ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Evidence that modern fires may be unprecedented during the last 3400 years in permafrost zone of Central Siberia, Russia

To cite this article: Elena Yu Novenko *et al* 2022 *Environ. Res. Lett.* **17** 025004

View the article online for updates and enhancements.

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
24 September 2021

REVISED
8 January 2022

ACCEPTED FOR PUBLICATION
13 January 2022

PUBLISHED
26 January 2022

LETTER

Evidence that modern fires may be unprecedented during the last 3400 years in permafrost zone of Central Siberia, Russia

Elena Yu Novenko[1,2,7], Dmitry A Kupryanov[1,7], Natalia G Mazei[1], Anatoly S Prokushkin[3,4], Leanne N Phelps[5], Aline Buri[6] and Basil A S Davis[6,*]

1 Department of Physical Geography and Landscape Science, Faculty of Geography, Lomonosov Moscow State University, Moscow, Russia
2 Department of Quaternary Research, Institute of Geography Russian Academy of Science, Moscow, Russia
3 Sukachev Institute of Forest SB RAS, Federal Research Center “Krasnoyarsk Science Center SB RAS”, Krasnoyarsk, Russia
4 Siberian Federal University, Krasnoyarsk, Russia
5 School of GeoSciences, University of Edinburgh, Edinburgh, United Kingdom
6 Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland
7 Faculty of Geography and Geoinformation Technologies, HSE University, Moscow, Russia
* Author to whom any correspondence should be addressed.

E-mail: basil.davis@unil.ch

Keywords: fire frequencies, fire regime, fire return interval, biomass burning, macroscopic charcoal, paleo-fire reconstruction, Putorana Plateau

Supplementary material for this article is available online

Abstract

Recent climate change in Siberia is increasing the probability of dangerous forest fires. The development of effective measures to mitigate and prevent fires is impossible without an understanding of long-term fire dynamics. This paper presents the first multi-site palaeo-fire reconstruction based on macroscopic charcoal data from peat and lake sediment cores located in different landscapes across the permafrost area of central Siberia. The obtained results show similar temporal patterns of charcoal accumulation rates in the cores under study, and near synchronous changes in fire regimes. The paleo-fire record revealed moderate biomass burning between 3.4 and 2.6 ka BP, followed by the period of lower burning occurring from 2.6 to 1.7 ka BP that coincided with regional climate cooling and moistening. Minimal fire activity was also observed during the Little Ice Age (0.7–0.25 ka BP). Fire frequencies increased during the interval from 1.7 to 0.7 ka BP and appears to be partly synchronous with climate warming during the Medieval Climate Anomaly. Regional reconstructions of long-term fire history show that recent fires are unprecedented during the late Holocene, with modern high biomass burning lying outside millennial and centennial variability of the last 3400 years.

1. Introduction

Wildfire is one of the most important disturbance agents in forest ecosystems worldwide and has a great impact on forest resources, air pollution and ecological succession (Bond and Keeley 2005). During the last few decades, the extent and severity of fires in arctic and boreal regions is increasing due to climate changes and human activity (Soja *et al* 2007, Turetsky *et al* 2011, Wang *et al* 2021). A number of studies on fire regimes in the high latitude area of Eurasia and North America demonstrated that fires have long affected permafrost thaw and the function of forest and tundra ecosystems (e.g. Schuur *et al* 2013, Abbott *et al* 2016, Sulphur *et al* 2016, Gajewski 2021, Li *et al* 2021). However, recent global warming in the circumpolar Arctic is increasing fire frequencies (Goetz *et al* 2007, Krylov *et al* 2014, Feurdean *et al* 2020, Fonti and Büntgen 2020).

In permafrost area of central Siberia, where larch forests are the dominant forest type, fire drives forest succession and vegetation patterns (Sofronov and Volokitina 2010). According to dendrochronological studies in central Siberia, the fire return interval (FRI) for the period spanning the 17th–20th centuries varies from 77 ± 20 in larch taiga to 320 ± 50 years at the northern forest limit, depending on topography and landscape features of the area (Kharuk *et al* 2011, 2021). Fire scar analysis on larch species in northern central Siberia demonstrated that the FRI

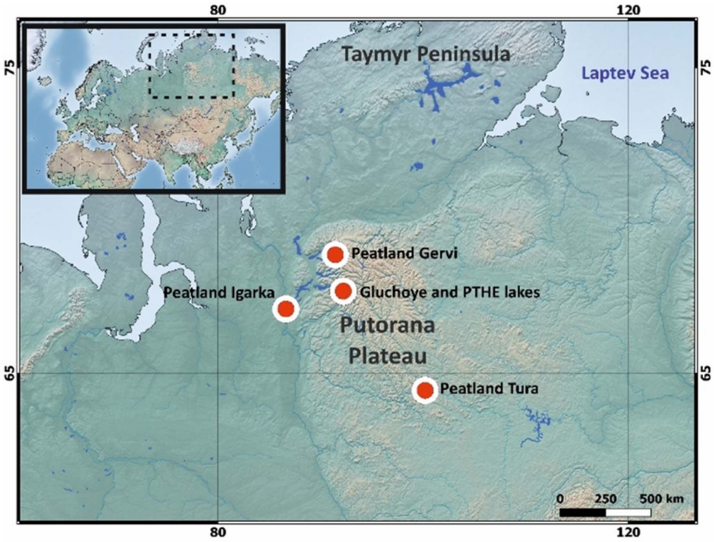

Figure 1. Location of the study areas.

tended to decrease during the last century (Kharuk *et al* 2011, 2021, Knorre *et al* 2019, Kirdyanov *et al* 2020, Wang *et al* 2021). Since in 1996 several severe fires caused extensive damage in different regions of Siberia (Kukavskaya *et al* 2016). Over the same time period exceptionally large fires (mega-fires) covering more than 10 000 ha became a prominent characteristic of the Siberian fire regime (Natole *et al* 2021).

