as the size of a single polygon encompassing the sampled locations within a studied landscape, or (b) the area is calculated as the total sum of the areas of inventoried locations (units). The first alternative causes underestimation of true ignition frequencies, since some smaller fires likely "escape" the existing network of sites, while the area where they occurred contributes to the area used for calculation. The second alternative can potentially inflate the ignition estimates since the sampled areas, often – more xeric and, therefore, more fire-prone than the rest of the landscape, represent only a small proportion of the area for which these estimates are commonly attributed to. In this study, we relied on a modified version of the first alternative, regarding the "studied area" as the sum of the recording units (for definition of units – see the previous sub-section). The solution was a balanced approach, which combined low probability of fires remaining undetected within the sampled portions of the landscape and, at the same time, allowing for the area of the whole landscape element to enter the calculation of the ignition rates. Following this approach, we based our estimates on the area of 22.24 km^2. We also calculated estimates obtained following the alternative protocol (the first alternative as specified above), using the area of 327 km^2.

To estimate the number of fires (i.e. the number of ignitions over a defined spatial and temporal frame), we need to address uncertainty in defining perimeters of historic fire evens result. The most conservative approach would be to equal a single fire year to a single fire, and the most opportunistic one – to equal each burned study location (unit) to a single fire. Assuming that two estimates encompass the true value, we report both of them for each of the fire epochs identified on the basis of reconstructed burned areas (see the previous sub-section).

The considerations outlined above assumed that the study period features a constant number of recording sites, a situation which is rarely observed with real data, since site reconstructions always vary in their length. To ensure that the period under consideration had a constant number of recording sites, we adjusted the number of recorded fire years, capitalizing on the relationship between the number of recorded fire years and the length of a period. In particular, we assumed that over the period with declining site coverage (from ~ 1800 to 1600 CE, Fig. 2) the fire regime had remained constant and changes in the number of reconstructed fire years was a function of the changing site replication. For the 20-year segments within this period, we obtained the number of fire years and the number of sites representing that segment. We then estimated the difference between the maximum number of sites over the whole period and the site replication for a focal segment. We then used this difference (*deltaS*) as an argument in the regression with the number of fire years as the dependent variable:

Number of fire years = f (*deltaS*)

The regression provided us with an estimation of the number of missing fire years, which was the difference between expected and observed fire years (SI Fig. 1). Finally, we added these years at random positions within that segment. The algorithm provided a conservative solution to the adjustment problem, since it assumed the same "process density".

2.7. Analysis of association between fire activity and environmental proxies

We used superposed epoch analysis (SEA) (Grissino-Mayer and Swetnam, 2000; Swetnam, 1993) and regression analyses of cumulative burned areas at the decadal scale to assess the role of climate forcing upon the fire activity (H2). For SEA, we used the nine largest fire years

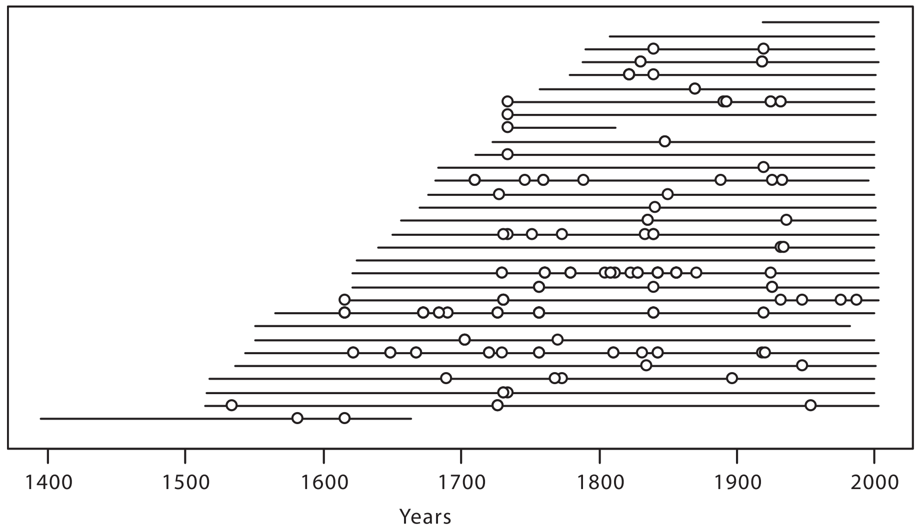

Fig. 2. Summary of dendrochronological reconstruction of the fire history in the Veps Highland. A single straight line represents each study site and a white circle represents a fire event on that site.

(LFYs) reconstructed over the period 1580 – 2000. A LFY had a reconstructed amount of area burned above 2.4 km^2, or about 10 % of the total area studied (22.24 km^2). We used seasonal precipitation (Pauling et al., 2006) and Berkeley surface temperature reconstructions (Rohde and Hausfather, 2020). Both reconstructions were gridded and extended to 1750 (temperature, 1° grid) and 1500 (precipitation, 0.50° grid).

To evaluate climate-fire relationships in the area for modern era (1996–2016), we used data from the Global Fire Emission database (Giglio et al., 2013; van der Werf et al., 2017). We selected an area within 59.21 – 60.87 N and 32.65 – 35.44 E (28 609 km^2), which was centered on the park. The selected area was larger than the park territory but allowed for a more meaningful fire chronology, e.g. avoiding the dominance of years with no fire activity recorded (that would be the case with the selection of a smaller area of the Nature Park).

We used ERA5 reanalysis dataset (C3S, C.C.C.S., 2021) to calculate three-month Standardized Precipitation-Evapotranspiration Index (SPEI). We then correlated the indices calculated for April-June and July-September with the amount of burned areas in respective periods.

