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Climate drove the fire cycle and humans influenced fire occurrence in the East European boreal forest

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Abstract

Understanding long-term forest fire histories of boreal landscapes is instrumental for parameterizing climate–fire interactions and the role of humans affecting natural fire regimes. The eastern sections of the European boreal zone currently lack a network of annually resolved and centuries-long forest fire histories. To fill in this knowledge gap, we dendrochronologically reconstructed the 600-year fire history of a middle boreal pine-dominated landscape of the southern part of the Republic of Komi, Russia. We combined the reconstruction of fire cycle (FC) and fire occurrence with the data on the village establishment and climate proxies and discussed the relative contribution of climate versus human land use in shaping historic fire regimes. Over the 1340–1610 CE period, the territory had a FC of 66 years (with the 90% confidence envelope of 56.8 and 78.6 years). Fire activity increased during the 1620–1730 CE period, with the FC reaching 32 years (31.0–34.7 years). Between 1740–1950, the FC increased to 47 years (41.9–52.0). The most recent period, 1960–2010, marks FC's historic maximum, with the mean of 153 years (102.5–270.3). Establishment of the villages, often as small harbors on the Pechora River, was associated with a non-significant increase in fire occurrence in the sites nearest the villages ($p = 0.07$–0.20). We, however, observed a temporal association between village establishment and fire occurrence at the scale of the whole studied landscape. There was no positive association between the former and the FC. In fact, we documented a decline in the area burned, following the wave of village establishment during the second half of the 1600s and the first half of the 1700s. The lack of association between the dynamics of FC and the dates of village establishments, and the significant association between large fire years and the early and latewood pine chronologies, used as historic drought proxy, indirectly suggests that the climate was the primary control of the landscape-level FCs in the studied forests. Pine-dominated forests of the Komi Republic may hold a unique position as the ecosystem with

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the shortest history of human-related shifts in fire cycles across the European boreal region.

KEYWORDS
boreal landscape, climate variation, fire regime, natural disturbances, natural hazards, northeastern Russia, pine-dominated forests

INTRODUCTION

Forest fires are an integral part of the natural disturbance regime in boreal regions (Johnson, 1992; Johnstone & Chapin, 2006), shaping the dynamics of this biome (Bowman et al., 2009; Buma, 2015; Granström, 2001) because they maintain ecosystem functions and complex successional pathways (Bergeron et al., 2004; Bourgeau-Chavez et al., 2000; Payette, 1992; Pyne, 1997). Regional fire activity is primarily controlled by climate (Clark, 1990; Flannigan & Wotton, 2001; Stocks & Lynham, 1996) that directly influences the moisture content of the fuels and ignition patterns and, indirectly, the fuel type and loads. Topography affects variation in soil moisture and vegetation cover that, in turn, introduces spatial variability in the fire regime at finer scales (Girardin et al., 2013; Hellberg et al., 2004; Kuosmanen et al., 2014; Pitkanen et al., 2003).

The reconstructions of fire activity in the European boreal forest have indicated that there is a considerable low-frequency variability in the amounts of forest burned area in Northern Europe since the 1400s C.E., which is likely to reflect both climatic and human forcing (Drobyshev et al., 2016; Pinto et al., 2020; Ryzhkova et al., 2020; Wallenius et al., 2007). An increase in the amount of burned forest areas during the coldest period of the Little Ice Age (LIA), the 1600s, (Drobyshev et al., 2016; Ryzhkova et al., 2020) was followed by a pronounced decline in fire activity that started in the mid-1800s. The decline was likely to have been driven by climate variability (Bergeron et al., 2004; Drobyshev et al., 2016; Girardin et al., 2006; Tardif, 2004), cessation of land-use practices involving fire, and some rudimentary fire suppression (Niklasson et al., 2010; Rolstad et al., 2017; Tryterud, 2003; Wallenius, 2011). The current net human impact on forest fire translates into a decrease in fire activity, even though increasing human densities are linked to a higher density of ignitions (Groven & Niklasson, 2005; Marlon et al., 2008; Niklasson & Granström, 2000; Zhang & Chen, 2007). For example, in the second half of the 20th century, the fire cycle (FC) in most parts of the Northern European boreal forests varied between hundreds or thousands of years (Drobyshev et al., 2021). In comparison, the FC prior to the 1700s ranged from 30 to 300 years (Drobyshev, Niklasson, et al., 2012; Niklasson & Granström, 2000; Pinto et al., 2020; Ryzhkova et al., 2020). These estimates largely reflect western sections of the European boreal biome because the vast majority of dendrochronological fire reconstructions in boreal Europe has been carried out in the Fennoscandia (Aakala et al., 2018; Drobyshev et al., 2014; Niklasson & Granström, 2000; Nilsen et al., 2019; Rolstad et al., 2017; Wallenius et al., 2004). The knowledge of historic forest fire regimes of the eastern sections of the boreal zone remains limited.

Humans have been an important agent of change in fire regimes across the European boreal biome (Groven & Niklasson, 2005; Knorr et al., 2016; Rolstad et al., 2017; Stocks et al., 2002; Wallenius, 2011; Weir et al., 2000). The extent that humans affected fire activity in the boreal zone is currently being debated, with some studies arguing for the almost comprehensive spread of fire-supported agriculture across the European boreal zone (Aleinikov, 2017b; Degteva et al., 2015; Gromtsev, 2002), while others suggesting a strong climate control of boreal fire activity (Aakala et al., 2018; Drobyshev et al., 2016). In Europe, and in particular in the Fennoscandia, population expansion increased fire frequency and reduced the dominant fire size through the use of slash-and-burn agriculture and associated forest clear-cutting (Hellberg et al., 2009; Lehtonen & Huttunen, 1997; Niklasson & Granström, 2000; Wallenius et al., 2004). The production of charcoal (Östlund, 1993) and reindeer herding (Hörnberg et al., 2018) further affected fire activity through their impact on forest fuels. In contrast with Fennoscandia, the eastern fringes of the European boreal zone currently lack studies on human–fire interactions, done at the annual or near-annual resolution and extending beyond the colonization period to debate the interplay among climate, humans, and fire over the most recent centuries.

The Pechora-Ilych Nature Biosphere Reserve (from this point forward Pechora-Ilych NBR) located in the southeastern portion of the Komi Republic protects an area of the European middle boreal forests, often designated as the Virgin Komi Forests (Anufriev, 2000; Yudin, 1954). The Reserve consists of two geographically separated sections: one with predominantly flat terrain lying within the Pechora Lowland in the vicinity of Yaksha village (Figure 1) and a mountainous area forming the Pechora-Ilych watershed (Dedeev, 1997; Varsanof'eva, 1940). Pine-dominated forests grow on areas with flat topography, and are particularly abundant on the sandy soils of the Pechora River and fluvioglacial lowland (Anufriev, 2000). The nutrient poor soils and the low population densities, well below 1 person/km^2, had limited the expansion of slash-and-burn agriculture in this area in the past (Aleinikov, 2014) (Figure 3). However, the area had an important geopolitical role between 1500 and the 1800s, due to the presence of three portage routes. Two of them connected the Northern Dvina and the Pechora watersheds (and in this way to the coasts of the Arctic Ocean) with the Kama Basin and Caspian Sea. The third connected the Northern Dvina and the Pechora watersheds with each other (Dmitriev, 1893; Korchagin & Lobanova, 2012; Velikanov, 1887). Colonization of the area by Russians as late as the middle 1400s, the harsh climate, the complex topography, and the lack of a developed market for timber products, all protected the region from large-scale timber harvesting until the late 1800s (Aleinikov, 2014; Popova et al., 2012). Although industrial forestry operations had a considerable impact on the regional forest cover in the early and middle parts of the 20th century, creation of the Pechora-Ilych NBR in 1930 helped to maintain a considerable portion of the landscape with well preserved fire-scarred live trees and deadwood.

