ORIGINAL ARTICLE

The first annually resolved analysis of slash-and-burn practices in the boreal Eurasia suggests their strong climatic and socio-economic controls

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Abstract

Slash-and-burn (SAB) was a widespread agricultural practice across large parts of the boreal region until the early 20th century. Despite its paramount importance in the procurement of food and particularly in supporting frontier populations of settlers during the colonization of the Eurasian boreal zone, analyses of spatial and temporal patterns in the use of SAB at annual and sub-annual scales are currently missing. We present the first such analysis of climatic and social controls of SAB practices in a remote region in the northern Ural mountains from 1880 to 1894. We observed a significant positive correlation between the total number of burns and the village population ($p = 0.005$, $R^2 = 0.26$), indicating that the frequency of burns directly reflected the local demand for food. The amount of agricultural land, regarded as a cumulative measure of burning activity over multiple decades, showed a strong positive correlation with the village population ($p < 0.001$, $R^2 = 0.60$). This result supported our interpretation of burns as an important food procurement tool, probably also positively affected by higher labour availability in larger villages. Villages where the number of burns were higher than predicted by the "the population vs. burns" regression tended ($p = 0.15$) to have larger areas of arable land than predicted by the "population vs. arable land" regression. This pattern implied that variability in the local environmental and/or socio-economic settings of the villages made some of them more (or otherwise less) favourable for agricultural activities based on SAB. Most reported burns occurred in June and July. The three years with the maximum number of reported burns had a tendency to be wetter during these months when compared to the same period during an "average" year ($p = 0.19$). The pattern suggested that farmers preferred conducting burns during years with a below-average climatological fire hazard. An earlier start of the fire season favoured burning activity ($p = 0.10$ $R^2 = 0.33$), while its later ending had no significant effect on the number of burns ($p = 0.53$). Our study documented strong climatic controls of SAB practices at the annual scale and their social controls at above-annual scales. These patterns emerged despite the common use of slash-and-burn to mitigate generally limited food availability in the northern Ural mountain region and likely conservative estimates of these practices in available records.

Keywords Forest fire history · Land use · Fire control by climate · Disturbance histories · Subsistence practices · Illegal activities · Slash and burn

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Introduction

The onset of the human use of fire in the boreal forests marks the start of the active exploration of forest resources, which greatly assisted human colonization of this bioclimatic domain. The fire, "the first great force hired by humans" (Stewart 1956), helped secure land for settlements, create and maintain agricultural land, and assist in hunting activities (Mellars 1976; Pausas and Keeley 2009; Coughlan et al. 2018; Hörnberg et al. 2018). Felling the forest and burning the cleared land to provide agricultural land has been a critical land use practice that particularly supported the frontier population of settlers facing initial shortages of cultivation-ready areas (Sovetov 1867; Tretyakov 1932; Sazonov 1993; Hörnberg et al. 2015; Smirnova et al. 2017b).

In the boreal forests of northern Europe, slash-and-burn (SAB) has been a widespread practice since around the 13th century CE. In northern Scandinavia, colonization waves dating to the late 1500s and 1600s led to the extensive use of SAB. Rapid loss of soil fertility necessitated frequent burns to maintain the pool of sufficiently fertile land in proximity to the villages. The human-mediated increase in fire ignitions led to higher frequencies of fires, although the majority of them were apparently much smaller than fires of natural origin (Aleinikov and Lisitsina, in press). This resulted in dramatic changes in the pattern of fire disturbances with small and frequent "agricultural" fires replacing large and infrequent fires as the dominant type of fire events (Niklasson and Granström 2000). It is no surprise that the notion of past forest fire activity, as driven largely by SAB practices, has been prevalent (Sonni 1839; Teploukhov 1856; Sovetov 1867; Lyubomudrov 1889; Arnol'd 1895). Even today, it remains the dominant opinion on the origins and drivers of historical fires in the European taiga region (Groven and Niklasson 2005; Eggers et al. 2008; Storaunet et al. 2013; Smirnova et al. 2017a). The most recent studies, however, have challenged this interpretation, pointing to an important role of the variability in climatological fire hazard in driving century-long changes in forest fire activity (Drobyshev et al. 2016). Studies have also documented a consistent and statistically strong association between periods of increased fire activity and anomalies in atmospheric circulation that likely overrode, to a considerable degree, the human impact on forest fire regimes (Ryzhkova et al. 2022).

A common use of SAB in the boreal zone suggests the existence of an extensive knowledge base on the application of such agricultural practices, accumulated by local populations. Indeed, the use of fire needs sufficiently dry fuel, while addressing the risk of uncontrolled fire spread. These settings called for a good understanding of the interplay between weather variability, fuels and seasonal patterns in the dynamics of fire hazard. Despite their large historical

importance, interactions between environmental and socio-economic settings shaping the use of SAB remain, however, poorly quantified (Osipov and Gavrilova 1983; Danilova and Sokolov 1998; Milov 2006). This is particularly the case of the fine temporal scales encompassing annual and within-annual (seasonal) dynamics of SAB, which remain largely ignored by the existing studies on the topic (Petrov 1968; Jõgiste et al. 2018; Tomson et al. 2018). The lack of historical SAB records featuring this temporal resolution naturally constrains such analyses. The fact that the SAB era preceded the period with instrumental meteorological observations makes the analyses of environmental controls of such practices even more challenging.