3. Results

We reconstructed a total of 74 fire years from 1534 to 1987. At least nine sites covered a period between 1580 and 2000, which was selected for the analyses (Fig. 2). Early season fires were predominat followed by late season fires during that period (Fig. 3A).

The mean historical FC was 91.4 years (95% confidence intervals, CI 66.2–137.6 years) over the 1580–1720 period. It decreased to 35.9 (CI 28.1–47.6 years) between1730 and 1770, and then increased again to 122.7 years (CI 91.0 – 178.0 years) over the 1780–2000 period (Table 1, Fig. 3B). A period with higher fire activity in the mid-1700s was a result of an increase in early season fires (Fig. 3C through 3D).

The largest reconstructed fire year was 1616 with 12.6 km^2 burned, followed by 1734 and 1731, with 6.3 and 4.7 km^2 burned, respectively. Contrasting the list of the nine largest fire years (in chronological order: 1616, 1622, 1649, 1673, 1727, 1731, 1734, 1757, 1840) with climate records in SEA revealed generally drier conditions during the spring and summer of these years, the pattern was particularly pronounced during the summer months (Fig. 4). Spring temperatures exhibited positive anomalies immediately south of the study area and over central Sweden (Fig. 4). At the same time, there were no significant anomalies observed for the summer temperatures during reconstructed LFYs.

The precipitation deficit during these years was accompanied by an increase in the reconstructed spring temperatures (but not in summer temperatures) in the region immediately adjacent to the study area (Fig. 4). The period with increased fire activity (1730–1770) was associated with one of the strongest decade-long declines in spring precipitation. The same pattern could be seen for another period of increased fire activity (1910–1950) which, however, did not result in statistically significant regime shift (Fig. 5A). This suggested that variability in decadal fire activity might be related to the changes in precipitation amounts at the same temporal scale. However, considered over the 1600–1940 period (the whole reconstructed period with largely fire-free post-1940 period excluded), a low frequency variability in the reconstructed precipitation did not correlate with the amount of burned areas at 20 year timeframes (Fig. 5B). Dynamics of ignition frequencies mirrored changes in FC with the highest frequencies being observed between 1730 and 1770, and the lowest – between 1580 and 1720 (Table 1). A linear regression of cumulative numbers of axe scars against the total amount burned during 20-year periods was non-significant and did not indicate any association between the two variables (SI Fig. 3).

Modern (1996–2016) fires over 59.21 – 60.87 N and 32.65 – 35.44 E burned the total of 428.6 km^2, corresponding to a regional FC of ~ 1300 years. The modern fire activity featured a pronounced pattern with early (April-June) and late (July–September) season fires (Fig. 6A). Both the early (April-June) and the late-season (July–September) SPEI was strongly correlated with the burned areas in respective periods (Fig. 6B and 6C).

4. Discussion

Fire history of the VH extends the Northern European network of spatially explicit multi-century reconstruction of fire activity to the eastern fringes of this region and opens for longitudinal analyses of its temporal patterns. Although the location of the VH in a mire-dominated landscape makes it less similar with most of other available reconstructions representing more xeric topographies, its geographical proximity to Fennoscandia (Fig. 1), broad similarity of bioclimatic conditions, and the sufficient reconstructed period (420 years), all warrant such analyses.

The reconstructed forest fire history featured a number of patterns clearly deviating from the trends documented in previous Northern European reconstructions. The most striking feature was the absence of a period with increased fire activity during the 1600s, a pattern widely observed in Fennoscandia (Drobyshev et al., 2016) and in Russian Karelia (Ryzhkova et al., 2020). We noted, however, that the current reconstruction is the shortest of those currently available and its