To advance our understanding of the interplay between climate and human forcing upon forest fire regimes in the eastern boreal forest, we developed a

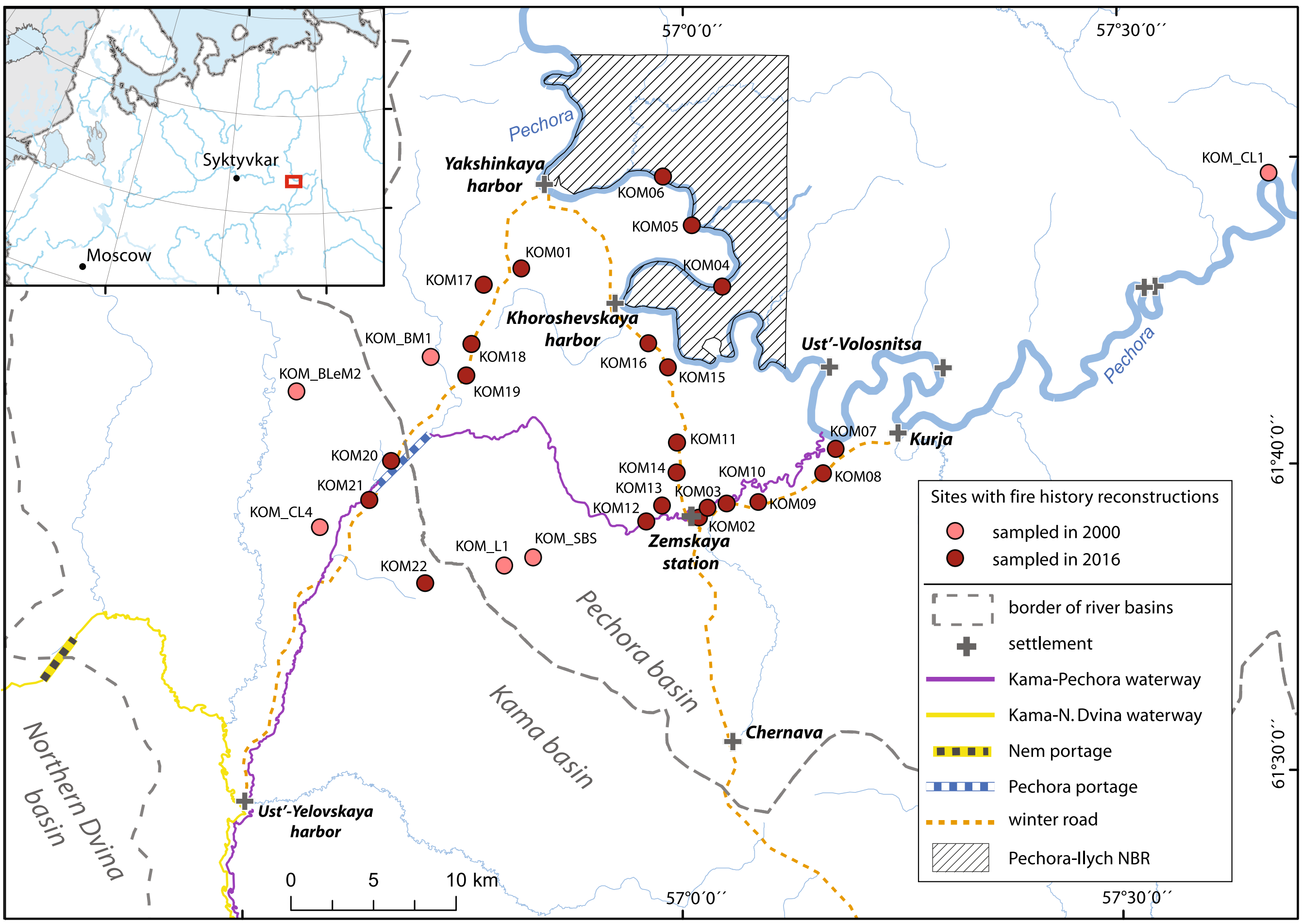

FIGURE 1 Location of the study area and the sampled sites within or in the vicinity of the Pechora-Ilych Nature Biosphere Reserve (NBR). The area is marked as Pechora-Ilych NBR on the map is the western portion of the Reserve.

600-year long spatially explicit reconstruction of the fire regime in a 20 × 30 km^2 area in the vicinity of Pechora-Ilych NBR, relying on the dating of fire-scarred living and dead Scots pines. We hypothesized that (H_1) the onset of the main wave of human colonization in the area resulted in the increases of both area burned ($H_{1.1}$) and fire occurrence ($H_{1.2}$). To support the discussion of H_1, we took advantage of the information on the location and establishment dates for individual villages, transit portages, and harbors that were recovered from documentary sources. We further hypothesized that (H_2) the Pechora-Ilych NBR exhibited the most fire-prone period during the LIA, a cold period of the Maunder Minimum, apparently characterized by a dry and unstable climate and centered on the 1600s and 1700s. Previous research in other parts of the European boreal zone has associated the LIA with increased fire activity levels and, possibly, more frequent conditions of extreme fire hazard (Drobyshev et al., 2016; Ryzhkova et al., 2020). H_2, therefore, tested for a broad similarity between the fire history of the Pechora-Ilych NBR and those in the western sections of the European boreal biome. Finally, considering the low population density and low intensity of historic forest management, we hypothesized (H_3) that the historic fire regime was strongly influenced by annual climate variability. To test H_3, we evaluated the associations between large fire years (LFYs) in the Pechora-Ilych NBR and the regional earlywood and latewood-width Scots pine chronologies, which served as a proxy for historic drought conditions.

MATERIALS AND METHODS

The study area

The study area was located in the southeastern part of the Komi Republic, which is one of the most forest-rich regions in European Russia (Taskaev, 2006). Climatologically, the area lies within the Atlantic–Continental province (Stolpovski, 1997) (Appendix S1: Figure S1). The annual average temperature is ~1°C and the average length of the growing season (i.e., the number of days with an average daily temperature above 10°C) is ~110 days. Average daily temperatures commonly exceed 10°C during the first 10-day period of June and then fall below this value in the first week of September. Annual precipitation averages 700 mm and accumulation of thick snow cover (70–80 cm) is characteristic for the winter period, which lasts for 130–200 days. Snow melt in the pine forests occurs in mid-May and the first snow cover usually occurs in the first week of October (Appendix S1: Figure S1).

The area is situated on the western fringe of the Russian Plain (Dedeev, 1997). The underlying bedrock is dominated by sand and moraine loam and covered by the quaternary glacial drifts (Zaboeva, 1997). The prevailing vegetation is of the middle taiga type (Larin, 1997), broadly corresponding to boreal mixed woods of Northern America. Scots pine (*Pinus sylvestris* L.), Siberian spruce (*Picea obovata* Ledeb.), and Siberian fir (*Abies sibirica* Ledeb.) dominate. Stands of Arctic white birch (*Betula pubescens* Ehrh.), silver birch (*B. pendula* Roth) and aspen (*Populus tremula* L.) typically mark the early stages of post-fire and post-felling succession. Siberian pine (*P. sibirica* Du Tour) and larch (*Larix decidua* Mill.) are both minor components of the vegetation.

Fire is the one of the major natural disturbance factors in the Komi pine-dominated forests (Manov & Kutyavin, 2018; Drobyshev & Niklasson, 2004; Drobyshev, Niklasson, & Angelstam 2004; Drobyshev, Niklasson, Angelstam, & Majewski, 2004). Historic stand-level fire frequency in the pine-dominated forests in the region ranged from 60 to 220 years (Barhoumi et al., 2020; Drobyshev, Niklasson, Angelstam, & Majewski, 2004).

