Dendrochronological reconstruction of historical fire activity on the Onega Peninsula, Arkhangelsk Region

Alexander Chkareuli

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Alexander Chkareuli

Supervisor:	**Igor Drobyshev, SLU, Southern Swedish Forest Research Centre**
Co-Supervisor:	**Nina Ryzhkova, University of Eastern Finland**
Examiner:	**Narayanan Subramanian, SLU, Southern Swedish Forest Research Centre**

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Swedish University of Agricultural Sciences
Faculty of Forest Sciences
Southern Swedish Forest Research Centre

Abstract

Historical fire activity was reconstructed for Scots pine stands on the Onega Peninsula, Arkhangelsk Region, using dendrochronological dating of fire scars. The fire chronology spans 1385–1942 and includes 98 fire scars representing 40 unique fire years. Regime-shift analysis identified alternating periods of shorter and longer fire cycles, with the strongest increase in fire occurrence during 1670–1820. Fire seasonality was dominated by early- and middle-season scars.

Historical land-use evidence indicates that the period of elevated fire occurrence coincided with intensive salt production and inland fuelwood extraction. Superposed epoch analysis linked selected large fire years to drier-than-average conditions in the preceding year, while recorded fire years overlapping the instrumental period were associated with negative North Atlantic–Arctic sea-surface temperature anomalies.

The results indicate that fire activity on the Onega Peninsula varied through time in association with both land-use history and climatic conditions. The modern period showed the lowest reconstructed burned area, expressed as the longest fire cycle on the record.

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Keywords: Dendrochronology, fire activity, forest fire history, boreal forests, climate impact, human impact

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Abbreviations

Abbreviation	Description
FC	Fire cycle
LFY	Large fire year
LW	Latewood
MDC	Monthly Drought Code
NAO	North Atlantic Oscillation
OP	Onega Peninsula
PDSI	Palmer Drought Severity Index
SEA	Superposed epoch analysis
SST	Sea-surface temperature
STARS	Sequential t-test Analysis of Regime Shifts

1. Introduction

Forest fire is a fundamental ecological process that shapes terrestrial ecosystems (Jones et al., 2022). Fire is a major driver of forest composition, structure, and ecosystem dynamics (Bergeron & Gauthier, 2016). Periodic disturbance via fire contributes to renewal of forest stands and development of heterogeneous landscapes, bringing diversity of stand age and structure (Bergeron et al., 1998). Successional development of boreal ecosystems affects the properties of fire regimes.

Fire frequency, fire occurrence, fire return intervals, fire size, severity, and seasonality characterize historical fire regimes (Flannigan et al., 2000). Fire occurrence describes the number of fire years recorded in a given period, while fire frequency and fire return intervals describe how often fires occur through time. Fire size, expressed as area burned, describes the spatial extent of fire activity. Severity describes the ecological impact of fire on vegetation and soils, while seasonality describes the timing of fire within the annual growth cycle. These properties provide a basis for comparing fire activity through time and across landscapes.

Fire regimes emerge from local interactions between fuels, weather, topography, and ignition sources. Variation in dominant tree species, fuel structure, landscape configuration, and environmental conditions can alter ignition probability, fire spread, intensity, and post-fire recovery (Pyne, 1996; Drobyshev et al., 2016; Rolstad et al., 2017). A comparison study between fire dynamics in North American and Eurasian boreal forests demonstrated that large fires in central Siberia were more greater in number and associated with shorter fire return intervals than in Canada, while Canadian fires were larger, more intense, and produced higher carbon emissions per ha due to greater forest-floor fuel loads and higher fuel consumption by crown fires (de Groot et al., 2013).

Reconstructions of fire history in northern Europe have demonstrated that recurring fires have influenced forest dynamics for centuries, contributing to the development of pine-dominated forest ecosystems characteristic of this region (Niklasson & Grantröm, 2000;).

Anthropogenic burning influenced fire regimes in forest ecosystems worldwide, including the European boreal zone. Fire was used to enact a variety of land-use practices including forest clearing, agricultural preparation, pasture management, hunting purposes and others (Wallenius, 2011). Changes in land-use affected both ignition patterns and spatial distribution of fires across landscapes (Niklasson & Grantröm, 2000). Humans contributed additional ignition sources, which likely increased fire frequency at the stand scale. In addition, attempts to control and manage fires influenced their spatial extent and severity. Together, these processes altered fire regimes in forest environments.

Slash-and-burn agriculture has been one of the most important drivers of anthropogenic fire in the European boreal zone. The cultivation system involved cutting forest stands, allowing the accumulated slash to dry, and subsequent burning to prepare land for crop production. The fire releases nutrients stored in the slash to temporarily increase soil fertility, enabling agricultural cultivation on otherwise nutrient-poor soils (Tomson et al., 2018; Viro, 1974). The fertility gains were relatively short-lived, resulting in repeated burning across portions of the forest landscape, effectively moving through it (Hamilton, 1997).

Population growth intensified human impacts on the fire regime. As settlement expanded, the number of anthropogenic ignitions increased within individual watersheds and landscapes. The timing of slash-and-burn activity varied across the European boreal zone, with its onset and cessation occurring at different times in different regions (Hamilton, 1997). Studies from Fennoscandia suggest that the expansion of anthropogenic burning after the late 17th century increased fire occurrence while reducing average fire size and spatial extent compared to earlier, predominantly natural fire regimes (Niklasson & Grantröm, 2000).

This influence has not remained constant over time. Since the beginning of the 19th Century, many traditional land-use practices involving fire gradually declined - agricultural systems modernized and the economic importance of timber production increased. In northern Europe, the transition toward organized, timber-oriented forestry reduced tolerance for uncontrolled fires, and efforts to prevent and suppress them increased (Pinto et al., 2020). Shifts in land use and culture having this effect are not unique to Fennoscandia, and similar patterns of fire decline can be seen in coniferous forests in the north- and southwestern US despite drought conditions conducive to fire activity (Wallenius, 2011). This presents a later trend of fire activity of both anthropogenic and natural origin substantially decreasing with passing decades.