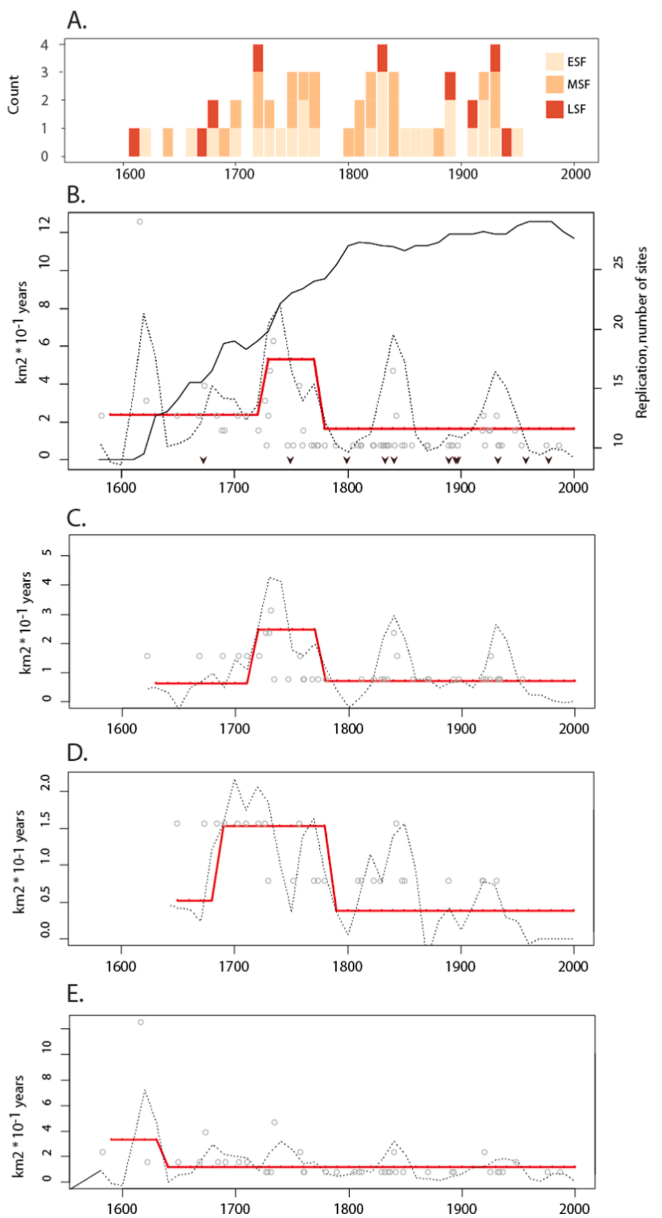

Fig. 3. The reconstructed fire seasonality (A) , and the burned area (B through E) in Veps Highland. The abbreviations for the seasons of the dated fire scars on (A): ESF – early season fires, MSF – mid-season fires, and LSF – late season fires. The black dashed lines denote the reconstructed burned areas for all fires (B), early season fires (C), mid-season fire (D), and late season fires (E). The fire cycle, as identified by the regime shift analysis (Rodionov, 2004), are represented by thick red lines. Site replication (B) is shown by the black solid line. On (B), the down-looking arrows at the bottom of the graph indicate dates of the axe scars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coverage of the 1600s (on average, 16 sites) was more limited than in other studies, which necessitates caution in interpreting this difference. On another hand, the largest fire year on record (year 1616 with 12.3 km^2 of burned area, corresponding to 51% of the total study area) did occur in the period commonly appearing as fire prone in Fennoscandinavian reconstructions (Drobyshev et al., 2016; Rolstad et al., 2017; Wallenius et al., 2007). In contrast, it was the period between 1730 and 1770 in this study, which exhibited the highest level of fire activity since 1580 CE. This interval, however, was still within the Little Ice Age, immediately following its coldest period in northern Europe (mid 1570–1700) (Melvin et al., 2013).

Table 1
Fire cycles (FC, years) and ignition frequencies ($km^{-2}year^{-1}$) in the Veps Highland for three periods, as identified by the regime shift analysis on the reconstructed area burned. FC estimates are mean values accompanied by the bootstrap-derived estimates of the 0.05 and 0.95 quantiles of respective distributions. See *Methods* section for explanations concerning the types of ignition estimates.

Period	Fire cycle	Ignitions		
		Type of estimate	Frequency	*n*
1580–1720	91.4 (66.2 – 137.6)	Conservative	$4.15*10^{-4}$	19
		Opportunistic	$9.39*10^{-3}$	32
1730–1770	35.9 (28.1 – 47.6)	Conservative	$7.65*10^{-4}$	10
		Opportunistic	$3.80*10^{-2}$	37
1780–2000	122.7 (91.0 – 178.0)	Conservative	$5.42*10^{-4}$	39
		Opportunistic	$1.62*10^{-2}$	87

Another unique characteristic feature of the Veps fire history was the dominance of early season fires, both across the whole population of reconstructed fire events (Fig. 3) and within its subset representing the five largest fire years (LFYs) in terms of the area burned. Out of the five largest fire years, three featured early season fires (years 1673, 1731, 1757), one had a mixed seasonality (1734), and one – was a late season LFY (1616). In contrast, Scandinavian fire regimes tend to reveal a pattern with large fire years being predominantly a product of late season fires driven by drought conditions accumulating over most of the fire season (Drobyshev et al., 2012). To this end, our reconstruction was similar to the one from the western Russian Karelia, where early season fires dominated (Ryzhkova et al., 2020). These early season fires are generally less severe than those occurring in the second half of the fire season, since they occur during the period when deeper layers of organic soil horizons are still wet, due to winter and spring precipitation. Their ecological impact, namely a reduction of soil organic layer, tree mortality, regeneration and the impact on forest fuels, is therefore more moderate (Risberg and Granström, 2009).

Does the dominance of early season fires in the VH fire reconstruction point to human-related ignitions, an association suggested in Fennoscandinavian studies (Granström and Niklasson, 2008)? We tend to provide a negative answer to this question, since the VH lies within the region with a natural dominance of spring fires. Climatological studies have documented the formation of high pressure cells that are established over the region above 59° N immediately following snowmelt (Kurbatsky, 1976; Stolyarchyuk and Belaya, 1982). An unofficial characterization of that region as “May-June forest fire belt” (Melekhov, 1946) reflects this pattern. Another line of indirect evidence arguing for the lightning as the origin of these fires is the analysis of ignition densities, which we present below.

4.1. Increase in fire activity during the 1730–1770s

We do not have a definitive explanation for an increase in fire activity between 1730 and 1770 (Fig. 3B). Available records of human population dynamics do indicate an increase in population density at the start of this period. In particular, the onset of the fire-prone period coincides with the termination of the Great Nordic War (*Stora nordiska kriget* in Swedish, and *Северная война* in Russian), which lasted between 1700 and 1720. The end of the war marked an influx of the farmers assigned to military factories and escapees from pre-war mobilization campaigns into the countryside (Zhukov, 2009). Between early 1720 and 1750 the number of villages in the VH increased by a factor of 1.6 (from 106 to 171) and the male population – by a factor of 4.5 (from 407 to 1803, Zhukov, 2009). The increase in human population necessitated increased agricultural production, which was traditionally based on slash-and-burn. Historical documents suggest that cultivation areas were not always adjacent to villages, with some as far as 20–50 km away (Zhukov, 2009). Difficulty in locating suitable arable land accounted for