A reconstruction of sediment charcoal data in the Komi Republic suggested a gradual Holocene-long increase in fire activity in the boreal Komi, driven largely by the climate, vegetation composition and, possibly, the human use of fires (Barhoumi et al., 2019). However, at the annual scale, fire activity in pine-dominated forests revealed a large temporal variability (Drobyshev, Niklasson, Angelstam, & Majewski, 2004) and its strong connection to the summer drought conditions (Drobyshev & Niklasson, 2004). Human settlements in the this region have been shown to modulate climate forcing upon the fire regime, with the distance from a site to the nearest village accounting for 50% of the variation in statistical fit between fire occurrence and tree-ring proxy of fire weather (Drobyshev, Niklasson, Angelstam, & Majewski, 2004).

Human population of the area

A mixture of several nationalities forms the population of the area. The main nationalities are Mansi (Voguls) and Russian people, each featuring characteristic land-use patterns. In the High Middle Ages (1000–1500 CE), the territory belonged to the nomadic Mansi people, who were a part of the aboriginal population of the Ural Mountains. Mansi people were involved in hunting, gathering, reindeer herding and fishing (Chagin, 2017; Popova et al., 2012).

During the 1500s to 1800s, the area had two major transit portages (*volok*, in Russian) bridging three important waterways: the Nemski portage connected the watersheds of the Kama and Northern Dvina rivers, whereas the Pechora portage connected the Kama and Pechora watersheds. The first reference to the Nemski portage dates back to 1517–1520 (Dmitriev, 1893; Zherebtsov et al., 2014). Its abandonment in the 1820s was associated with the construction of the Northern Catherine Canal (Chagin, 2017; Dmitriev, 1893; Rychkov, 1770). The Pechora route was first mentioned in the records in the 1671–1681 period (Chagin, 2017) and the establishment of Ust'-Volosnitsa village has been linked to the route activities (Chagin, 2015; Popova et al., 2012). To increase the storage capacity for the goods transported along the trade routes, several river harbors were established. Two of them were Ust'-Elovka on the Elovka River and Khoroshevskaya harbor on the Pechora River. In 1770, the latter was moved to the current location of the Yaksha village, which is currently the largest village in the area. The establishment of trade routes and villages followed the immigration of Russians into the area from 1650 to the 1700s. Russians worked mostly with various transportation services associated with the trade routes. Since the late 1800s, Russians shaped the timber market by actively engaging in the timber harvesting (Popova et al., 2012). An expedition in the area, arranged in 1912, noted numerous signs of selective cuts in the area (Nat, 1915a, 1915b).

Field sampling

The sampled sites were located within and in proximity to the Pechora-Ilych NBR, within 61°43′–63°16′ N and 56°52′–59°39′ E (Figure 1). Using the existing forest road network and the Pechora River, we placed sites by randomly locating points for sampling along the roads and the river. To ensure sufficient site density for estimating the size of individual fires, we kept the distance between neighboring sites within 2–5 km. We sampled both forested areas and areas with recent clear-cuts, because they both provided material for dendrochronological dating. Mires (mostly fens) were generally not sampled, because these locations were generally devoid of old wood. However, we collected a large number of samples on the interfaces between mires and the drier portions of the landscape. Each site represented an area of two to three hectares. To ensure an equally distributed sampling effort, we inventoried each site during a 1.5–2-h period, by thoroughly searching the area for the presence of living and dead trees with fire scars. At a site, we inventoried the area, using a combination of the random walk approach and an inventory of the habitats located at the interfaces between more xeric and more humid areas. These locations often host old and fire-scarred deadwood. We used chainsaws to extract wedges from living trees and snags and, for stumps, cross-sections. Between six and 15 samples were collected on each site. We acquired a total of 179 samples of 51 living and 128 dead pine trees. We carried out our sampling in 2016 and integrated this dataset with a portion of the data from our earlier study (Drobyshev, Niklasson, & Angelstam, 2004). In particular, we screened the 2004 dataset and selected the oldest sites without a suspected hiatus in site fire chronologies. In total (2004 and 2016 data sets), our analyses operated on 30 sites and 247 trees.

Because all of our sites were located along the transport routes, the fire history reconstructed on these sites might, to a certain degree, reflect the use of fire by the local population. In particular, the use of fire for agricultural purposes, typically in the vicinity of the villages, could inflate the estimates of the natural fire activity as reconstructed on such sites. In this study, we explicitly test this assumption, by analyzing fire return intervals prior to and following the dates of village establishment in the area (please refer to the subsection *Analyzing the effect of human settlements* in this section).

To evaluate similarity in fire ignitions over the dendrochronologically reconstructed period and modern times (i.e., the second half of the 20th century), we used records of fires available for the area of the Yaksha section of the Reserve, which was partly covered by our reconstruction. The area of the Yaksha section is 15,800 ha and has a vegetation cover dominated by pure and mixed pine forests, that is, similar to the cover of the area sampled for the dendrochronological reconstruction. The record spanned the 1936–1996 period and contained information on the date and origin of recorded fires.

Development of fire chronologies

We air dried and sanded samples with progressively finer sandpapers with up to 400-grit to secure a clear view of the rings and fire scars under a binocular microscope with ×40 magnification. We cross-dated samples using the visual pointer year method (Stokes & Smiley, 1968), capitalizing on the point year chronology developed for that area. We provided information on the most useful pointer years in the Appendix S1: Section S1. To verify the dating, we correlated sample chronologies with an earlier developed Scots pine ring-width chronology (Drobyshev, Niklasson, & Angelstam, 2004). Measuring rings and building ring-width chronologies provided the means to verify the dating quality. To measure tree rings, we obtained high-resolution (2400–3200 dpi) digital images of the samples with a flatbed scanner and used a Cybis AB CooRecorder and CDendro 9.0 to measure the rings (Larsson, 2018). As a proxy of correlation strength, we relied on a *t*-test calculated in the programs COFECHA (Grissino-Mayer, 2001; Holmes, 1983, 1999) and CDendro (Larsson, 2018).

Dating of scars allowed us to associate the calendar years with (1) fire scars, (2) oldest and (3) youngest rings on each sample and to develop site-specific fire chronologies. We also attempted to identify scar position within a dated ring, which provided information on the seasonal occurrence of fire. We assigned to the fire scars one of the following four categories: no seasonal dating, earlywood scar (a scar located in early, middle and late earlywood), latewood scar (a scar located in early, middle or late latewood), and dormant scar. Dormant scars were located on the interface between two rings. The exact determination of the year for that scar was not possible. 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. This approach is supported by the observation that in the parts of the boreal zone with extensive snow cover during the cold season, the "survival" of forest fires over such a period and their occurrences in two consecutive years on the same site were highly unlikely.

Reconstruction of historic FC and identification of FC regime shifts

Spatial reconstruction of fires relied on the fire dates independently identified across the network of sites. To convert point data (i.e., frequency estimates for a site) into the areal estimates, we assumed that a site fire chronology 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. The studied territory featured the mosaic of boreal vegetation types that included pine and spruce-dominated stands, transitional mires and, rarely, bogs. Because the Pechora River was the only permanent waterbody in the area, we excluded the proportions of the units containing the river surface from calculations. In the analyses, we tested unit radii ranging from 200 to 600 m, which corresponded to unit sizes of 12.5 to 113.1 ha. By doing so, we wanted to check for the sensitivity of our FC reconstruction to changes in unit size. We elected to use the unit with the size of 78.5 ha (500 m radius), which tend to place the units within one element of the landscape mosaic. We refer the reader to the Supplementary Information section (AppendixS1: Figure S2) for the results obtained with other unit sizes.

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:

$$\mathrm{FC} = \frac{\mathrm{TSA}}{\mathrm{TBA} \times \mathrm{TI}}$$

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. To account 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 an earlier developed protocol (Ryzhkova et al., 2020). We estimated fire occurrence as the number of fire years aggregated into 10-year periods in the whole area studied.

