



HAL
open science

Temperature and fire controls on vegetation dynamics in Northern Ural (Russia) boreal forests during the Holocene based on brGDGT and pollen data

Chéïma Barhoumi, Guillemette Ménot, Sébastien Joannin, Adam Ali, Salomé Ansanay-Alex, Yulia Golubeva, Dmitry Subetto, Alexander Kryshen, Igor Drobyshev, Odile Peyron

► To cite this version:

Chéïma Barhoumi, Guillemette Ménot, Sébastien Joannin, Adam Ali, Salomé Ansanay-Alex, et al.. Temperature and fire controls on vegetation dynamics in Northern Ural (Russia) boreal forests during the Holocene based on brGDGT and pollen data. *Quaternary Science Reviews*, 2023, 305, pp.108014. 10.1016/j.quascirev.2023.108014 . hal-04012482

HAL Id: hal-04012482

<https://hal.science/hal-04012482>

Submitted on 17 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Temperature and fire controls on vegetation dynamics in Northern Ural (Russia) boreal**
2 **forests during the Holocene based on brGDGT and pollen data**

3

4 **Chéïma Barhoumi¹, Guillemette Ménot², Sébastien Joannin³, Adam A. Ali³, Salomé Ansanay-Alex², Yulia Golubeva⁴, Dmitry Subetto^{5, 6,}
5 ⁷, Alexander Kryshen⁸, Igor Drobyshev^{9, 10} and Odile Peyron³**

6 ¹Department of Palynology and Climate Dynamics, Albrecht-von-Haller Institute for Plant Sciences, University of Göttingen, Germany

7 ²University of Lyon, ENS de Lyon, Univ Lyon 1, CNRS, LGL-TPE, Lyon, France

8 ³Institut des Sciences de l'Evolution de Montpellier, Université de Montpellier, CNRS, IRD, EPHE, Montpellier, France

9 ⁴Institute of Geology of the Komi Science Centre, Russian Academy of Sciences, Syktyvkar, Russia

10 ⁵Herzen State Pedagogical University of Russia, Saint Petersburg, Russia

11 ⁶Northern Water Problem Institute of the Karelian Research Centre of Russian Academy of Sciences, Petrozavodsk, Russia

12 ⁷Institute for Water and Environmental Problems of the Siberian Branch of the Russian Academy of Sciences, Barnaul, Russia

13 ⁸Forest Research Institute of the Karelian Research Centre of Russian Academy of Sciences, Petrozavodsk, Russia

14 ⁹Southern Swedish Research Center, Swedish University of Agricultural Sciences, Alnap, Sweden

15 ¹⁰Institut de recherche sur les forêts, Université du Québec en Abitibi-Témiscamingue, Québec, Canada

16

17 **Corresponding author: cheima.barhoumi@gmail.com**

18

19 **Abstract**

20 Boreal vegetation is influenced by multiple factors such as climate and fire, but interactions between long- and short-term effects of climate upon
21 fire activity are complex and remain poorly studied, especially in Eurasia. To understand the relationships between climate, fire and vegetation
22 in Eurasia, we reconstruct the climate changes during the Holocene for the western section of the Northern Urals region, in the southern part of
23 the Republic of Komi. We relate these temperature reconstructions to pollen and charcoal records from the same region (Yaksha site, Republic
24 of Komi, Russia). We use here a combined approach based on pollen and molecular biomarkers (branched Glycerol Dialkyl Glycerol Tetraethers
25 or brGDGTs) to provide independent estimates of past temperatures. Our objectives were: (1) to understand the relationships between climate,
26 fire, vegetation and human activity during the Holocene at the local scale of Yaksha and (2) to provide a robust regional-scale climatic
27 reconstruction of the southern part of the Republic of Komi. Our study shows that climate had a major influence on the regional vegetation
28 between 10,000 and 4000 cal. yr BP. Subsequently, fire activity had a joint and growing impact on vegetation dynamics between 4000 and 600
29 cal. yr BP. Finally, from 600 until the present (2016 AD), human presence and activities had a greater impact on the fire regime and vegetation
30 than earlier in time, and combined with climate to influence the dynamics of the boreal forest. At the regional scale of the Republic of Komi and
31 the local scale of Yaksha, the Holocene Thermal Maximum was detected between 6800 and 4000 cal. yr BP, using pollen-based temperature
32 estimates but in brGDGT calibration (at 4000 cal. yr BP) commonly shared in the literature, together with evidence from neighboring regions in
33 the Eurasian boreal biome which were studied for different proxies (pollen, chironomids), and also with reference to climate models (General
34 Circulation Models).

35

36 **Keywords:** brGDGT; Pollen; Quantitative climate reconstructions; Holocene; Republic of Komi, Northern Urals, boreal forests, fire histories

37

38 1. Introduction

39 Boreal regions are among the most sensitive regions to current and future climate change (IPCC-AR6, Pörtner *et al.*, 2022). Climate influences
40 boreal biomes through direct control of the biomass accumulation rates and shapes natural disturbance regimes such as wildfires. General
41 Circulation Models (GCMs) integrating these effects, suggest that the circumboreal zone will shrink by 2071-2100 (Feng *et al.*, 2014). The
42 simulated decline of the boreal biome is attributed to a precipitation increase (especially in winter), and a temperature increase (between +6° and
43 +8°C), driving an increase in fire activity (Goetz *et al.*, 2007; de Groot *et al.*, 2013; Feng *et al.*, 2014; Hoegh-Guldberg *et al.*, 2018).

44 Climate and fire are the main drivers of vegetation, but interactions between them are complex and poorly studied in Eurasian boreal forests
45 (Glückler *et al.*, 2020; Goldammer and Furyaev, 1996; Kharuk *et al.*, 2021). Climate impacts fire frequency, fire severity and burned area. An
46 increase in fire activity likely increases the share of serotinous tree species such as *Betula pendula* Roth., *B. pubescens* Ehrh. (hereafter *Betula*
47 spp.) and *Pinus sylvestris* L. (hereafter *Pinus sylvestris*) (de Groot *et al.*, 2013; Goetz *et al.*, 2007). In contrast, enhanced summer precipitation
48 counteracts this effect and favors *Picea abies* (L.) H.Karst. (hereafter *Picea abies*) and *Pinus sibirica* Du Tour (hereafter *Pinus sibirica*) (Feng
49 *et al.*, 2014; Hoegh-Guldberg *et al.*, 2018). In North American boreal forests, fire events were found to be influenced by climate and human
50 activity, but also by the type of vegetation (eg Ali *et al.*, 2012; Camill *et al.*, 2009; Girardin *et al.*, 2013; Hu *et al.*, 2006; Remy *et al.*, 2017). For
51 example, in Canada, during the Mid-Holocene (6000 cal. yr BP), forest dominated by boreal mixed woodland vegetation was associated with low
52 fire frequency, while the climate was warm and dry. But from 3000 cal. yr BP, despite colder and wetter conditions, fire frequency increased,
53 because of the vegetation shift toward a dense needleleaf landscape (Girardin *et al.*, 2013).

54 Recent regional climate synthesis studies have pointed out specific regional patterns of climate variability during the Holocene period (Kaufman
55 *et al.*, 2020; Marcott *et al.*, 2013; Marsicek *et al.*, 2018; Mauri *et al.*, 2015; Herzschuh *et al.*, 2022). In Europe, the climate synthesis by Kaufman
56 *et al.*, (2020) based on various proxies such as pollen, chironomids, and molecular biomarkers, indicated a warming trend in the Northern latitudes
57 during the Early Holocene followed by a cooling since 6000 yr BP. This study also showed that the climate patterns are proxy-specific. For
58 example, the temperature optimum was recorded at 10,000 years BP from reconstructions based on chironomids and at 6000 years BP from
59 reconstructions based on pollen (Kaufman *et al.*, 2020). The climate synthesis by Herzschuh *et al.* (2022) based on pollen data only, also indicate
60 a temperature optimum between 8000 to 6000 yrs cal BP, but the timing and the amplitude of this optimum is strongly dependent on latitude, and
61 appears more marked at high latitudes (70 to 80 °N) and less marked between 60 to 70°N. These global syntheses also highlight the poor “past
62 climate” coverage of Eurasia and particularly of Russia, despite their geographical extent and role in global biochemical cycles. The general lack

63 of data is particularly apparent in the Republic of Komi, West of the Northern Urals area (Golubeva, 2008), despite its climatic relevance, at the
64 confluence of several atmospheric meteorological mechanisms (Ural Blocking, Siberian High, Arctic Oscillations) (Wang et al., 2010; Dole et
65 al., 2011; Cheung et al., 2012; H. Cheung and Zhou, 2015). Our earlier investigations of pollen and charcoal records in the Republic of Komi, in
66 the Yaksha area, revealed a shift in the boreal forest tree species as well as increasing fire activity during the Holocene (Barhoumi et al., 2020,
67 2019). However, the role of climate in the interactions between fire and vegetation has not yet been well documented. The only study of Holocene
68 climate in this area reconstructs increasing temperatures between 6000 and 4800 cal. yr BP (Golubeva, 2008). In the neighboring sub-regions of
69 Northern Europe and Fennoscandia, several studies based on pollen and chironomids indicate an increase in temperatures between 8000 and 3500
70 cal. yr BP (e.g. Seppä *et al.*, 2009; Salonen *et al.*, 2011). On the eastern side of the Urals, some studies of the Holocene climate have been carried
71 out in the Taymyr peninsula (Andreev et al., 2002; Velichko et al., 2002). These studies suggest that in the Early Holocene (between 10,300 and
72 9000 cal. yr BP), temperatures were slightly cooler (-1 °C) than today, but wetter (+ 50 mm precipitation compared to present). At the Entarny
73 site (Velichko et al., 2002), the Early Holocene also showed colder temperatures (-2.5 °C), but also less precipitation (- 25 mm compared to
74 today). The main studies of Holocene climate-vegetation-fire relationships in the east of the Republic of Komi were carried out in Siberia, around
75 Lake Baikal (Barhoumi et al., 2021; Bezrukova et al., 2013, 2003; Demske et al., 2005; Feng et al., 2014; Tarasov et al., 2007, 2009). According
76 to these studies, from the Early Holocene to the Mid-Holocene (11,000-8000 cal. yr BP), conditions were colder and wetter. From 8000 to 5000
77 cal. yr BP, the Lake Baikal region experienced its climatic optimum with wet conditions. From 5000 to 3000 cal. yr BP temperatures and
78 precipitation decreased before increasing again from 3000 to the present day. Most of these studies are based on pollen records and transfer
79 functions (eg Chevalier *et al.*, 2020) and vegetation-independent studies are needed to provide more reliable climate reconstructions.

80 With this study, we reconstruct Holocene temperature and precipitation patterns in the Republic of Komi using a coupled approach including
81 pollen data and organic biomarkers Glycerol Dialkyl Glycerol Tetraethers (GDGTs) (Dugerdil et al., 2021; Martin et al., 2020; Ramos-Román et
82 al., 2022; Robles et al., 2022). GDGTs are membrane lipid molecules of bacterial origin (Damsté et al., 2000; Weijers et al., 2006b), ubiquitously
83 found in oceans, lakes and rivers, peats and soils. GDGT distributions in these environments broadly correlate to mean annual temperatures and
84 pH (e.g. Weijers et al., 2007a; Petersee et al., 2010). Different calibrations were performed on soils, lake sediments and peatlands to infer
85 temperatures for GDGTs and more specifically brGDGTs (branched-GDGTs, Damsté *et al.*, 2000; Weijers, Schouten, van den Donker, *et al.*,
86 2007; Weijers, Schouten, Sluijs, *et al.*, 2007; Peterse *et al.*, 2012; Foster *et al.*, 2016; Naafs *et al.*, 2017; Dearing Crampton-Flood *et al.*, 2020).
87 To our knowledge, there are very few Holocene temperature reconstructions based on pollen grains and brGDGTs, which are independent climate

88 proxies (Dugerdil et al., 2021; Martin et al., 2020; Ramos-Román et al., 2022; Robles et al., 2022), and the brGDGT calibrations have never been
89 used to reconstruct Holocene temperatures in Russia.

90 The objective of this study is first to understand the links between climate, fire regime, vegetation dynamics and human activity over the Holocene
91 at the local scale of the Yaksha area, and secondly, to provide a robust reconstruction of the climate changes during the Holocene in the southern
92 part of the Republic of Komi, in the Northern Urals area. Temperature reconstructions for Yaksha are based on two independent proxies, pollen
93 and brGDGT. They are discussed in relation to the dynamics of both fire regimes and forest vegetation reconstructed from charcoal and pollen
94 by Barhoumi *et al.*, (2019, 2020). We provide a regional perspective on the climate trends through the Holocene by applying the same pollen
95 transfer functions to the other pollen records available from the area. Finally, we compare our results with climate reconstructions developed for
96 Northern Europe and neighboring regions.

97

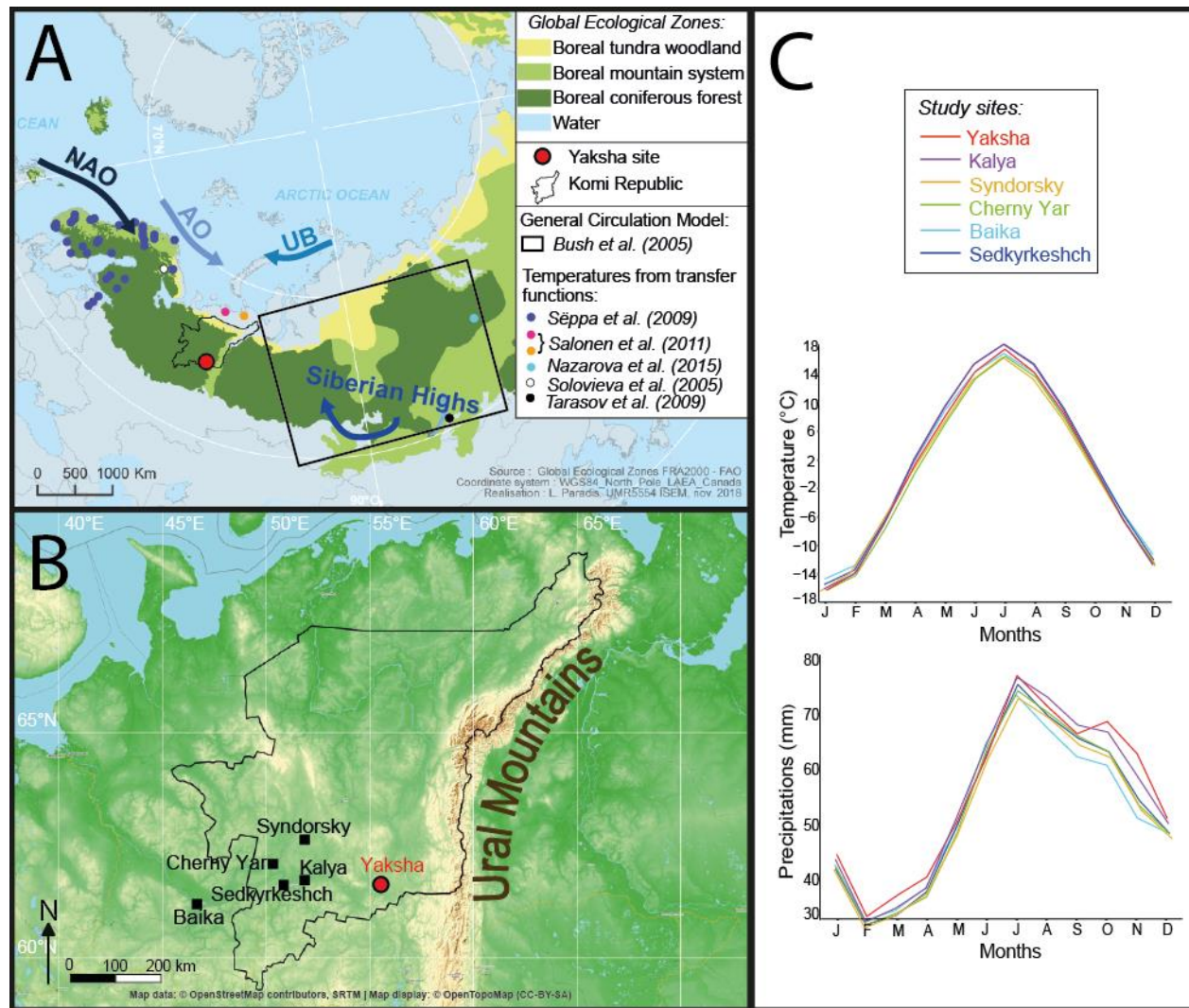
98 **2. Material and Methods**

99 *2.1 Environmental setting of the study area*

100 European boreal forests are constituted of patches of "light taiga" forests type dominated by *Pinus sylvestris*, *Larix sibirica* Ledeb. (hereafter
101 *Larix sibirica*) and *Betula* sp, associated with a surface fire regime in drier environments, and the "dark taiga" forests type, in wetter environments
102 dominated by *Picea abies*, *Pinus sibirica*, and *Abies sibirica*, where crown fires can occur (Goldammer, 2015; Lapenis et al., 2005; Schulze et
103 al., 2005; Shorohova et al., 2009). In the western part of the Northern Urals, the boreal vegetation is dominated by *Larix sibirica* and *Pinus* sp.