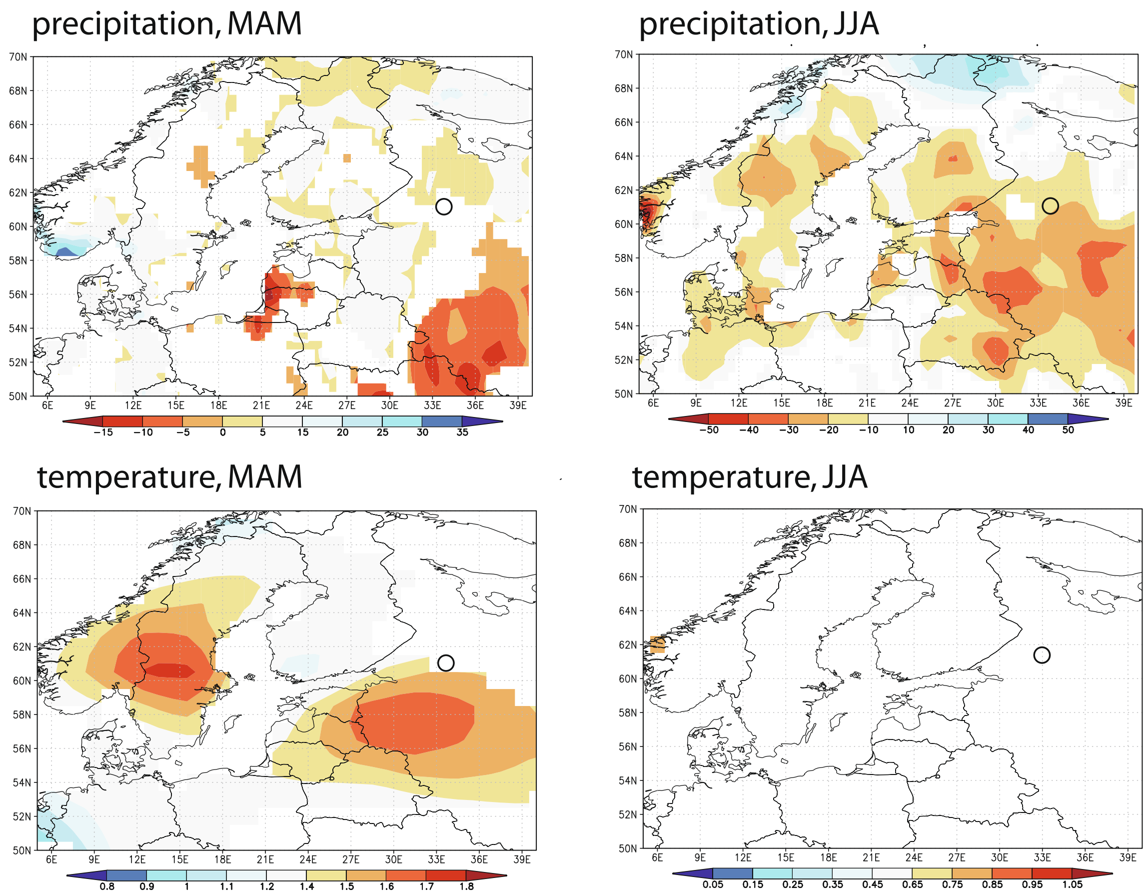

Fig. 4. Relation between the nine largest fire years reconstructed over the period between 1580 and 2000 in the Veps Nature Park and independently reconstructed precipitation (Pauling et al. 2006) and temperature (Rohde and Hausfather, 2020). MAM and JJA stand for March through May, and June through August, respectively. The circle refers to the location of the study area.

the remoteness of the farmland from the settlements (Lyubomudrov, 1889; Vinokurova, 2019). The similar pattern has been documented in the Komi Republic in East European Russia, where farmers made slash-and-burn sites at a distance of 50–75 km from the settlements and even had to transport firewood to these sites (Kolonist, 1913; Lyubomudrov, 1889).

The subsequent increase of the population towards the end of the 1700s and through the 1800s coincided, however, with a decline in fire activity beginning in 1780 (Fig. 3), which did not support the notion of the humans as the dominant factor causing the observed increase in fires in early 1700s. Likewise, our axe scar chronology (Fig. 3B) did not indicate any increase in human land use during that period. We realize that reconstructed human population densities is a sub-optimal proxy for the level of human ignitions, since changes in livelihoods and land use practices may not necessarily be correlated with changes in population density (Dietze et al., 2018; Roos et al., 2014). This reservation, however, may not be relevant in the interpretation of changes in fire activity in the study area during the 1700s, since slash-and-burn agriculture was widely used across the VH until the 1930s (Vinokurova, 2019).

Climatic forcing of increased fire activity during the mid-1700s appears likely. First, we observed an association of LFYs naturally driving the dynamics of the burned areas, with the independently reconstructed summer precipitation (a negative association) and spring temperature (a positive association, Fig. 4). It follows that an increase in the area burned between 1720 and 1770 was associated with regionally more fire prone conditions. The documented increase in the fire activity coincided with a half-century long negative anomaly in spring precipitation, centered around 1750 (Fig. 5A), which was consistent with the dominance of the early season fires in our dataset and a tendency for spring precipitation to be negatively associated with LFYs (Fig. 4). A similar negative association was also observed during the early 1900s, when a strong negative precipitation anomaly was associated with a period with increased burn area (Fig. 5A). This period, however, was not identified as a new regime by sequential *t*-test algorithm. A linear regression on 20-year time frames between spring precipitation and the cumulative amounts of burned areas for the respective periods did not reveal any pattern of association between the two variables (Fig. 5B). It remains, therefore, unclear to what degree decadal variability in spring precipitation drove the dynamics of fire activity in the area.