In light of these recent and future projected changes in fire regime, it is important to improve our understanding of fire dynamics in these sensitive ecosystems. Long-term records of past fire regimes can be used to better understand natural fire variability, the role of fires in forcing land cover change, and subsequently to reduce uncertainties in the potential effects of future fire damage. The most commonly used method for reconstructing Holocene fire frequency and intensity is to study charcoal concentrations in peat and lacustrine sediments (Power *et al* 2008, Carcaillet *et al* 2009, Higuera *et al* 2009, Whitlock *et al* 2010, Carcaillet and Blarquez 2017, Feurdean *et al* 2020). Often these methods are used in combination with other paleoecological approaches when reconstructing past environmental changes, including plant macrofossil and pollen analysis. Studies in Yakutia in Siberia have shown the ability of charcoal records to indicate fire impact on vegetation and permafrost dynamics (Katamura *et al* 2009).

In this paper we present new charcoal data from four key areas located in a remote and poorly investigated region of central Siberia. Our objectives are (a) to reconstruct late Holocene biomass burning in four areas of permafrost, (b) to reveal the influence of climate change on fire dynamics and (c) to compare anthropogenically-driven changes in the modern fire regime.

2. Regional setting

Charcoal records were obtained from three peat and two lacustrine sediment cores across different landscape regions of central Siberia (figure 1 and table 1). Two lacustrine and one peat records are situated in the northwestern part of the Putorana Plateau and are represented by the low elevation peatland site Gervi and the high elevation lake sites Gluchoye and PTHE. One peatland record (Igarka) is located at the western margin of central Siberia near Yenisei River valley, and one peat core (Tura) was obtained from the Central Siberian Plateau in the Lower Tunguska River basin (the right tributary of the Yenisei River).

The climate of the study area, according to the Köppen–Geiger climate classification, is sub-Arctic (or subpolar) with long, usually very cold winters, and short, cool summers (Beck *et al* 2018). The mean annual air temperature varies from −7.8 °C in Igarka to −8.8 °C in Tura, although this is likely to be lower at the higher altitude sites in the Putorana Plateau. The mean annual precipitation in the western margin of central Siberian Plateau and at foothills of Putorana Plateau is about 650 mm yr^{-1} and its value decreases considerably to 370 mm yr^{-1} in the central part of central Siberia (Tura area). The region under study belongs to a zone of continuous permafrost. The vegetation cover is dominated by larch forests (*Larix gmelinii*). Mountain slopes above 400 m asl are occupied by woodlands (*Alnus fruticosa, Betula nana, B. tortuosa, B. cajander*) and alpine tundra cover the uppermost part of mountain ridges (Flora of Putorana 1976). *Larix sibirica, Picea obovata* and *Pinus sibirica* occur in the study area at Igarka (table 1).

Table 1. Summary characteristics of the lakes and peatlands with details of the cores.

Lakes and peatlands	Peatland Gervi	Glukhoe Lake	PTHE Lake	Peatland Igarka	Peatland Tura
Latitude (°N)	69°28′15.5437′	68°10′14.14′	68°12′17.33′	67°31′53.50′	64°17′23.35′
Longitude (°E)	91°26′27.0263′	92°12′12.23′	92°11′01.76′	86°38′08.69′	100°11′51.30′
Surface area (ha)	10.4	230.9	6.3	12.4	6.9
Elevation (m asl)	51	569	805	43	144
Length of sediment (cm)	50	28	34	120	64
Median sedimentation time (yr cm^{-1})	0.1	0.01	0.01	0.03	0.02
Median sampling resolution (yr $sample^{-1}$)	10	135.5	104	35	51
Vegetation	Woodlands (*Larix gmelinii, Betula nana, B tortuosa, B. cajander*)	Open woodlands (*L. gmelinii, Alnus fruticosa, B. nana, Salix*)	Sparse vegetation, prostrate *Salix* and lichens	Woodlands (*L. sibicica, Picea obovata, Pinus sibirica, A. fruticosa*)	Woodlands (*L. gmelinii, B. pendula, B. pubescens, A. fruticosa*)

3. Materials and methods

Coring and sediment description were carried out in July 2019 (Gervi, Tura) and August 2020 (Igarka). Cores from the seasonally thawed layer of permafrost were extracted using a Russian peat corer (inner chamber length of 50 cm and diameter of 5 cm). Sediment cores from Gluchoye Lake and PTHE Lake were collected in July 2006 as part of an earlier study by Self *et al* (2015). Cores were obtained from the deepest point of each lake using a 7 cm diameter HON-Kajak corer with a 50 cm Perspex coring tube.

Samples for the macroscopic charcoal analysis were taken continuously with the 1 cm interval from all cores under study. Probes were prepared following Mooney and Tinner (2011). Charcoal particles with a size >125 μm were counted under a stereomicroscope MOTIC SMZ-171 at 40-fold magnification. Charcoal concentrations or charcoal counts (pieces cm^{-3}) were transformed into charcoal accumulation rates or influx (CHAR, pieces cm^{-2} yr^{-1}; figure 2) by multiplying charcoal concentration by sediment accumulation rates (cm yr^{-1}) using the CharAnalysis software (Higuera 2009) adapted for the R language environment (R Core Team 2020). The CharAnalysis user independently determines a filtering method for interpolated charcoal accumulation rate (C_{int}) and a smoothing window, which describes a reconstruction of fire history. Table 2 shows the CharAnalysis parameters used in the present study. Sediment accumulation rates were calculated based on age-depth models constrained by radiocarbon dates (see details in supplementary materials 1, table suppl. 1 available online at stacks.iop.org/ERL/17/025004/mmedia).