104 Yaksha. One of the study sites (Fig. 1, Table 1), is a forested peatbog of 4 hectares located in the south of the Republic of Komi (Barhoumi et al.,
105 2019, 2020). The Republic of Komi (Fig. 1) is a Russian administrative division of 415 900 km², occupying the western side of the Ural
106 Mountains. The soils of the region are mainly moraine and surface loams (Drobyshev et al., 2004a; Zaboeva, 1997), with podzolic soils and the
107 topography is flat except near the Ural Mountains (Naryshkin, 2003).

108 The local forest cover (assessed within a 10 km radius around the Yaksha site) consists today mainly of Scots pines (*Pinus sylvestris*, 84%),
109 spruce (*Picea abies*, 13%) and birch (*Betula pendula* and *B. pubescens*, 2%). In contrast, spruce forests dominate regionally.



110

111 *Figure 1 : A: The Republic of Komi in the Eurasian boreal biome (highlighted black contours). Location of the Yaksha coring site (red dot) as*
 112 *well as available temperature reconstructions cited in the text ((colored dots Solovieva, Tarasov and MacDonald, 2005; Seppä et al., 2009;*
 113 *Tarasov, Bezrukova and Krivonogov, 2009; Salonen et al., 2011; Nazarova et al., 2015a; Novenko and Olchev, 2015; Druzhinina et al., 2020).*
 114 *The black square corresponds to the zone for which climate outputs are available from the General Circulation Model GFDL (Bush, 2005), UB:*
 115 *Ural Blocking; AO: Arctic Oscillations; NAO: North Atlantic Oscillations. B: The Republic of Komi and the pollen records used for the Holocene*
 116 *climate regional synthesis (Yaksha – this study, Kalya, Syndorsky, Cherny Yar, Baika and Sedkyrkeshch (Borisova, 2002), Sedkyrkeshch*
 117 *(Golubeva, 2008), Kalya (Karmanov et al., 2011), Cherny Yar (Marchenko-Vagapova and Marieva, 2001) and Syndorsky (Golubeva, 2008)). C:*
 118 *Ombrothermic diagrams of each studied site (Grieser et al., 2006).*

119

120 In the Northern Urals region in Republic of Komi, a blocking, which is an anticyclonic or cyclonic vortex on a large scale and which remains
 121 quasi stationary, takes place (Ural Blocking, UB or also so-called Ural-Siberian Blocking, USB) (Cheung et al., 2013, 2012). UB (Fig. 1A) is
 122 generally more active and intense during boreal winter, acting as a barrier to Siberian Highs during this period, but amplifying its effect on the
 123 east-Asian sub-continent and causing harsher winters (Wang et al., 2010; Cheung et al., 2013; Cheung and Zhou, 2015). The intensity of UB

124 during winter is also linked to the phases of the Arctic Oscillation (AO) (Cheung et al., 2012). On the other hand, Rossby waves, another
125 atmospheric phenomena, occur and have an impact on the climate of Europe and Western Russia (Dole et al., 2011; Schubert et al., 2011, 2014).
126 For example, during summer 2010, strong heat waves occurred and had direct effects on wildfire activity in the Ural Mountains (Cheung et al.,
127 2013; Dole et al., 2011; Lau and Kim, 2012; Matsueda, 2011). In the study area, a UB occurring during the NAO positive phase may lead to a
128 regional warming in the atmospheric winter temperatures (Huang et al., 2017).

129 In the North of the Republic of Komi, the mean annual temperature is -6°C , while it is $+1^{\circ}\text{C}$ in the South (Figure 1C). Annual precipitation varies
130 between 450 and 700 mm (Drobyshev et al., 2004b; Grieser et al., 2006) (Figure 1C).

131

132 *2.2 Study sites and material*

133 We extracted two peat cores (Yak2-A and Yak3-A) using an 8-cm diameter Russian peat corer from the centers of the selected *Sphagnum*
134 peatlands. We built a composite sequence from the two cores Yak2-A and Yak3-A to obtain the longest chronology (Barhoumi et al., 2019, 2020).
135 The 0 to 300 cm interval of core Yak3-A provided the best temporal resolution of the Yaksha composite core. Although having a lower temporal
136 resolution than Yak3-A, the deeper part of core Yak2-A is constituted of organic-rich sediments reaching 11,000 cal. yr BP (Barhoumi et al.,
137 2019). The chronology was based on 12 radiocarbon dates, with the age model discussed in detail in Barhoumi et al. (2019) (see Appendix SI 1).
138 The Yaksha core provided both a charcoal record (Barhoumi et al., 2019) and a pollen record (Barhoumi et al., 2020). This study focuses on the
139 pollen-inferred climate reconstruction, the brGDGT analysis and the brGDGT-inferred temperature reconstruction.

140 We also benefited from five published pollen sequences (Fig. 1B, Table 1) located close to the Yaksha site to reconstruct the climate in the area
141 during the Holocene. From South to North, these pollen sequences were Baika (Borisova, 2002), Sedkyrkeshch (Golubeva, 2008), Kalya
142 (Karmanov et al., 2011), Cherny Yar (Marchenko-Vagapova and Marieva, 2001) and Syndorsky (Golubeva, 2008). Modern values for annual
143 temperatures and precipitation were established with the software New_Locclim (Grieser et al., 2006), a local climate estimator using the updated
144 FAOCLIM database (<https://www.faoswalim.org>). The 2010-2018 meteorological records for the coordinates of these sites, from the Worldclim
145 database, at a spatial resolution of 2.5 minutes, were used to verify the correlation between the mean annual temperatures, the mean summer
146 temperatures (June, July, August, corresponding to the fire season) and the mean temperatures of the months above 0°C (from April to October)
147 (Fick and Hijmans, 2017; Harris et al., 2014).

148

149 *Table 1: Pollen records selected for the climate reconstruction synthesis*

Name of the site	Coordinates	Elevation (a. s. l. in m)	Time covered (cal. yr BP)	References
Yaksha	61°43'N, 55°29'E 61°41'N, 55°34'E	135	10,047 to -50	This study; Barhoumi <i>et al.</i> , 2019, 2020.
Baika	61°16'N, 46°44'E	60	8775 - 50	Borisova, 2002
Cherny Yar	62°13'N, 50°17'E	90	8532 - 2876	Marchenko-Vagapova and Marieva, 2001
Kalya	61°48'N, 51°47'E	101	10,150 - 0	Karmanov <i>et al.</i> , 2011
Sedkyrkeshch	61°43'N, 50°51'E	95	4244 - 1197	Golubeva, 2008
Syndorsky	62°44'N, 51°51'E	138	9434 - 4727	Golubeva, 2008

150

151 These pollen sequences provide a vegetation synthesis in the Southern part of the Komi Republic as follows (Appendix SI 2):

152 At Yaksha, from 10,000 cal. yr BP to 5000 cal. yr BP, the vegetation was dominated by *Pinus sylvestris* and *Betula spp.* This vegetation fits with
153 the present description of a light taiga system. From 6050 BP to 100 cal. yr BP the pollen assemblages show an increase of *Picea* and the
154 occurrence of *Pinus sibirica*, suggesting the establishment of a predominantly dark taiga. From 3200 to 100 cal. yr BP, the dark taiga decreased
155 slowly and the light taiga reappeared, with an increase of *Pinus sylvestris*. From 100 cal. yr BP to 0 cal. yr BP, there was a strong increase in
156 *Betula spp.*

157 At Kalya, close to Yaksha, vegetation changes are consistent with the Yaksha ones: in the first half of the Holocene, from 9000 to 6000, light
158 taiga taxa were predominant. In the Mid-Holocene, *Picea abies* disappeared. Then from 5000 to 3500 cal. yr BP *Picea abies* increased again but
159 remained less numerous than *Pinus sylvestris* and *Betula spp.* From 3500 cal. yr BP, the light taiga was predominant with *Pinus sylvestris* and
160 *Betula spp.*

161 In Sedkyrkeshch, Syndorsky and Cherny Yar, pollen diagrams only cover part of the Holocene. At Sedkyrkeshch, few changes were observed
162 between 4000 and 1000 cal. yr BP. *Betula spp.* was the main taxa. *Pinus sylvestris* and *Picea abies* were equally present. In Syndorsky, *Betula*
163 *spp.* dominated in the Early Holocene (from 9000 to 6500 cal. yr BP), followed by *Pinus sylvestris* from 6500 to 5000 cal. yr BP. *Picea abies*
164 (dark taiga) culminated around 8000 cal. yr BP. In Cherny Yar, as in Yaksha and Kalya, the first half of the Holocene showed landscapes mostly
165 consisting of forests dominated by *Betula spp.* up to 6000 cal. yr BP. From 6000 to 3000 cal. yr BP, *Betula*-dominated forests and dark taiga
166 (*Picea abies*) were both present.

167 At Baika, before 10,000 cal. yr BP, the forests had not yet significantly developed; subsequently, *Picea abies*, *Pinus sylvestris* and *Betula spp.*
168 Forests developed. From 10,000 to 5000 cal. yr BP, dark taiga with *Picea abies* was predominant. From 5000 to 2500 cal. yr BP, *Picea abies*
169 decreased in favor of light taiga taxa, before developing again from 2500 cal. yr BP until the present day.

170

171 2.3 Pollen-inferred climate reconstructions: a multi-method approach

172 The pollen-based climate reconstructions were performed using two different methods, in order to increase the reliability of our reconstruction:
173 the Modern Analogue Technique (MAT; Guiot, 1990) and the Weighted Averaging Partial Least Squares Regression (WA-PLS; ter Braak and
174 Juggins, 1993). Transfer functions (such as WA-PLS) and assemblage approaches (such as MAT) require a robust modern pollen calibration
175 dataset. The MAT compares the composition of modern pollen assemblages compiled in the modern dataset with fossil pollen assemblages by
176 calculating a chord distance (a Euclidian distance on square-root-transformed abundances) (Guiot, 1990). When the chord distance reaches a
177 threshold value, modern pollen assemblages samples are rejected. On the other hand, the closest modern pollen samples are retained as the best
178 analogues, and the weighted average of their climate parameters is calculated to provide the past climate estimates (where the weights used are
179 the inverse of the chord distance) (Guiot, 1990). We chose between 6 to 8 analogues (depending on the site and the climatic parameters), using a
180 leave-one-out cross-validation test. WA-PLS is a transfer function, a regression method that assumes that the relationships between pollen
181 percentages and climate are unimodal, and that for each taxon there is an optimal climate variable value. With this method, the modern pollen
182 data set used can be considered as a large multidimensional matrix. Since there is collinearity between pollen taxa, and since some taxa are linked
183 to the climatic parameters of interest, it is possible to resize the dataset to a reduced number of components based on the linear predictors of the
184 parameter of interest and on the residual structure of the data when these predictors are removed (Peyron et al., 2013).

185 The modern dataset used here for the Yaksha and other sequences climate reconstructions was a sub-dataset from a Eurasian database (Peyron et
186 al., 2005), with more than 3000 sites (Peyron et al., 2008; Dugerdil et al., 2021). The sub-dataset selected here includes 2115 sites located mainly
187 in Russia but also in Northern and Central Europe. We chose to constrain the original dataset to increase the robustness of the climatic parameter
188 reconstruction. With that objective, we selected biomes comparable to the climate and ecosystems in the region of the Republic of Komi. The
189 sites corresponding to the biomes Cold Deciduous Forest, Cold Mixed Forest, Cold Coniferous Forest, Cold Steppe, Pioneer Environments, Taiga
190 forest and Tundra (Peyron et al., 1998; Prentice et al., 1996) were selected in the sub-dataset.

191 The R package ‘Rioja’ was used to reconstruct the past climate parameters with both methods (Juggins, 2009; Juggins and Juggins, 2020). Climate
192 parameters are: mean annual temperatures (TANN) and annual precipitation (PANN), mean summer temperatures (MTWA) and summer
193 precipitation (SUMMERPR). The performance of the two methods was tested on the database by randomly using 60% of it to calibrate and the
194 remaining 40% to test the transfer functions. The same test was carried out by selecting the 19 samples from the database between latitudes 40
195 and 50°N and longitudes 40 and 50°E, representing the closest samples from the database to the Yaksha site. The correlations between the
196 reconstructed values and the observed values of the database are presented in Appendix SI 3 and SI 4. A redundancy analysis (RDA) was
197 performed to compare the main pollen taxa (*Betula* spp., *Pinus sylvestris*, *Pinus sibirica*, *Picea abies*, *Abies sibirica* and Other taxa) with
198 reconstructed climate parameters inferred from pollen MAT (TANN, PANN, MTWA and SUMMERPR), fire activity (mFRI) and human
199 population density. The fire activity data come from Barhoumi et al. (2020, 2019) who calculated and computed temporally the mean Fire Return
200 Interval of Yaksha study site. The human population density numerical data come from the HYDE 3.1 database (Klein Goldewijk et al., 2011)
201 and were downloaded here: <https://landuse.sites.uu.nl/datasets/>.

202

203 2.4 GDGT analysis

204 Key samples representative of the sedimentary sequences and the lithologic transitions were processed for GDGT analyses at ENS de Lyon
205 (LGLTPE, France): 26 and 12 from Yak3-A and Yak2-A, respectively. Samples were freeze-dried and grounded. To aliquots of less than a gram,
206 a C₄₆ GDGT standard solution, at 10 ng.µL⁻¹ was added (Huguet et al., 2006). Then, lipids were microwaved (MARS, CEM) with dichloromethane
207 (DCM):MeOH (3:1). Total lipid extracts were separated into polar and apolar fractions on an Al₂O₃ column (1 g) with hexane:DCM (1:1) and
208 DCM/MeOH (1:1). The separated fractions were then analyzed using a High Performance Liquid Chromatography Mass Spectrometer (HPLC-
209 MS, Agilent 1200) (Hopmans et al., 2016; Davtian et al., 2018). The detected peak signals were integrated on the Agilent, LC/MS Chemstation
210 Software. Branched-GDGT compositions (brGDGTs, Damsté *et al.*, 2000; Weijers, Schouten, Sluijs *et al.*, 2007, 2007) were quantified.