4.2. *Ignition frequencies in the Veps Highland*

VH ignition rates were generally low over the last 420 years, not reaching the levels reported in other sections of the European boreal zone. Our conservative estimates of ignition rates ranged from 0.005 to 0.012 (Table 1), and the opportunistic estimates – from 0.009 to 0.037 ignitions per year and km^2. The VH ignition rates were below historical estimates from the southern Komi Republic, an area located about 1100 km east of the VH and at the eastern fringes of the European boreal zone (0.05 – 0.08, Ryzhkova et al, submitted). Similarly, these rates did not exceed the estimates of the lightning strike ignitions obtained on the modern data in central and northern Sweden (0.05–0.15 per year and km^2, Granström, 1993). It is noteworthy that, even during the most fire-prone period in the Veps Highland, between 1730 and 1780, the ignition rates (0.012 to 0.037 ignitions per km^2 and year) were still well below the modern Swedish and Komi estimates.

Historical ignition rates in VH showed a considerable variability in

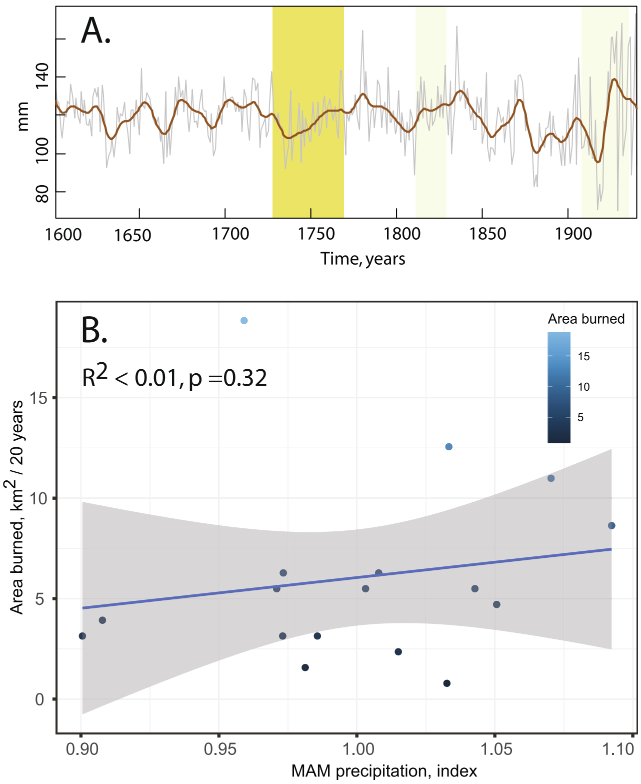

Fig. 5. Reconstructed spring (MAM) precipitation (Pauling et al., 2006) and the fire activity in the Veps Highland. (A) MAM precipitation chronology and smoothing spline function with 50% frequency cut-off at 64 years with periods with increased fire activity indicated by yellow bars. Dark yellow refers to the period with significantly increased burned areas. (B) Regression between mean spring precipitation and amount of burned areas for 20 year periods between 1600 and 1940 with R^2, significance level and confidence interval (shaded area) indicated on the graph. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time, with the period with the highest estimates (1730–1770) having more than twice the number of ignitions than the period with the lowest ignition rate (1580–1720, Table 1). Such an abrupt change might suggest a contribution of human-associated ignitions. However, decadal and interannual variability in the lightning ignitions has been recently proposed as one of the drivers of large fire years in the boreal forest (Veraverbeke et al., 2017), pointing to possible climatic origin of this dynamics.

The modern lightning strike frequency in the VH is between one and two flashes per year and km^2, which is one order of magnitude higher than in Sweden (0.2 to 0.6 flashes per year and km^2, Cecil, 2006). Assuming that the differences between these frequencies are stable over the modern and historical periods, one would expect a higher lightning strike frequency, and therefore, a higher frequency of effective ignitions (i.e. situation when a strike actually ignites a fire) in VH, as compared to Sweden. However, our fire reconstruction revealed an inverse pattern, indicating low ignition and propagation rates for fires in the VH landscape. The pattern also indirectly indicated a potentially low contribution of humans to the total pool of ignitions. This interpretation is consistent with the general wetness of the area (Fig. 1) limiting fire spread (as documented in Hellberg et al., 2004) and low historic population densities ranging between 0.08 and 0.4 person/km^2 for the period between 1720 and 1749 (SI Text A).