Climate is a strong driver of fire activity in boreal ecosystems. The variability in climate affects both probability of ignition and fire spread. Fire occurrence depends strongly on climate conditions, but the mechanisms vary across temporal scales. At multi-year to decadal scales, climate influences vegetation productivity and fuel accumulation, determining the amount of available biomass. At seasonal to sub-annual scales, climate controls fuel moisture.

Over sub-annual timescales, weather conditions during a fire season determine immediate fire hazard through fuel dryness. Warm temperatures and reduced precipitation promote drier forest fuels. Conversely, wetter conditions can suppress fire activity.

At interannual to multidecadal timescales, regional climate variability can produce observable fluctuations in fire activity. Large Fire Years (LFY) often occur during anomalously warm and dry periods, reflecting strong climatic control over fire activity (Bergeron et al., 2004). Climate can synchronize fire activity over large geographic areas and lead to simultaneous fire events across multiple forest regions.

In northern Europe and north-western Russia, dendrochronological reconstructions of fire history have provided important insights into the interactions between climate variability, human land use, and forest disturbance dynamics. Studies in northern Scandinavia have shown that variability of the North Atlantic Sea Surface Temperature (NASST) and summer North Atlantic Oscillation (NAO) can affect regional fire activity through influence on atmospheric circulation and moisture availability, dictated by development and maintenance of high-pressure atmospheric zones (Drobyshev et al., 2015; Drobyshev et al., 2016).

Fire history reconstructions from Karelia demonstrate that periods of elevated fire activity are frequently associated with climatic conditions that favor the drying of forest fuels and the development of fire conducive weather patterns (Ryzhkova et al., 2020).

This indicates that climate variability plays an important role in determining the timing and extent of fires in the European boreal forest zone.

However, many areas of the eastern European boreal forests remain poorly represented in existing fire-history datasets. One such region is the Onega Peninsula (OP), belonging to Arkhangelsk Oblast, Russia. The OP is characterized by boreal forest landscapes, large wetlands and relatively low levels of historical infrastructure development in its interior. The long-term fire history and its role in forest dynamics of the OP remains poorly understood.

The relationship between fire regimes and North Atlantic atmospheric anomalies represents a further gap in regional fire-history research. Studying this relationship will assess how far the influence of North Atlantic atmospheric anomalies on fire regimes extends eastward and its importance relative to anthropogenic influence.

The aim of this study is to reconstruct the historical fire regime of forests on the peninsula using dendrochronological analysis of fire-scarred samples of Scots pine. By identifying and dating past fire events recorded in tree ring series, the study will characterize the patterns of fire occurrence over time and test their correlation to climate variability and human activity to address the following hypotheses:

H1: Historical fire activity correlated to the North Atlantic SST;

H2: Periods of intensified historical land use were associated with increased fire occurrence; and

H3: Modern (20th century) level of fire activity is the lowest over the last 500 years in the area.

2. Materials and methods

Scots pine *(Pinus sylvestris L.*) is one of the dominant tree species in many European boreal forest ecosystems due to a range of adaptations to low and medium intensity fires. This resistance is caused primarily by the tendency to self-prune and thick tree bark (Agee, 1998; Keeley, 2012). As Scots pine ages, the likelihood of surviving a fire increases (Fernandes et al., 2008). This makes the species particularly suitable for long-term dendrochronological reconstruction.

Evidence of fire disturbance is frequently preserved in Scots pine trees in the form of fire scars. Trees that survive past fires may retain visible scar tissue and deformity in subsequent tree ring formation within their annual growth rings, providing a record of past fire events that can be dated using dendrochronological techniques. Presence of multiple fire scars within the same living trees and deadwood indicates that non-stand-replacing fires were common in many pine-dominated boreal forests (Niklasson & Granström, 2000; Niklasson & Drakenberg, 2001).

The accumulation of fire-scarred trees and deadwood across stands provides valuable evidence for the reconstruction of long-term fire history. Dendrochronological analysis can identify timing and frequency of past fires, as well as severity and spatial extent - and assess their variability through time (Cook, 2006).

2.1 Study area

The study was conducted on the OP, located along the southern coast of the White Sea in Arkhangelsk Oblast, north-western Russia (64.58° N, 38.00° E). Instrumental records indicate a mean July temperature of 15.7 °C and mean annual precipitation of 491 mm for Arkhangelsk over the period 1813–1988. Highest mean precipitation is detected for August at 61.2mm and lowest for February at 22.9mm (Global Historical Climatology Network).

The topography is mostly flat to gently sloping, with elevations of 100–150 m a.s.l. and occasional steep river ravines. The peninsula forms a largely roadless boreal landscape dominated by coniferous forests and extensive wetlands.

Mineral soils are generally dominated by Norway spruce (*Picea abies (L.) H. Karst.*), with European white birch *(Betula pubescens Ehrh.*) commonly occurring in the understory. Peatlands are dominated by Scots pine and cover approximately 30% of the peninsula. They are covered by *Sphagnum spp.* Mosses with *Eriophorum vaginatum* being the most abundant herbaceous species. Other common plant species are *Vaccinium uliginosum*, *Vaccinium oxycoccos* and *Carex globularis* (Wallenius, 2002).

Human presence in the region dates back several millennia, with more permanent Slavic settlement established by the medieval period (Kirisheva, 2006). The peninsula has very low population density, with settlement concentrated along the coast. From the late medieval period to the late 18th century, land use was dominated by coastal salt production, which required substantial fuelwood extraction (Bogdanova, 2014; Gerasimova, 2025). Following its decline, land use shifted toward fishing, hunting, and small-scale resource use, while the interior of the peninsula remained largely uninhabited (Kulyasova & Kulyasov, 2008; Savich, 1927; Sokolova, 1937). More intensive forest exploitation in interior regions began only in the late 20th to early 21st century, while parts of the peninsula are currently protected under the Onezhskoye Pomorye National Park (Braslavskaya et al., 2020).

A previous study on fire activity was conducted on the OP to find evidence of fire activity in Norway spruce stands. The majority of 43 examined forest stands (70%) were found to be older than 200 years. Evidence of fire was absent from 15 of 43 studied plots and fire scars were rare. The study concluded that fire was an infrequent disturbance in *Picea*-dominated stands, with fire rotation time of at least 300 years (Wallenius, 2002).