We used a regime shift detection algorithm (Rodionov, 2004) to identify changes in FC and fire occurrence over the period covered by the reconstruction (1400–2010, minimum number of sites = 5). The algorithm uses sequential *t*-tests to identify a regime change. 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 predefined moving timeframe. Please refer to 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 level of the whole studied area. To assess the sensitivity of the results to a particular combination of sites, we used bootstrapping to obtain 10% and 90% confidence limits for the FC, resampling our pool of sites 1000 times. We did not introduce any adjustments for the fire occurrence chronology to account for the decline in sampling coverage in the early period. The rationale for that was our interest in avoiding an additional assumption on the spatial distribution of fire ignitions over our study area.

Analysis of association between fire history and environmental proxies

We used superimposed epoch analysis (SEA) (Grissino-Mayer & Swetnam, 2000; Swetnam, 1993) to assess the role of climate forcing upon the fire activity. In the analysis, we used two LFYs data sets. The selection of the LFYs for the SEA was a trade-off between (1) maximizing the climate forcing upon fire activity in selected years and

(2) ensuring sufficient replication of data for the analysis itself. Two "extreme" solutions, that is, consideration of the largest fire year and the use of all fire years, would make the analysis impossible due to the lack of replication (the first alternative) or due to a diluted climate signal in the fire record (Drobyshev, Goebel, et al., 2012). Keeping these considerations in mind, we selected for the SEA, the five LFYs, based on our spatial reconstruction of fire activity in the Pechora-Ilych NBR. This number corresponded to ~4% of all fire years dating from AD 1400. We run two versions of SEA, feeding the routine with years dominated by fires of different seasonality. In doing so, we wanted to test whether the differences in fire seasonality during LFYs have an effect on the statistical significance of the results.

The region of the southeastern Komi Republic does not currently possess precipitation or drought reconstructions, which could act as a proxy for historic climate variability in fire-prone conditions. We, therefore, elected to use earlywood and latewood width chronologies of Scots pine, developed within the framework of our earlier study (Drobyshev, Niklasson, Angelstam, & Majewski, 2004). These chronologies served as a proxy for early- and late-season drought conditions. To ensure the presence of the drought signals in these chronologies, we ran response function analyses correlating that chronology with the monthly drought code (MDC) over the period when both data sets were available (1901–1998). The MDC calculation used the instrumental monthly precipitation total and maximum monthly temperatures from the CRU dataset TS v.4.02 (Harris et al., 2014). Details on the protocol of MDC calculation is available in the Appendix S1: Section S2.

Prior to SEA, we fitted an autoregressive time series model to the pine chronology, using R function *dplR::chron* (Bunn, 2010). The routine used Akaike Information Criterion to choose the order of the autoregressive model and Tukey's Biweight Robust Mean to produce the master chronology.

Analyzing the effect of human settlements

To study the association between shifts in fire activity and human activities, we obtained establishment dates for villages or small harbors on the Pechora River from historic sources (Chagin, 2015; Popova et al., 2012; Rychkov, 1770; Sivokha, 2001). We evaluated differences in the distributions of fire intervals prior to and following the establishment of the villages with a χ^2 test utilizing both complete (uncensored) and censored observations. We combined fire histories of three sites nearest to a village into a composite (village-specific) chronology for three villages located within the sampled area. To represent the probability of a fire in the sites nearest to the villages, we used the survivorship analysis and the Kaplan–Meier estimator (Kaplan & Meier, 1958):

$$S(t) = \prod_{j=1}^{t} [(n-j)/(n-j+1)]^{\delta(j)},$$

where $S(t)$ is the site survivorship function estimated for a period t; n is the total number of observations; $\prod$ is the product (geometric sum) across all cases less than or equal to t (in years), and δ (j) is a constant that equals 1 in case of complete and 0 in case of censored intervals. In the context of the current study, survivorship was understood as a probability for a site to escape fire over period t.

RESULTS

We dated 449 fire scars found on 247 dated samples corresponding to a total of 106 unique fire years, from both currently developed and earlier published data sets combined (Figure 2). The fire chronology for the study area covered 739 years, with the first fire dated to 1271 CE and the most recent fire dated to 2010 CE. To ensure sufficient density of sites for spatial reconstruction of fire activity, we selected the period from 1400 CE to 2010 CE, for which each year was represented by at least 10 sites (Figure 2). Fire seasonality was successfully identified for 65% of the fires. Our evaluation of the fire season based on the intra-annual position of scars showed that 97% of fires occurred during the growing season, 60% of scars were in the earlywood and 37% were in the latewood. Dormant-season fires constituted 3% of all scars dated with seasonal resolution.

We assessed the regime shifts separately for the FC (Figure 3a) and for the fire occurrence (Figure 3b). In the reconstructed area burned, we observed four periods with FC changes according to regime shift analysis (Table 1 and Figure 3a). In the earliest epoch, 1340–1610 CE, the mean FC was 66 years with a 90% confidence envelope of 57–79 years. In the next epoch, 1620–1730 CE, the FC was reduced to 33 years and then increased to 47 years during 1740–1950 CE. In the latest epoch, 1960–2010 CE, the FC increased to 152 years with a confidence envelope of 102–270 years.

We identified three regimes in the historic dynamics of fire occurrence since 1340 CE. During the first period, 1340–1660 CE, fires occurred at a relatively low rate (1.52 per decade) (Table 1 and Figure 3b). The fire occurrence was maximum (3.55 fires per decade) during 1670–1950 CE. In the latest period, 1960–2010 CE, the number of the fires (0.83 per decade) had declined two- to four-fold, compared with the previous period.

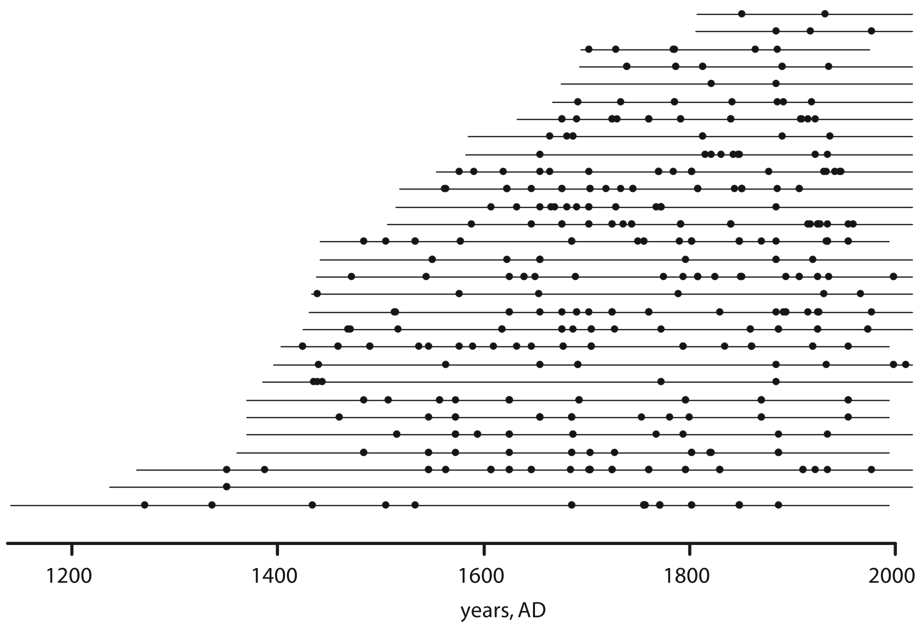

FIGURE 2 Dendrochronological reconstruction of the fire history in the Pechora-Ilych Nature Biosphere Reserve (NBR) over the 1271–2010 period. A single straight line represents each study site and a dark circle represents a fire event.

The response function analysis confirmed the presence of early- and late-season drought signal in the earlywood and latewood pine chronologies, respectively (Figure 4a,b). Earlywood chronology exhibited a significant negative correlation with May MDC (Figure 4a). This was consistent with the assumption that negative anomalies in the earlywood chronology reflected drier than average conditions and indicated periods with increased fire risk early in the fire season. The latewood chronology revealed a significant positive correlation with September MDC (Figure 4b), justifying its use a proxy for late-season fire weather conditions.