In the western piedmont of the Ural Mountains, SAB and shifting cultivation remained widespread until the first third of the 20th century (Igoshina 1930; Oborin 1957; Chagin 2017; Aleinikov et al. 2018). Although the region features generally inferior conditions for agricultural production due to short and cold growing seasons, SAB was important to support the local population and especially so in smaller villages along the banks of the Pechora and Kolva rivers and their tributaries, surrounded by natural taiga forests. Although the SAB practice in this region was criminalized in 1885 (Beldytsky 1901), it did not stop the local population from burning the forest. SAB practices ultimately ended in the 1930-40s, following improvements in cultivation techniques, aggregation of single farms into larger units, and a large influx of food coming from outside the region through trade and governmental aid (Chagin 2017; Aleinikov 2021). Forest use history in the region reflected, therefore, the general temporal trends of fire usage as an agricultural tool over the European boreal zone. Analysis of the factors driving annual and above-annual SAB dynamics in the northern Ural piedmont could, therefore, provide insights about environmental constraints in the application of this practice by settlers beyond the region in question.

The current study aimed to decipher temporal and spatial variability in SAB within the western piedmont of the Ural mountains and better understand its climatic and socioeconomic controls. We did so by merging records of daily weather with annual records of SAB practices documented in the notes of forest rangers tasked with reporting illegal forest use. These notes provided information on the exact location and timing of such burns.

Prior to SAB prohibition, the local population relied on three- and two-field systems with rye as the primary crop. The technique evolved towards the end of the 1800s: farmers cultivated rye during the first year (i.e. immediately after burning), oats during the second year, and again rye during the third (Anonymous 1901). Importantly, these three- and two-field systems were in use in the fields, which were formally regarded as "land for agricultural production". In

contrast, SAB recorded by rangers represents examples of "illegal activities". Fields created by such SAB were often used only once, but allowed for a better harvest per unit of area than fields cultivated for several seasons (Sonni 1839; Shildaev 1917).

The available SAB records reflect the use of fire very late in 19th century, at a time when burning of the forest was already illegal. In contrast, the amount of arable land in the proximity of a village was a product of agricultural land expansion occurring incrementally since village establishment (ESM Table 1). SAB was the primary tool facilitating this expansion and its application in this case occurring prior to the onset of SAB prohibition in 1885. Local authorities delineated and formally recognized these fields as "agricultural land" in local inventories (cadasters), along with hayfields and pastures (Kavelin 1912).

We hypothesized that (H1) larger local populations were associated with a higher frequency of SAB, (H2) burns tended to avoid periods with increased climatological fire hazard, (H3) the annual number of burns correlated with the properties of the fire season and (H4) the local village settings (apart from village population and the amount of arable land) played a role in controlling the SAB activities. We discuss the study results in the context of the separation of natural vs. human-driven fire activity and the role of such burns in the transformation of natural forest cover. Due to the short period (10 years) jointly covered by annual fire data and daily weather records, and the likely conservative nature of fire data, we intentionally avoided discussion on absolute estimates and long-term trends in SAB use.

The study region

We conducted the study on the western slopes of the northern Ural mountains, which remains the largest intact forest landscape in the northeastern part of European Russia (Fig. 1; Taskaev 2006; Aleinikov 2021). This area lies within the Atlantic-continental climatic province (Stolpovski et al. 1997), with an annual average temperature around 1 °C. The average length of the growing season, which is the number of days with an average daily temperature above 10 °C, is around 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. Thick snow cover (70–80 cm) accumulates during the winter, which lasts for 130–200 days. Snow melt in the spruce forests occurs during the end of May and the first snow cover in the first week of October. The start of the fire season dates from the last week of May to the first week of June, while the last week of September marks its end.

The prevailing vegetation is of the middle taiga type (Larin 1997). *Pinus sylvestris* L. (Scots pine) dominates in the levelled areas with sandy soils. *Picea obovata* Ledeb. (Siberian spruce), *Abies sibirica Ledeb.* (Siberian fir) and *Pinus sibirica* (Siberian pine) dominate the mountainous segment of the area with clay soils. Stands of *Betula pubescens* Ehrh. (white birch), *B. pendula* Roth (silver birch) and *Populus tremula* L. (aspen) typically mark the early stages of post-fire and post-felling successions. *Larix decidua* Mill. (larch) appears as a minor component of the vegetation (Smirnova et al. 2017a). The vegetation in the immediate proximity of the villages is dominated by dark coniferous forests with *Abies* and *Picea* (*parma* in the Komi language) with canopy gaps of various sizes being the main feature of the disturbance regime.

Human population and land use practices

Mansi (Voguls) and Russians are the dominant ethnic groups in the area, each with their own pattern of land-use. Mansi people occupied the territory of the north Urals during the High Middle Ages (1000 to 1500 CE). Mansi were a nomadic group, a part of the aboriginal population of the Ural mountains. They lived from hunting, gathering, reindeer herding and fishing (Aleinikov 2017a; Chagin 2017; Popova et al. 2012). Russians initially colonized the area between 1650 and the 1700s. The first Russian settlements in the Kolva river basin occurred in the second half of the 17th century, upstream of the river Kolva (village of Korepino), by the river Beryozovaya (village of Beryozovo) and by the Visherka River (village of Fadino). The first settlements in the basin of the river Pechora date back to the 1700s. Due to the absence of roads, transport was almost exclusively by river. Therefore, all the settlements were located by two navigable rivers, the Pechora with its tributary the Unja and the Kolva with its tributaries the Visherka and Beryozovaja (Aleinikov 2017ab; Chagin 2017).