2.2 Sample collection

Samples were collected in 2021 from fire-scarred Scots pine stands. Sites were selected within a 45x40km area in the southeastern part of the OP. In total, 24 sites were sampled.

At each site, 10 - 25 trees were sampled, including both old living trees and deadwood (snags and logs). Sampling targeted trees with visible fire scars or other indicators of past fire disturbance. Wedge samples were taken from living trees to minimize damage, while full cross-sections were collected from deadwood when possible. All samples were collected using a chainsaw.

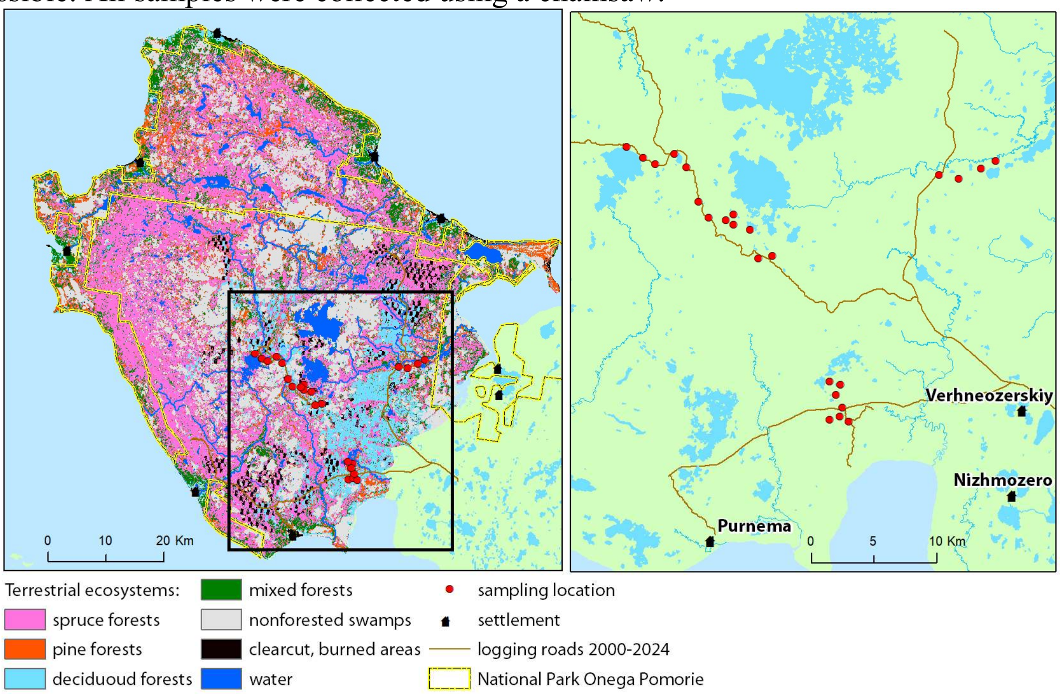

Figure 1. Location of the study sites.

2.3 Sample preparation and dendrochronological analysis

Samples were air-dried prior to preparation. All samples were sanded with progressively finer grit to enhance the visibility of annual rings and fire-scar features. All mounted and sanded samples were scanned at the resolution of 2400 dpi. Ring widths were measured using the programs CooRecorder and CDendro (Cybis Elektronik & Data AB). Cross-dating was performed against an existing master chronology from the Karelia region (Ryzhkova et al., 2020), which provided reliable alignment for younger tree-ring series. For older samples, where correspondence with the reference chronology was weaker, a new master chronology was progressively built by incorporating well-dated local series until sufficient replication was achieved.

T-values calculated in CDendro were used to assess the correlation between individual series and the reference chronology (Holmes, 1983, 1999; Grissino-Mayer, 2001). Cross-dating was further verified through visual comparison of ring-width patterns using the pointer year method (Stokes and Smiley, 1968). Common pointer years included 1801 (dark latewood), 1757 (dark latewood), 1696 (dark latewood), 1601 (pale latewood), 1453 (pale latewood) and others.

The final stage of laboratory work involved dating fire scars and identifying their position within annual rings to assign fire events to calendar years and determine their seasonal timing. Fire scars were classified into three within-ring seasonal categories: early, middle, and late fire season. This classification was based on the intra annual position of the scar relative to ring boundaries and latewood formation, following dendrochronological approaches (e.g. Ryzhkova et al., 2020, 2022). In the study region, the early, middle, and late fire season broadly correspond to May-June, July, and August-September, respectively, although exact timing may vary among years.

2.4 Identification of fire regime shifts

I analyzed fire activity using decadal time series of reconstructed burned areas and fire occurrence (number of fire events per decade). To identify regime shifts in fire activity, I applied the Sequential t-test Analysis of Regime Shifts (STARS; Rodionov, 2006) separately to reconstructed burned areas and fire occurrence.

Before the analysis, I adjusted burned-area estimates to account for temporal variation in the number of sites capable of recording fire. For each decade, I used the proportion of fire-recording sites to estimate the possible contribution of non-recording sites, thereby reducing bias associated with declining sample replication in older parts of fire chronology (Ryzhkova et al. 2020, 2022).

I identified regime shifts as statistically significant and persistent changes in mean values between consecutive periods, using a period cut-off length (L) of 10 years and a significance level (α) of 0.05. Finally, I calculated fire cycle (FC) for each identified regime as the time required for an area equivalent to the total study area to burn (van Wagner, 1978), based on total burned area and the duration of the regime:

$$FC = (TSA \times TI) / TBA$$

where TSA is the total studied area, TI is the duration (years), and TBA is the total burned area within that period.

2.5 Superposed epoch analysis (SEA)

I used superposed epoch analysis (SEA) (Grissino-Mayer & Swetnam, 2000; Swetnam, 1993) to evaluate the influence of climate variability on fire activity. I conducted two separate SEAs.

The first analysis evaluated whether fire-prone climate conditions (i.e. drought) coincided with the period of elevated fire activity within the reconstructed fire record. I identified fire event years with the highest mean adjusted burned area from the currently compiled fire history data as stand-ins for LFY. I then applied the SEA to these selected years within the period with high fire activity period identified by regime-shift analysis.