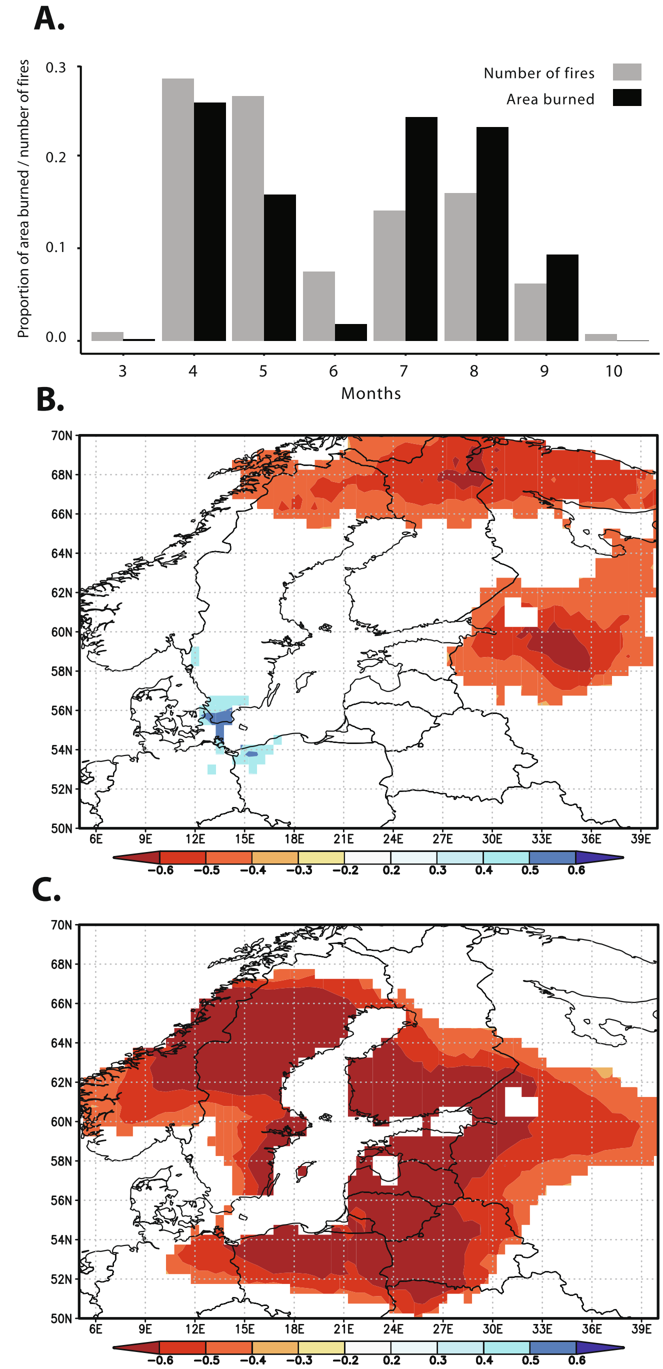

Fig. 6. Seasonal distribution of modern (1996–2016) fires over the area encompassing the Veps Highland, 59.21 – 60.87 N and 32.65 – 35.44 E (A), and the correlation of the area burned in the early- (B, April-May) and the late-season (C, July-September) with the gridded three-month SPEI for the corresponding periods.

4.3. *Humans vs. Climate variation: In search for the dominant control of fire activity*

The VH deviates from other Nordic fire history reconstructions with a period of increased fire activity during the 1700s, a pattern not observed in more westerly parts of the European boreal zone. Although the leading drivers of temporal variability in fire activity are challenging to identify with certainty, our results support to climate as the main driver. This conclusion is supported by (1) an association between large fire years and reconstructed precipitation variability, (2) moderate variability in FCs since the 1600s, (3) an association of the period characterized by increased fire activity with a decline in spring precipitation, and (4) low reconstructed ignition frequencies, even during the most fire prone period of 1730–1780. The view of humans as the principal control of fire dynamics is based exclusively on the association between the end of the Great Nordic War and the onset of the fire-prone period in VH fire chronology.

Is our reconstruction representative of the area of a broader region where the VH is located? Although we believe that this well may be the case for historic data, a comparison between dendrochronologically reconstructed area for the 1900s and the modern observational data does not support this assumption. Indeed, the FC estimate obtained on dendrochronological data for the end of 20th century was 123 years, while the satellite-based estimate was ~ 1300 years. Evidently, fire suppression policies and fragmentation of forest fuels in the modern landscape override the effect of climate in other parts of the study region. This observation and the general similarity of FCs in our study area and in Northern European dendrochronological reconstruction prior to the 1800s, highlights the proximity of fire regime within the Veps Nature Park to its levels during the pre-fire-suppression era.

Extending the analysis beyond single landscapes should be instrumental in better deliniating climate vs. human signals, which might be acting together to shape historical fire regimes. Increasing the density of the existing network with dendrochronological reconstructions in Northern Europe, and specifically – its extension towards the eastern fringes of European boreal domain is, therefore, highly warranted.

Author contribution

Igor Drobyshev was responsible for conceptualization, methodology, sample collection, analyses, and writing. **Nina Ryzhkova** participated in sample dating and contributed to the writing. **Mats Niklasson** assisted with conceptualization, dating of samples, and writing. **Alexander Kryshen'**, **Alexei Zhukov**, **Irma Mullonen** contributed to the writing. **Guilherme Pinto** contributed with spatial analyses, GIS work and writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120007.

References

Aakala, T., Pasanen, L., Helama, S., Vakkari, V., Drobyshev, I., Seppä, H., Kuuluvainen, T., Stivrins, N., Wallenius, T., Vasander, H., Holmström, L., 2018. Multiscale variation in drought controlled historical forest fire activity in the boreal forests of eastern Fennoscandia. Ecol. Monogr. 88 (1), 74–91. https://doi.org/10.1002/ecm.1276.

Adrijashev, A.M., 1930. Scribe books of Obonezh area, 1496 and 1563. Publishing house of Russian Academy of Sciences, Leningrad.

Anonymous, 1999. Resolution of the Leningrad Region of September 14, 1994 No. 302-pg.

Belyaeva, K.A., 2019. Landscape distribution of forest communities of south-west part of Veps Upland. Mod. trends Phys. Geogr. Res. Educ. issues Context Sustain. Dev, 340–343.

C3S, C.C.C.S., 2021. ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS) [WWW Document]. URL https://cds.climate.copernicus.eu/cdsapp#!/home (accessed 7.17.21).

Cecil, D.J., 2006. LIS/OTD 0.5 Degree High Resolution Annual Climatology (HRAC). https://doi.org/undefined.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., Vitart, F., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137 (656), 553–597.