The reconstruction of past fire events using CharAnalysis includes the decomposition of the charcoal record into a background signal (C_{back}), together with a high frequency peak component. The smoothing method and window width were defined by the ensemble-member strategy for separating charcoal peaks from background charcoal data (Blarquez *et al* 2013). The charcoal peaks (i.e. local fire episodes) were defined as a residual ($C_{peak} = C_{int} - C_{back}$). Significant charcoal peaks are defined based on a minimum-count peak screening test. FRIs in each charcoal sequences were determined as the time between two consecutive charcoal peaks (Whitlock *et al* 2010). The distributions of fire-free intervals were compared for each site using the nonparametric Kruskal–Wallis (for fire series >2) and the Wilcoxon signed-rank tests.

We used the Paleofire R package version 1.2.4 (Blarquez *et al* 2014) as the standardization technique of the obtained data to compare the local fire reconstructions from the study area. We used three stages of data transformation in the Paleofire package: the min–max rescaling of the CHAR values, a box–cox transformation to homogenize within-charcoal record variance and a final transformation to Z-score (Power *et al* 2008). Confidence intervals were calculated using a bootstrap resampling of the binned charcoal series and calculating the mean of each 1000 times. Zero Z-score values correspond to the mean charcoal influx over the base period (0.1–2.0 ka BP), and positive/negative Z-score values represent greater-than mean/lower-than-mean charcoal influx over the base period. We have limited our reconstruction to 3.4 ka BP because only two sediment cores under study covered a longer time interval.

4. Results

4.1. Charcoal accumulation

Charcoal accumulation showed similar temporal dynamics, but CHAR values differ by an order of magnitude between sites as C_{int} at Tura ranged from 3 to 37 pieces cm^{-2} yr^{-1} while that in PTHE Lake varied between 0.01 and 0.1 pieces cm^{-2} yr^{-1} (figure 2(c)). Charcoal influx at Gluchoye Lake amounted 0.02–0.22 pieces cm^{-2} yr^{-1} (figure 2(b)) and CHAR values at Igarka fluctuated between 0.1 and 4 pieces cm^{-2} yr^{-1} (figure 2(d)). This difference

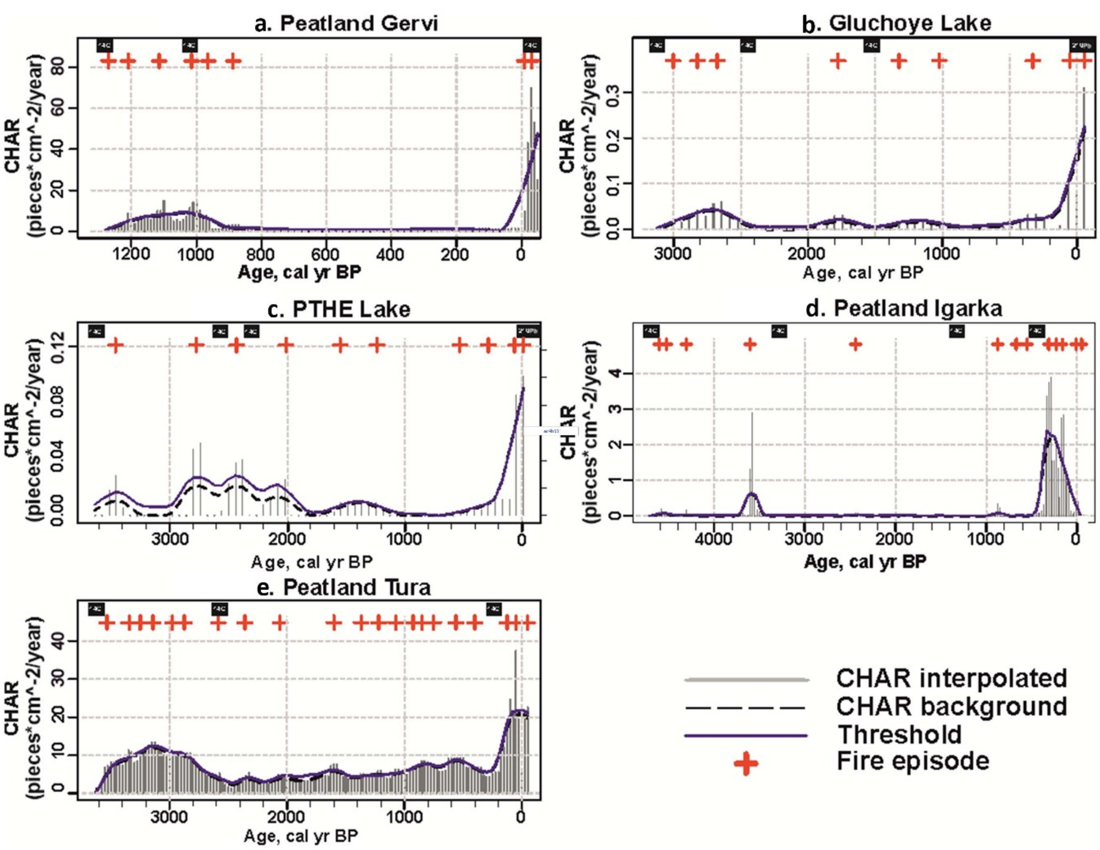

Figure 2. Results of macroscopic charcoal analysis of the lake and peat core from central Siberia: (a) Gervi, (b) Gluchoye Lake, (c) PTHE Lake, (d) Igarka, (e) Tura.

Table 2. Summary of CharAnalysis parameters for each study sites.

Core	Gervi	Glukhoe	PTHE	Igarka	Tura
Time range of chronology (calendar years BP)	−59–1285	−56–3134	−6–3675	−60–4704	−59–3634
Years to interpolate record	10	60	60	20	25
Years to smooth record over for estimating background CHAR	300	500	500	300	300
Years to smooth fire frequency and FRIs over	1250	2400	1500	3500	3600
Median signal-to-noise index	2.86	3.26	3.01	3.88	3.17

could be a result of the lower charcoal productivity and flammability of mountain vegetation composed mainly of *B. nana, Salix* and *A. fruticosa* (Gluchoye Lake) and high altitude sparse vegetation, including prostrate willows and lichens (PTHE Lake) compared to *Larix* forests (Higuera *et al* 2009, Carcaillet and Blarquez 2017) at Tura and Gervi.