The study region lacks precipitation or drought reconstructions that could serve as proxies of historical fire-prone conditions. Therefore, I used Scots pine latewood-width chronologies developed in a previous study from a nearby area in the Komi Republic (Drobyshev et al. 2004) as a proxy for late-season drought. That study showed a clear drought signal in the latewood chronology based on response function analyses relating latewood width to the Monthly Drought Code (MDC) over 1901–1998 (Drobyshev et al. 2004), justifying the use of this chronology as proxy for drought in this study. Details of the MDC calculation protocol are given in Appendix S1: Section S2 of Ryzhkova et al. (2022).

In the second SEA, I compared all recorded fire years with large-scale sea-surface temperature anomalies to test whether North Atlantic SST variation affected fire activity. For the dataset I used the NOAA Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5; Huang et al., 2017). This global monthly SST dataset extends from 1854 to 2026, limiting SEA to the fire years overlapping the instrumental record, 1854 to 2019.

2.5 Estimation of human population dynamic

Modern population on the peninsula is sparse with a total of 2,402 individuals (Arkhangelskstat, 2012). Historical population censuses conducted in 1744 and

1763 record 508 and 597 male souls, respectively, distributed across 5 of the 8 settlements known to have existed at the time (Bogdanova, 2015). In absence of sufficient data on human population over the required time span, I represented settlement dynamics using the first historical mention years of known settlements as a proxy and visually assessed them against a decadal fire occurrence plot spanning the length of the fire chronology.

3. Results

I dated 98 fire scars found on the measured and dated samples, corresponding to a total of 40 unique fire years (Fig. 2). The fire chronology for the study area spanned from 1385 to 1942. Site replication ranged from 5 to 15 sites during the period with recorded fire events. The most frequently recorded fire year was 1804, with fire scars identified on 13 trees at two sites, whereas the most spatially widespread fire year was 1746, with fires recorded at four sites.

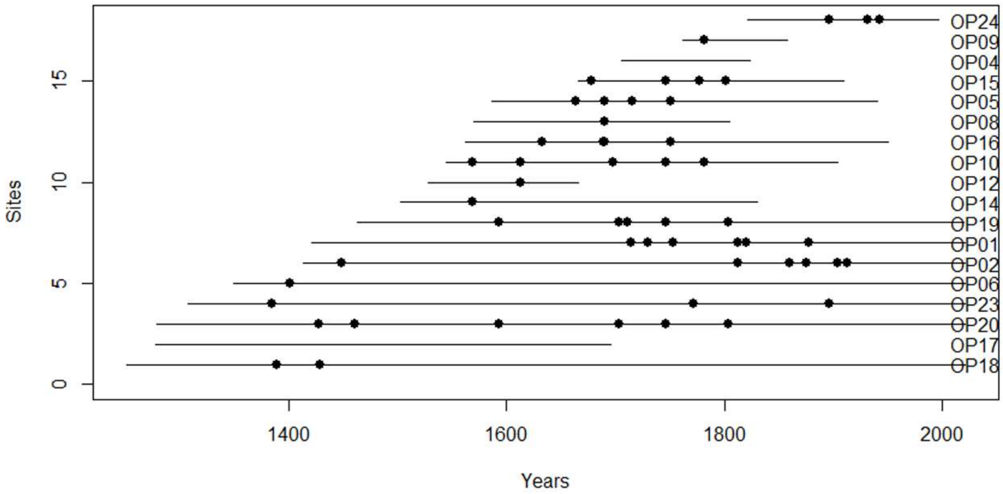

Figure 2. Dendrochronological reconstruction of the fire history in the OP over 1400 –2020. A single straight line represents each study site, and a black circle represents a fire event.

Early- and middle-season scars dominated the fire seasonality record, whereas late-season scars remained rare (Fig.3). This pattern was consistent in both the all-scar and site-level summaries. Late-season fires were concentrated in the earlier part of fire chronology and became nearly absent after the 17th century.