Villages appeared along the river banks and often consisted of no more than just one or two households (Anonymous 1889). During the 1500-1800 s, the area had two major transit portages (*volok*, in Russian) which linked three important waterways in the region, the rivers Kama, northern Dvina and Pechora. Russians worked mostly in transport and trade. Since the late 1800s, they shaped the timber market by actively engaging in timber harvesting (Popova et al. 2012). Even at the start of the 20th century, the area remained sparsely populated and the 1900 census reported a population density of 0.14 people/km^2 (Anonymous 1901).

Slash-and-burn was particularly widespread during initial village establishment (Sokolov 1909). *Hordeum vulgare* (barley), *Secale cereale* (rye), *Brassica* spp. (turnips) and *Linum usitatissimum* (flax) were the main crops grown in
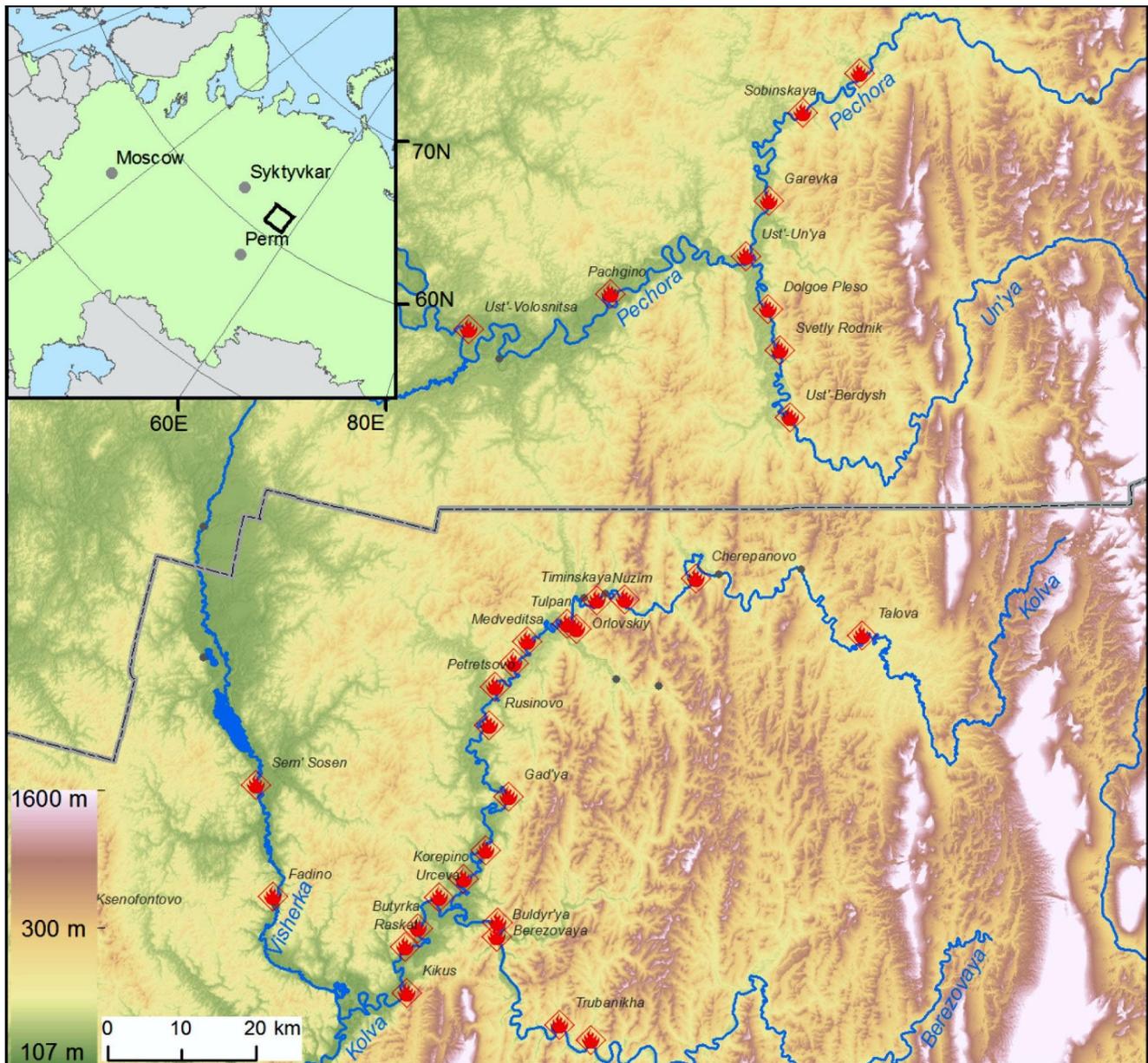
Fig. 1 Top left, map of Russia showing location of study area as small square; Main figure, the study area and location of the villages. Red dots, villages with reported slash-and-burn; black dots, villages without SAB. The grey line marks the administrative boundary between the Komi republic and the Perm' region

the western foothills of the Ural mountains during the late 19th century (Varopai 1880; Sokolov 1909; Oborin 1957), but *Triticum* spp. (wheat) was not grown in the region due to its poor resistance to cold. A typical succession of crops on a newly established field were *Secale* (rye) in the first year, *Avena* (oats) in the second and *Secale* again in the third. Land cleared by slash-and-burn was usually cultivated for three seasons and was then left uncultivated as fallow for 10–15 years (Anonymous 1901).