The macroscopic charcoal analysis revealed the relatively high charcoal accumulation in the period from 3.4 to 2.7 ka BP at Tura and Gluchoye (figures 2(b)–(e)). In Tura C_{int} ranged from 8 to 12 pieces cm^{-2} yr^{-1}, reaching the maximum value at 3.1 ka BP, while at Gluchoye C_{int} amounted 0.02–0.05 pieces cm^{-2} yr^{-1} with the maximum value of 0.07 pieces cm^{-2} yr^{-1}. At PTHE the period of the high charcoal input occurred later (figure 2(c)). Between 3.4 and 3.0 ka BP, CHAR values at this sediment core ranged between 0.01 and 0.02 pieces cm^{-2} yr^{-1} and from 3.0 to 2.0 BP C_{int} increased to 0.04 pieces cm^{-2} yr^{-1}.

The charcoal accumulation rate declined notably since 2.7 ka BP at Tura and Gluchoye and since 2.0 ka BP at PTHE. Between 2.7 and 0.17 ka BP the CHAR influx at Tura reduced to a range of 3–8 pieces cm^{-2} yr^{-1}. No charcoal pieces were recorded in sediment cores from Putorana lakes except for samples formed in time intervals 1.9–1.7, 1.35–1.0 and 0.5–0.25 ka BP, where C_{int} was about 0.25 pieces cm^{-2} yr^{-1} at Gluchoye and 0.01 pieces cm^{-2} yr^{-1} at PTHE.

Charcoal accumulation at Igarka was low for the entire Late Holocene (figure 2(d)). Between 4.7 and 0.5 ka BP, the CHAR influx did not exceed the value of 0.1 pieces cm^{-2} yr^{-1} with exception of a distinct peak

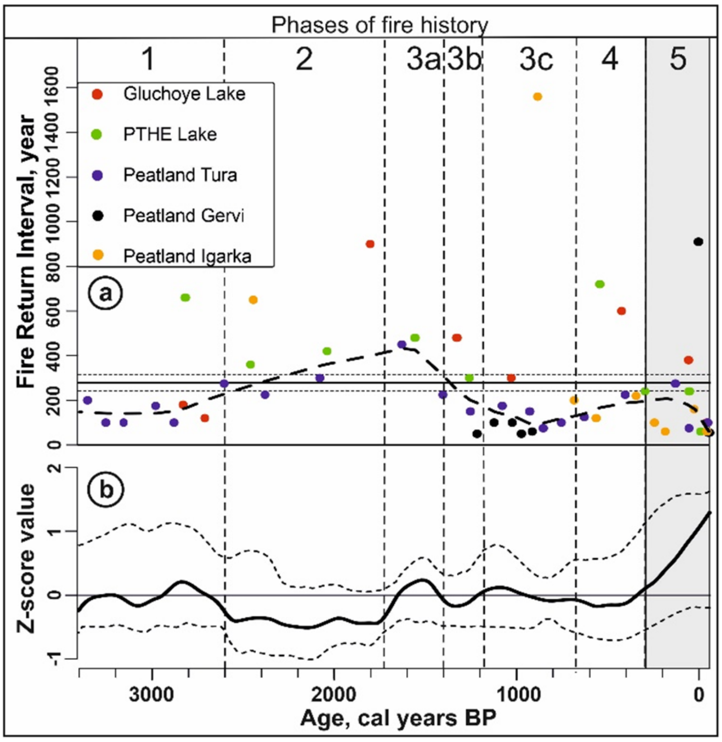

Figure 3. FRIs and biomass burning. (a) FRIs of studied sites plotted against time. The heavy dark line is computed with a locally weighted least-squares error method (weight value 10). The horizontal line indicates the mean FRI calculated on five series, and the dashed lines are the limits of the standard error. (b) Biomass burning in study area during the last 3400 years. The heavy dark line represents charcoal influx (Z-score values), dashed lines indicate 95% confidence intervals, calculated by bootstrap resampling the binned charcoal series and calculating the mean of each bin 2000 times. Gray band indicates modern periods with high biomass burning.

at 3.6–3.5 ka BP. C_{int} formed several maximums with the highest value at 2.9 pieces cm^{-2} yr^{-1}. Apparently, this period of the high charcoal input suggested a relatively long fire episode lasting about 100 years that included several forest fires. The next peak of charcoal accumulation detected at 0.85 ka BP when C_{int} reached 0.4–0.5 pieces cm^{-2} yr^{-1}.

The macroscopic charcoal analysis of Gervi shows the relatively high charcoal accumulation in the period from 1.3 to 0.9 ka BP (figure 2(a)), when CHAR values ranged from 7 to 15 pieces cm^{-2} yr^{-1}. In the subsequent period 0.9–0.15 ka BP, C_{int} decreased significantly and did not exceed 3 pieces cm^{-2} yr^{-1}.

The last 250 years was characterized by a sharp increase of the charcoal accumulation rate in all sediment cores under study achieving their highest values throughout the past 3400 years (figures 2(a)–(e)). The CHAR values at Grvi increased from 3 to 50 pieces cm^{-2} yr^{-1}, with a maximum value of 70 pieces cm^{-2} yr^{-1}. At Tura CHAR influx raised from 8 to 21 pieces cm^{-2} yr^{-1}, with C_{int} reaching maximum values of the entire sediment core at 25 and 38 pieces cm^{-2} yr^{-1}. In lakes Gluchoye and PTHE charcoal accumulation gradually increased since about 0.5 ka BP. A sharp rise of the charcoal input occurred during the last 170 years. C_{int} grew from 0.01 to 0.1 pieces cm^{-2} yr^{-1} at PTHE and from 0.02 to 0.31 pieces cm^{-2} yr^{-1} at Gluchoye. A sharp rise of the charcoal input at Igarka occurred earlier than in other regions. CHAR influx grew explosively from 0–0.1 to 4 pieces cm^{-2} yr^{-1} at 0.5 ka BP. During the last 150 years charcoal accumulation in this site gradually declined to minimum values.