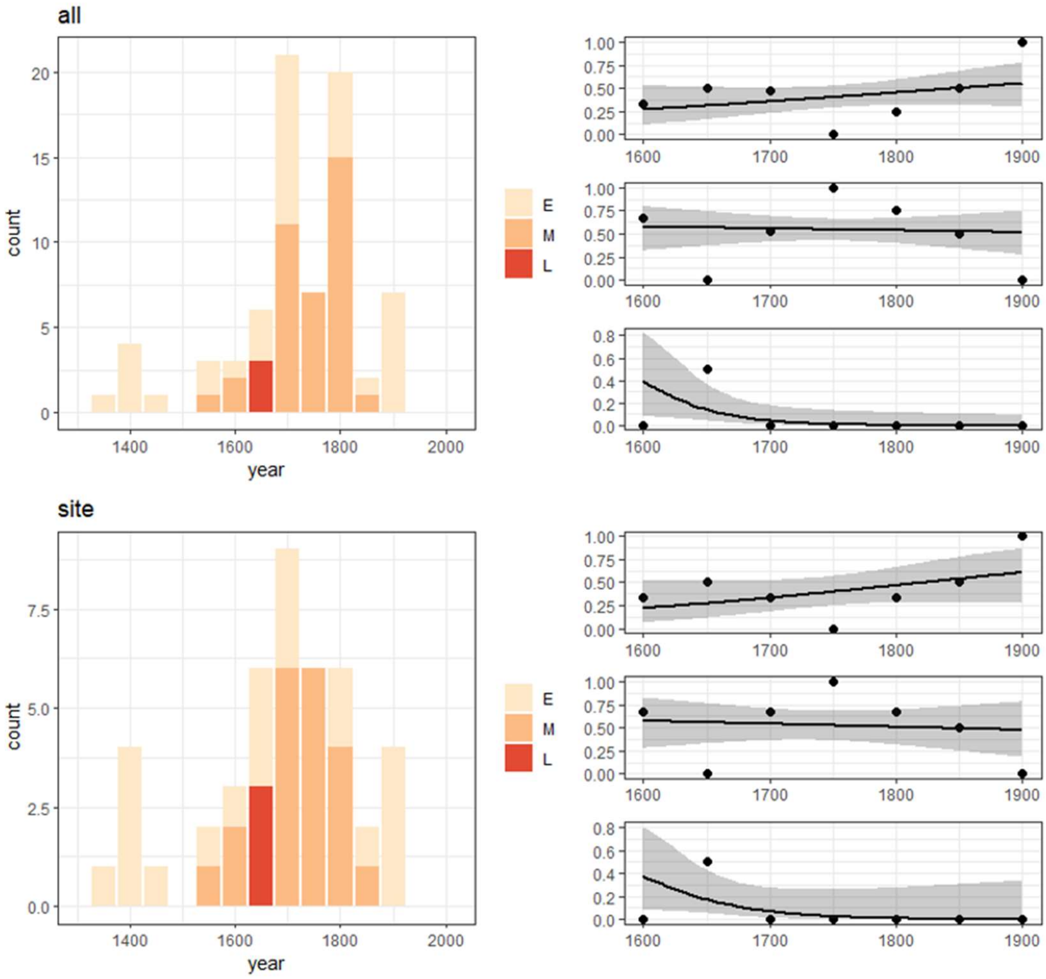

Figure 3. Fire seasonality through time. Left panels show counts of dated fire scars by seasonal position: early (E), middle (M), and late (L). Right panels show modeled proportional changes in each seasonal class through time. The all-scar summary (upper panels) counts every dated scar, while the site-level summary (lower panels) counts each seasonal signal once per site, reducing the influence of heavily scarred stands.

I assessed the regime shifts separately for the FC (Fig. 4 and table 1) and for the fire occurrence (Fig. 5 and table 2). In the reconstructed area burned, we observed four periods with FC changes according to regime shift analysis (Fig. 4 and table 1). During the earliest epoch, 1380-1470, the mean FC was 77.14 years (95% confidence interval: 49.09-180 years; Table 1). The FC increased to 300 years in the subsequent period, 1480–1680, before declining to 75.48 years during 1690–1820. In the most recent period, 1830–2010 CE, the FC reached 324 years (95% confidence interval: 202.5–648 years).

Table 1. Reconstructions of the fire cycle (FC) in the OP for the periods identified by the regime shift analysis.

Period	Epoch Start	Epoch End	FC	95% CI Lower	95% CI Upper
1	1380	1470	77.14	49.09	180.00
2	1480	1680	300.00	171.43	720.00
3	1690	1820	75.48	58.50	106.36
4	1830	2010	324.00	202.50	648.00

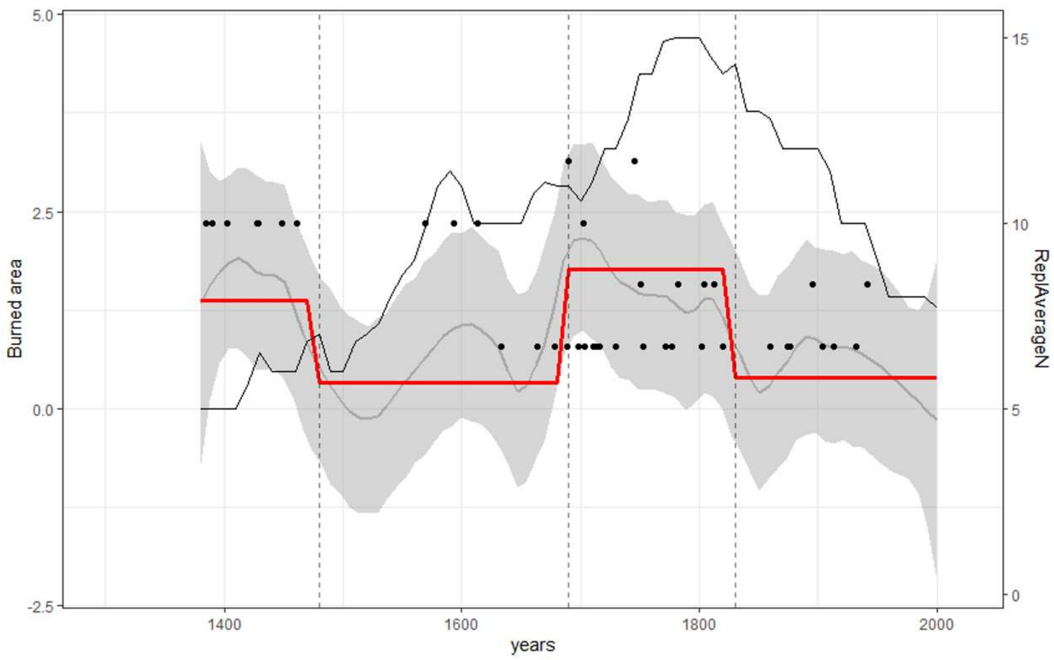

Figure 4. The reconstructed burned area per decade is shown by the grey solid line. Shifts in the fire cycle as identified by the regime shift analysis (Rodionov, 2004), are represented by red lines. Solid black line represents site replication.

I identified three regimes in the historic dynamics of fire occurrence since 1380. During the first period, 1380–1660, fires occurred at a relatively low rate (0.38 per decade) (Table 2 and Figure 5). Fire occurrence reached its maximum during the second period, 1670–1820, with 1.31 fires per decade. In the most recent period, 1830–2010, fire occurrence declined to 0.42 per decade, returning to levels similar to the first period.

Table 2. Reconstruction of decadal fire occurrence in the OP for the period 1380–2010.

Period	Epoch Start	Epoch End	Decadal Mean Fire Freq.	95% CI Lower	95% CI Upper
1	1380	1660	0.38	0.21	0.59
2	1670	1820	1.31	0.94	1.69
3	1830	2010	0.42	0.21	0.63