Despite the fact that the Russian government prohibited SAB in 1885 in an attempt to preserve timber resources, it was still widespread in the area after that date (Beldytsky 1901; Batuev 1902; Sokolov 1909; Krylov 1926). Prohibition caused farmers to use areas they had burnt more intensively, cultivating them for three to five years in a row. The poor harvests on these fields, worsened by more frequent cultivation, encouraged the spread of three- and two-field agricultural systems towards the end of the 19th century. These systems, known in the region already since the 15th century (Smirnov 1952), relied largely on the same crops (ESM Table 2). From the beginning of the 20th century,

the addition of manure to the fields became an increasingly common way to support soil fertility (Anonymous 1901).

The proportion of inhabitants making their livelihood from agriculture in the region at the end of 19th century is impossible to estimate with certainty. However, ethnographic studies in the region suggest that a typical family relied on a mixture of resources and activities, including hunting, gathering berries and mushrooms, yields from their own fields and purchases of flour from local traders (Anonymous 1889, 1901; Krylov 1926; Aleinikov 2017b). The data from the studied villages suggest that boat building, forestry, hunting and fishing were the dominant occupations (ESM Table 3).

Materials and methods

Data sources

We obtained records of village inventories and forest code violations for three forest districts in the Cherdyn municipality (*Чердынский уезд* in Russian) of Perm province (*Пермский край*). The records from the Kolvinsky district (*Колвинское лесничество*) covered 1880 to 1910, and the records from the Chusovskoj (*Чусовское*) and Verhne-Pechorsky (*Верхне-Печорскоек*) forest districts, 1894 to 1910 (ESM Fig. 1). These documents recorded the establishment of new settlements, construction of roads, sizes of hay meadows, cultivated fields, local trades and the number of families buying flour (Anonymous 1889, 1894, 1901).

Records of forest code violations featured a wide range of activities considered illegal. These included felling trees, grazing cattle, hunting, fishing, haymaking and slash-and-burn. Each record provided personal data and the place of residence of the accused. The exact month of forest burning was available in 22 cases, out of which 11 provided exact dates for the burning.

We obtained information on the number of inhabitants and the list of settlements from the first census survey of this region (Anonymous 1889, 1901) and the ethnographic studies dating back to the end of the 19th and early 20th century (Teploukhov 1856; Varopai 1880; Beldytsky 1901; Onchukov 1901; Belousov 1915; Krylov 1926). The positions of settlements were established with the help of historical records and modern topographic maps (ESM Table 1).

As a source of climate data, we used daily records of precipitation and temperature from the Cherdyn' meteorological station (ECA code 2960) located at 60.40 N, 56.52E, 208 m a.s.l. The record is a part of the European Climate Assessment and Dataset project and is publicly available (https://www.ecad.eu/, summary in ESM Table 4).

Statistical analyses

To test the association between the size of village populations and SAB frequencies (Hypothesis 1), we used regression analysis. Specifically, we regressed the number of SABs reported for villages against the village populations over the study period. To extend the analyses towards a decade-long perspective, we regressed the total amount of arable land around villages, which could only have been created by burning the forest, against the village population. To meet assumptions of linear regression analysis, we log-transformed the amount of arable land (originally in ha) and number of burnings.

We studied the association of burns with climatological fire hazard (H2) by superposed epoch analysis (SEA, Swetnam 1993). SEA calculated the departure of a time series from its long-term mean during event years. In our case, these were the three years with the largest number of reported burns (1888, 1892, 1894). Although replication for the analysis was minimal ($n = 3$), we considered it as a reasonable compromise between our interest to select the years with the highest fire activity and the need to address the shorter period (14 years) jointly covered by the climate and burn data. SEA used non-parametric bootstrapping to assess the significance of departures of the number of burnings during the selected three years from the mean calculated over the 14 year period (Swetnam and Betancourt 1990). By averaging data from the event years, the algorithm enhanced the signal-to-noise ratio and was well suited to the analyses of "noisy" data. As a source of proxy of climatological fire hazard, we used the mean June-July monthly drought code (MDC) (Girardin and Wotton 2009). MDC is a monthly version of the daily drought code (DC), which is a part of the Canadian Forest Fire Weather Index System and rates the average moisture content of deep, compact organic layers (van Wagner 1987). Both MDC and DC require maximum temperature and precipitation as data inputs. Since wind data were not available for this study, the calculation of other fire weather indices was not possible. The choice of June and July as our "focus months" was based on the observation that all of the burns documented with seasonal resolution occurred during these two months (see Results). We used R package *cffdrs* (Wang et al. 2017) to calculate DC and subsequently MDC, and the length of the fire seasons.