The five largest years selected for SEA were 1625, 1655, 1573, 1563, and 1676 (in the order of the amount of area burned). During these years, the fires burned 12.6, 10.2, 6.3, 5.5, and 5.5 km^2, respectively. Out of these years, the three largest featured mid-season fires (1625, 1655, and 1573), and two early-season fires (1563, 1676). SEA revealed a significant ($p = 0.04$) negative departure of earlywood pine chronology during these years (Figure 4c). Because none of these years featured late-season fires as the dominant type of fire events, we re-ran the analysis using the five largest fire years with fires in the late season. These years were 1686 (4.7 km^2 burned), 1702 (5.5 km^2), 1761 (3.14 km^2), 1885 (5.5 km^2), and 1934 (3.9 km^2). We observed a significant positive departure of the latewood chronology (Figure 4d), which was consistent with the notion of drier than average conditions at the end of the fire season during these years.

The site survivorship function, reflecting time-dependent probability for an area in the vicinity of the village to escaping a fire event, showed a non-significant ($p = 0.07$–0.20) increase in the fire occurrence for the period following the village's establishment (Figure 5; Appendix S1: Figure S3). For example, during the period prior to the village establishment, the site nearest to the village had an ~50% probability of escaping fire after 30 years since the last time it burned. This probability was, on average, only 25% after the village establishment dates. The pattern, although non-significant, was consistent across other combinations of number of sites and the period lengths considered (Appendix S1: Figure S3).

Observational records of fires in the Yaksha section of the Reserve over the 1936–1996 period documented 60 fires ignited by lightning strikes, which corresponded to 0.63 ignitions per km^2 and year.

DISCUSSION

For the past 670 years, the forest fire has been a common disturbance agent in the Scots pine-dominated forests of the Pechora-Ilych NBR. The fire activity revealed a considerable historic variability: the early period (1340–1610 CE) had a FC of 66 years, followed by a period (1620–1730 CE) of an increase in fire activity (FC = 32 years) and then two periods with progressively decreasing fire activity. Since the 1960s, the estimated FC was 153 years, the longest over the last 600 years that was covered by our reconstruction. The dynamics of FC and fire occurrence, and the SEA results representing largely the period prior to 1900 (Figure 4), suggested that climate was a driver of the FC

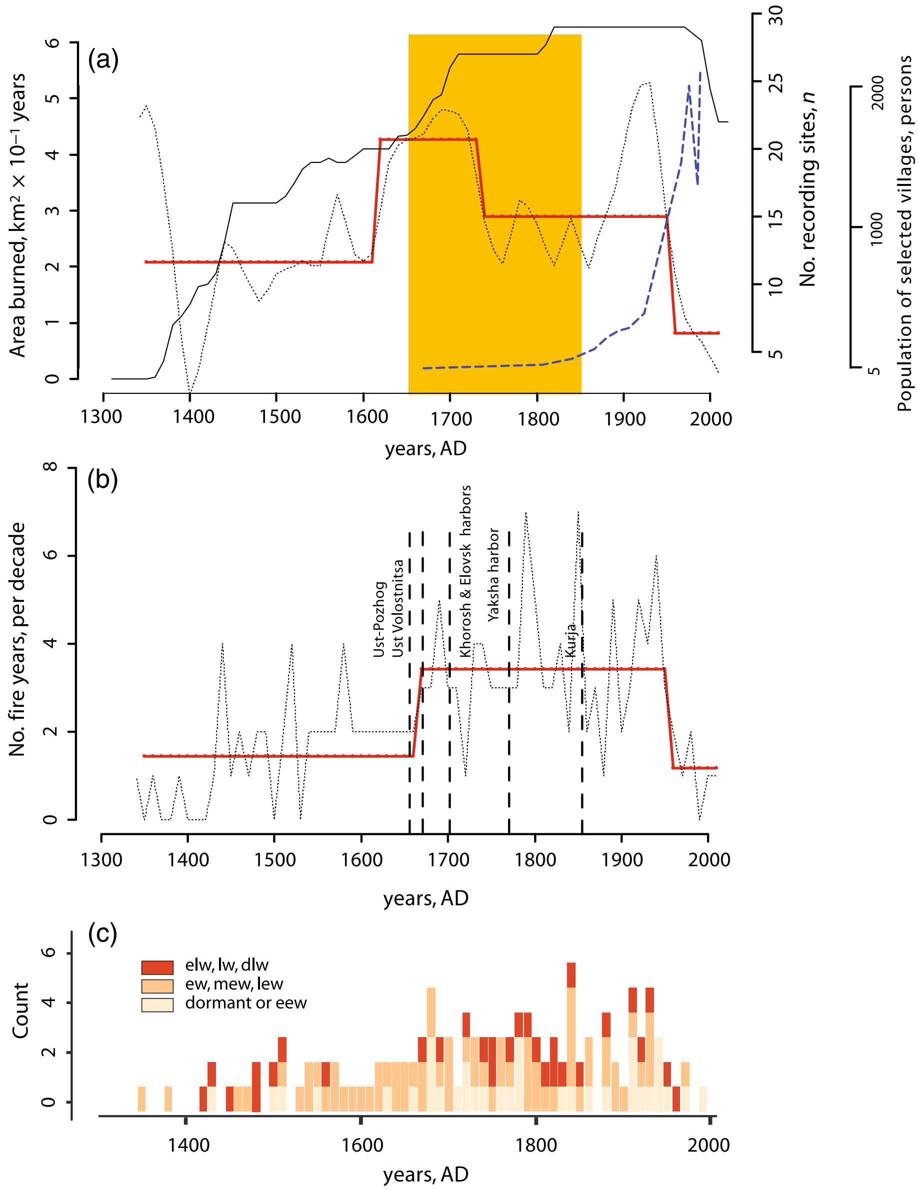

FIGURE 3 The reconstructed burned area (a) and the number of fire years (b), both per decade, are shown by the black dashed lines. Shifts in the fire cycle (a) and the fire occurrence (b) as identified by the regime shift analysis (Rodionov, 2004), are represented by red lines. Site replication (a) is shown by the black solid lines. Blue dashed lines indicate the dynamics of the total population of four villages (Ust' Pozheg, Yaksha, Kurja and Ust'-Volosnitsa) (Sivokha, 2001). The period when villages were established is indicated by a yellow bar (a). The establishment date of settlements are shown by solid dashed lines (b). (c) Dynamics of fire seasonality for fires dated with seasonal resolution. The abbreviations for the seasons of the dated fire scars: dlw, dormant latewood; elw, early latewood; ew, earlywood; lew, late earlywood; lw, latewood; mew, middle earlywood.

prior to the 20th century, whereas human activities were the factor controlling decadal fire occurrence. We discuss these findings in detail below.

Impacts of land-use changes on the historic fire regime

The presence of the temporary hunting camps and sites identified as mammoth burial grounds suggested that human occupation of the area around the Pechora-Ilych NBR started in ~40,000 BC (Degteva et al., 2015; Guslitser & Kanivets, 1965; Pavlov et al., 2004). Although human presence in the area has been well documented since that time, it is unlikely that it had a tangible impact on fire regimes. There is no evidence suggesting that ancient humans used even rudimentary slash-and-burn agriculture during this period (Degteva et al., 2015). From ~900 CE until the late 1700s, nomadic Mansi (Voguls) people had inhabited this area, subsisting mainly on

TABLE 1 Reconstructions of the fire cycle (FC) and fire occurrence in the Pechora-Ilych NBR for the periods identified by the regime shift analysis.