4.2. Fire return intervals (FRIs)

The FRI over the last 3400 years was generally of a long duration at Igarka and PTHE and reached (mean ± SE) 344 ± 127 and 386 ± 70 years respectively. The FRI at Gluchoye and Tura was shorter and determined as 182 ± 96 and 180 ± 21 years. The mean FRI at Gervi over a period of 1300 years was 189 ± 120 years. The average FRI at the regional scale derived by integrating the data from the five sites during the study period was 344 ± 34 years (figure 3). Table 3 shows the temporal distribution of the FRI between the different sites. Comparison of the FRI distributions in two periods 3.0–1.6 ka BP and 1.6 ka BP—present indicated that all sites experienced very similar fire regimes likely triggered by the same processes during the first and second time intervals (table 2 in suppl.; Wilcoxon test, $P > 0.05$).

The median FRI, ranging between 360 and 60 years (figure 4). The one-way analysis of variance shows no significant differences of FRIs ($p = 0.17$) along the elevation gradient from higher to lower

Table 3. Temporal distribution of FRIs in studied sites. FRIs before 3.4 ka BP were not taken into account.

	3.4–0 ka BP		3.4–2.6 ka BP		2.6–1.7 ka BP		1.7–0.7 ka BP		0.7–0 ka BP	
	Mean ± SD	Number of peaks	Mean ± SD	Number of peaks	Mean ± SD	Number of peaks	Mean ± SD	Number of peaks	Mean ± SD	Number of peaks
Gervi	—	—	—	—	—	—	72 ± 12	5	482 ± 427	2
Glukhoe	182 ± 96	8	150 ± 30	2	900 ± 0	1	390 ± 90	2	360 ± 145	3
PTHE	386 ± 70	9	660 ± 0	1	390 ± 30	2	390 ± 90	2	315 ± 142	4
Igarka	344 ± 127	12	333 ± 188	3	650 ± 0	1	880 ± 680	2	131 ± 24	6
Tura	180 ± 21	17	135 ± 22	4	132 ± 48	3	126 ± 22	6	160 ± 38	4

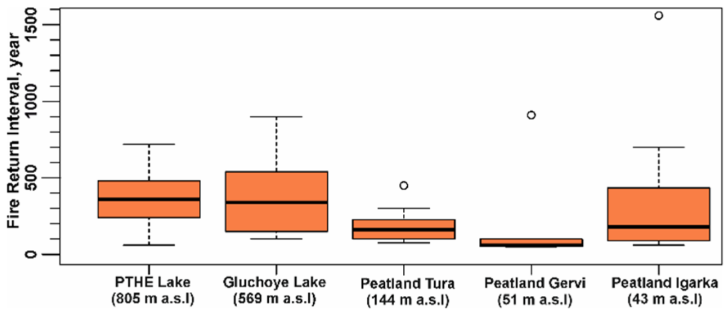

Figure 4. Box plots of the FRIs along the elevation gradient. The box limits represent the 25th, median, and 75th percentiles. The error bars indicate ± SD from the mean value. The dots represent the outlier values.

altitudes (tables 3 and 4 in suppl.). The longer FRI at Igarka could be explained by the difference of the local topography and environmental conditions between study sites. The peatland Igarka is located within poor drained and wet lowland where ignition and fire spread weaker compared to dissected plateaus at Tura, Gervi and Putorana lakes. Although, the FRIs are site-specific, temporal variability of the fire frequency (figure 3) showed that trends of FRI changes are homogeneous.

4.3. Biomass burning

Biomass burning was moderate in the period between 3.4 and 2.6 ka BP with fluctuation of the Z-score value around zero (figure 3(b)). During the period 2.6–1.7 ka BP, biomass burning decreased significantly in comparison to the earlier time interval. The composite curve indicates a negative Z-score value, representing lower-than-mean charcoal influx. The next periods were characterized by a positive Z-score value indicating a high fire activity and increased biomass burning between 1.7 and 1.4 ka BP followed by a decline of the Z-score value during the time interval 1.4–1.3 ka BP. The moderate biomass burning with around zero Z-score value occurred between 1.3 and 0.7 ka BP. Since 0.7 ka BP the biomass burning gradually declined, with the minimum Z-score value occurring around 0.5 ka BP. The last 300 years were characterized by notable rise of biomass burning and the highest Z-score value for the entire period.

5. Discussion

Analysis of macroscopic charcoal in lacustrine and peat sediments from four study areas in central Siberia has allowed us to determine four main phases of fire regime variability (figure 3) that is clearly traceable in both the regional trend in biomass burning and individual charcoal records. Despite differences in FRIs and charcoal accumulation between sites, the trends and the time of changes were rather synchronous over the last 3400 years.

Biomass burning and fire activity was moderate between 3.4 and 2.6 BP. (phase 1, figure 3). The charcoal records from Tura and Gluchoye Lake revealed an increase of CHAR index during this time. While the extremely low charcoal values were recorded from Igarka except for a high sharp peak of CHAR around 3.6–3.5 ka BP that suggested a severe fire episode in vicinity of the peatland. The FRI varied from 135 ± 22 years in Tura to 333 ± 188 years in Igarka which is longer than modern times. According to fire scar analysis in larch stems, the current FRI is estimated at 82 ± 7 years in Tura area (Kharuk *et al* 2011) increasing to 320 ± 50 years at the northern treeline, which lies 50–70 km north to the Igarka peatland (Shahgedanova *et al* 2002).