To test the association of the number of burns with the timing of onset and end of the fire season (H3), we used linear regression analysis. The annual number of burns was the dependent variable and the Julian date of the start/end of the fire season was the predictor. We did not use log-transformation of the number of burns for this analysis as the distribution of this variable, as the use of raw data did not violate the assumptions of regression analysis (ESM Fig. 2). Using
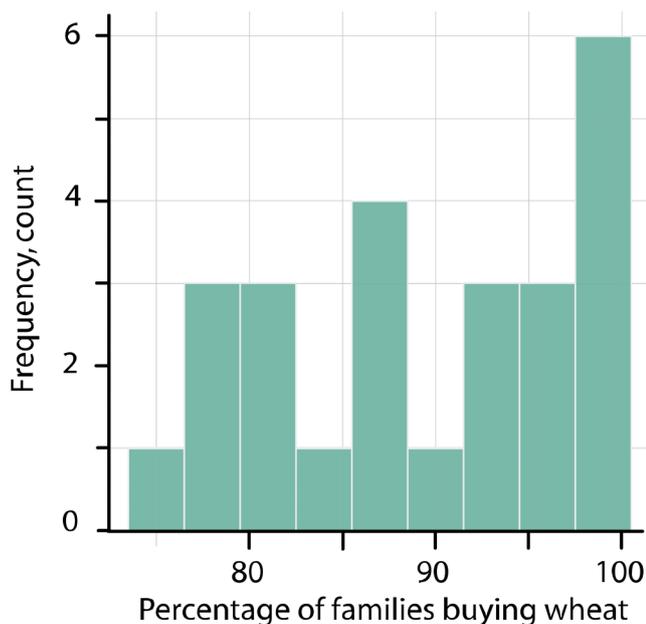
Fig. 2 Distribution of the number of families buying wheat in the villages of the study region in 1880 to 1910

daily climate data for the study area, we calculated the start of the fire season as the time when the temperature stayed at or above 12 °C for three or more consecutive days. The end of the fire season was determined when the daily maximum temperature stayed at or below 5 °C for three or more days. In establishing these criteria, we followed the standard definition of the length of the fire season used by the Canadian Fire Weather System (Lawson and Armitage 2008).

To test the role of local village settings on the frequency of SAB activities (H4), we regressed the residuals obtained in the regression between the village population and SAB against the residuals obtained in the regression between village population and the log-transformed amount of arable land. In particular, we wanted to test whether the variability in SAB occurrence, which was not accounted for by the variation in the human population sizes among villages, could be related to the variation in the amount of arable land, not explained by the population sizes of the respective villages. We argued that a positive association between the two groups of residuals would be indicative of persistent features of village locations, promoting the use of SAB. Following the regression analyses, we checked the results for linearity of the data, normality of residuals, homogeneity of residuals variance (homoscedasticity) and independence of residuals error terms (ESM Fig. 2). Data used in the paper are available in ESM Table 5.

Results

We analysed SAB data from 26 villages (Fig. 1). The mean size of a village was 91.3 inhabitants (± 71.0 SD) or 15.7 families (± 12.0 SD). The largest village, Kikus, had 239 inhabitants in 40 families. Seven people lived as two families in the smallest village, Sem' Sosen. The majority of the families in the study region could not sustain themselves entirely with their own produce and regularly bought wheat (Fig. 2).

The mean number of recorded burns per village over the study period (1885–1894, the period with the most complete village-level data) was 5.7 (± 6.9 SD). Seasonal data were available for a subset of registered burns ($n = 20$) over the 1887–1912 period. All of them occurred either in June (70%) or July (30%). The total number of burns positively correlated with the village population ($R^2 = 0.21$, $p = 0.012$, Fig. 3A). Similarly, the amount of agricultural land showed a strong and positive correlation with village population ($R^2 = 0.69$, $p < 0.001$, Fig. 3B). Villages where the number of burns was higher than predicted by the population vs. burns regression tended to have larger areas of arable land than predicted by the population vs. arable land regression ($R^2 = 0.11$, $p = 0.06$, Fig. 3C).

The three years with the maximum number of reported burns tended to be wetter during these months, when compared to the same period in an average year ($p = 0.19$, Fig. 4A). The length of the fire season positively correlated with the number of burns ($R^2 = 0.33$, $p = 0.10$, Fig. 4B). An earlier start of the fire season favoured burning activity ($R^2 = 0.45$, $p = 0.06$, Fig. 4C), while its later ending had no significant effect on the number of burns ($p = 0.53$, ESM Fig. 3).