Dietze, E., Theuerkauf, M., Bloom, K., Brauer, A., Dörfler, W., Feeser, I., Feurdean, A., Gedminienė, L., Giesecke, T., Jahns, S., Karpińska-Kołaczek, M., Kołaczek, P., Lamentowicz, M., Latałowa, M., Marcisz, K., Obremska, M., Pędziszewska, A., Poska, A., Rehfeld, K., Stančikaitė, M., Stivrins, N., Święta-Musznicka, J., Szal, M., Vassiljev, J., Veski, S., Wacnik, A., Weisbrodt, D., Wiethold, J., Vannière, B., Słowiński, M., 2018. Holocene fire activity during low-natural flammability periods reveals scale-dependent cultural human-fire relationships in Europe. Quat. Sci. Rev. 201, 44–56.

Drobyshev, I., Bergeron, Y., Linderholm, H.W., Granström, A., Niklasson, M., 2015. A 700-year record of large fire years in northern Scandinavia shows large variability and increased frequency during the 1800 s. J. Quat. Sci. 30, 211–221.

Drobyshev, I., Bergeron, Y., Vernal, A.d., Moberg, A., Ali, A.A., Niklasson, M., 2016. Atlantic SSTs control regime shifts in forest fire activity of Northern Scandinavia. Sci. Rep. 6 (1) https://doi.org/10.1038/srep22532.

Drobyshev, I., Granström, A., Linderholm, H.W., Hellberg, E., Bergeron, Y., Niklasson, M., McGlone, M., 2014. Multi-century reconstruction of fire activity in northern European boreal forest suggests differences in regional fire regimes and their sensitivity to climate. J. Ecol. 102 (3), 738–748. https://doi.org/10.1111/1365-2745.12235.

Drobyshev, I., Niklasson, M., Linderholm, H.W., 2012. Forest fire activity in Sweden: Climatic controls and geographical patterns in 20th century. Agric. For. Meteorol. 154-155, 174–186. https://doi.org/10.1016/j.agrformet.2011.11.002.

Dyrenkov, S.A., 1984. Structure and dynamics of the taiga spruce forests. Nauka Publishing House, Leningrad (St. Petersburg).

Egorov, S.B., 2014. Veps people, in: Studies of the Nationalities in the Leningrad Region. Local Government Committee on interethnic and interfaith relations of the Leningrad region, St. Petersburg, pp. 38–53.

FAO, 2014. World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps, World Soil Resources Reports No. 106.

Fedorchuk, V.N., Kuznetsova, M.L., Andreyeva, A.A., Moiseyev, D.V., 1998. Reserve Veps Forest: Forestry Studies, Proceedings of the St.Petersburg Research Forestry Research Institute. St. Petersburg Forestry Research Insitute, St. Petersburg.

Giglio, L., Randerson, J.T., van der Werf, G.R., 2013. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). J. Geophys. Res. 118 (1), 317–328.

Granström, A., 2001. Fire management for biodiversity in the European boreal forest. Scand. J. For. Res. 16 (sup003), 62–69.

Granström, A., 1993. Spatial and temporal variation in lightning ignitions in Sweden. J. Veg. Sci. 4, 737–744.

Granström, A., Niklasson, M., 2008. Potentials and limitations for human control over historic fire regimes in the boreal forest. Philos. Trans. R. Soc. B-Biological Sci. 363 (1501), 2351–2356.

Grissino Mayer, H.D., Swetnam, T.W., 2000. Century-scale climate forcing of fire regimes in the American Southwest. Holocene 10 (2), 213–220.

Hamilton, H., 1997. Slash-and-burn in the history of the Swedish forests. Netw. Pap. - Rural Dev. For. Netw, 19–24.

Hellberg, E., Niklasson, M., Granström, A., 2004. Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. Can. J. For. Res. Can. Rech. For. 34 (2), 332–338.

Isachenko, A.G., Dashkevich, Z.V., Karnaukhova, E.V., 1965. Physical geography of the Russian North-West. Publishing house of the St. Petersburg State University, St. Petersburg.

Johnson, E.A., Wagner, C.E.V., 1985. The theory and use of two fire history models. Can. J. For. Res. 15 (1), 214–220.

Kochkurkina, S.I., Linevsky, A.M., 1985. Mounds of the annalistic vesti of the X - early XIII century. Petrozavodsk: Karelia.

Kolonist, 1913. Podsechno-ognevoye khozyaystvo Ust'-Sysol'skogo zyryanina (Slash-and-burn farm of the Ust-Sysolsk Zyryanin). News Arkhangelsk Soc. Study Russ. North 57–62.

Kurbatsky, N.P., 1976. On the mechanism of forest fire generation by lightning. Sylvics 3, 95–98.

Kurilov, M., 2016. Villages of the upper reaches of Ojat' river. Anima, St. Petersburg.

Larsson, L.A., 2018. Cybis dendro dating program v. 9.1.

Lehtonen, H., Huttunen, P., 1997. History of forest fires in eastern Finland from the fifteenth century AD - The possible effects of slash-and-burn cultivation. Holocene 7 (2), 223–228. https://doi.org/10.1177/095968369700700210.

Lyubomudrov, M., 1889. K stat'ye "L'nyanyye i rzhanyye podseki (To the article "Linen and rye slash-and-burn cultivations). For. J. 360–366.

Melekhov, I.S., 1946. Forest fire seasons and building the geographical scheme of forest fire belts. Proc. Arkhangelsk For. Inst 1–15.

Melvin, T.M., Grudd, H., Briffa, K.R., 2013. Potential bias in "updating" tree-ring chronologies using regional curve standardisation: Re-processing 1500 years of Tornetrask density and ring-width data. Holocene 23, 364–373.