Statistics	Epoch, years CE	Mean, years	95% CI lower bound	95% CI upper bound
FC	1340–1610	66	56.77	78.55
	1620–1730	33	30.98	34.68
	1740–1950	47	41.89	52.00
	1960–2010	153	102.47	270.29
Decadal fire occurrence	1340–1660	1.52	1.18	1.85
	1670–1950	3.55	3.10	3.96
	1960–2010	0.83	0.67	1.50

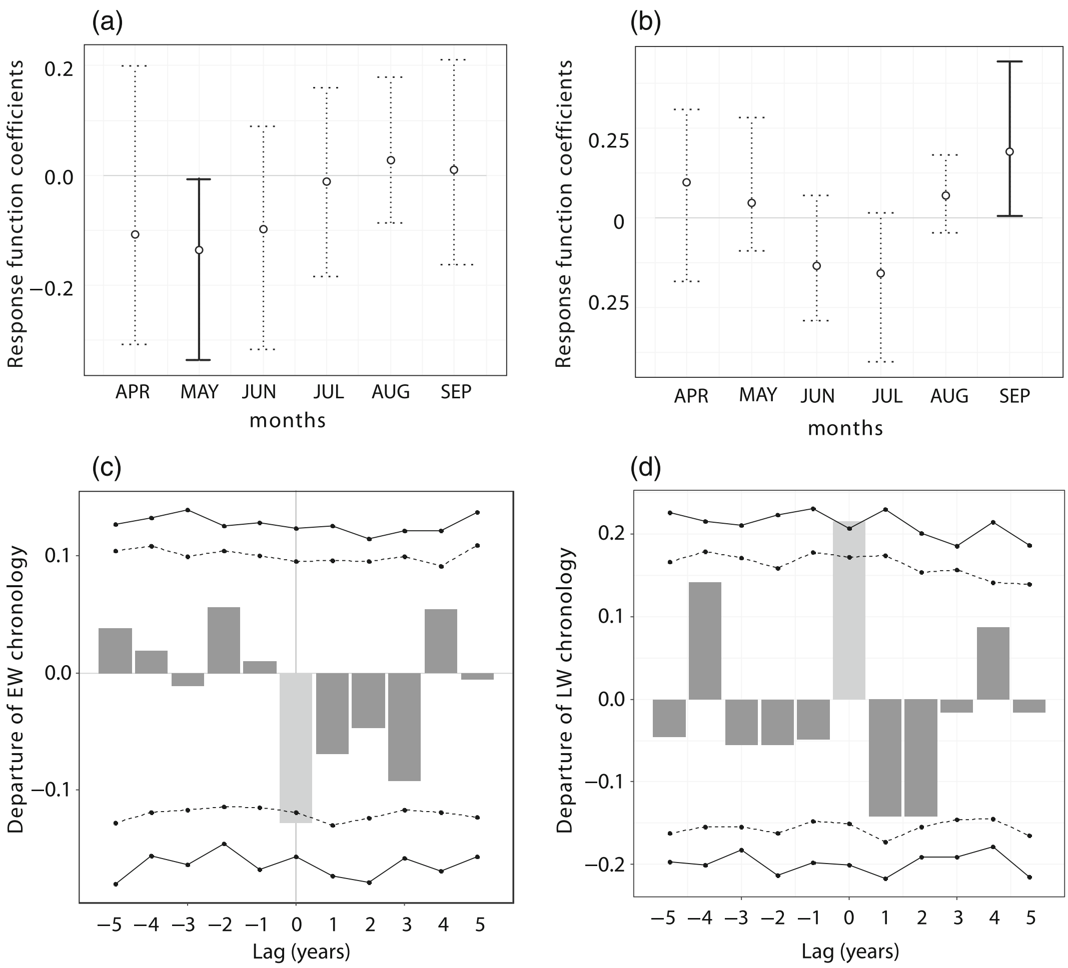

FIGURE 4 Response function analysis of the earlywood (a) and latewood (b) Scots pine chronologies, used as a proxy of fire weather conditions, and monthly drought code (MDC) during April through September. (c, d) Results of superimposed epoch analyses (SEA). (c) SEA on the largest fire years in the Pechora-Ilych Nature Biosphere Reserve (NBR) (all early- and mid-season fires) and the earlywood (EW) chronology ($n = 5$); (d) SEA on the largest late-season fire years and the latewood (LW) chronology ($n = 5$). Solid lines on (a) and (b) refer to significant response function coefficients. Dashed and solid lines in (c) and (d) refer to the 0.95 and 0.99 confidence intervals, respectively, as estimated by bootstrapping.

reindeer herding, hunting, fishing, and gathering (Chagin, 2012; Melnikov, 1852; Sokolova, 2009). The use of fires by the Mansi people in the pine-dominated forest of the Pechora-Ilych NBR is currently being debated (Abramov, 2017; Aleinikov, 2017b; Golovnev, 1993; Slezkine, 1994). It has been hypothesized that the Mansi people could have burned mesic spruce forests in the upper reaches of Pechora, for example, spruce forests of

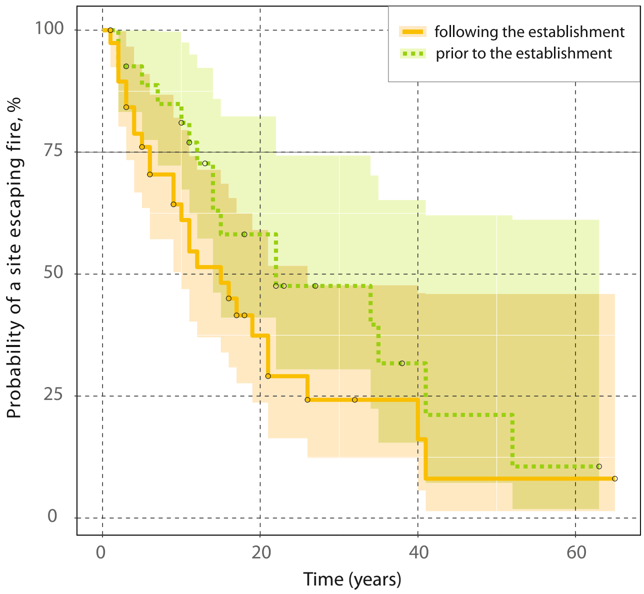

FIGURE 5 Effect of village establishment on the frequency of fires in the neighboring sites, as estimated by the Kaplan–Meier estimator. Green and orange lines represent the dynamics of the probability for a site to escape fire along the time gradient. The 95% confidence intervals are shown as shaded areas of the respective colors. Small empty circles represent fire return intervals on the studied sites.

Myrtillus type, to maintain early successional stands dominated by young deciduous trees as forage grounds for moose, which were hunted (Aleinikov, 2017a). However, the common pine lichen forests in the study area were unlikely targets for such burns because they served as winter pastures for the reindeers until the late 1800s. Records document the fear from the local population of escaping fires that could destroy reindeer feeding grounds (Milovanovich, 1926; Varsanofieva, 1929). Similarly, studies in the Nordic countries have suggested that reindeer herders were careful in their use of fire because it removed the ground lichens (Collins et al., 2011; Laestadius, 1833; Sarvas, 1937; Wallenius et al., 2005; Wretlind, 1934), with their recovery taking up to 100 years in this forest type (Gorshkov et al., 1996).

FC did not reveal changes associated with the colonization waves (refuting $H_{1.1}$), whereas a change in fire occurrence was synchronized with the second colonization wave, supporting $H_{1.2}$ (Figure 2). The first wave of colonization was formed by Russians coming from the East and dates back to the middle of the 1400s. Russians pushed the Mansi people eastward, into the highlands of the Ural mountains (Glushkov, 1900; Popov, 1892). Development of the network of portages was both the sign and the driver of this colonization wave. The earliest portage, the Nemski portage route, dates back to 1517–1520, and was actively used until the construction of the Northern Catherine Canal in the 1820s (Chagin, 2017; Dmitriev, 1893; Rychkov, 1770).