Discussion

Annual and directly measured (i.e. not proxy) data on slash-and-burn activity and daily data on climate allowed for the first annual analysis of SAB practices in the Eurasian boreal zone. Merging climatological metrics of fire hazard (based on daily weather data) with data on burns for specific fire seasons provided a much deeper insight into the interplay of factors driving fire activity around the settlements, going beyond the discussion of SAB dynamics at decadal and century-long periods. We discuss our finding below, presenting separately the results obtained on aggregate data at the above annual scale and those obtained from annual data.
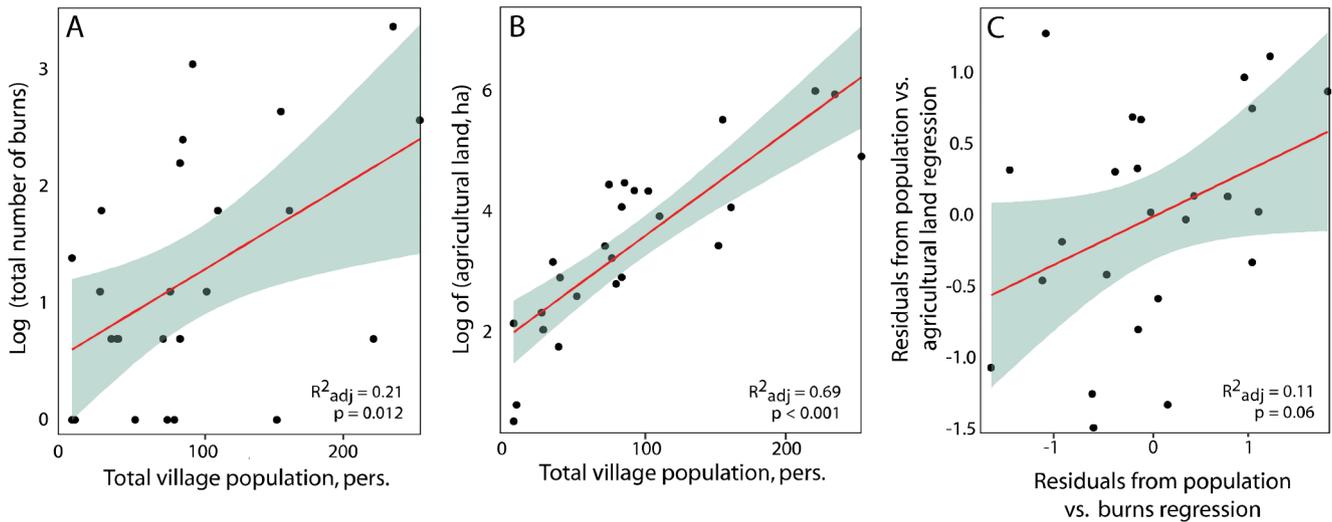
Fig. 3 A, linear regression between the village populations and the number of burns; **B**, linear regression between the village populations and the total amount of arable land. The 95% confidence envelopes for the regressions are shaded in blue green. **C**, regression with two sets of residuals, from the "the population vs. burns" and "population vs. arable land" regressions. Coefficient of determination R^2 and significance level p are given for each of the regressions
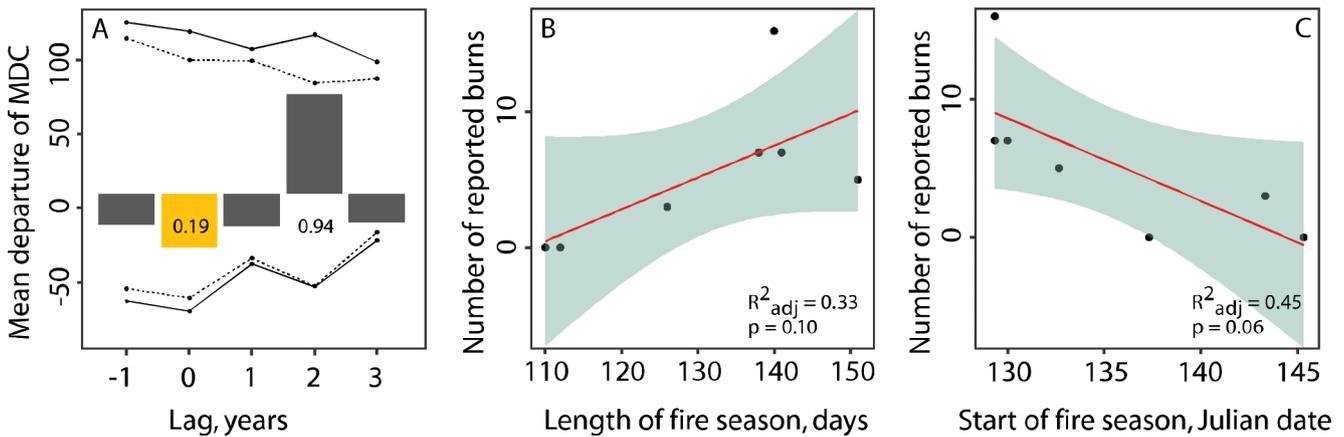

Fig. 4 A, superposed epoch analysis of annual number of burns with the mean June-July drought code. The yellow bar indicates the focal year and the numbers below the zero line indicate the statistical significance of departures from the mean drought code during the focal year and the year with t+2 lag. Confidence levels (0.95 and 0.99) are marked as dashed and solid lines. **B**, regression between annual number of burns and length of the fire season; **C**, regression between annual number of burns and date of the start of the fire season. 95% confidence envelopes for the regressions shaded in blue green. R^2 and significance level "p" are given for each of the regressions

Pattern of slash and burn activities at above-annual scale

Colonization of the western piedmont of the northern Urals was a challenging venture coupled with constant food shortages due to the difficulties of growing crops in this climate. The records showing that a large proportion of families bought wheat (Fig. 2) suggested that their own fields could not produce enough for them to live from and showed that food availability was a concern for the local populations at that time. A note from an ethnographer visiting these villages supports this interpretation: "[farmers] sow two to three pudy of rye [~32−24 kg] per person and a bit of

barley, which not always escapes frosts, forcing each family to buy [cereals]" (Varopai 1880).