211 The reproducibility and stability of the analytical process was assessed through regular chemistry and analysis of an internal standard peat sample.
212 Reproducibility of the measurements was calculated by replicate analyses of two contrasted samples of the sediment core.

213

214 2.5 GDGT indices and temperature reconstructions

215 BrGDGTs (see compound shape in Figure 1 from Naafs *et al.*, 2018) are distinguished by the proportions of tetra- (I), penta- (II) and hexa- (III)
 216 methylated forms and by the number of cyclopentane moieties, which can be 0 (a), 1 (b), or 2 (c). brGDGT fractional abundances were combined
 217 into several indices (Table 2) such as the Branched and Isoprenoid Tetraether Index (BIT - Hopmans *et al.*, 2004), the IIIa/IIa ratio (Xiao *et al.*,
 218 2016), in which we included the 5/6 and 7-Methylated form, the Cyclization ratio of Branched Tetraethers (CBT - Weijers *et al.*, 2007a) and the
 219 Methylation of Branched Tetraether (MBT' - Peterse *et al.*, 2012 and MBT'_{5Me} - De Jonge *et al.*, 2014b).

220 *Table 2: Indices and temperature calibrations based on brGDGT fractional abundances*

Indices/Temperature calibrations	Formula or model	References
CBT	$= -\log \left(\frac{Ib + IIb + IIb6Me}{Ia + IIa + IIa6Me} \right)$	(Weijers <i>et al.</i> , 2007b)
MBT'	$= \frac{Ia + Ib + Ic}{Ia + Ib + Ic + IIa' + IIa'' + IIa7Me + IIb' + IIb'' + IIc' + IIc'' + IIIa' + IIIa'' + IIIb' + IIIb'' + IIIc'}$	(Peterse <i>et al.</i> , 2012)
MBT' _{5Me}	$= \frac{Ia + Ib + Ic}{Ia + Ib + Ic + IIa + IIb + IIc + IIIa}$	(De Jonge <i>et al.</i> , 2014)
CI	$= \frac{Ia}{Ia + IIa + IIIa}$	(De Jonge <i>et al.</i> , 2019)
MAT _{Peterse}	$= 0.81 - 5.67 \times CBT + 31.0 \times MBT'$	(Peterse <i>et al.</i> , 2012)
MAT _{Naafs}	$= 52.18 \times MBT'_{5Me} - 23.05$	(Naafs <i>et al.</i> , 2017)
MAT _{Crampton-Flood}	<i>Bayesian regression model (BayMBT0, for mean annual temperatures above zero)</i>	(Dearing Crampton-Flood <i>et al.</i> , 2020)
MST _{Foster}	$= 18.7 + (80 \times Ib) - (23.05 \times II) - (19.4 \times III) + (369.9 \times IIIb)$	(Foster <i>et al.</i> , 2016)

221

222 Temperature reconstructions were based upon several indices, including the Methyl Index of Branched Tetraether (MBT - (Weijers *et al.*, 2007b).
 223 This has been modified by Peterse *et al.* (2012) to yield MBT', and by Naafs *et al.* (2017) to give MBT'_{5Me}, excluding brGDGT 6-methyl. We
 224 tested four calibration equations and models, assessed on global datasets of soils and peats. This allowed us to derive Mean Annual Air
 225 Temperature (hereafter called MAT_{Peterse} and MAT_{Naafs}), Mean Annual Temperature above 0°C (hereafter called MAT_{Crampton-Flood}) and Mean
 226 Summer Air Temperature (hereafter called MST_{Foster}). These calibrations are respectively based on Peterse *et al.* (2012), Naafs *et al.* (2017),
 227 Dearing Crampton-Flood *et al.*, (2020) and Foster *et al.*, (2016).

228

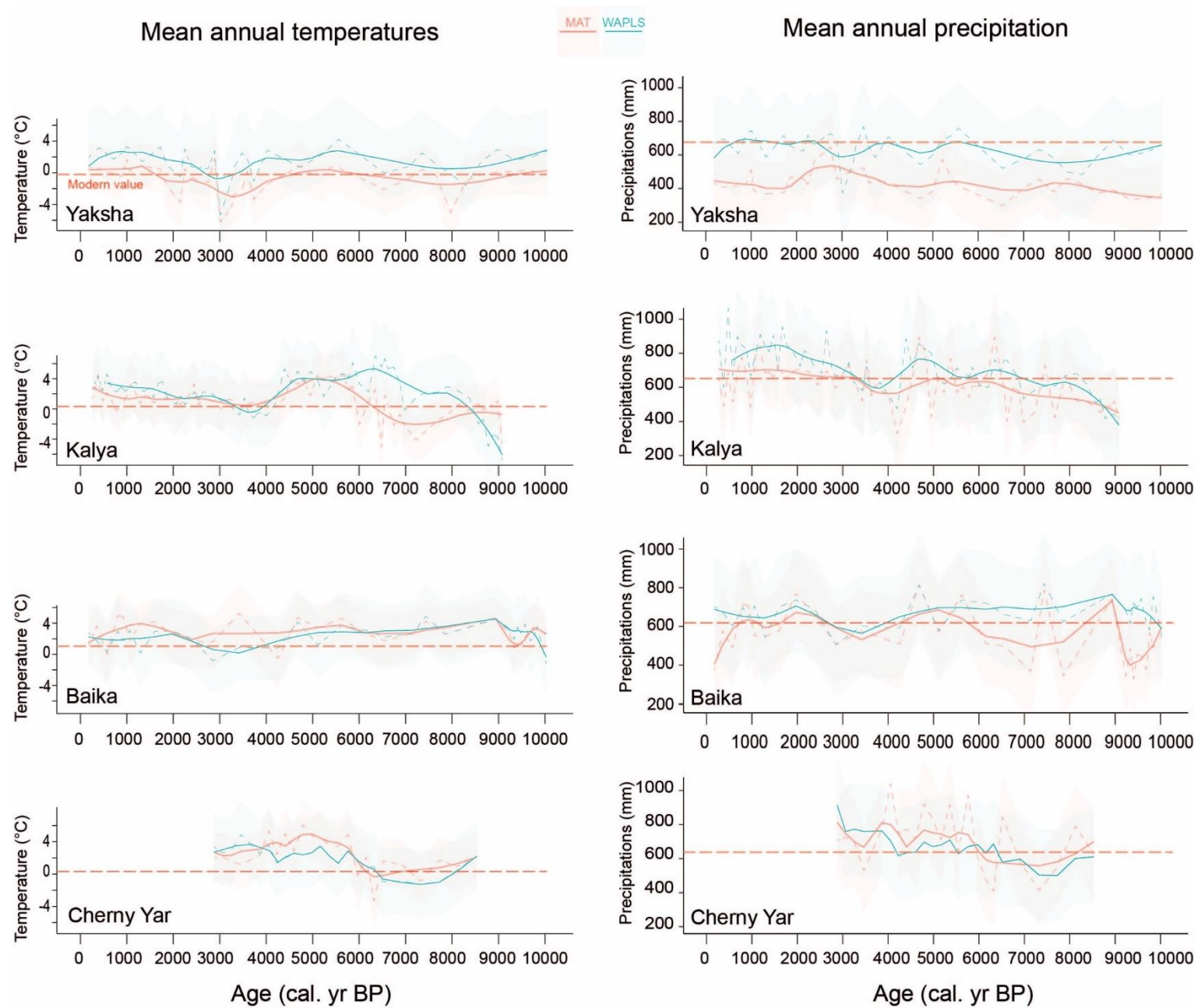
229 **3. Results**

230 *3.1 Pollen-inferred climate patterns*

231 The mean annual temperatures (TANN) and annual precipitation (PANN) of the Yaksha, Kalya, Baika and Cherny Yar sites are presented in Fig.
232 2. The two other sites (Sedkyrkeshch and Syndorsky), which cover only a small part of the Holocene, are presented in Appendix SI 5, as well as
233 mean summer temperatures (MTWA) and summer precipitation for each site.

234 During the Holocene, the mean annual temperatures reconstructed using the Modern Analogue Technique and the Weighted Averaging Partial
235 Least Squares Regression, from the different cores (Yaksha, Kalya, Baika, Cherny Yar) were broadly similar in terms of trends and amplitudes
236 (Fig. 2). In Yaksha, Kalya and Baika, the temperature values reconstructed from the most recent samples were very close to the measured modern
237 values (-0.37°C at Yaksha, $+0.39^{\circ}\text{C}$ at Kalya and $+1.46^{\circ}\text{C}$ at Baika). From 10,000 to 7000 cal. yr BP, higher than present day temperatures were
238 reconstructed for Yaksha and Baika ($+3^{\circ}\text{C}$). At Kalya, however, the temperature trends reconstructed with the two methods were similar only
239 from 5500 to 0 cal. yr BP (Fig. 2). Notably, the climate reconstruction began from 9000 cal. yr BP with lower values than today and the
240 temperature increased until 7000 cal. yr BP. Yaksha, Kalya and Baika records show a Holocene Thermal Maximum (HTM) extending between
241 6800 cal. yr BP and 4000 cal. yr BP, with temperature values from $+1^{\circ}\text{C}$ (MAT) to $+3^{\circ}\text{C}$ (WA-PLS) relative to the present. From 4000 to 3000
242 cal. yr BP, the results show a general decrease in temperatures, with values lower than today (Yaksha) or very close to modern values (Baika and
243 Kalya). Then, from 3000 to 0 cal. yr BP, the temperatures rose gradually and reach current values.

244 Mean annual precipitation (PANN) estimates at Yaksha show differences between the two methods but for Kalya, Baika and Cherny Yar, the
245 precipitation reconstructions were very similar for MAT and WA-PLS (Fig. 2). For all these sites (except Baika), there was a general increase in
246 precipitation during the Holocene. At the onset of the Holocene, between 10,000 and 8000 cal. yr BP, Yaksha and Kalya show precipitation values
247 slightly below the modern values (about 630 mm/year, especially with MAT results). Baika recorded a decrease of precipitation from 9000 to
248 8000 cal. yr BP. Then, from 8000 to 5000 cal. yr BP, the PANN at Baika shows an increasing trend, as do all the other sites. From 5000 cal. yr
249 BP, a precipitation decrease was observed (WA-PLS at Yaksha), up to about 3500 cal. yr BP. From 3500 cal. yr BP, PANN stabilized at modern
250 values for Yaksha (WA-PLS) and Baika. They increased up to 1500 cal. yr BP in Kalya, before gradually decreasing to the later values up to the
251 present day.



252

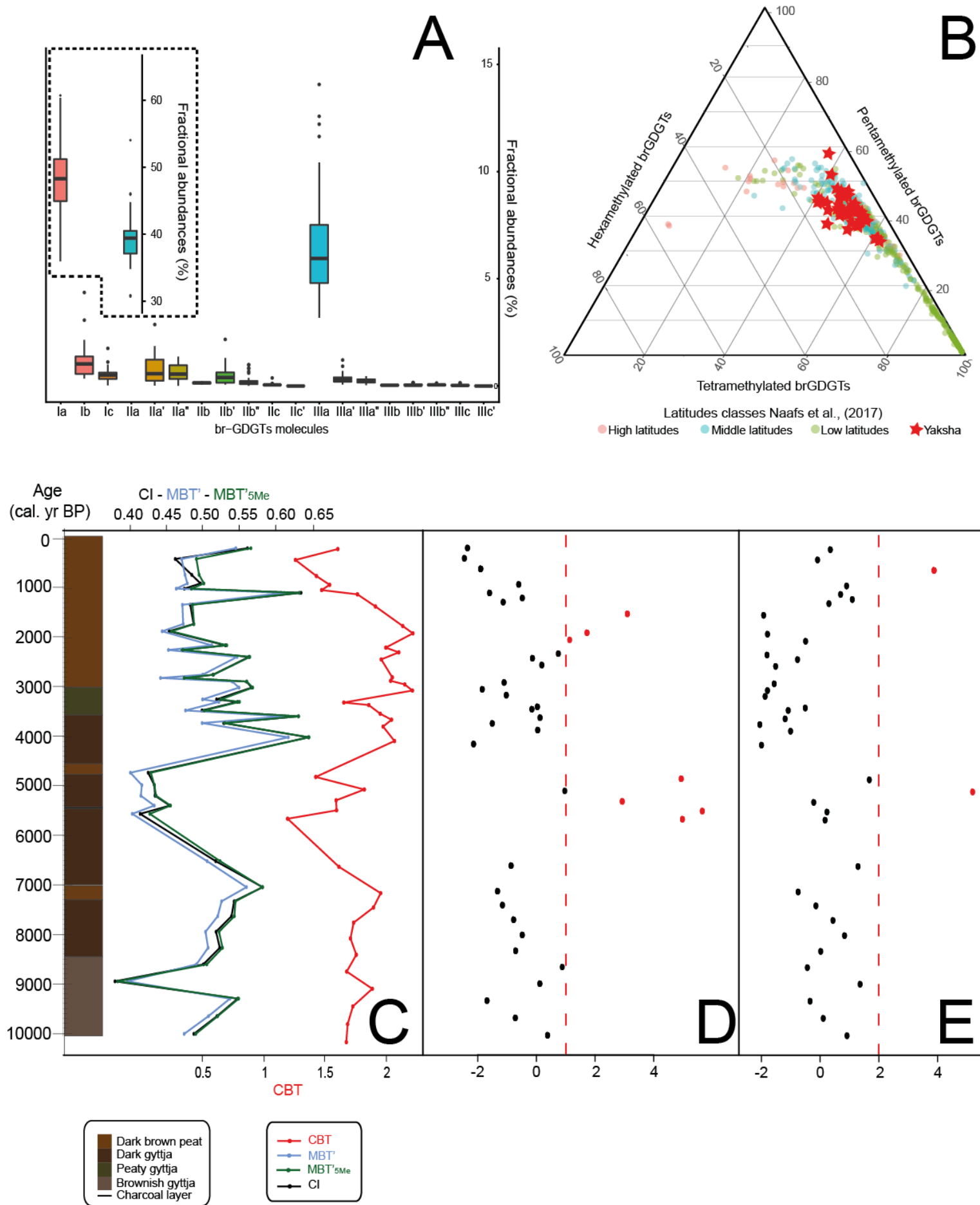
253 *Figure 2: Regional climatic synthesis for the Republic of Komi from pollen-based reconstructions. Mean annual temperature and mean annual*
 254 *precipitation (dashed lines) were calculated with the Modern Analogue technique (MAT) and the Weighted Averaging Partial Least Squares*
 255 *Regression (WA-PLS) and smoothed with Loess (span = 0.3, solid lines). Shaded areas are confidence interval. Red dashed lines are modern*
 256 *values for each site.*

257

258 *3.2 GDGT abundances and indices*

259 Within the Yaksha record, the majority of brGDGTs are tetramethylated Ia (48%) and pentamethylated forms IIa (39%) (Fig. 3A). The
260 hexamethylated form IIIa represents 6% of the total brGDGTs. The remaining brGDGTs are present at values below 2%. The GDGT signatures
261 from Yaksha were similar to those in the global database (Naafs *et al.*, 2017) and were characteristic of mid- and high-latitude sites (Fig. 3B).
262 The average BIT index is 0.998 ± 0.005 . The MBT'_{5Me} and MBT' signals (used to infer temperature) vary little along the core (Fig. 3C), but show
263 the lowest values (0.39 - 0.4) between 4740 and 5580 cal. yr BP and at 8980 cal. yr BP. The maximum value of 0.64 is at 4020 cal. yr BP. CI
264 (Community Index, Table 2, De Jonge *et al.*, 2019) shows the same variations as the MBT'_{5Me} and MBT' signals and values similar to those of
265 MBT'_{5Me}. These indices show high values at the very beginning of the Holocene, from 10,000 to about 9200 cal. yr BP. There are also high values
266 between 8600 and 6500 cal. yr BP, and again between 4500 cal. yr BP. until the end of the record. PCA of Yaksha brGDGTs was performed (see
267 SI 6). The eigenvalues of the first 2 axes of this PCA are presented in Fig. 3D (axis 1) and 3E (axis 2). Outlier brGDGT samples were highlighted
268 by cutoff values of 1 (for axis 1) and 2 (for axis 2).