Biomass burning and fire activity decreased significantly during the period 2.6–1.7 ka BP (phase 2, figure 3). All charcoal records indicated a decline in charcoal accumulation with exception of the PTHE where the CHAR index was higher from 3.0–2.1 ka

BP (figure 2). A decrease in charcoal influx and low biomass burning was recorded in the taiga area of West Siberia at Plotnikovo Mire, located on the eastern margins of the Great Vasyugan Mire system (Feurdean *et al* 2020).

A decrease in fire activity in Siberia since 2.6 ka BP (phase 2, figure 3) could have been caused by climate cooling and increase in humidity which has been widely recorded at this time, not only at the regional, but also at the global scale. Climatic reconstructions based on chironomid assemblages from lakes Gluchoye and PTHE revealed a noticeable decrease in summer temperature (Self *et al* 2015), which paralleled evidence of July temperature decline inferred from pollen and diatom data from Lama Lake (Andreev *et al* 2004, Kumke *et al* 2004). In addition, pollen data from lakes in northern Siberia (Klemm *et al* 2016) and tree ring inferred climate reconstructions in Yamal and Taimyr (Hantemirov and Shiyatov 2002, Naurzbaev *et al* 2002) also indicated cooler conditions. Climate cooling in Siberia also coincided with an increase in K + deposition in the GISP2 ice core, indicating the strength of Siberian High, which may suggest changes in atmospheric circulation occurred (Meeker and Mayewski 2002).

The period between 1.7 and 0.7 ka BP is characterized by variable biomass burning and FRI (phase 3, figure 3). The time interval from 1.7–1.4 ka BP was marked by heightened biomass burning but extended FRIs, while the subsequent phases revealed low and moderate charcoal flux together with clear tendency of FRI to decrease. The divergence between charcoal flux and fire frequency could be a result of the probable high occurrence of low intensive fires. According to Kharuk *et al* (2021) about 90% of modern forest fires in Siberia are surface fires which spread along the forest floor, damaging vegetation litter and understory. The shortest FRIs for most of the areas under study were detected in the interval 1.3–0.7 ka BP (figure 3). The FRI at Gervi and Tura were determined as 72 ± 12 and 126 ± 22 years, respectively, indicating an increase fire frequency compared to the previous phase. Signs of a fire at 0.85 ka BP were identified at Igarka. This fire episode was preceded by a 2500 year long interval when forest fires were not detected. The reduction of FRI about 1.0 ka BP were also recorded at Plotnikovo Mire in western Siberia (Feurdean *et al* 2020).

The period of increased fire frequency from 1.7–0.7 ka BP included the climate warming of the Medieval Climate Anomaly (MCA, 800–1300 AD (1.15–0.65 ka BP); Mann *et al* 2009). An increase in summer temperatures at this time has been traced in tree-ring chronologies from northern Siberia (Hellmann *et al* 2016). Reconstructions of temperature and moisture conditions in Eurasia indicate a significant warming during the MCA at a global scale and a summer drought in several regions (PAGES 2k Consortium 2013). Studies in western Siberia (Feurdean *et al* 2019) and central Asia (Chen *et al* 2010) revealed an alternation of relatively wet and dry phases during the MCA.

The next phase of relatively low fire activity that occurred between 0.7 and 0.25 ka BP (phase 4, figure 3) may be synchronous with the climate cooling of the Little Ice Age (LIA, 1300–1850 AD (0.65–0.1 ka BP), PAGES 2k Consortium 2013). A climate deterioration during the LIA was observed in tree ring based paleoclimate reconstructions from eastern Taimyr, Yamal Peninsula and north-eastern Yakutia (Naurzbaev *et al* 2002; Hellmann *et al* 2016) and in multi-proxy records from a great number of regions in northern Eurasia (PAGES 2k Consortium 2013). According to the results of dendrochronological studies, the fire frequency in larch forests in the permafrost zone of central Siberia during the LIA was significantly lower than in previous and subsequent epochs (Kharuk *et al* 2011). During the shorter and possibly colder summers of the LIA, evaporation was reduced, which could lead to an increase in ground moisture in many habitats (Molinari *et al* 2018), creating an unfavorable environment for the occurrence and spread of forest fires. Our macroscopic charcoal records indicated rare fire events during the LIA across the study areas.

During the last 300 years, charcoal accumulation increased significantly in all sediment cores under study, as biomass burning reached its maximum values for the entire Late Holocene (phase 5, figure 3). Heightened CHAR and peak magnitude values detected in the peat and lake sediments suggest that fires became larger and more severe. Charcoal accumulation during the last two centuries exceeded its average values by an order of magnitude for all sediment cores (figure 2).

Over the last century, increases in temperature and the frequency of dry summer conditions across Siberia apparently enhanced fire activity (Groisman *et al* 2012). Human impact on fire activity was low in the Putorana Plateau. The areas around Gervi peatland, and the lakes at Gluchoye and PTHE are inhabited, but human influence is limited to rare tourist groups. The settlements of Tura and Igarka appeared in the 1920s. Modern observations in Siberia show that despite fire suppression measures, fires often occur during dry summers around settlements and can spread over large areas (Kukavskaya *et al* 2016). Therefore, we suggest that both human induced and wildfire may have occurred during the last two centuries in these study areas.

The increase of the CHAR at Igarka occurred earlier than in the other cores. Charcoal accumulation started to rise at the end of 14th—beginning 15th centuries and then charcoal input declined. We supposed that human induced fires led to the biomass burning. According to historical data the Russian colonization of this part of Siberia began in the 17th century (Toschev 2013), but the first Russian settlers already found a local hunter population in the area of Igarka. The settlement lies on the banks of the Yenisei River, historically one of the main trading routes in Siberia. During the 20th century wood-using industry and a river harbor were developed in Igarka, was obviously accompanied by active deforestation that led to some reducing the forest fire occurrence.