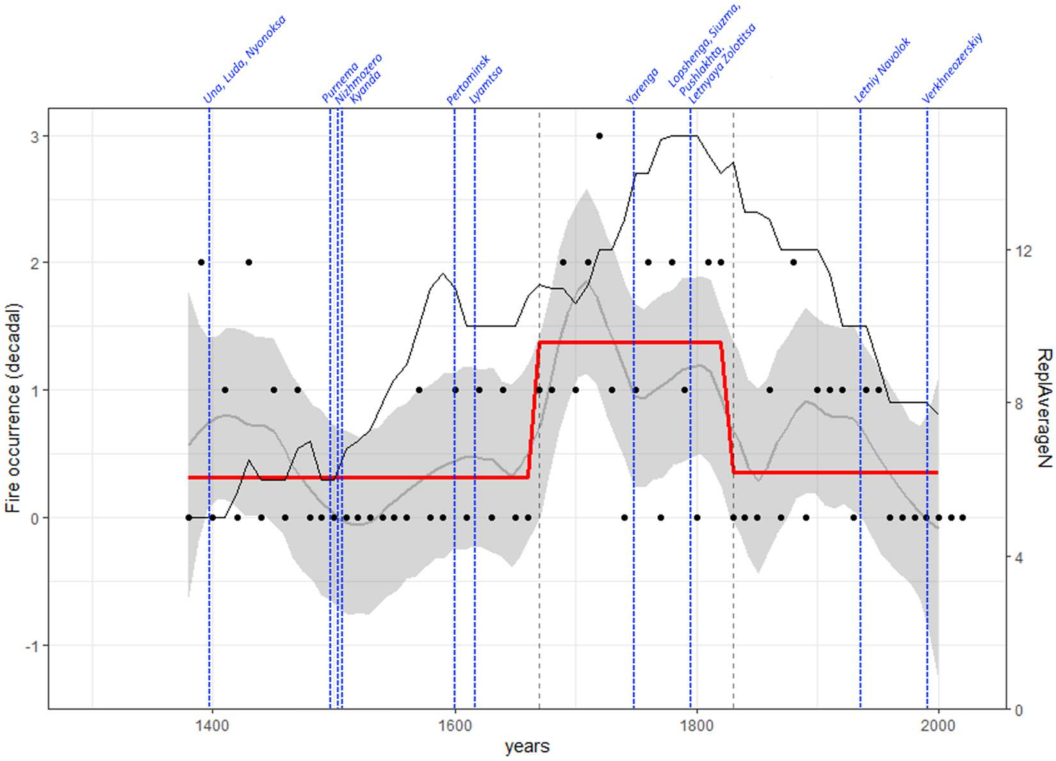

Figure 5. Decadal fire occurrence from 1380 to 2010, shown by the grey solid line. Shifts in mean decadal fire occurrence identified by the regime shift analysis (Rodionov, 2004) are represented by red lines. Black dots mark individual decades. Blue dotted vertical lines stand for first historical mention years of known settlements (labeled).

Analysis of NOAA ERSSTv5 showed that recorded fire years overlapping the instrumental period were associated with significant summer sea-surface temperature anomalies (Fig. 6). During fire years, June-August SSTs were warmer than average in Kara Sea and a part of Barents Sea. Smaller positive anomalies also occurred in the western North Atlantic. The eastern North Atlantic presents with cooler SST anomalies. These results indicate association of fire years in the OP record with broad-scale summer SST anomalies in the North Atlantic–Arctic sector.

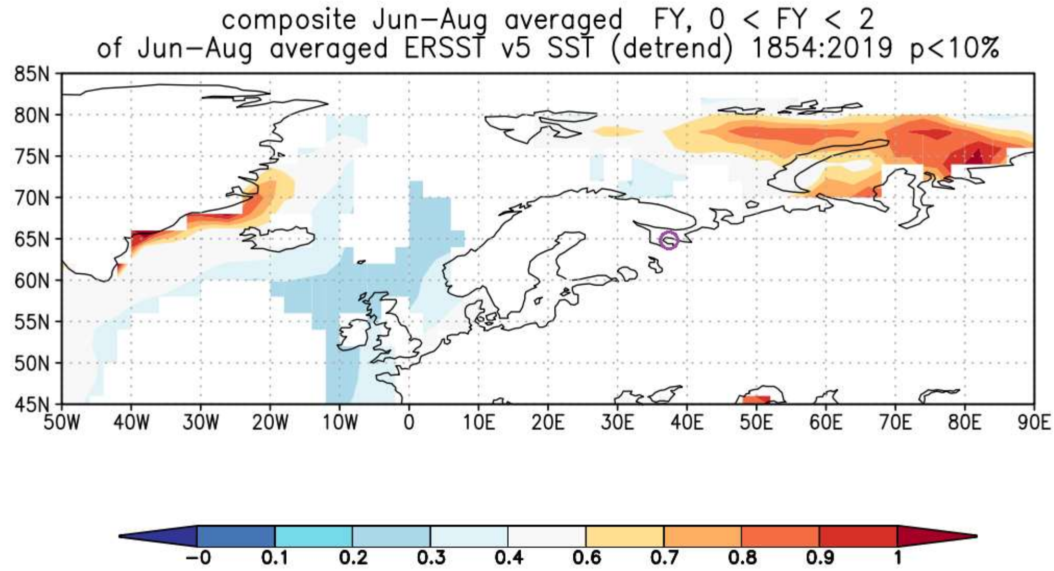

Figure 6. Relationship between fire years in the OP and June–August temperature anomalies from the ERSSTv5 sea surface temperature dataset (Huang et al., 2017) over the period 1854–2019. The location of the study area is marked with a purple circle. Colored areas indicate temperature anomalies that are significant at $p < 0.10$.

The largest fires during the period of elevated fire activity selected for SEA occurred in 1613, 1690, 1703, and 1746 CE. SEA of these years and the Komi latewood chronology revealed a significant positive departure at lag −1 (mean departure = 0.32, exceeding the 95% confidence envelope; Fig.7), indicating drier than average late-season conditions in the year preceding the largest fires.