269



271 *Figure 3: A: brGDGT fractional abundances in the Yaksha sequence measurement represented against two % scales. B: Ternary plot of the*
272 *relative abundances of tetra-, penta-, and hexamethylated brGDGTs compared to the general database from Naafs et al. (2017) sorted by latitude*
273 *classes. C: CBT, CI, MBT' and MBT'_{5Me} indices. D and E: Individual PCA eigenvalues according to axis 1 (D) and axis 2 (E). Red dots are*
274 *samples above the threshold separating main samples from outlier points*

275

276

277 **4. Discussion**

278 *4.1 Yaksha local temperature reconstructions: brGDGT and pollen comparison*

279 *4.1.1 brGDGT origins*

280 The brGDGT signal from the Yaksha study site is consistent with a terrigenous origin: the BIT index remains very close to 1 throughout the
281 sediment core (Hopmans et al., 2004).

282 BrGDGT forms without cyclopentane moieties, Ia and IIa, are the main compounds within the Yaksha sedimentary core (Fig. 3A). This agrees
283 with several studies on brGDGTs from soils and peatlands (Li et al., 2017; Loomis et al., 2014; Sun et al., 2011; Weijers et al., 2010, 2007b,
284 2006a, 2006b). This observation also confirms that the production of Yaksha brGDGTs is mainly of terrigenous origin since *in situ* production
285 contains more methyl groups and cycle forms (Loomis et al., 2014; Tierney et al., 2012, 2010). Form IIIa, which is the third most abundant
286 brGDGT compound here, is therefore likely to have come from the small amount which would have been produced *in situ*, when the peatland
287 was submerged (Buckles et al., 2014; Cao et al., 2017; Loomis et al., 2014, 2011; Tierney et al., 2010). The variations in CI appear to coincide
288 with the sample outliers indicated by the PCA eigenvalues of the brGDGTs samples. This could indicate a shift in brGDGT-producer communities,
289 since they may respond differently to varying atmospheric temperatures (De Jonge et al., 2019). These samples (at 400 cal. yr BP ; from 1330 to
290 1870 cal. yr BP and from 4740 to 5580 cal. yr BP) were therefore not considered in the discussion and interpretation of the results of the
291 temperature calibrations.

292 Moreover, peatland is an environment in which one part (catotelm) is anoxic and constantly saturated with water, while another part (acrotelm)
293 contains living *Sphagna* and exhibits large variability in oxygen content. Studies have shown that the concentration of brGDGTs is significantly
294 higher in catotelm than in acrotelm (Weijers et al., 2004). This differentiates the dynamics of brGDGT communities depending on the nature of
295 the sediment through the core and has an impact on reconstruction of the annual air temperatures. For this reason we tested four calibrations, one

296 for soil environments, $\text{MAT}_{\text{Peterse}}$ (Peterse et al., 2012), and two specific to peatland environments, $\text{MAT}_{\text{Naafs}}$ and $\text{MAT}_{\text{Crampton-Flood}}$, (Dearing
297 Crampton-Flood et al., 2020; Naafs et al., 2017). We tested another calibration, reconstructing summer temperatures or temperatures of the months
298 above 0°C, regionally adapted for Antarctic and sub-Antarctic lakes, $\text{MST}_{\text{Foster}}$ (Foster et al., 2016), which is close to the climate of the Republic
299 of Komi. (Fig. 4).

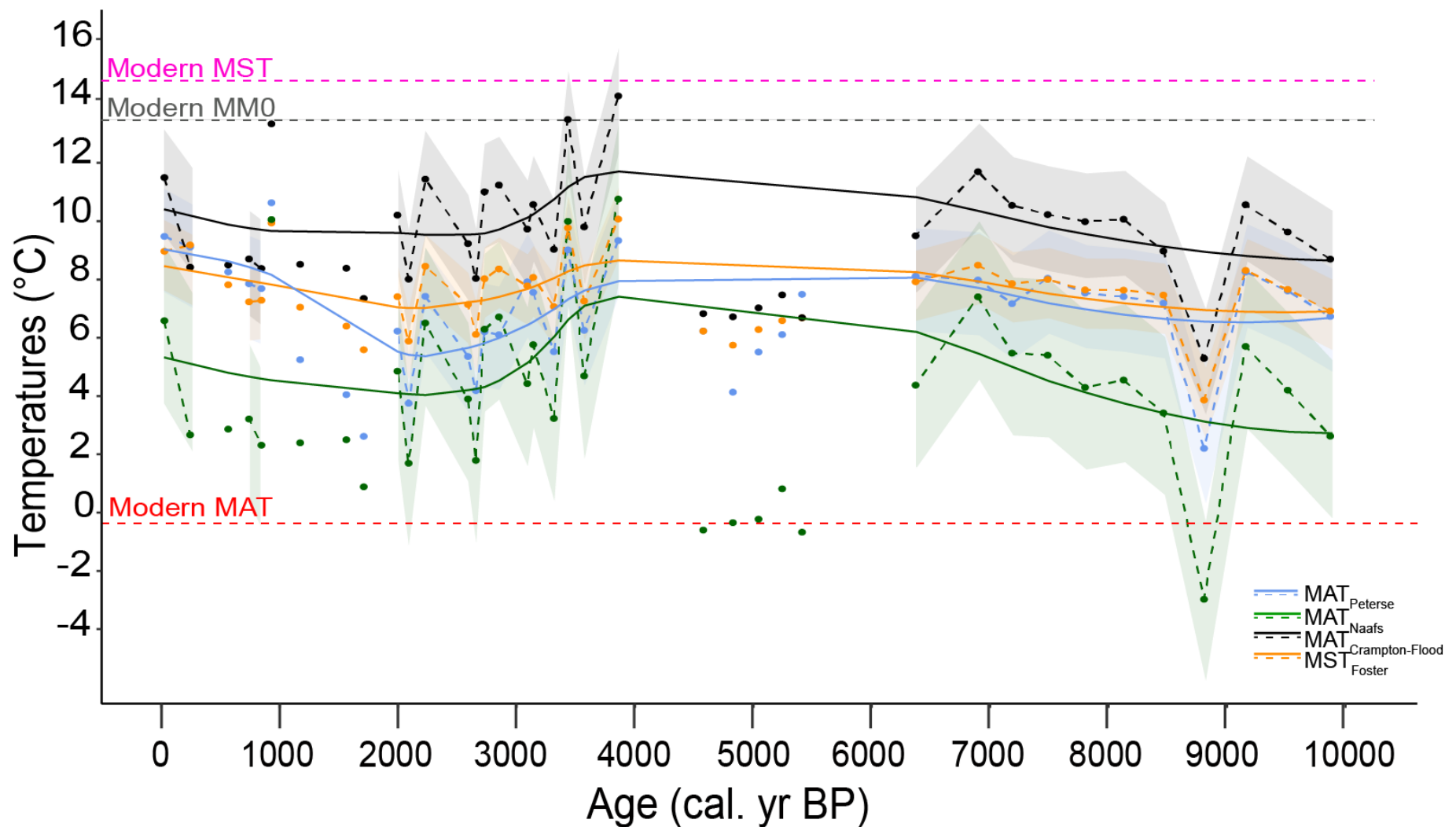
300

301 4.1.2 *brGDGT calibration for mean annual temperatures reconstruction*

302 The brGDGT reconstructed temperatures (Fig. 4) ranged between: $\text{MAT}_{\text{Peterse}}$: +2.5 to +10.5°C, $\text{MST}_{\text{Foster}}$: +5.5 to +9.9°C, $\text{MAT}_{\text{Naafs}}$: -3 to +10.6°C
303 and $\text{MAT}_{\text{Crampton-Flood}}$: +5.2 to +14.1°C. The four calibrations show similar patterns. The first half of the Holocene, from 10,000 to 6500 cal. yr
304 BP, shows a steady increase of the temperatures (+2°C). Then, from 4000 cal. yr BP to 2100 cal. yr BP, temperatures decrease before increasing
305 again in the Late Holocene. Both peat calibrations, $\text{MAT}_{\text{Naafs}}$ and $\text{MAT}_{\text{Crampton-Flood}}$, show more marked trends than the lake calibrations, $\text{MAT}_{\text{Peterse}}$
306 and $\text{MST}_{\text{Foster}}$. Highest temperature values are not reconstructed by the summer calibrations, but by the mean annual temperatures above zero
307 calibration from Crampton-Flood *et al.* (2020). The GDGT-based temperature values are higher than the current values, and differ from those of
308 pollen transfer-functions: we will therefore discuss trends rather than absolute values.

309 The warmest Holocene temperature appears to be at 4000 cal. yr BP, just before a temperature drop that spans the next 2000 years. This
310 corresponds to the end of the HTM time frame reconstructed by the pollen transfer functions. However, it should be noted that from 6500 to 4000
311 cal. yr BP and from 1870 to 1330 cal yr BP and at 400 cal. yr BP, there is no interpretation of the calibration results, these samples having been
312 excluded because of suspected correspondence to another community of brGDGTs. BrGDGTs analyzed in this study came from a peat sediment
313 core, which adds temperature reconstruction biases (Weijers et al., 2010). It is more notably more difficult to set up reconstructions of peatland
314 or soil temperatures, because the modern data are less well known and/or less available, and also generally less used in paleoecology (Weijers et
315 al., 2011, 2007b). The dual origin (terrestrial and lacustrine) of brGDGTs blurs the signal between the composition of brGDGTs and the
316 calculation of CBT and therefore contributes to the error that accompanies them (Sun et al., 2011). Other biases in the reconstruction of
317 temperatures from brGDGTs have been brought to light. The literature shows that brGDGT temperature calibrations are likely to both
318 underestimate past temperatures (Li et al., 2017; Pearson et al., 2011; Tyler et al., 2010; Zink et al., 2010) but and at other times to overestimate
319 them (Wang et al., 2012; Li et al., 2017), and this even with regional calibrations. The temperature seasonality, which is high in the region of the

320 study site, is a factor that enhances the overestimation of temperatures (Dearing Crampton-Flood et al., 2020) and this is what is clearly observed
321 with all the calibrations that have been tested, compared to the modern average annual temperatures at Yaksha. Although bacterial communities
322 are present and active in winter (Drotz et al., 2010; Nedwell, 1999), bacterial activity appears to be more intense in summer, with different
323 bacterial communities than in the winter season (Schostag et al., 2015; Sun et al., 2011). The calibrations provided for high latitudes such as that
324 of Foster *et al.* (2016), but also that of Dearing Crampton-Flood *et al.* (2020), more recently, with the use of their BayMBT0 model, would
325 therefore correspond more to growing season, rather than to the mean annual temperature. External factors can also influence brGDGT
326 distributions and temperature reconstructions, such as precipitation and humidity changes (Dearing Crampton-Flood et al., 2020). Finally,
327 vegetation can also be an element of variability in the brGDGT production (from soils and from the watershed) (Ayari et al., 2013; Huguet et al.,
328 2013; Naeher et al., 2014; Weijers et al., 2011). At Yaksha, the time periods that show the highest variability in the brGDGT signal are between
329 9100 and 8500 cal. yr BP, 5600 and 4700 cal. yr BP and 1500 cal. yr BP to the present day (Fig. 3C, CBT and IIIa/IIa indices, tetramethylated
330 brGDGTs, rings tetra- and pentamethylated 5 Me brGDGTs). The alternation of light taiga and dark taiga could therefore have played a role in
331 the diversity of the brGDGT present. This role is however not fully assessed so far (Buckles et al., 2014; Davtian et al., 2016; Weijers et al.,
332 2010).



333

334 *Figure 4: Yaksha GDGT temperature reconstructions. Blue: Mean Annual Temperature ($MAT_{Peterse}$) after Peterse et al. (2012), green: Mean*
 335 *Annual Air Temperature (MAT_{Naafs}), after Naafs et al. (2017), black: Mean Annual Temperature above 0 ($MAT_{Crampton-Flood}$), after Dearing*
 336 *Crampton-Flood et al. (2020), orange: Mean Sub-Arctic Air Temperature (MST_{Foster}) after Foster et al. (2016). The reconstructed temperatures*
 337 *are smoothed with the R function Loess (span = 0.3). Modern Mean Annual Temperature (Modern MAT) is represented in red dotted line, Modern*
 338 *Mean Summer Temperature (Modern MST) is represented in pink dotted line and Modern Mean Months above 0°C Temperature (Modern MM0)*
 339 *is represented in grey dotted line.*

340

341

4.1.3 Pollen-inferred climate reconstructions

342 The reconstructed climatic parameters of the Holocene in the Republic of Komi show similar trends in the two-methods: MAT and WA-PLS
 343 (Fig. 2). A comparable agreement between the climate reconstructions obtained with the two methods can be observed at a more regional scale,
 344 namely the comparison between Europe and the Northern Hemisphere (Herzschuh et al., 2021). Here, the results from the MAT generally indicate
 345 more variability than the WA-PLS method, as has already been observed in other studies, because of the degree of sensitivity of the method (Birks