The second wave of Russian colonization began in the second half of the 1600s, followed by the establishment of new trade routes. The Pechora route, first referenced between 1671–1681 (Chagin, 2017), contributed to the increase in the traffic of commercial goods between the basin of the Pechora River with the basin of the Kama, a tributary of the Volga (Korchagin & Lobanova, 2012; Popova et al., 2012; Zherebtsov et al., 2014). Since the late 1600s, and possibly earlier, people from the Perm region actively traveled into the Upper Pechora area to fish and hunt (Lashuk, 1958). These activities might contribute to fire ignitions and the amount of burned areas. A similar pattern has been documented in Fennoscandia, where hunter and shepherd camps were sources of ignitions (Groven & Niklasson, 2005). In the studied area, this development resulted in the establishment of homesteads, each consisting of one to five families, between 1670 and 1810 (Zherebtsov, 1972). Their livelihoods relied on fishing, hunting, and their services as construction workers to build barges on the trade route between the river Kama basins and the Pechora area. The appearance of these homesteads, often as small harbors on the Pechora River, coincided with the doubling of the decadal fire occurrence in the area (Table 1, Figure 2). We propose that this pattern was a result of human activities contributing with additional sources of ignitions that are consistent with hypothesis $H_{1.2}$. However, village-centered analysis showed a non-significant increase in fire occurrence (Figure 4), suggesting a limited effect of these ignitions, even at the local scale.

Fire cycle and fire occurrence in the Pechora-Ilych NBR appeared to have been driven by different sets of factors. Indeed, in contrast with fire occurrence (i.e., the frequency of fire years, estimated at the decadal scale), there was no obvious temporal synchrony between the dynamics of the FC and known trends in regional colonization events, which disproved the hypothesis $H_{1.1}$. Specifically, the dynamics of the FC did not reveal any synchrony with the second colonization wave: the increase in fire activity (i.e., the shortening of the FC) occurred half a century earlier, approximately in the 1610s. The increase occurred approximately one century after the onset of the Nemski portage activities (1517 CE). We also noted that the shorter FC was associated with the period of minimal population density, whereas the onset of the longer FC happened during the late 1700s, the period when the portage-centered transportation activities were at their highest.

A common view of the fire history of the European boreal forest is that human forest use and, particularly, slash-and-burn agriculture, resulted in higher fire activity

(Lehtonen & Huttunen, 1997; Niklasson & Granström, 2000; Rolstad et al., 2017; Wallenius et al., 2004). This pattern may not hold in the Upper Pechora region. At the beginning of 1600s, the use of fire to create arable land in the Upper Pechora was very limited due to climate conditions that were unfavorable for cultivation and generally infertile soils (Krivoshchekov, 1914; Popov, 1801). The wheat and rye was actually delivered to the Upper Pechora through the Pechora portage (Zherebtsov et al., 2014). An expedition diary into the study area in early 1800s reads: "There were few people that are engaged in agriculture: rye rarely ripen, and they do not have a profit from cattle breeding either. Hunting is the main trade" (Latkin, 1843). The importance of Yaksha harbor and Ust'-Volosnisa, the first Russian village established in 1671 (Popova et al., 2012; Sivokha, 2001), as principal hubs on the Pechora trade route further disfavored investments in agriculture and, in particular, in slash-and-burn practices. However, historic records documented the building of riverboats, including steamships in Ust'-Volosnisa (Aleinikov & Chagin, 2015; Krivoshchekov, 1914; Popov, 1801), suggesting that the clearing of the forest and eventual human-related ignitions did occur in proximity to the villages.

Continuing colonization of the area by Russians contributed to a population increase during the 1800s–1900s (Popova et al., 2012; Sivokha, 2001). The increase in the economic value of timber and profit from the transportation services drove the economic development at that time. Barge building, fishing and fur extraction were popular occupations among the local population until the late 1800s (Sivokha, 2001). The increasing presence of humans in the forest was likely to have contributed with additional ignition sources. However, our reconstruction did not indicate an increase in the fire occurrence nor in the amount of burned area during that period, indicating that the effect of these land-use patterns on the fire regime was minimal. We speculate that a combination of few slash-and-burn activities, a rudimentary fire control, and a progressively less fire-prone climate in the post-LIA era could explain the observed pattern.

The earliest available documented evidence of fires in proximity to the Pechora-Ilych NBR dates back to forestry reports of the late 1800s and early 1900s, indicating that the majority of the fires were caused by lightning strikes (Cherdyn Regional Museum, 1894, 1910) (Table 2). The report listed four fires, three of which were present in our dendrochronological record. One of these years, 1885, was noted as a year with just 6 ha burned in a single fire. In contrast, the dendrochronological reconstruction identified this year as the year with one of the largest amounts of reconstructed area burned in the studied area since the 1400s. Two other fires, in 1887 and 1907, were dated as multisite fires, with the location of the sites corresponding well to the fire localization in the forestry records (Table 2). The size of the 1907 fire was probably larger than the size reported in the historic sources, because it affected a large portion of the area outside the area focused on in the historic records. This comparison exercise suggested that historic sources, while providing important information about fire occurrence, may severely underestimate the levels of fire activity, the bias probably was considerable in poorly populated regions.

Some impact of general economic recession following the coup-d'état of 1917 and the establishment of the Pechora-Ilych NBR in 1930 that effectively halted most of the traditional activities in the area (Aleinikov et al., 2015; Degteva et al., 2015) and might have further reduced fire activity by lowering the number of human-related ignitions. The observed decline in fire activity that occurred in approximately the 1960s probably reflected the onset of active fire suppression. Effective fire suppression in Russia began in the early 1930s, following the establishment of the forest protection program based on

TABLE 2 The earliest forestry records on forest fires in the proximity of Pechora-Ilych NBR (Cherdyn Regional Museum, 1894, 1910).

Date	Area burned, ha		Location	Notes from forestry records
	Reported	Reconstructed		
September 1875	N/A	Not recorded	In proximity of Ust'-Elovka harbor	N/A
27 August 1885	6	3.86 km^2 (386 ha)	Vogulka river	"The cause of the fire is unknown. Surface fire, growing pines were not damaged"
20 July 1887	1250	1.55 km^2 (155 ha)	Right coast of the Volosnitsa river, along the portage and south to the Vogulka river	"Lightning-ignited fire. Young pine-dominated forests were burned down"
1–2 July 1907	110	0.77 km^2 (77 ha)	1 km far away from Ust'-Volosnitsa village	"Lightning-ignited forest fire following a severe drought"
6–8 July 1907	N/A	…	Yaksha route	"Lightning-ignited forest fire following a severe drought"

aerial reconnaissance and airborne fire suppression brigades. Demobilized military paratroopers joined these brigades, following the end of World War II (Kozubov & Taskaev, 1999; Stocks & Conard, 2000). The 1960s also marked the onset of the extensive use of helicopters by the Russian Aerial Forest Protection Service (Avialesookhrana) (Bryukhanov & Korshunov, 2017), coinciding with the shift from high to significantly lower fire activity in the Pechora-Ilych NBR. Until the early 1990s, Russia had the world's largest fire suppression system, which led to the successful reduction of the burned area, especially around settlements (Goldammer, 2006). The State Forest Enterprise (Lespromkhoz) drove industrial-scale harvesting operations in the area during1940–1960s (Popova et al., 2012). Road building associated with these activities improved the possibility of suppressing fires (Kozubov & Taskaev, 1999).

Climate and fires

Lack of regional reconstruction of drought conditions, preserving variability at both low and high frequency bands, makes it difficult to convincingly discuss the role of climate in shaping fire activity in the Pechora-Ilych NBR. Because the region lies on the eastern fringes of the European boreal domain, it is generally not represented by reconstructions done in more western sections of the boreal Europe. Analysis of recent dynamics of fire weather suggest, in fact, that summer drought conditions over the Komi Republic tended to be in antiphase with those in the western section of Northern Europe (Drobyshev et al., 2021). To address this challenge, we relied on the earlywood and latewood pine chronologies, which were sensitive to the drought conditions in the study area (Figure 4a).