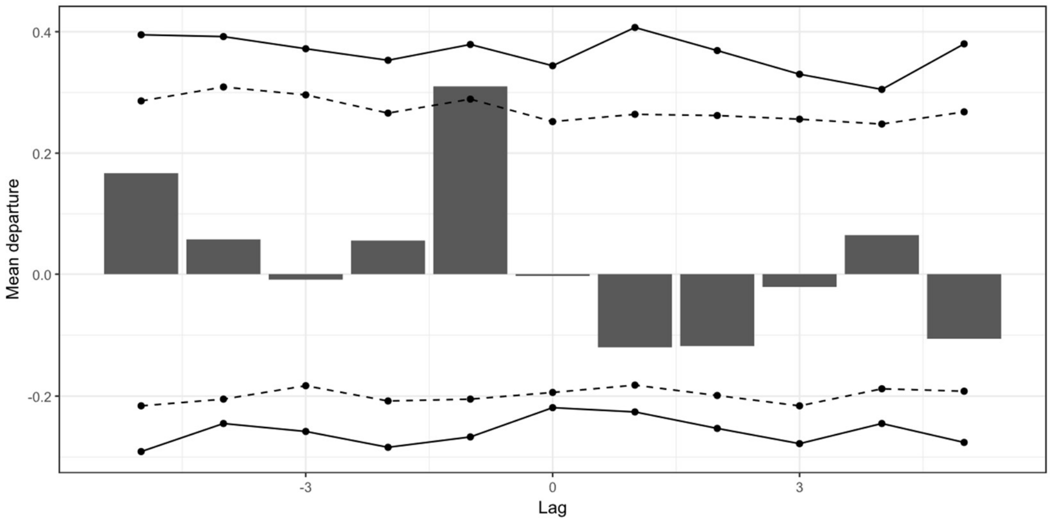

Figure 7. Results of superposed epoch analyses (SEA) on 4 largest fire years (period of 1670-1820) and the latewood (LW) chronology. Solid bars refer to departures from the mean. Dashed and solid lines refer to the 0.95 and 0.99 confidence envelopes, respectively.

5. Discussion

5.1 Climate impact

On the interannual scale, fire years in the OP were associated with negative June–August SST anomalies in the eastern North Atlantic and positive anomalies in the Barents and Kara seas (Fig.6). North Atlantic SST variability could influence the formation of high-pressure atmospheric systems over northern Europe. Those high-pressure zones blocked or displaced westerly storm tracks and reduced the transport of moist Atlantic air into the region. Displacement of storms lowered precipitation and cloud cover, increased sun exposure and promoted lower fuel moisture content, increasing the probability that ignitions developed into spreading fires. This would be consistent with the mechanism proposed for northern Scandinavia, where burned area was negatively correlated with North Atlantic SST in the northwest North Atlantic and warmer Atlantic conditions were associated with a higher Palmer Drought Severity Index (PDSI), indicating more humid and less fire-prone conditions (Drobyshev et al., 2016). In the same study, LFY in northern Sweden coincided with high-pressure systems over Scandinavia and the British Isles during the fire season, linking North Atlantic SST variability to atmospheric circulation patterns that reduce precipitation and dry fuels (Drobyshev et al., 2016). The pattern observed in this study, linking fire years with colder summer SST anomalies in the eastern North Atlantic and warmer anomalies in the Barents and Kara Sea, therefore suggested that North Atlantic SST variability may influence fire activity farther east than previously demonstrated, extending into the White Sea region.

The SEA analysis of the largest fire years in the OP during the 1690-1820 peak in fire activity and the Scots pine latewood chronology indicates that these fires were significantly associated with drier-than-average conditions in the years preceding those fires (Fig.7). Drought in the previous year could lead to increased tree mortality and contribute to the pool of forest floor fuels and standing deadwood. Once human or natural ignitions were available, these preconditioned fuels would have increased the probability of fire spread during early and middle season. This provides one plausible explanation for one-year lag in the SEA signal and for the observed dominance of early- and mid-season fire events during the period analyzed. However, because winter and spring precipitation can reset surface-fuel conditions, this lagged relationship should be interpreted cautiously.

5.2 Human influence on historic fire activity

The 1670–1820 increase in fire occurrence can be explained by intensified land use. Half of currently existing 16 settlements were first mentioned in historical records before the 1670-1820 period (Fig. 5), indicating that land-use context was more important than establishment itself to explain elevated fire activity. Slash-and-burn agriculture, while common to boreal settlement practices, was unlikely to have had a tangible impact on fire activity, since the population was likely not large enough to require extensive agricultural clearing beyond the immediate boundaries of settlements. The most impactful economic activity was the production of salt. By the mid-15th century, this industry was already actively developing (Gerasimova, 2025). This trend continued with the establishment of additional settlements and monasteries and peaked by the early 18th century. At that time, external demand for salt produced in the area began to decline due to the emergence of more profitable competing salt industries in the Urals. As a result, the local population shifted back to fishing, hunting, and the production of firewood and hay for fodder (Savich, 1927).

Elevated fire activity during 1670-1820 connects to salt production industries through local demand for large quantities of fuel wood. As coastal salt production intensified, fuel had to be obtained in larger amounts from progressively farther distances. By mid-18th century that amounted to between $9.7–29\times10^4$ cubic meters of wood annually and had to be collected as far as 20-30 verstas (an obsolete Russian unit of measurement; 21-32km) from the settlements (Bogdanova, 2014; Savich, 1927). Due to lack of inland roads, the interior became traversable for logging for a relatively short time span within the year. Boreal settlers typically harvest in winter, and sources mention floating harvested wood down rivers to settlements in springtime (Savich, 1927). This implies increased human presence in the forest within the onset of the early fire season (May-June), consistent with seasonal proportions of ignitions in the fire record (Fig.3).

Increased human presence in the interior during the salt production period likely contributed to higher ignition frequency. Manual harvest of large volumes in a short timespan would have multiple effects on the landscape. Since wood had to be sourced progressively farther from permanent settlements, many temporary lumber camps likely operated in the interior and may have shifted location annually. Salt production fuel and construction wood demand small- to large-diameter logs - thin branches are undesirable and likely not transported back to the settlement in meaningful amounts. Left at harvest sites, these byproducts would contribute to combustible slash pools on the forest floor. More forest floor slash extends fuel continuity, providing more propagation pathways for ignitions to develop into larger fires.

The argument for human presence and increase in available forest floor fuels leading to elevated fire occurrence does not account for area burned, which for the 1690-1820 FC (covering almost the entire period of elevated fire occurrence) remain similar to the 1380-1470 FC (Table 1). If this discrepancy is to be explained by human influence, it could potentially be a result of continuous cover fragmentation, whereby spatial separation of forest stands through logging created open spaces that would be more difficult for fire to spread over to neighboring stands. Landscape characteristics such as water barriers could also play a part in limiting area burned, but this cannot be reliably assessed within this study as site hydrology was not factored in at the time of analysis.