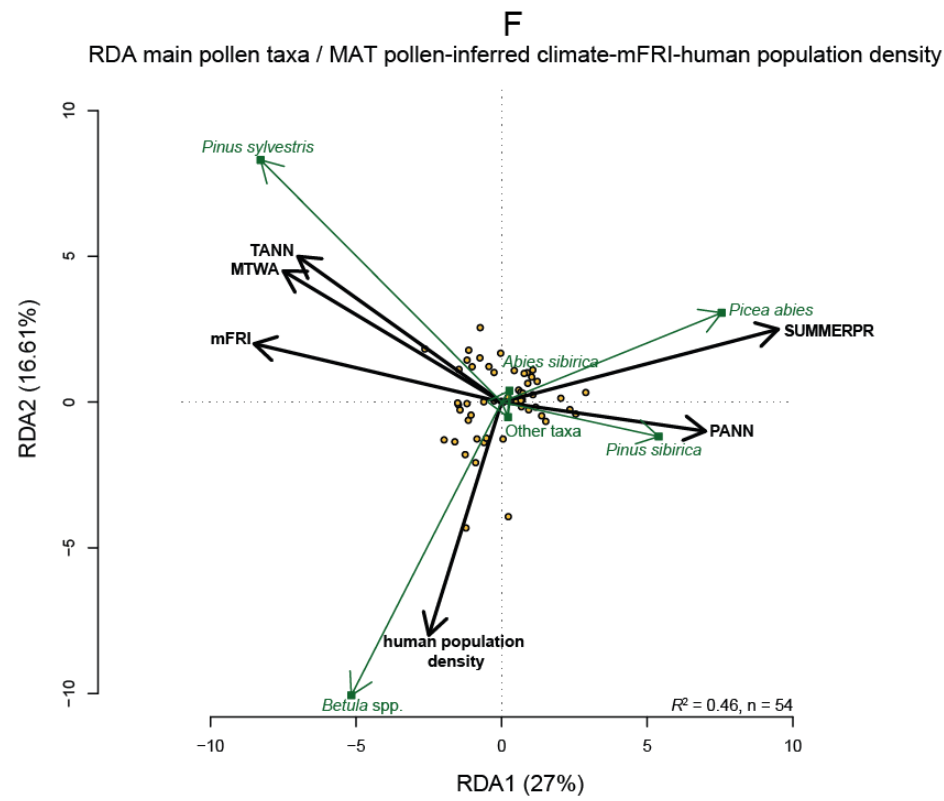
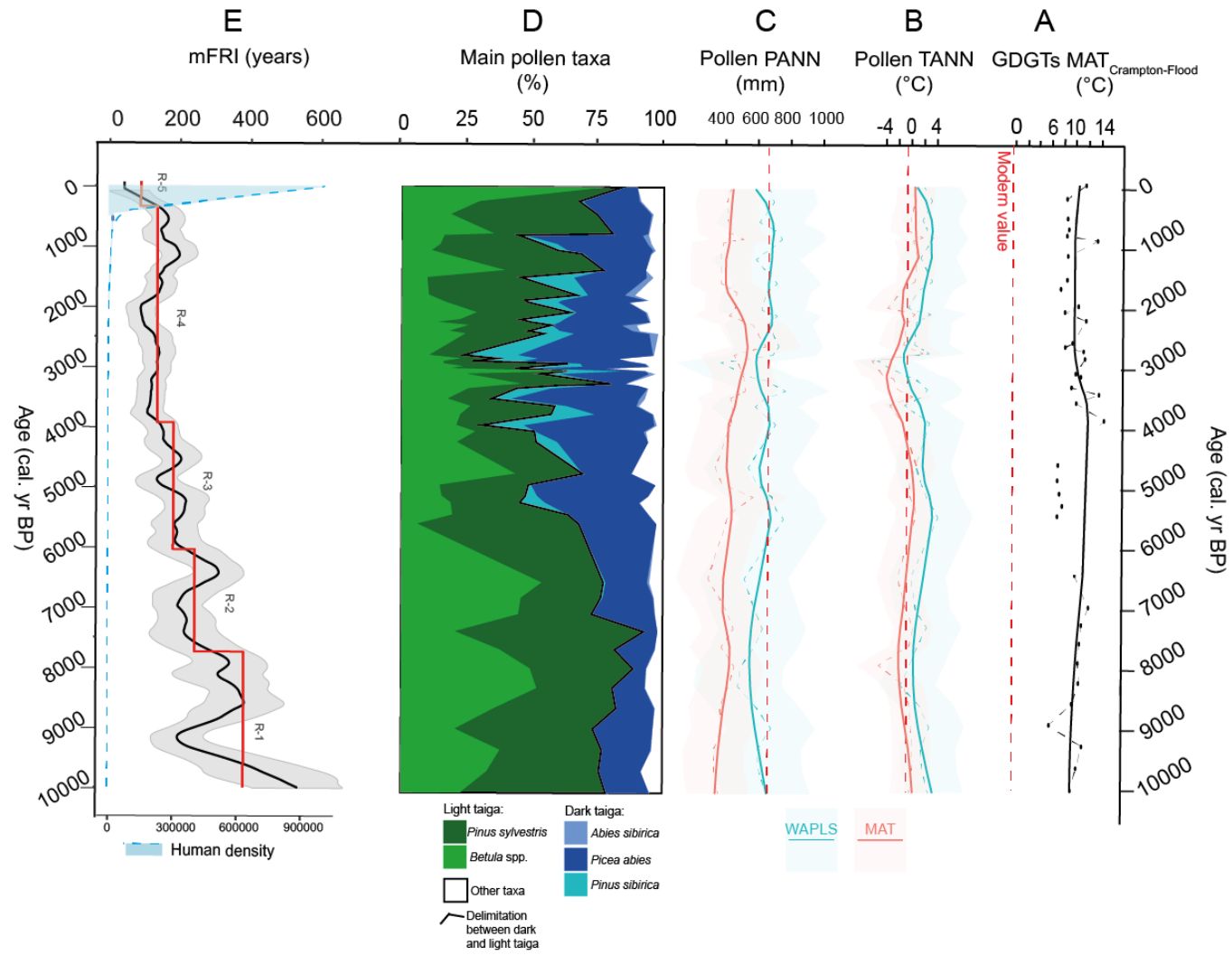
346 and Seppä, 2004; Brewer et al., 2008; Dugerdil et al., 2021; Robles et al., 2022). The MAT has been widely used to reconstruct the climate
347 changes in Europe over the Late Glacial and Holocene (Peyron et al., 2005, 2011, 2013; Mauri et al., 2015; Ponel et al., 2022) as the MAT is
348 usually more sensitive to minor variations in the pollen assemblage, compared to the WA-PLS (Brewer et al., 2008; Sinopoli et al., 2019, Hershuzh
349 et al., 2022). However, the MAT may be less reliable when the vegetation is only dominated by two or three taxa, as is the case in our study
350 (Salonen et al., 2012). This is the reason the WA-PLS has been more often used than the MAT to reconstruct Holocene temperatures in the boreal
351 regions of Scandinavia (Seppä et al., 2009; Salonen et al., 2011, 2012). The WA-PLS method is generally less efficient when the modern pollen
352 dataset is large (Chevalier et al., 2020; Dugerdil et al., 2021), but in this study the dataset was reduced to records comparable in terms of biomes,
353 which is also recommended as a method to increase the sensitivity of the MAT (Birks and Seppä, 2004). Moreover, the main disadvantage of
354 WA-PLS is that it tends to overestimate values (Birks, 1998), which is observed in the results of our study. Our results show that in the Republic
355 of Komi, the margins of error from the MAT (RSEP = 3.1 for TANN ; RSEP = 197.6 for PANN) are lower than those from the WA-PLS (RSEP
356 = 4.3 for TANN ; RSEP = 266.7 for PANN). However, both methods appear fairly reliable because they provide similar trends for the Holocene.

357

358 *4.1.4 Comparison of brGDGT- and pollen-inferred temperature reconstructions*

359 The reconstructions based on brGDGTs and pollen show different absolute values and amplitudes of variations (Fig. 5A, B). With the brGDGT
360 calibration of the temperatures, the amplitude of temperature variation is more than 7°C. In contrast with pollen records, the amplitude is around
361 4°C. However, the Holocene temperature variations comparing the two methods show more similarity. The Early Holocene begins with a slight
362 drop in pollen-inferred temperatures, till about 8000 cal. yr BP, from which time the temperature trends rise. This corresponds fairly well with
363 the brGDGT calibration $MAT_{\text{Crampton-Flood}}$, which shows an increase in temperatures during whole Early Holocene. The warmest period from
364 pollen-inferred temperatures is recorded between 6800 and 4000 cal. yr. BP. At 4000 cal. yr. BP., the $MAT_{\text{Crampton-Flood}}$ calibration also shows its
365 highest temperature, thus presenting a shared identification of the HTM between the two temperature reconstruction methods (the mid-Holocene
366 part of the brGDGT temperature calibrations being put to one side and not compared with pollen-inferred temperatures). Thereafter, trends for
367 both signals are similar, since a synchronous decrease in temperatures is indicated after 4000 cal. yr BP, followed by a net increase from 3000
368 cal. yr BP for the pollen signal and from 2000 cal. yr BP for the brGDGT calibration.

369



371 *Figure 5: Yaksha local dynamics. A: brGDGT-inferred temperatures $MAT_{Crampton-Flood}$, after Dearing Crampton-Flood et al. (2020). B: Pollen-*
372 *inferred mean annual temperatures TANN. C: Pollen-inferred mean annual precipitation MAP. D: Main pollen taxa cumulative diagram. E:*
373 *Mean Fire Return Interval and human population density in the Republic of Komi (mFRI, Barhoumi et al., 2019, 2020). F: RDA for Yaksha main*
374 *pollen taxa, MAT reconstructed climate (TANN, PANN, MTWA, SUMMERPR); fire activity (mFRI) and human activity (human population*
375 *density).*

376

377 *4.2 Yaksha local dynamics: interactions between climate, vegetation, fire and human presence*

378 *4.2.1 From 10,000 to 4000 cal. yr BP: a first half of the Holocene mainly influenced by climate*

379 To evaluate the background for fire dynamics, a Pearson correlation test was carried out between modern annual temperatures (from 2010 to
380 2018), for the studied sites, and the mean temperatures of the warmest months, (June, July, August) , corresponding to the fire season, as well as
381 correlation with mean temperatures of the months above 0°C (Tabatabai et al., 2021). The Pearson's correlation indicates that modern mean annual
382 temperatures are positively correlated with mean modern summer temperatures (correlation of 0.45) and mean modern temperatures of months
383 above 0°C (correlation of 0.48). It is therefore assumed that past annual mean temperatures, reconstructed from pollen and brGDGTs were also
384 positively correlated with past mean summer temperatures and past mean temperatures of months above 0°C.

385 Temperatures close to the modern ones are reconstructed from 10,000 to 9000 cal. yr BP (Fig. 5B) with vegetation mainly representative of the
386 light taiga type, with the taxa *Pinus sylvestris* and *Betula* spp. being dominant (75 %, Fig. 5D). These results are consistent with those for the
387 modern period.

388 Even though the light taiga remained in the main forest system up to 5500 cal. yr BP, the warming occurring since 8000 and including the HTM,
389 which lasted until 4000 cal. yr BP, is associated with an increase of dark taiga taxa (increase in *Picea abies* and appearance of *Pinus sibirica*).
390 These two taxa seem to be influenced by the increase in the mean annual and summer precipitation, as shown by the RDA (Fig. 5F), which occurs
391 at the same time. The increase in dark taiga taxa is consistent with the recognised characteristics of this taiga system, which is favored by
392 precipitation (Goldammer and Furyaev, 1996; Golubeva, 2008; Schulze et al., 2005). The increase could also demonstrate the substantial influence
393 of climate on vegetation dynamics during this period. Moreover, between 10,000 and 6000 cal. yr BP, the mean Fire Return Interval (mFRI)
394 based on charcoal analysis (Barhoumi et al., 2019) is high (median mFRI greater than 200 years, Fig. 5E), which would be indicative of a boreal
395 forest with larger occurrence of the dark taiga type in the earlier part of the Holocene, because the dark taiga is usually associated with low fire
396 frequency (de Groot et al., 2013; Goldammer and Furyaev, 1996; Sannikov and Goldammer, 1996). Since the human presence and its impact on

397 the environment is negligible in the first half of the Holocene (between 10,000 and 5000 cal. yr BP; Drobyshev *et al.*, 2004; Karmanov *et al.*,
398 2011; Klein Goldewijk *et al.*, 2011), the climate appears to have been the main factor influencing the vegetation in Yaksha. This is consistent
399 with the conclusions of a previous study based on pollen analysis and vegetation cover modeled by REVEALS, over the period from 10,000 to
400 6000 cal. yr BP (Barhoumi *et al.* (2020).

401

402

4.2.2 From 4000 to 600: an increasing impact of fires

403 The period between 4000 and 2500 cal. yr BP corresponds to a significant decrease in temperature (Fig. 5A, B). The percentage ratio between
404 dark taiga and light taiga shows great variability and seems to demonstrate the establishment of a boreal forest consisting of dark and light taiga
405 mosaic patches, equally distributed, supported by high precipitation favouring dark taiga. However, this period coincides with the crossing of a
406 threshold in the fire regime of Yaksha: the mFRI goes from 180 years (Fig 5E, phase R-3) to 135 years (phase R-4) from 4000 cal. yr BP up to
407 600 cal. yr BP. An mFRI value of *circa* 200 years corresponds to a fire frequency still tolerable by the representative taxa of the dark taiga
408 (Goldammer and Furyaev, 1996; Sannikov and Goldammer, 1996). But from 4000 cal. yr BP, the mFRI value is well below this threshold and
409 should no longer allow dark taiga to develop (Goldammer and Furyaev, 1996; Schulze et al., 2005). A higher fire frequency would benefit the
410 maintenance of a light taiga system, while high precipitation would maintain the presence of dark taiga taxa such as *Picea abies*. The contrasting
411 influences of the climate and the fire regimes could explain the maintenance of a forest composed of a mosaic of patches of dark and light taiga
412 The gradual return to a light taiga dominance between 2500 and 600 cal. yr BP therefore seems favored by the increase of temperatures, but also
413 by the establishment of the lower mFRI, since this type of forest is made up of fire-tolerant species well adapted to high fire frequency (see RDA,
414 *Pinus sylvestris* correlated with mean temperatures and mFRI), (Goldammer and Furyaev, 1996; Schulze et al., 2005). Fire frequency could be
415 the cause of the decline of *Abies sibirica* and *Pinus sibirica*, which are not resistant to frequent fire events and whose seed production and life
416 cycle may need a longer time than the time interval available between two fire events during this phase (Goldammer and Furyaev, 1996; Sannikov
417 and Goldammer, 1996; Schulze et al., 2005). The dominant presence of light taiga over dark taiga from 2500 cal. yr BP, does not prevent *Picea*
418 *abies* remaining well established. Barhoumi *et al.*, (2020) suggested that this may be due to the local establishment of *Picea abies* tree stands,
419 growing along small streams and moist soils and with precipitation staying high between 3000 and 2000 cal. yr BP (Zaretskaya et al., 2014). As
420 these systems are also present in light taiga, it is surprising to note that *Picea abies* does not suffer drastically from the drop in mFRI to below
421 200 years. In theory, *Picea abies* cannot develop if surface fires reach its critical regeneration time range (about 200 years after a fire event)

422 (Goldammer and Furyaev, 1996; Schulze et al., 2005). We therefore suggest that these surface fires were not able to reach the peat wetlands on
423 which *Picea abies* grew. That interpretation was highlighted by the first study on the dynamics of fires of the Yaksha site by Barhoumi *et al.*
424 (2019). This study highlights that most of the recent fires revealed by the analysis of fire scars on trees at the Yaksha site, have affected the
425 vegetation in a very localized way, while others have affected the site Yaksha as a whole. This demonstrates that the surface fires at the Yaksha
426 site could have been mostly local, and so were not able to reach the populations of *Picea abies*, because of their location on highly moist soils.

427

428 *4.2.3 From 600 to modern times: the combined influence of human activity and climate?*

429 The period between 600 and 0 cal. yr BP shows slightly increasing temperature values to levels similar to those of the Early Holocene, and stable
430 precipitation (Fig. 5A). The light taiga is well established and *Betula spp.* is dominant (Fig. 5D). *Betula* is a pioneer species in a disturbed
431 environment and is also a sign of the opening of the boreal forest in this zone (Goldammer and Furyaev, 1996). The strong presence of *Betula*
432 *spp.* during this phase is strongly associated with human population density in the RDA (Fig. 5F) and could be a sign of a human influence on the
433 vegetation. In the Republic of Komi in particular, logging is now a highly developed activity and its production represents a major economic
434 resource for this region (Naryshkin, 2003). The mFRI is at its lowest value within the Holocene interval (less than 100 years, phase R-5, Fig. 5E).
435 This time frame corresponds to the highest density of the human population in the Republic of Komi and its increasing activity and impact on its
436 environment (Drobyshev et al., 2004b; Klein Goldewijk et al., 2011; Naryshkin, 2003). It therefore seems that fire events could have been induced
437 by human activity and that the generally high fire activity of this period could be related to both anthropogenic influences and a more favorable
438 climate (Drobyshev et al., 2004b; Naryshkin, 2003). However, a recent study has nuanced the impact of human presence during this period.
439 Different waves of human colonization during this period were indeed indicated, but were not synchronous with the changes in the fire cycles
440 reconstructed by dendrochronological analyses (Ryzhkova et al., 2022). These authors deduced that the climate was the main factor in the
441 dynamics of the forest and that the human impact on fire activity was more pronounced after the 1900s. This is also consistent with the increase
442 in temperature reconstructed by brGDGTs, which started from 1800 cal. yr BP but intensified from about 700 cal. yr BP (Fig. 5A).