The frequency of burns reflected the demand for food, which was likely proportional to village size: we observed a significant positive correlation between the number of burns and the village population (Fig. 3A). This interpretation was consistent with the positive correlation between the total area of arable land, regarded as a cumulative measure of burning activity over many decades, and the village population (Fig. 3B). These results supported H1 (larger local populations were associated with a higher frequency of SAB) and our interpretation of burns as important for obtaining

food, the use of which in larger villages might have been further promoted by higher labour availability there.

The use of slash-and-burn in the western foothills of the northern Urals was common (Sokolov 1909). However, the short growing season and challenging topography there lowered the productivity of the fields and the overall efficiency of this way of farming. A strong and highly significant positive relationship between the total village population and the total amount of arable land around settlements (Fig. 3B) highlighted the dependence on the use of slash and burn in the forest for food supplies. Spruce forests were preferred over woodlands on river floodplains and pine forests for such burns (Sonni 1839; Sokolov 1909; Igoshina 1930). The former provided more nutrient-rich soils, which could sustain more cultivation cycles and higher yield levels. Since dark coniferous forests cover most of the study area, it appeared unlikely that the number of spruce-dominated areas was the primary factor discriminating the villages along the gradient for suitability for burning. Evidence of such a gradient has been suggested in the analysis of residuals from the regressions "the population vs. burns" and "population vs. arable land" (Fig. 3C). However, the result was inconclusive with $p = 0.15$. Our data could not, therefore, confirm H4 (local village settings is a factor in controlling SAB activities), although the observed pattern clearly warrants further analysis. We speculate that a combination of particular topographical features, such as the presence of south-facing and gentle slopes with moderately deep organic soil layers, could have affected the long-term levels of burning activity around villages.

Annual dynamics of burns

The annual climate affected the level of burning activity. An early start of the fire season favoured burnings that supported our H3 (the annual number of burns correlated with the properties of the fire season) (Fig. 4C). The results pointed to the farmers' interest in minimizing the risk of escaping fires that would be likely during burns starting during prolonged dry periods in the high summer. Early season wildfires are generally not severe, since the deep organic layers of the soil remain sufficiently wet after the winter. At this period in the fire season, the local mosaic of vegetation and topographic conditions provided a diversity of conditions for burning, helping the farmers to benefit from natural firebreaks and making it possible to control the spread of wildfires to some extent. The intention to sow crops in the same year as burning could be another reason to plan burns as early as possible in a fire season.

In contrast to the start of the fire season, the timing of its end date did not relate to the number of burns (ESM Fig. 3). We speculate that towards the end of the fire season, farmers had limited opportunity to time the burnings during sufficiently dry episodes, while avoiding periods with an accumulated strong water deficit in the forest. Consistent with this interpretation, years with the highest number of burns coincided with wetter than average months in June and July, supporting H2 and indicating that farmers preferred conducting burns during years with below-average climatological fire hazard. An association of SAB with the first half of the fire season has been reported from other parts of northern Europe. In southern Norway, slash and burn was generally done before mid-June (Groven and Niklasson 2005) and Swedish practices similarly advocated for the earliest possible use of prescribed burns (Cogos et al. 2020). The fear of escaping fires coupled with highly limited means of fire control, followed by discovery of burns by the authorities and subsequent prosecution of the farmers, was a plausible explanation of the pattern in this study. It is worth noting that burns in the study area were generally small, varying from 0.03 to 2.7 ha (Aleinikov 2019). However, during the drought years of 1934 and 1936, historical records have documented escaping fires with their final size exceeding 10,000 ha (Aleinikov et al. 2018).

Despite its widespread use, slash-and-burn in the northern Ural mountains would have been unlikely to have affected landscape-scale fire regimes, in particular the regional fire cycle driven by climate variability (Drobyshev et al. 2004). The small sizes of the burned plots and the fact that the area has been dominated by dark and mesic coniferous forests suggested that the impact of human ignitions on the fire cycles (rotation) was minimal. In contrast, their impact on fire occurrence was more pronounced. Increases in forest fire occurrence in the region has been documented following village establishment during the 1700s. However, the dynamics of the regional fire cycle have shown little correspondence to the colonization pattern of the area (Ryzhkova et al. 2022). Although being quite limited in its spatial extent, the use of fire by farmers modulated, nevertheless, local fire regimes. The distance from a site to the nearest village has accounted for 50% of the variation in statistical fit between fire occurrence and tree-ring proxy of fire weather: sites located farther away from the villages revealed increasingly stronger association with the fire weather proxies (Drobyshev et al. 2004).

The lack of a distinct link between climatic conditions and human-related fires during the high summer supported the use of the association between years with large areas being burned and climate variability as a means to elucidate the degree to which the climate affected fire regimes (for example, Drobyshev et al. 2015). Significant positive anomalies in drought conditions associated with such years point to the climate and not human land use as the driver of fire activity. Conversely, periods with an increase in the

frequency of fires, not associated with climatological proxies of fire hazards, would indicate human impact, as the current study suggests. In boreal forests of eastern European Russia, the dominance of naturally occurring early season fires (Melekhov 1946) may complicate the partitioning of climate vs. human signals in fire chronologies and necessitate the use of seasonally resolved proxies of fire weather (as in Ryzhkova et al. 2020, 2022).