Niklasson, M., Drobyshev, I., Zielonka, T., 2010. A 400-year history of fires on lake islands in south-east Sweden. Int. J. Wildl. Fire 19 (8), 1050. https://doi.org/10.1071/WF09117.

Niklasson, M., Granström, A., 2000. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81 (6), 1484–1499.

Östlund, L., 1993. Exploitation and structural changes in the north Swedish boreal forest, Dissertati. ed. Sveriges lantbruksuniv., Umeå.

Pauling, A., Luterbacher, J., Casty, C., Wanner, H., 2006. Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation. Clim. Dyn. 26 (4), 387–405.

Petrov, O.V., Morozov, A.F., Chepkasova, T.V., 2014. Map of Quaternary deposits of Russia [WWW Document]. URL https://vsegei.ru/ru/info/quaternary-2500/ (accessed 12.26.21).

Pinto, G.A.S.J., Rousseu, F., Niklasson, M., Drobyshev, I., 2020. Effects of human-related and biotic landscape features on the occurrence and size of modern forest fires in Sweden. Agric. For. Meteorol. 291, 108084. https://doi.org/10.1016/j.agrformet.2020.108084.

Popova, T.A., Berezkina, L.I., Bichkova, E., Leontieva, E.B., Semenova, N.N., Shubina, M. A., 2005. Nature Park Vepsski Forest. St, Petersburg.

Reed, W.J., 2006. A note on fire frequency concepts and definitions. Can. J. For. Res. 36 (7), 1884–1888.

Risberg, L., Granström, A., 2009. The effect of timing of forest fire on phenology and seed production in the fire-dependent herbs Geranium bohemicum and G. lanuginosum in Sweden. For. Ecol. Manage. 257 (8), 1725–1731.

Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophys. Res. Lett. 31 (9), n/a–n/a.

Rohde, R.A., Hausfather, Z., 2020. The Berkeley Earth Land/Ocean Temperature Record. Earth Syst. Sci. Data 12, 3469–3479. https://doi.org/10.5194/essd-12-3469-2020.

Rolstad, J., Blanck, Y.-l., Storaunet, K.O., 2017. Fire history in a western Fennoscandian boreal forest as influenced by human land use and climate. Ecol. Monogr. 87 (2), 219–245.

Roos, C.I., Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Cochrane, M., D'Antonio, C.M., DeFries, R., Mack, M., Johnston, F.H., Krawchuk, M.A., Kull, C.A., Moritz, M.A., Pyne, S., Scott, A.C., Swetnam, T.W., Whittaker, R., 2014. Pyrogeography, historical ecology, and the human dimensions of fire regimes. J. Biogeogr. 41 (4), 833–836. https://doi.org/10.1111/jbi.12285.

Rubel, F., Brugger, K., Haslinger, K., Auer, I., 2017. The climate of the European Alps: Shift of very high resolution Koppen-Geiger climate zones 1800–2100. Meteorol. ZEITSCHRIFT 26, 115–125. https://doi.org/10.1127/metz/2016/0816.

Ryzhkova, N., Pinto, G., Kryshen', A., Bergeron, Y., Ols, C., Drobyshev, I., 2020. Multi-century reconstruction suggests complex interactions of climate and human controls of forest fire activity in a Karelian boreal landscape North-West Russia. For. Ecol. Manage. 459, 117770. https://doi.org/10.1016/j.foreco.2019.117770.

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

Stolyarchyuk, L.V., Belaya, A.Y., 1982. Rainless thunderstorms and forest fires. Lesovedenie 7, 49–50.

Storaunet, K.O., Rolstad, J., Toeneiet, M., Blanck, Y.-l., 2013. Strong anthropogenic signals in historic forest fire regime: a detailed spatiotemporal case study from south-central Norway. Can. J. For. Res. Can. Rech. For. 43 (9), 836–845.

Swetnam, T.W., 1993. Fire history and climate-change in Giant Sequoia groves. Science 262 (5135), 885–889.

van der Werf, G.R., Randerson, J.T., Giglio, L., van Leeuwen, T.T., Chen, Y., Rogers, B.M., Mu, M., van Marle, M.J.E., Morton, D.C., Collatz, G.J., Yokelson, R.J., Kasibhatla, P. S., 2017. Global fire emissions estimates during 1997–2016. Earth Syst. Sci. Data 9, 697–720. https://doi.org/10.5194/essd-9-697-2017.

Wagner, C.E.V., 1978. Age class distribution and the forest fire cycle. Can J For. Res 8 (2), 220–227.

Veraverbeke, S., Rogers, B.M., Goulden, M.L., Jandt, R.R., Miller, C.E., Wiggins, E.B., Randerson, J.T., 2017. Lightning as a major driver of recent large fire years in North American boreal forests. Nat. Clim. Chang. 7 (7), 529–534.

Vinokurova, I.J., 2019. Traditional occupations of Veps people. In: Nations of Karelia. Historical and Ethnographical Notes. Periodika, Petrozavodsk, pp. 357–361.

Wallenius, T., 2011. Major Decline in Fires in Coniferous Forests - Reconstructing the Phenomenon and Seeking for the Cause. Silva Fenn. 45, 139–155.

Wallenius, T.H., Lilja, S., Kuuluvainen, T., 2007. Fire history and tree species composition in managed Picea abies stands in southern Finland: Implications for restoration. For. Ecol. Manage. 250 (1-2), 89–95.

Zhukov, A.J., 2009. Traditional land uses in the border regions of Karelia and the state (XIII-XVII centuries). Proc. Karelian Cent. Russ. Acad. Sci. 2. Green b, 103–114.