If salt production-associated timber extraction was the primary driver of fire activity, then periods with established salt production prior to 1670-1820 should demonstrate higher fire activity than periods after its decline. Results do not reflect this. The 1480–1680 and 1830–2010 periods both had long fire cycles and similar fire frequency in coinciding occurrence shifts (Table 1; Table 2), despite very different land-use contexts. Historical records suggest that during the 1480-1680 period, salt production had already been well established (Gerasimova, 2025), but by early 19th century, salt production and associated timber extraction practices had largely ceased (Savich, 1927). For human impact to be the primary driver behind fire activity in the area, the fire record would need to reflect a shorter FC and higher fire frequency in the 15th-17th centuries. This suggests that human activity alone cannot explain the reconstructed fire regime and was more likely a contributor, rather than the main driver, behind fire regimes in the area.

5.3 Modern decline in fire activity

The hypothesis of the most recent period demonstrating the lowest fire activity in 500 years is supported for reconstructed burned area, but not for recorded fire occurrence. During 1830–2010, the FC reached 324 years, the longest value in the reconstruction (Table 1). Fire occurrence also decreased after 1830, from 1.31 fires per decade during 1670–1820 to 0.42 fires per decade during 1830–2010. However, this value was close to the 0.38 fires per decade estimated for 1380–1660.

The modern period therefore represents a regime of rare or spatially limited fire activity rather than a complete absence of fire. This is consistent with findings on the peninsula in regard to declining fire activity in *Picea abies* stands on the OP (Wallenius, 2002).

Similar declines in recent fire activity have been reported from other northern European boreal fire-history reconstructions and are commonly linked to the decline of traditional fire use, changing land use, increased value of timber resources and fire suppression (Wallenius, 2011; Pinto et al., 2020; Ryzhkova et al., 2020).

This decline likely followed the collapse of large-scale salt production in the 19th century and a shift toward fishing, hunting, small-scale agriculture, and local resource use, none of which required inland fuelwood extraction at the scale documented for the earlier salt-production period (Kulyasova & Kulyasov, 2008; Gerasimova, 2025). Salt production was briefly restored during the Second World War and continued until 1953, but its effect on the fire record remains uncertain. The location of timber harvest, the timing of cutting and transport, and the degree of overlap with the sampled sites are unknown. If wood was harvested mainly in winter or outside the sampled area, restored salt production would not necessarily produce a detectable increase in fire scars. Intensive logging in the central peninsula began only in the early 2000s, after the last recorded fire in this reconstruction, while the creation of Onezhskoye Pomorye National Park in 2010 further separates the modern landscape from the historical salt-production system (Braslavskaya et al., 2020).

5.4 Study limitations

Not all samples with identified fire scars taken from the sites were dated at the time of the study. This prevented the identification of true LFY, which led to having to select years with the largest proportion of area burned on the record I had. The amount of samples covering the oldest section of the chronology was also low, which makes accurate assessment of the earliest fire cycle more difficult. For the latest fire cycle, only future studies on the OP will shed light on the true duration of the ongoing fire regime.

Finally, the first historical mentions of settlements should be treated as approximate indicators of settlement presence rather than exact establishment dates. The settlement chronology is better suited for identifying broad overlap between known human presence and fire-regime shifts than for testing whether individual settlements caused specific increases in fire occurrence. Undocumented settlements, temporary lumber camps, and other unrecorded activity may have contributed to ignition pressure before the first written mentions used in this study. Likewise, the presence of a written mention does not indicate the intensity of land use. Settlement dates were therefore treated as contextual evidence, while the main human-impact interpretation relies more heavily on documented salt-production activity and associated fuelwood demand.

6. Conclusion

This study reconstructed historical fire activity on the Onega Peninsula from Scots pine fire-scar records. Fire activity varied substantially over time, with the clearest increase in fire occurrence during 1670–1820 and the longest FC during 1830–2010. The fire regime on the OP exhibited temporal dynamics which was broadly consistent with the ones observed in other parts of the European boreal domain. A combination of SEA and historical land use analysis suggests highly temporally varied interactions between fire regimes, human influence and climate conditions.

The results suggest that human activity increased ignition frequencies during the salt-production period. Climate likely regulated whether ignitions developed into spreading fires, as shown by the association between large fire years, antecedent drought conditions, and North Atlantic–Arctic SST anomalies. Overall, the OP fire regime was shaped by interactions between land use, fuel conditions, and climate variability. H1 was supported by the SST association, H2 was partly supported through the likely ignition effect of salt production-related land use, and H3 was supported for reconstructed area burned, but not uniquely for fire occurrence.

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Appendix 1

Sample site names, coordinates and altitude.

SiteID	Coordinates	Altitude
OP01	64.585763, 37.516636	148
OP02	64.583609, 37.494324	146
OP04	64.623357, 37.391867	135
OP05	64.653416, 37.297116	133
OP06	64.660834, 37.269799	128
OP08	64.647366, 37.370573	139
OP09	64.469265, 37.618296	57
OP10	64.471671, 37.635342	54
OP12	64.478167, 37.639388	67
OP14	64.486800, 37.627907	17
OP15	64.496385, 37.616650	90
OP16	64.649369, 37.317921	141
OP17	64.614564, 37.451120	155
OP18	64.603944, 37.478579	160
OP19	64.607198, 37.450686	167
OP20	64.610217, 37.438389	159
OP23	64.651307, 37.862131	37
OP24	64.656752, 37.886259	37

Appendix 2

List of known settlements on the OP, their coordinates and the first year of their historical mention.

Settlement	Coordinates	Year of Mention
Una	64.600000, 38.150000	1397
Luda	64.966667, 38.150000	1397
Nyonoksa	64.620556, 39.180278	1397
Purnema	64.366667, 37.416667	1544
Nizhmozero	64.415833, 37.926667	1556
Kyanda	64.300000, 38.100556	1562
Pertominsk	64.795000, 38.412778	1599
Lyamtsa	64.433333, 37.066667	1630–1640
Krasnaya Gorka	64.761117, 38.608291	Unclear
Yarenga	64.879167, 37.938056	1744
Lopshenga	64.971389, 37.691944	1785
Siuzma	64.704722, 39.015000	1785
Pushlakhta	64.811111, 36.576111	1785
Letnyaya Zolotitsa	64.955556, 36.825556	1785
Letnii Navolok	65.156389, 37.098611	1941
Verkhneozerskii	64.478056, 37.934722	1984

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