Fire regime studies in northern central Siberia based on the analysis of fire scars in larch wood showed that the number of fires increased during the 20th century, and that FRI declined in several regions (Kharuk *et al* 2021). According to this data, the most severe fires around Tura occurred in 1846, 1896–1899 and 1914–1916 (Knorre *et al* 2019). The large and devastating fire in 1899 covered an area of about 250 km^2 (Kirdyanov *et al* 2020), including the coring site. We hypothesize that this fire corresponds to the sharp peak in CHAR at a depth of 5 cm (∼150 BP) in the sediment core at Tura.

6. Conclusions

This study provides the first evidence for a late Holocene fire regime in the permafrost area of central Siberia. The data obtained from four study areas located in different landscapes revealed relatively low biomass burning between 3.4 and 1.7 ka BP, with minimum fire activity occurring from 2.6 to 1.7 ka BP and during regional climate cooling and moistening of the LIA (0.7–0.15 ka BP). Fire activity increased during the interval 1.7–0.7 ka BP, which appears to be partly synchronous with climate warming during the MCA. Reconstructions of fire history based on macroscopic charcoal records have shown that recent fires may be unprecedented during the late Holocene, and that the modern fire regime lies outside a 3400 year trend in fire activity. The charcoal accumulation rate during the modern era is in an order of magnitude greater than the average values for each cores. Extraordinary high peak magnitude detected in the last 200 years in peat and lake sediment suggests that fires during this period became larger and likely more severe compared with the long-term past. This trend was observed even at sites remote from human disturbance, and suggests that modern climate change was the main cause, consistent with predictions of increased fire risk across Siberia as a result of anthropogenic greenhouse warming (Groisman *et al* 2012).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

Field work and macroscopic charcoal analysis in the Putorana Plateau and Tura area were supported by the project 'Holocene climate and environmental records from the Central Siberian Plateau' funded by the Swiss Polar Institute. Field work and macroscopic charcoal analysis in Igarka area, data analysis and paper preparation were supported by Russian Science Foundation, Project 20-17-00043.

References

Abbott B W *et al* 2016 Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment *Environ. Res. Lett.* **11** 034014

Andreev A, Tarasov P, Klimanov V, Melles M, Lisitsyna O and Hubberten H 2004 Vegetation and climate changes around the Lama Lake, Taymyr Peninsula, Russia during the Late Pleistocene and Holocene *Quat. Int.* **122** 69–84

Beck H, Zimmermann N, McVicar T, Vergopolan N, Berg A and Wood E 2018 Present and future Köppen-Geiger climate classification maps at 1-km resolution *Sci. Data* **5** 180214

Blarquez O, Girardin M, Leys B, Ali A, Aleman J, Bergeron Y and Carcaillet C 2013 Paleofire reconstruction based on an ensemble-member strategy applied to sedimentary charcoal *Geophys. Res. Lett.* **40** 2667–72

Blarquez O, Vannière B, Marlon J, Daniau A, Power M, Brewer S and Bartlein P 2014 Paleofire an R package to analyse sedimentary charcoal records from the global charcoal database to reconstruct past biomass burning *Comput. Geosci.* **72** 255–61

Bond W and Keeley J 2005 Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems *Trends Ecol. Evol.* **20** 387–94

Carcaillet C, Ali A A, Blarquez O, Genries A, Mourier B and Bremond L 2009 Spatial variability of fire history in subalpine forests: from natural to cultural regimes *Écoscience* **16** 1–12

Carcaillet C and Blarquez O 2017 Fire ecology of a tree glacial refugium on a nunatak with a view on Alpine glaciers *New Phytol.* **216** 1281–90

Chen F, Chen J, Holmes J, Boomer I, Austin P, Gates J, Wang N, Brooks S and Zhang J 2010 Moisture changes over the last millennium in the arid central Asia: a review, synthesis and comparison with monsoon region *Quat. Sci. Rev.* **29** 1055–68

Feurdean A *et al* 2020 Recent fire regime in the southern boreal forests of western Siberia is unprecedented in the last five millennia *Quat. Sci. Rev.* **244** 106495

Feurdean A, Gałka M, Florescu G, Diaconu A-C, Tanţău I, Kirpotin S and Hutchinson S M 2019 2000 years of variability in hydroclimate and carbon accumulation in western Siberia and the relationship with large-scale atmospheric circulation: a multi-proxy peat record *Quat. Sci. Rev.* **226** 105948

Flora of Putorana 1976 *Materials for Understanding the Composition and Genesis of Mountain Subarcts. Flora of Siberia* ed L I Malysheva (Novosibirsk: Nauka-Press) p 245

Fonti M and Büntgen U 2020 Long-term ecological consequences of forest fires in the continuous permafrost zone of Siberia *Environ. Res. Lett.* **15** 034061

Gajewski K 2021 Climate, fire and vegetation history at treeline east of Hudson Bay, northern Quebec *Quat. Sci. Rev.* **254** 106794

Goetz S, Mack M, Gurney K, Randerson J and Houghton R 2007 Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America *Environ. Res. Lett.* **2** 045031

Groisman P *et al* 2012 Climate changes in Siberia *Regional Environmental Changes in Siberia and Their Global Consequences* ed P Y A Groisman and G Gutman (Berlin: Springer) pp 57–109

Hantemirov R and Shiyatov S 2002 A continuous multimillennial ring-width chronology in Yamal, northwestern Siberia *Holocene* **12** 717–26

Hellmann L *et al* 2016 Regional coherency of boreal forest growth defines Arctic driftwood provenancing *Dendrochronologia* **39** 3–9

Higuera P E, Brubaker L B, Anderson P M, Hu F S and Brown T A 2009 Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska *Ecol. Monogr.* **79** 201–19

Higuera P 2009 *CharAnalysis 0.9: Diagnostic and Analytical Tools for Sediment-Charcoal Analysis User's Guide* (Montana State University: Bozeman MT) p 27

Katamura F, Fukuda M, Bosikov N and Desyatkin R 2009 Charcoal records from thermokarst deposits in central Yakutia, eastern Siberia: implications for forest fire history and thermokarst development *Quat. Res.* **71** 36–40