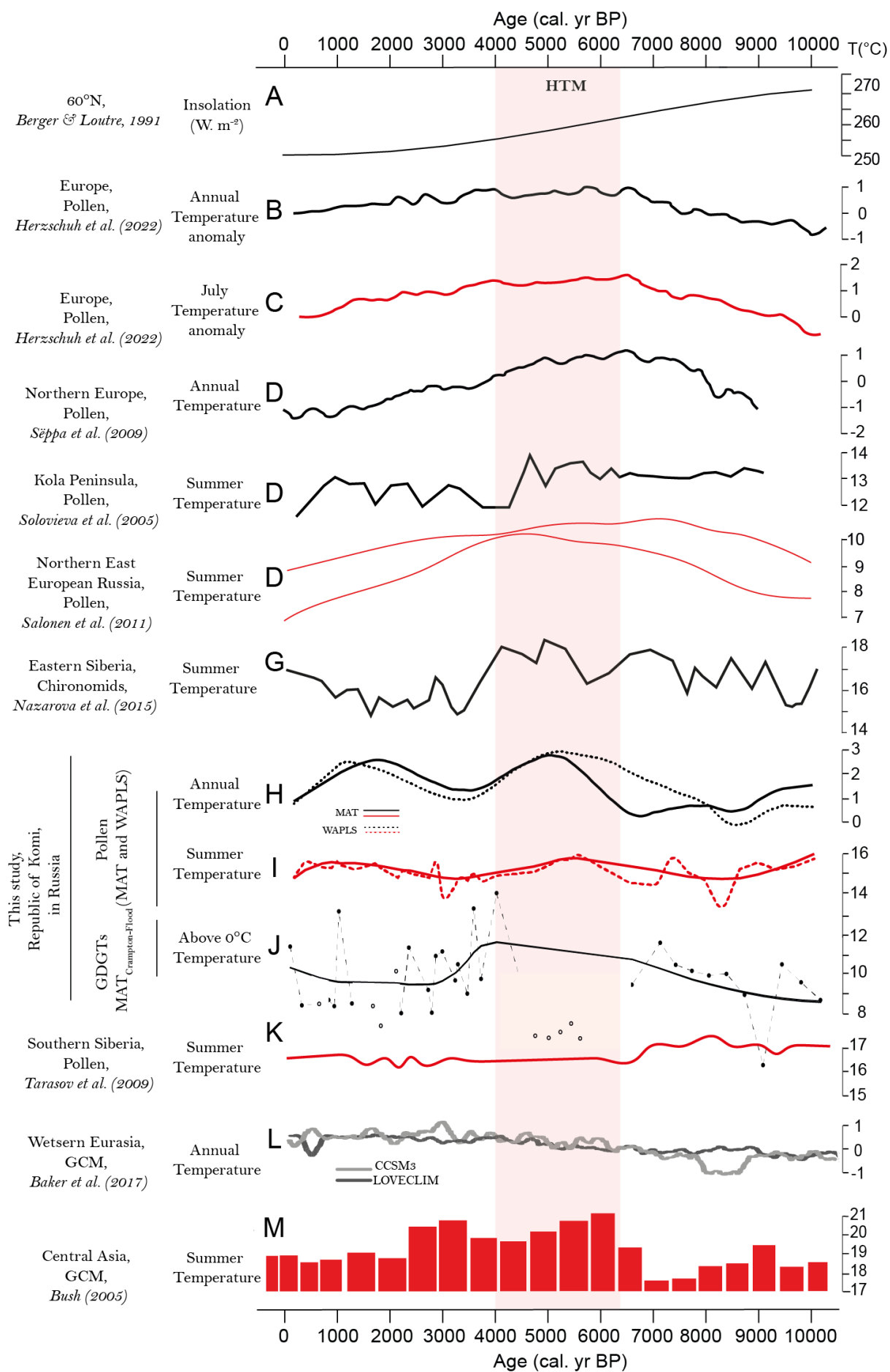
443

444 *4.3 Regional climate pattern in the South of the Republic of Komi*

445 *4.3.1 From 10,000 to 8000 cal. yr BP, a cold Early Holocene*

446 Although AO/NAO dynamics influence the climate of Republic of Komi region (*Raspopov et al., 2013*), climate records from the region can be
447 different from those recorded, for example, in Siberia because the Republic of Komi is located in a boundary zone, at the limit between the regions
448 positively or negatively influenced by atmospheric processes and solar irradiation (*Raspopov et al., 2013*). The regional climate signal in the
449 South of the Republic of Komi indicates a cooling and drying in the Early Holocene (Fig. 6H, 6I and 8A). This is in agreement with (1) the
450 brGDGT temperature calibration being the coldest of the records at the Yaksha site (Fig. 6J), (2) reconstructions of mean annual temperatures in
451 Eastern-central European Russia (from +1 to -1°C, Fig. 6E, Novenko and Olchev, 2015), summer temperatures in Eastern Siberia inferred from
452 chironomids (from +17 to +14°C, Fig. 6G, Nazarova *et al.*, 2015), (3) climate model simulations and mean temperature anomalies of Europe,
453 inferred from pollen (WA-PLS), showing the lowest temperatures of the Holocene during this time (between -1 to 0°C anomaly for annual
454 temperatures, Fig. 6B, C, Herzschuh *et al.*, 2022) The GCM outputs also simulate a drop in summer temperatures for Central Asia with a loss of
455 about 0.5°C, Fig. 6M, (Bush, 2005). However, in North Eastern European Russia, a rise in summer temperatures is reconstructed from pollen
456 data (+1°C approximately, Fig. 6D, Salonen *et al.*, 2011). The South of the Republic of Komi, therefore, seems to have undergone climatic
457 influences similar to those occurring in Western Russia and in Siberia.

458

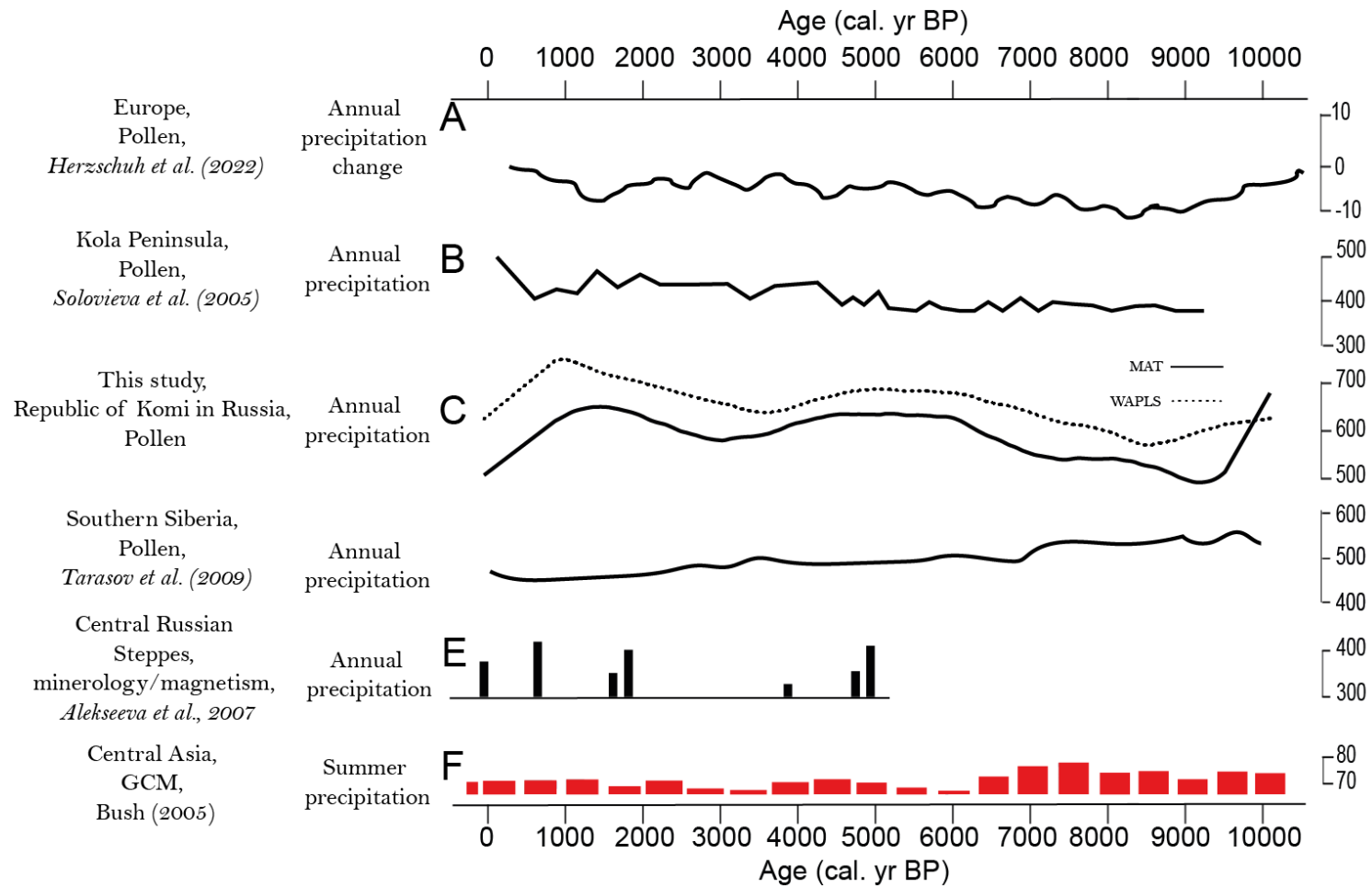


460 *Figure 6: Synthesis of Holocene temperature reconstructions in the Republic of Komi and neighboring regions, based on pollen, GDGTs,*
461 *chironomids and GCM outputs. Mean annual and summer temperatures are represented in black and in red, respectively. Location of the sites*
462 *are represented in Fig. 1. Insolation at 60°N after Berger and Loutre (1991). The red rectangle indicates the HTM period.*

463

464 4.3.2 Timing of the HTM

465 In the Republic of Komi, pollen results suggest the occurrence of the HTM between 6800 and 4000 cal. yr BP (this time frame includes the high
466 mean annual temperature values for both MAT and WA-PLS methods, Fig. 6H). This finding is consistent with the brGDGT MAT_{Crampton-Flood}
467 calibration, recording its warmest temperature value at 4000 cal. yr BP (Fig. 6J). The increase in annual temperatures in the Republic of Komi is
468 also associated with an increase in precipitation (Fig. 7B). This HTM time window is consistent with but broader than the one suggested by
469 Golubeva (2008), with the same pollen data set (except Yaksha site) but using other methods of temperature reconstruction (Klimanov, 1976).
470 This time-range for the HTM reconstructed with MAT/WA-PLS techniques is consistent with that reconstructed by Herzschuh *et al.* (2022),
471 showing a pollen-inferred (WA-PLS method) HTM at 5600 cal. yr BP for Europe annual temperatures. This time range is also consistent with
472 the Russian Arctic region and Kola Peninsula pollen-based temperature reconstructions (Fig. 6K; Tarasov *et al.*, 1999; Andreev and Klimanov,
473 2000; Solovieva, Tarasov and MacDonald, 2005), in the North of the Republic of Komi. The Russian Arctic HTM was explained because the
474 Arctic Ocean coast was about 100 to 300 km further North at this time than it is today, which contributed to a warmer and more continental
475 climate (Andreev and Klimanov, 2000; Baranskaya *et al.*, 2018). Studies from the west of the Republic of Komi, in Siberia and in Central Yakutia
476 also show an climatic optimum included in this interval (Biskaborn *et al.*, 2016; Blyakharchuk and Sulerzhitsky, 1999; Nazarova *et al.*, 2015b;
477 Subetto *et al.*, 2017; Ulrich *et al.*, 2017). Moreover, from 10,000 cal. yr BP until 4000 cal. yr BP, climate was the most moist of the Holocene
478 (Blyakharchuk and Sulerzhitsky, 1999; Tarasov *et al.*, 2009, 1999), which partially corresponds with the precipitation records from the Republic
479 of Komi (since it was low between 10,000 and 8500 cal. yr BP, and high between 6500 and 4000 cal. yr BP). The climate became moist again
480 between 3000 and 600 cal. yr BP. This time frame corresponds well with the annual precipitation reconstruction from Herzschuh *et al.* (2022),
481 suggesting that the Holocene increase in precipitation could be due to enhanced cyclonic activity. The HTM in the Republic of Komi is not as
482 long as in Northern Europe and Fennoscandia, where it began as early as 8000 cal. yr BP (Fig. 6B and 7D; Seppä *et al.*, 2009; Salonen *et al.*,
483 2011). Another extended HTM was observed by Kultti *et al.* (2003), still closer to Republic of Komi, between 9000 to 5200 cal. yr BP. Some of
484 the sites in the Kultti study were located at high altitudes in the Urals. The altitude may have had an impact on the different climatic influences
485 affecting the area from Arctic Russia to the Vychegda river basin in Republic of Komi. Many studies highlight the role of increased insolation in
486 global warming during the HTM (Bartlein *et al.*, 2011; Kultti *et al.*, 2003; Mayewski *et al.*, 2004; Wohlfarth *et al.*, 2007).



487

488 *Figure 7: Synthesis of Holocene precipitation reconstructions in the Republic of Komi and neighboring regions, based on pollen,*
 489 *minerology/magnetism and GCM outputs. Annual sum of precipitation is represented in black and the summer sum of temperatures, in red.*
 490 *Location of the sites are represented in Fig. 1*

491

492 Atmospheric processes could also explain this HTM period: a strong Westerly circulation, with a strong AO/NAO positive phase in winter (which
 493 would have generated warm and moist climates in Northern Europe) and a weaker AO/NAO positive phase in summer (warm and dry climate)
 494 (Mauri et al., 2015). Salonen *et al.* (2011) have also discussed the observed lags in HTM from Fennoscandia to the Ural region. Their assumptions
 495 are (1) there is a geographical timing gradient of the HTM; (2) some reconstructions may be wrong due to biases in the temperature inference
 496 methods used; (3) the different proxies for calculating temperatures may have non-synchronous responses to warming and (4) the complex history
 497 of tree lines in Russia may add uncertainties regarding pollen-based reconstructions.

498

500 A fluctuating and colder phase is marked in the Republic of Komi between 4000 and 2500 cal. yr BP. This cooling seems to have been also
501 registered in Siberia by chironomids (summer temperatures) (Nazarova et al., 2015b) and in Arctic Russia (Andreev and Klimanov, 2000). In
502 Northern Europe, a large period of continuous and gradual cooling has extended since the end of the HTM, around 4000 cal. yr BP, up to 1000
503 cal. yr BP, and has been largely explained by the influence of the decrease in summer insolation (Fig. 6D; Salonen *et al.*, 2011).