SEA revealed a significant ($p = 0.04$) negative departure of the earlywood pine chronology in the analysis with the five largest fire years (all early- and mid-season fires) and a significant ($p = 0.01$) negative departure of the latewood chronology for the largest late-season fires (Figure 4c,d). The pattern was broadly consistent with the notion of LFYs occurring during drier than average conditions that supported hypothesis H_3. Because the five largest years included both early- and mid-season fires, the significant results of SEA suggested that spring droughts might predispose high levels of fire activity toward the mid-season. This pattern has been recently demonstrated in the attribution study of the 2018 fire season in Sweden (Krikken et al., 2019). The early-season fires were likely to have been of lightning origin: these types of fires in the European part of the Russian boreal zone have been reported to predominantly occur early in the fire season, due to fuel-drying high-pressure cells being common early in the fire season (Kurbatsky, 1976; Stolyarchyuk & Belaya, 1982). In Russian fire literature, this period has been known as "May–June forest fire belt" (Melekhov, 1946). The association between LFYs dominated by late-season fires and the latewood chronology exhibited a higher degree of statistical significance (compared with the earlywood chronology), possibly pointing to the stronger climate forcing upon late-season fires.

Concerning the low-frequency variability in fire activity, we documented an increase in forest fire activity in the early 1600s. The region of southern Komi currently lacks precipitation or drought reconstructions that extended over the period covered by our fire reconstruction, and which would support discussion of low-frequency trends in climate forcing upon fire activity. However, borehole temperature reconstructions have indicated that the temperature in the Ural region was $\sim 1^{\circ}$C lower during the 1600–1800s, compared with the year 2000 (Pollack et al., 2003), supporting a wider pattern of cooling of the Northern Hemisphere during the LIA. It follows that the observed pattern was broadly similar to the pattern observed in the Northern Hemisphere boreal forest, where shortening of FCs (i.e., increase in the amount of area burned) tended to coincide with the cold period of the LIA with unstable atmosphere and the dominance of dry Arctic air masses over the boreal region (Bergeron & Flannigan, 1995; Drobyshev et al., 2016; Gagen et al., 2011). This suggests a climate forcing of this shift. Indeed, the timing of the increase in fire activity in the study area was not synchronized with a shift in the land-use patterns of the region, as suggested by the history of land use and, specifically, the dates of village establishments. The relative role of climate versus fire suppression in the decline in fire activity since the 1960s remains unclear, although it is highly probable that fire suppression played a role in this dynamic (please refer to the previous subsection *Impacts of land-use changes on the historical fire regime*).

Ecology and fire regime of the Komi pine-dominated forests

Extending the analyses to the less exploited sections of the European boreal zone provides a possibility to better parameterize the role of fires in shaping disturbance regimes of this biome.

Modern lightning ignition frequency in the studied forests was 0.63 per km^2 and year. This is a much high level than previously reported for other sections of the European boreal region. For example, in central and northern Sweden these levels have been estimated at 0.05–0.15 per km^2 and year (Granström, 1993). The difference might be due to a variation in the density of lightning flashes. The majority of the Komi Republic experiences two to four lightning flashes per km^2 and year, which is considerably higher than in the Swedish central and northern boreal regions (0.2–0.6 flashes per km^2 and year; Cecil, 2006).

Under the assumption that a fire year corresponded to a single fire within our study area, the reconstructed ignition frequencies in the Komi boreal forests were at the range 0.02–0.03 per km^2 and year. These estimates were close to those obtained in the Swedish boreal forest. We noted, however, that more than 75% of the years in the modern dataset had multiple lightning-ignited fires within a single year, which indicated that our historic estimates of ignition frequencies were overly conservative. Reanalysis of the modern dataset under the same assumption (i.e., assuming that one fire year "hosts" a single fire) gave 0.25 ignition per km^2 and year, that is a three-fold decrease. Adjusting for this bias in the reconstructed data would result in ignition frequencies in the range 0.05–0.08 per km^2 and year over the reconstructed period. The reasons for a large difference between the modern and reconstructed ignition frequencies are less clear. We can speculate that a portion of smaller fires was not picked up by our reconstruction. These fires were common among lightning-ignited fires in the modern dataset, with 33% of all these fires covering less than 1 ha and 53% less than 5 ha.

Both variability in ignition frequencies and frequency of fire-prone episodes were likely to have contributed toward high variability in the FC prior to the onset of the modern fire suppression era. We documented two-fold changes in the FC between the most and least fire-prone periods over that time (Table 1). However, we observed a limited variability in the absolute estimates of the FCs under generally low levels of human forest use. Indeed, prior to the 1960s, the variability in the reconstructed FC was limited from ~30 to 70 years. The observation highlights a degree of resilience of the boreal fire regime to variability in climate settings. The fact that we reconstructed such short FCs during the 1800s, the period when most Fennoscandian studies have documented a sharp decline in the fire activity (Granström & Niklasson, 2008; Lehtonen et al., 1996), supports the notion of that decline being driven primarily by the change in land-use patterns, and not climate variability.

As our sampling protocol excluded humid sites with very limited availability of fire-scarred and old trees, our FC estimates reflected predominantly a more xeric portion of the landscape. This explains why most of the previous studies reported longer FCs (please refer to reviews in Ryzhkova et al., 2020; Wallenius, 2011). Such short FCs and commonly observed multiple scars on living and dead trees pointed to low severity of the historic fires, which did not impede pine regeneration in the studied stands. Low-severity surface fires are often considered as a characteristic feature of the Eurasian boreal fire regimes (de Groot et al., 2013), and our study supported this assertion. The dominance of early-season fires (Figure 3) (Shvidenko & Nilsson, 2000), which occur when deep organic layers are still well hydrated following the snow melting, is a feature of the seasonal fire dynamics that probably keeps the fire severity low and also removes the portion of fuels that would be available for late-season fire activity. It also appears that such short FCs were controlled, to a considerable degree, by fuel accumulation rates (Schimmel & Granström, 1996) rather than the frequency of extreme fire-prone periods. Fuel recovery time in both Eurasian and North American boreal forests has been reported to approach a few decades (Bernier et al., 2016; Schimmel & Granström, 1997). A study of a gradient of boreal forest types in North American boreal forest has estimated fuel recovery times in most of the forest types to vary between six and 30 years (Thompson et al., 2017). Both estimates are very consistent with the suggestion of an important role of fuel recovery in controlling FCs in the pine-dominated Komi forests and is of direct relevance for the development of nature-based fire management strategies (Adams, 2013; Bergeron et al., 2001; Swetnam et al., 1999).

Does variability in reconstructed FC prior to the onset of modern fire suppression reflect the dynamics of its natural drivers? We tend to answer positively to this question. Previous studies of fire activity in Fennoscandia have consistently pointed to the strong influence of human colonization (Niklasson & Granström, 2000; Rolstad et al., 2017; Wallenius, 2011), and the impact of in forest-use practices (Hellberg et al., 2009; Lehtonen et al., 1996; Wallenius et al., 2004) on forest fires in European boreal forest. In our study, however, we observed no synchronization between the colonization waves and the dynamics of the FC. Although earlier analyses of historic records has suggested that Russian colonists played an important role in shaping the historic fire regimes in Upper Pechora (Aleinikov, 2019; Aleinikov & Chagin, 2015), these impacts might have been relatively local and largely limited to the dynamics of fire occurrence. Humans did affect FC in these ecosystems, but it happened as late as in the 1960s, approximately one to two and a half centuries later than in Fennoscandia (Lehtonen et al., 1996; Niklasson et al., 2010; Pinto et al., 2020; Wallenius, 2011). The pine-dominated forests of the Komi Republic may, therefore, hold a unique position as the ecosystem with the shortest history of human-related shifts in FCs across the European boreal region.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Snow data (Robinson, et al., 2012) were obtained from https://doi.org/10.7289/V5N014G9. Temperature and precipitation data (Scientific Data Curation Team, 2020) were obtained from https://doi.org/10.6084/m9.figshare.11980500. The fifth-generation ECMWF reanalysis data (ERA5) (Hersbach et al., 2019) were obtained at https://doi.org/10.24381/cds.f17050d7. Fire reconstruction data (Drobyshev, 2022) are available from the Swedish National Data Service at https://doi.org/10.5878/sqk4-gg83.

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