Quality of monitoring data as a source of potential error

Our analyses focused on the annual dynamics of slash and burn and its geographical variability within the studied landscape, making them robust against underestimation of the absolute levels of burning. Indeed, large areas of the virgin forests, absence of road networks, low population density and location of the burned sites, which could be as far as 7.5 km away from the village (Aleinikov 2019), likely resulted in underestimation of SAB activities as reported in the official statistics. We had no means to estimate the scale of such bias. This, however, did not appear to compromise our findings, as it was unlikely that an eventual underestimation of burning activities introduced a systematic bias in the data. Analyses of cumulative estimates of burning activities (see the following paragraph) revealed no signs of underestimation of burns in small villages due to lower monitoring intensity, nor any signs of higher than expected burn frequencies, which would be indicative of better monitoring and reporting around larger settlements.

The quality of monitoring of fires by local authorities probably varied across the study region due to the difficulties of travel, which was almost exclusively by boats along the river Pechora and its tributaries. This might introduce a potential source of error into our analyses. We could not account for this variability, as the location of the rangers' offices and/or their living quarters were unknown. However, analysis of residuals in the regression between the total population and the total number of burns did not provide a reason to question the quality of the monitoring data. It was reasonable to expect that forest rangers were stationed in the larger villages. Forests around such villages were likely monitored better as compared to settlements with just a few families, where a monitoring occasion would necessitate a boat trip. If this assumption holds, one should expect burns in smaller settlements to be under-reported. The resulting pattern would then show the dominance of negative departures at the start of the population gradient in the regression between the total village population and the total number of burns. Such a pattern, however, was absent in the data: the smallest villages with a population below 50 exhibited an equal number of positive and negative departures (Fig. 3A).

On the other side of the gradient, featuring villages with a population above 150 inhabitants, we observed two data points lying effectively on the regression line, two points with large negative and two with large positive residuals. The observed pattern indicated that larger villages were not better monitored than smaller villages. If this had been the case, larger villages would have shown positive residuals, with higher numbers of burns than projected by regression.

The fact that the years with the highest number of burns had a below-average summer drought (Fig. 4A) did not suggest mistakes or deliberate data manipulation associated with the misclassification of prescribed burns. An interest to hide forest code violations would be one of the driving factors for such a misclassification. Large fire years commonly occur during years with more intense drought conditions promoting natural fires (Drobyshev and Niklasson 2004; Drobyshev et al. 2004). If such mis-classifications were widespread, they should manifest themselves by positive anomalies in drought conditions during the years featuring peaks in the burn numbers. The lack of such a pattern in our results supports the notion of unbiased reporting that fed data into the village inventories.

Conclusions: climatic and social constraints of burn practices

Our results and historiographic research (Petrov 1968) support the view on forest burnings as an intricate trade-off among interests to secure agricultural production, the need to control the risk of uncontrolled fire spread, and generally limited access to labour, particularly when this burning of the forest was already prohibited. SAB was a common and likely an "opportunistic" practice driven by the variability in climatological conditions and local population density in the northern Ural foothills. On an annual scale, variability in summer climates affected burn frequencies. At a decadal scale, human population density strongly controlled the levels of burning activity, as expressed by the positive correlation between the cumulative number of burns and the amount of arable land around the villages.

The nature of survey data made it difficult to estimate the exact extent of the SAB practices, that is the total annual burning activity in the region. Using village-specific data on the number of households, the overall frequency of burns appeared low, with just 0.04 burns per household and year, which corresponded to about 25 years between burns. This appears to be a highly conservative estimate, given the short period following a burning which gave acceptable harvests there. Records from Swedish Dalarna, for example, suggest that burns were carried out almost every year (Johansson 1987). However, our estimate was close to the fire frequency reconstructed by dendrochronology at the scale of a forest

stand in the Finnish boreal forest during the widespread use of SAB, between 1650 and 1850 (32.2 years, Lehtonen and Huttunen 1997). Similar estimates are available for northern Sweden (52 years, Niklasson and Granström 2000) and Russian Karelia (30–50 years, Ryzhkova et al. 2020). Although these estimates are not directly comparable to numbers of burns, assessed from the "household point of view" (this study), they point to possible variability in the levels of burning activities across the European boreal zone.

In northern Europe, dendrochronological reconstructions have shown a strong association between fire frequency viewed as a proxy for the extent of slash-and-burn cultivation and human population dynamics. Studies have attributed large increases in forest fire occurrence to waves of human colonization, which were particularly pronounced during late 1500s through to the 1700s (Niklasson and Granström 2000; Rolstad et al. 2017; Ryzhkova et al. 2022). However, the use of SAB was labour-intensive, resulting in a short-lived period with acceptable harvests (often limited to three years, Petrov 1968), and came with an inherent difficulty to plan such activities at annual and above-annual scales. All of these features likely prevented this practice from serving as a steady means to procure food in the European boreal region (Hamilton 1997).

We are aware that the limited data availability directly affected the way we conceptualized our findings in the current study. Climate variability at an above-annual scale as well as annual variability of access to food were possibly both at play in determining when and where burns occurred. The role of topographic features, properties of vegetation cover and soils in affecting burn practices remains currently unclear and warrants further study. To this end, the study of the village locations, which were likely chosen with consideration of prospects for agricultural production, could be a reasonable starting point for further research.

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