504 According to Seppä *et al.*, (2009), the Medieval Warm Period (MWP, 1550-650 cal. yr BP (Camill et al., 2009)) is not a distinct temperature peak
505 in Northern Europe, but “represents the final centuries of a longer warm period before the onset of cooling”. Pollen signals from the Republic of
506 Komi clearly indicate a period of warming between 2000 and 900 cal. yr BP. This signal is also registered by pollen assemblages from the Kola
507 Peninsula, which is located in the Northern part of European Russia (Solovieva et al., 2005) and a general slight increase in summer temperatures
508 has been simulated for Central Asia (Bush, 2005). This period coincides with the wettest recorded in the Republic of Komi, the Kola Peninsula
509 and the Central steppes of Russia, based on pollen grains and magnetism/minerological analysis (Fig. 7B, A and E; Solovieva, Tarasov and
510 MacDonald, 2005; Alekseeva *et al.*, 2007).

511 The subsequent short and rapid decrease in temperatures in the Republic of Komi from 500 cal. yr BP (WA-PLS), may correspond to the Little
512 Ice Age (LIA, 650-150 cal. yr BP (Camill et al., 2009)) . This cooling was also noted in records from Northern Europe by Seppä *et al.* (2009)
513 until ca. 400 cal. yr BP, in West-central Eurasia by the LOVECLIM model (Baker *et al.*, 2017), in Northern East European Russia by Salonen *et*
514 *al.* (2011), and in the Kola Peninsula (Solovieva et al., 2005). However, the resolution of our records is too low to corroborate (or to refute) these
515 results, but there are consistent with these observations.

516 At the end of the 19th century, a global warming trend was recorded by tree-rings in the Northern Urals (Moiseev et al., 2010) (Moiseev *et al.*,
517 2010) but in the Republic of Komi, the results do not show any general warming trend during this period, except for the sites Yaksha (MAT) and
518 Kalya. The brGDGT calibrations also showed also an increase in temperature over this interval.

519

520 5. Conclusions and remarks on the Republic of Komi boreal forest

521 This study presents (1) the first Holocene temperature reconstruction at a regional scale of the southern part of the Republic of Komi, based on
522 the study of pollen- transfer functions based on six different sites. (2) the first study of the local dynamics in Yaksha, between climate (based on
523 pollen-transfer functions and brGDGT temperature calibrations), fire, vegetation and human activities.

524 Regional climate reconstructions for the Republic of Komi show an increase in precipitation and a mid-Holocene HTM between 6800 and 4000
525 cal. yr BP which is in line with neighboring regions in Northern Europe, and also with Siberia, through the analysis of different proxies and
526 analytical methods (pollen, chironomids, model outputs).

527 At the local scale of Yaksha, the temperature reconstructions based on pollen assemblages and brGDGTs show common warmest temperature
528 phases around 4000 cal. yr BP. Further studies of cold environments are needed to improve the calibrations for brGDGTs, in particular for the
529 Holocene, where factors others than temperature influence the composition of brGDGT communities.

530 Finally, our study showed that climate had a major influence on the vegetation and dynamics of the boreal forest in Yaksha. Fires had an additional
531 and growing impact on vegetation dynamics between 4000 and 600 cal. yr BP. Finally, from 600 BP to the present day, both climate and increasing
532 human impacts have influenced the dynamics of the boreal forest in this region. In modern times, the fire regime induced by anthropogenic
533 activities corresponds to an overexploitation of the forest, whose coniferous species have rapidly declined in favor of a pioneer deciduous species
534 (the explosion of *Betula spp.* from 600 to the modern age is demonstrates this effect (Naryshkin, 2003; Sannikov and Goldammer, 1996). It is
535 likely that the wetter dark taiga growing on organic soils has been weakened by this fire regime. This can then lead to a reversal of the balance in
536 the carbon cycle, which could lead to massive releases into the atmosphere. This observation was made by Naryshkin, (2003) and Walker *et al.*
537 (2019): not only do these forests no longer play the role of carbon sinks as they have done in the past, but they are gradually becoming sources
538 of atmospheric carbon. With global warming, the temperature and dryness conditions of the environment may increase even more, and induce a
539 greater dryness of the soil, allowing the spread of fires even on previously more moist areas and therefore affect tree populations which were not
540 previously vulnerable. This was the case for example in the years 1972, 1974, 1977, 1982, 1987, 1998 in Siberia and in more recent years in
541 Siberia and in the Ural region (Goldammer et al., 2005; Goldammer and Furyaev, 1996). Managing the structure of forest stands by establishing
542 species more adapted to the new local climatic conditions may help to reverse the impact on the increase in fire activity that is evident today.

543

544 **6. Acknowledgements**

545 This study was funded by the Russian Fund for Basic Research (RFBR) under the project #20-04-00568 (to I.D.) and was supported by the
546 Canadian National Research Council Canada through Discovery Grant (grant # DDG-2015-00026 to I.D.), the Swedish Research Council
547 FORMAS (grant #239-2014-1866 to I.D.), the Swedish Institute funded networks CLIMECO, the BalticFire (#10066-2017-13 and #24474/2018
548 to I.D.), the Scientific and Educational Center “Russian Arctic: New Materials, Technologies and research Methods” (to A.K.), the Belmont
549 Forum Project PRERREAL (grant #292-2015-11-30-13-43-09 to I.D.) and the Ministry of Education of the Russian Federation (project #FSZN
550 2020-0016 to D.S.; #0185-2021-0018 to A.K.). The study was conducted within the framework of the NordicProxy network, which is supported
551 by the Nordic Forest Research (SNS), the consortium GDRI Cold Forests and Institut Universitaire de France of Adam A. Ali. For the analytical
552 work completed at LGLTPE- ENS de Lyon, this research was funded by Institut Universitaire de France funds to Guillemette Ménot. This is an
553 ISEM contribution No... We would like to thank Nina Ryzhkova and the team of the Siberian Institute of Plant Physiology and Biochemistry,
554 directed by Viktor Ivanovich Voronin in Irkutsk, for helping us with logistics during one of our fieldwork expeditions, related to the PhD project
555 from which this paper is issued, and Sandrine Canal for her general contribution towards technical analysis of Yaksha samples. We would also
556 like to thank Mary Robles for her general help with discussion of pollen transfer functions and brGDGT analysis.

557

558 **7. Bibliography**

- 559 Alekseeva, T., Alekseev, A., Maher, B.A., Demkin, V., 2007. Late Holocene climate reconstructions for the Russian steppe, based on
 560 mineralogical and magnetic properties of buried palaeosols. *Palaeogeography, Palaeoclimatology, Palaeoecology* 249, 103–127.
 561 <https://doi.org/10.1016/j.palaeo.2007.01.006>
- 562 Ali, A.A., Blarquez, O., Girardin, M.P., Hély, C., Tinquaut, F., El Guellab, A., Valsecchi, V., Terrier, A., Bremond, L., Genries, A., 2012.
 563 Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. *Proceedings of the National*
 564 *Academy of Sciences* 109, 20966–20970.
- 565 Andreev, A., Klimanov, V., 2000. Quantitative Holocene climatic reconstruction from Arctic Russia. *Journal of Paleolimnology* 24, 81–91.
- 566 Andreev, A.A., Klimanov, V.A., n.d. Quantitative Holocene climatic reconstruction from Arctic Russia 12.
- 567 Andreev, A.A., Siegert, C., Klimanov, V.A., Derevyagin, A.Y., Shilova, G.N., Melles, M., 2002. Late Pleistocene and Holocene vegetation and
 568 climate on the Taymyr lowland, northern Siberia. *Quaternary Research* 57, 138–150.
- 569 Ayari, A., Yang, H., Wiesenberg, G.L., Xie, S., 2013. Distribution of archaeal and bacterial tetraether membrane lipids in rhizosphere-root
 570 systems in soils and their implication for paleoclimate assessment. *Geochemical Journal* 47, 337–347.
- 571 Baker, J.L., Lachniet, M.S., Chervyatsova, O., Asmerom, Y., Polyak, V.J., 2017. Holocene warming in western continental Eurasia driven by
 572 glacial retreat and greenhouse forcing. *Nature Geosci* 10, 430–435. <https://doi.org/10.1038/ngeo2953>
- 573 Baranskaya, A.V., Khan, N.S., Romanenko, F.A., Roy, K., Peltier, W.R., Horton, B.P., 2018. A postglacial relative sea-level database for the
 574 Russian Arctic coast. *Quaternary Science Reviews* 199, 188–205. <https://doi.org/10.1016/j.quascirev.2018.07.033>
- 575 Barhoumi, C., Ali, A.A., Peyron, O., Dugerdil, L., Borisova, O., Golubeva, Y., Subetto, D., Kryshen, A., Drobyshev, I., Ryzhkova, N., 2020.
 576 Did long-term fire control the coniferous boreal forest composition of the northern Ural region (Komi Republic, Russia)? *Journal of*
 577 *Biogeography* 47, 2426–2441.
- 578 Barhoumi, C., Peyron, O., Joannin, S., Subetto, D., Kryshen, A., Drobyshev, I., Girardin, M.P., Brossier, B., Paradis, L., Pastor, T., 2019.
 579 Gradually increasing forest fire activity during the Holocene in the northern Ural region (Komi Republic, Russia). *The Holocene*
 580 0959683619865593.
- 581 Barhoumi, C., Vogel, M., Dugerdil, L., Limani, H., Joannin, S., Peyron, O., Ali, A.A., 2021. Holocene Fire Regime Changes in the Southern
 582 Lake Baikal Region Influenced by Climate-Vegetation-Anthropogenic Activity Interactions. *Forests* 12, 978.
 583 <https://doi.org/10.3390/f12080978>
- 584 Bartlein, P.J., Harrison, S., Brewer, S., Connor, S., Davis, B., Gajewski, K., Guiot, J., Harrison-Prentice, T., Henderson, A., Peyron, O., 2011.
 585 Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis. *Climate Dynamics* 37, 775–802.
- 586 Berger, A., Loutre, M.-F., 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews* 10, 297–317.
- 587 Bezrukova, E.V., Hildebrandt, S., Letunova, P.P., Ivanov, E.V., Orlova, L.A., Müller, S., Tarasov, P.E., 2013. Vegetation dynamics around
 588 Lake Baikal since the middle Holocene reconstructed from the pollen and botanical composition analyses of peat sediments:
 589 Implications for paleoclimatic and archeological research. *Quaternary International* 290–291, 35–45.
 590 <https://doi.org/10.1016/j.quaint.2012.10.043>
- 591 Bezrukova, E.V., Letunova, P.P., Vershinin, K.E., Krivonogov Sergey, K., Abzaeva, A.A. (Abzayeva, Krapivina, S.M., Khomutova, M.Y.,
 592 2003. Paleoenvironmental changes in Baikal Basin in the late glacial and Holocene. *Berliner Palaeobiologische Abhandlungen* 4, 111–
 593 120.
- 594 Birks, H., 1998. DG Frey and ES Deevey Review 1: Numerical tools in palaeolimnology—Progress, potentialities, and problems. *Journal of*
 595 *paleolimnology* 20, 307–332.
- 596 Birks, H.J.B., Seppä, H., 2004. Pollen-based reconstructions of late-Quaternary climate in Europe—progress, problems, and pitfalls. *Acta*
 597 *Palaeobotanica* 44, 317–334.
- 598 Biskaborn, B.K., Subetto, D.A., Savelieva, L.A., Vakhrameeva, P.S., Hansche, A., Herzsuh, U., Klemm, J., Heinecke, L., Pestryakova, L.A.,
 599 Meyer, H., Kuhn, G., Diekmann, B., 2016. Late Quaternary vegetation and lake system dynamics in north-eastern Siberia: Implications
 600 for seasonal climate variability. *Quaternary Science Reviews, Special Issue: PAST Gateways (Palaeo-Arctic Spatial and Temporal*
 601 *Gateways)* 147, 406–421. <https://doi.org/10.1016/j.quascirev.2015.08.014>
- 602 Blyakharchuk, T.A., Sulerzhitsky, L.D., 1999. Holocene vegetational and climatic changes in the forest zone of Western Siberia according to
 603 pollen records from the extrazonal palsa bog Bugristoye. *The Holocene* 9, 621–628. <https://doi.org/10.1191/095968399676614561>
- 604 Borisova, O.K., 2002. The Holocene flora and vegetation of the northern Russian Plain (the Vycheгда River basin). *Acta Palaeontologica*
 605 *Sinica* 41, 478–486.

606 Brewer, S., Guiot, J., Sánchez-Goñi, M., Klotz, S., 2008. The climate in Europe during the Eemian: a multi-method approach using pollen data.
607 Quaternary Science Reviews 27, 2303–2315.

608 Buckles, L., Weijers, J., Tran, X.-M., Waldron, S., Sinninghe Damsté, J., 2014. Provenance of tetraether membrane lipids in a large temperate
609 lake (Loch Lomond, UK): implications for glycerol dialkyl glycerol tetraether (GDGT)-based palaeothermometry. Biogeosciences 11,
610 5539–5563.

611 Bush, A.B.G., 2005. CO₂/H₂O and orbitally driven climate variability over central Asia through the Holocene. Quaternary International,
612 Paleolimnological records from Asian lacustrine systems: archives of large scale seasonal atmospheric circulation changes in the
613 northern hemisphere 136, 15–23. <https://doi.org/10.1016/j.quaint.2004.11.004>

614 Camill, P., Barry, A., Williams, E., Andreassi, C., Limmer, J., Solick, D., 2009. Climate-vegetation-fire interactions and their impact on long-
615 term carbon dynamics in a boreal peatland landscape in northern Manitoba, Canada. Journal of Geophysical Research: Biogeosciences
616 114.

617 Cao, J., Rao, Z., Jia, G., Xu, Q., Chen, F., 2017. A 15 ka pH record from an alpine lake in north China derived from the cyclization ratio index
618 of aquatic brGDGTs and its paleoclimatic significance. Organic Geochemistry 109, 31–46.

619 Cheung, H., Zhou, W., 2015. Implications of Ural blocking for East Asian winter climate in CMIP5 GCMs. Part II: Projection and uncertainty
620 in future climate conditions. Journal of Climate 28, 2217–2233.

621 Cheung, H.H., Zhou, W., 2015. Implications of Ural blocking for east Asian winter climate in CMIP5 GCMs. Part I: biases in the historical
622 scenario. Journal of Climate 28, 2203–2216.

623 Cheung, H.N., Zhou, W., Mok, H.Y., Wu, M.C., 2012. Relationship between Ural–Siberian blocking and the East Asian winter monsoon in
624 relation to the Arctic Oscillation and the El Niño–Southern Oscillation. Journal of Climate 25, 4242–4257.

625 Cheung, H.N., Zhou, W., Shao, Y., Chen, W., Mok, H.Y., Wu, M.C., 2013. Observational climatology and characteristics of wintertime
626 atmospheric blocking over Ural–Siberia. Climate dynamics 41, 63–79.

627 Chevalier, M., Davis, B.A., Heiri, O., Seppä, H., Chase, B.M., Gajewski, K., Lacourse, T., Telford, R.J., Finsinger, W., Guiot, J., 2020. Pollen-
628 based climate reconstruction techniques for late Quaternary studies. Earth-Science Reviews 103384.

629 Damsté, J.S.S., Hopmans, E.C., Pancost, R.D., Schouten, S., Geenevasen, J.A., 2000. Newly discovered non-isoprenoid glycerol dialkyl
630 glycerol tetraether lipids in sediments. Chemical Communications 1683–1684.

631 Davtian, N., Bard, E., Ménot, G., Fagault, Y., 2018. The importance of mass accuracy in selected ion monitoring analysis of branched and
632 isoprenoid tetraethers. Organic geochemistry 118, 58–62.