Kharuk V I, Ponomarev E I, Ivanova G A, Dvinskaya M L, Coogan S C P and Flannigan M D 2021 Wildfires in the Siberian taiga *Ambio* **50** 1953–74

Kharuk V, Ranson K, Dvinskaya M and Im S 2011 Wildfires in northern Siberian larch dominated communities *Environ. Res. Lett.* **6** 045208

Kirdyanov A *et al* 2020 Long-term ecological consequences of forest fires in the continuous permafrost zone of Siberia *Environ. Res. Lett.* **15** 034061

Klemm J, Herzschuh U and Pestryakova L 2016 Vegetation, climate and lake changes over the last 7000 years at the boreal treeline in north-central Siberia *Quat. Sci. Rev.* **147** 422–34

Knorre A, Kirdyanov A, Prokushkin A, Krusic P and Büntgen U 2019 Tree ring-based reconstruction of the long-term influence of wildfires on permafrost active layer dynamics in central Siberia *Sci. Total Environ.* **652** 314–9

Krylov A, McCarty J, Potapov P, Loboda T, Tyukavina A, Turubanova S and Hansen M 2014 Remote sensing estimates of stand-replacement fires in Russia, 2002–2011 *Environ. Res. Lett.* **9** 105007

Kukavskaya E, Buryak L, Shvetsov E, Conard S and Kalenskaya O 2016 The impact of increasing fire frequency on forest transformations in southern Siberia *For. Ecol. Manage.* **382** 225–35

Kumke T, Kienel U, Weckström J, Korhola A and Hubberten H 2004 Inferred Holocene paleotemperatures from diatoms at Lake Lama, central Siberia *Arct. Antarct. Alp. Res.* **36** 624–34

Li X-Y *et al* 2021 Influences of forest fires on the permafrost environment: a review *Adv. Clim. Change Res.* **12** 48–65

Mann M, Zhang Z, Rutherford S, Bradley R, Hughes M, Shindell D, Ammann C, Faluvegi G and Ni F 2009 Global signatures and dynamical origins of the Little Ice Age and medieval climate *Anomaly Sci.* **326** 1256–60

Meeker L and Mayewski P 2002 A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia *Holocene* **12** 257–66

Molinari C, Lehsten V, Blarquez O, Carcaillet C, Davis B A S, Kaplan J O, Clear J and Bradshaw R H W 2018 The climate, the fuel and the land use: long-term regional variability of biomass burning in boreal forests *Glob. Change Biol.* **24** 4929–45

Mooney S and Tinner W 2011 The analysis of charcoal in peat and organic sediments *Mires Peat* **7** 1–18

Natole M, Ying Y, Buyantuev A, Stessin M, Buyantuev V and Lapenis A 2021 Patterns of mega-forest fires in east Siberia will become less predictable with climate warming *Environ. Adv.* **4** 100041

Naurzbaev M, Vaganov E, Sidorova O and Schweingruber F 2002 Summer temperatures in eastern Taimyr inferred from a 2427-year late-Holocene tree-ring chronology and earlier floating series *Holocene* **12** 727–36

PAGES 2k Consortium 2013 Continental-scale temperature variability during the past two millennia *Nat. Geosci.* **6** 339–46

Power M *et al* 2008 Changes in fire regimes since the last glacial maximum: an assessment based on a global synthesis and analysis of charcoal data *Clim. Dyn.* **30** 887–907

R Core Team 2020 R: a language and environment for statistical computing; R foundation for statistical computing (Vienna) (available at: www.r-project.org/index.html)

Schuur E A G *et al* 2013 Expert assessment of vulnerability of permafrost carbon to climate change *Clim. Change* **119** 359–74

Self A E, Jones V J and Brooks S J 2015 Late Holocene environmental change in arctic western Siberia *Holocene* **25** 150–65

Shahgedanova M, Perov V and Mudrov Y 2002 The mountains of northern Russia *The Physical Geography of Northern Eurasia* ed M Shahgedanova (Oxford: Oxford University Press) pp 284–313

Sofronov M A and Volokitina A V 2010 Wildfire ecology in continuous permafrost zone *Permafrost Ecosystems: Siberian Larch Forests, Ecological Studies* vol 209 ed A Osawa, O A Zyryanova, Y Matsuura, T Kajimoto and R W Wein (Dordrecht: Springer) pp 59–82

Soja A J, Tchebakova N M, French N H, Flannigan M D, Shugart H H, Stocks B J, Sukhinin A I, Parfenova E I, Chapin III F S and Stackhouse P W Jr 2007 Climate-induced boreal forest change: predictions versus current observations *Glob. Planet. Change* **56** 274–96

Sulphur K C, Goldsmith S A, Galloway J M, Macumber A, Griffith F, Swindles G T, Patterson R T, Falck H and Clark I D 2016 Holocene fire regimes and treeline migration rates in sub-arctic Canada *Glob. Planet. Change* **145** 42–56

Toschev A I 2013 The light from Igarka through 300 years *Igarka Ancient, Igarka Mysterious. Collection of Essays on the History of the Igarka Region* vol 2 ed A I Toschev (Krasnoyarsk: KLASS PLUS) pp 6–45

Turetsky M R, Kane E S, Harden J W, Ottmar R D, Manies K L, Hoy E and Kasischke E S 2011 Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands *Nat. Geosci.* **4** 27–31

Wang Z, Huang J G, Ryzhkova N, Li J, Kryshen A, Voronin V, Li R, Bergeron Y and Drobyshev I 2021 352 years long fire history of a Siberian boreal forest and its primary driving factor *Glob. Planet. Change* **207** 103653

Whitlock C, Higuera P E, McWethy D B and Briles C E 2010 Paleoecological perspectives on fire ecology: revisiting the fire-regime concept *Open Ecol. J.* **3** 6–23