633 Davtian, N., Ménot, G., Bard, E., Poulénard, J., Podwojewski, P., 2016. Consideration of soil types for the calibration of molecular proxies for
634 soil pH and temperature using global soil datasets and Vietnamese soil profiles. Organic Geochemistry 101, 140–153.
635 <https://doi.org/10.1016/j.orggeochem.2016.09.002>

636 de Groot, W.J., Cantin, A.S., Flannigan, M.D., Soja, A.J., Gowman, L.M., Newbery, A., 2013. A comparison of Canadian and Russian boreal
637 forest fire regimes. Forest Ecology and Management 294, 23–34.

638 De Jonge, C., Radujković, D., Sigurdsson, B.D., Weedon, J.T., Janssens, I., Peterse, F., 2019. Lipid biomarker temperature proxy responds to
639 abrupt shift in the bacterial community composition in geothermally heated soils. Organic Geochemistry 137, 103897.
640 <https://doi.org/10.1016/j.orggeochem.2019.07.006>

641 De Jonge, C., Stadnitskaia, A., Hopmans, E.C., Cherkashov, G., Fedotov, A., Sinninghe Damsté, J.S., 2014. In situ produced branched glycerol
642 dialkyl glycerol tetraethers in suspended particulate matter from the Yenisei River, Eastern Siberia. Geochimica et Cosmochimica Acta
643 125, 476–491. <https://doi.org/10.1016/j.gca.2013.10.031>

644 Dearing Crampton-Flood, E., Tierney, J.E., Peterse, F., Kirkels, F.M.S.A., Sinninghe Damsté, J.S., 2020. BayMBT: A Bayesian calibration
645 model for branched glycerol dialkyl glycerol tetraethers in soils and peats. Geochimica et Cosmochimica Acta 268, 142–159.
646 <https://doi.org/10.1016/j.gca.2019.09.043>

647 Demske, D., Heumann, G., Granoszewski, W., Nita, M., Mamakowa, K., Tarasov, P.E., Oberhänsli, H., 2005. Late glacial and Holocene
648 vegetation and regional climate variability evidenced in high-resolution pollen records from Lake Baikal. Global and Planetary Change
649 46, 255–279. <https://doi.org/10.1016/j.gloplacha.2004.09.020>

650 Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., Quan, X.-W., Xu, T., Murray, D., 2011. Was there a basis for
651 anticipating the 2010 Russian heat wave? Geophysical Research Letters 38. <https://doi.org/10.1029/2010GL046582>

652 Drobyshev, I., Niklasson, M., Angelstam, P., 2004a. Contrasting tree-ring data with fire record in a pine-dominated landscape in the Komi
653 republic (Eastern European Russia): Recovering a common climate signal. Silva Fennica 38, 43–53.

654 Drobyshev, I., Niklasson, M., Angelstam, P., Majewski, P., 2004b. Testing for anthropogenic influence on fire regime for a 600-year period in
655 the Jaksha area, Komi Republic, East European Russia. Canadian Journal of Forest Research 34, 2027–2036.

656 Drotz, S.H., Sparrman, T., Nilsson, M.B., Schleucher, J., Öquist, M.G., 2010. Both catabolic and anabolic heterotrophic microbial activity
657 proceed in frozen soils. *Proceedings of the National Academy of Sciences* 107, 21046–21051. <https://doi.org/10.1073/pnas.1008885107>

658 Druzhinina, O., Kublitskiy, Y., Stančikaitė, M., Nazarova, L., Syrykh, L., Gedminienė, L., Uogintas, D., Skipityte, R., Arslanov, K.,
659 Vaikutienė, G., Kulkova, M., Subetto, D., 2020. The Late Pleistocene–Early Holocene palaeoenvironmental evolution in the SE Baltic
660 region: a new approach based on chironomid, geochemical and isotopic data from Kamyshovoye Lake, Russia. *Boreas* 49, 544–561.
661 <https://doi.org/10.1111/bor.12438>

662 Dugerdil, L., Joannin, S., Peyron, O., Jouffroy-Bapicot, I., Vanni re, B., Boldgiv, B., Unkelbach, J., Behling, H., M not, G., 2021. Climate
663 reconstructions based on GDGT and pollen surface datasets from Mongolia and Baikal area: calibrations and applicability to extremely
664 cold–dry environments over the Late Holocene. *Climate of the Past* 17, 1199–1226. <https://doi.org/10.5194/cp-17-1199-2021>

665 Feng, S., Hu, Q., Huang, W., Ho, C.-H., Li, R., Tang, Z., 2014. Projected climate regime shift under future global warming from multi-model,
666 multi-scenario CMIP5 simulations. *Global and Planetary Change* 112, 41–52.

667 Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of*
668 *Climatology* 37, 4302–4315. <https://doi.org/10.1002/joc.5086>

669 Foster, L.C., Pearson, E.J., Juggins, S., Hodgson, D.A., Saunders, K.M., Verleyen, E., Roberts, S.J., 2016. Development of a regional glycerol
670 dialkyl glycerol tetraether (GDGT)–temperature calibration for Antarctic and sub-Antarctic lakes. *Earth and planetary science letters*
671 433, 370–379.

672 Girardin, M.P., Ali, A.A., Carcaillet, C., Blarquez, O., H ly, C., Terrier, A., Genries, A., Bergeron, Y., 2013. Vegetation limits the impact of a
673 warm climate on boreal wildfires. *New Phytologist* 199, 1001–1011.

674 Gl ckler, R., Herzsuh, U., Kruse, S., Andreev, A., Vyse, S.A., Winkler, B., Biskaborn, B.K., Pestryakova, L., Dietze, E., 2020. Wildfire
675 history of the boreal forest of southwestern Yakutia (Siberia) over the last two millennia documented by a lake-sedimentary charcoal
676 record. *Biogeosciences Discussions* 1–42.

677 Goetz, S.J., Mack, M.C., Gurney, K.R., Randerson, J.T., Houghton, R.A., 2007. Ecosystem responses to recent climate change and fire
678 disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America. *Environmental*
679 *Research Letters* 2, 045031.

680 Goldammer, J.G., 2015. Vegetation fires and global change–challenges for concerted international action: a white paper directed to the United
681 Nations and International Organizations. *Planet@ risk* 3.

682 Goldammer, J.G., Furyaev, V.V., 1996. *Fire in Ecosystems of Boreal Eurasia*. Springer Netherlands, Dordrecht.

683 Goldammer, J.G., Sukhinin, A., Csiszar, I., 2005. The current fire situation in the Russian Federation: implications for enhancing international
684 and regional cooperation in the UN framework and the global programs on fire monitoring and assessment. *Int. Forest Fire News* 32,
685 13–42.

686 Golubeva, Yu., 2008. Climate and vegetation of the Holocene in Komi Republic. (in Russian). *Litosfera* 124–132.

687 Grieser, J., Gommers, R., Bernardi, M., 2006. New LocClim–the local climate estimator of FAO. *Geophys. Res. Abstr.* 8.

688 Guiot, J., 1990. Methodology of the last climatic cycle reconstruction in France from pollen data. *Palaeogeography, Palaeoclimatology,*
689 *Palaeoecology* 80, 49–69.

690 Harris, I., Jones, P. d., Osborn, T. j., Lister, D. h., 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10
691 Dataset. *International Journal of Climatology* 34, 623–642. <https://doi.org/10.1002/joc.3711>

692 Herzsuh, U., B hmer, T., Chevalier, M., Dallmeyer, A., Li, C., Cao, X., H bert, R., Peyron, O., Nazarova, L., Novenko, E.Y., Park, J.,
693 Rudaya, N.A., Schl tz, F., Shumilovskikh, L.S., Tarasov, P.E., Wang, Y., Wen, R., Xu, Q., Zheng, Z., 2022. Regional pollen-based
694 Holocene temperature and precipitation patterns depart from the Northern Hemisphere mean trends. *EGU sphere* 1–23.
695 <https://doi.org/10.5194/egusphere-2022-127>

696 Herzsuh, U., B hmer, T., Li, C., Cao, X., 2021. Northern Hemisphere temperature and precipitation reconstruction from taxonomically
697 harmonized pollen data set with revised chronologies using WA-PLS and MAT (LegacyClimate 1.0).

698 Hoegh - Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K., Engelbrecht, F., Guiot, K.,
699 Hijjoka, Y., Mehrotra, S., Payne, A., Seneviratne, S., Thomas, A., Warren, R., Zhou, G., Halim, S., Achlatis, M., Alexander, L., Allen,
700 M., Berry, P., Boyer, C., Brilli, L., Buckeridge, M., Cheung, W., Craig, M., Ellis, N., Evans, J., Fisher, H., Fraedrich, K., Fuss, S.,
701 Ganase, A., Gattuso, J., Greve, P., Guillen, T., Hanasaki, N., Hasegawa, T., Hayes, K., Hirsch, A., Jones, C., Jung, T., Kanninen, M.,
702 Krinner, G., Lawrence, D., Lenton, T., Ley, D., Liveman, D., Mahowald, N., McInnes, K., Meissner, K., Millar, R., Mintenbeck, K.,
703 Mitchell, D., Mix, A., Notz, D., Nurse, L., Okem, A., Olsson, L., Oppenheimer, M., Paz, S., Peterson, J., Petzold, J., Preuschmann, S.,
704 Rahman, M., Rogelj, J., Scheuffele, H., Schleussner, C.-F., Scott, D., Seferian, R., Sillmann, J., Singh, C., Slade, R., Stephenson, K.,
705 Stephenson, T., Sylla, M., Tebboth, M., Tschakert, P., Vautard, R., Wartenburger, R., Wehner, M., Weyer, N., Whyte, F., Yohe, G.,

706 Zhang, X., Zougmore, R., 2018. Chapter 3: Impacts of 1.5°C global warming on natural and human systems, in: *Global Warming of 1.5*
707 *°C an IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse*
708 *Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*. Intergovernmental Panel
709 on Climate Change.

710 Hopmans, E.C., Schouten, S., Damsté, J.S.S., 2016. The effect of improved chromatography on GDGT-based palaeoproxies. *Organic*
711 *Geochemistry* 93, 1–6.

712 Hopmans, E.C., Weijers, J.W., Schefuß, E., Herfort, L., Damsté, J.S.S., Schouten, S., 2004. A novel proxy for terrestrial organic matter in
713 sediments based on branched and isoprenoid tetraether lipids. *Earth and Planetary Science Letters* 224, 107–116.

714 Hu, F.S., Brubaker, L.B., Gavin, D.G., Higuera, P.E., Lynch, J.A., Rupp, T.S., Tinner, W., 2006. How climate and vegetation influence the fire
715 regime of the Alaskan boreal biome: the Holocene perspective. *Mitigation and Adaptation Strategies for Global Change* 11, 829–846.

716 Huang, J., Zhang, X., Zhang, Q., Lin, Y., Hao, M., Luo, Y., Zhao, Z., Yao, Y., Chen, X., Wang, L., Nie, S., Yin, Y., Xu, Y., Zhang, J., 2017.
717 Recently amplified arctic warming has contributed to a continual global warming trend. *Nature Clim Change* 7, 875–879.
718 <https://doi.org/10.1038/s41558-017-0009-5>

719 Huguet, A., Fosse, C., Laggoun-Défarge, F., Delarue, F., Derenne, S., 2013. Effects of a short-term experimental microclimate warming on the
720 abundance and distribution of branched GDGTs in a French peatland. *Geochimica et Cosmochimica Acta* 105, 294–315.
721 <https://doi.org/10.1016/j.gca.2012.11.037>

722 Huguet, C., Hopmans, E.C., Febo-Ayala, W., Thompson, D.H., Damsté, J.S.S., Schouten, S., 2006. An improved method to determine the
723 absolute abundance of glycerol dibiphytanyl glycerol tetraether lipids. *Organic Geochemistry* 37, 1036–1041.

724 Juggins, S., 2009. Package “rioja”—analysis of quaternary science data. The Comprehensive R Archive Network.

725 Juggins, S., Juggins, M.S., 2020. Package ‘rioja.’

726 Karmanov, V., Zaretskaya, N., Panin, A., Chernov, A., 2011. Reconstruction of local environments of ancient population in a changeable river
727 valley landscape (The Middle Vychehga River, Northern Russia). *Geochronometria* 38, 128–137.

728 Kaufman, D., McKay, N., Routson, C., Erb, M., Dätwyler, C., Sommer, P.S., Heiri, O., Davis, B., 2020. Holocene global mean surface
729 temperature, a multi-method reconstruction approach. *Scientific data* 7, 1–13.

730 Kharuk, V.I., Ponomarev, E.I., Ivanova, G.A., Dvinskaya, M.L., Coogan, S.C., Flannigan, M.D., 2021. Wildfires in the Siberian taiga. *Ambio*
731 1–22.

732 Klein Goldewijk, K., Beusen, A., Van Drecht, G., De Vos, M., 2011. The HYDE 3.1 spatially explicit database of human-induced global land-
733 use change over the past 12,000 years. *Global Ecology and Biogeography* 20, 73–86.

734 Klimanov, V., 1976. To the method of reconstruction of quantitative parameters of past climate. *Vestnik MGU Ser Geogr* 2, 92–98.

735 Kultti, S., Väiliranta, M., Sarmaja-Korjonen, K., Solovieva, N., Virtanen, T., Kauppila, T., Eronen, M., 2003. Palaeoecological evidence of
736 changes in vegetation and climate during the Holocene in the pre-Polar Urals, northeast European Russia: HOLOCENE OF THE PRE-
737 POLAR URALS. *J. Quaternary Sci.* 18, 503–520. <https://doi.org/10.1002/jqs.765>

738 Lapenis, A., Shvidenko, A., Shepaschenko, D., Nilsson, S., Aiyyer, A., 2005. Acclimation of Russian forests to recent changes in climate.
739 *Global Change Biology* 11, 2090–2102.

740 Lau, W.K., Kim, K.-M., 2012. The 2010 Pakistan flood and Russian heat wave: Teleconnection of hydrometeorological extremes. *Journal of*
741 *Hydrometeorology* 13, 392–403.

742 Li, X., Wang, M., Zhang, Y., Lei, L., Hou, J., 2017. Holocene climatic and environmental change on the western Tibetan Plateau revealed by
743 glycerol dialkyl glycerol tetraethers and leaf wax deuterium-to-hydrogen ratios at Aweng Co. *Quaternary Research* 87, 455.

744 Loomis, S.E., Russell, J.M., Damsté, J.S.S., 2011. Distributions of branched GDGTs in soils and lake sediments from western Uganda:
745 implications for a lacustrine paleothermometer. *Organic Geochemistry* 42, 739–751.

746 Loomis, S.E., Russell, J.M., Eggermont, H., Verschuren, D., Damsté, J.S.S., 2014. Effects of temperature, pH and nutrient concentration on
747 branched GDGT distributions in East African lakes: Implications for paleoenvironmental reconstruction. *Organic geochemistry* 66, 25–
748 37.

749 Marchenko-Vagapova, T.I., Marieva, N.A., 2001. Palynological and diatomic characteristics of environment in Holocene near middle
750 Vychehga. *Vestnik Institute of Geology*. 2001. № 10. C. 6—9 6–9.

751 Marcott, S., Shakun, J., Clark, P., Mix, A., 2013. A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. *Science*
752 (New York, N.Y.) 339, 1198–201. <https://doi.org/10.1126/science.1228026>

753 Marsicek, J., Shuman, B.N., Bartlein, P.J., Shafer, S.L., Brewer, S., 2018. Reconciling divergent trends and millennial variations in Holocene
754 temperatures. *Nature* 554, 92–96. <https://doi.org/10.1038/nature25464>

755 Martin, C., Menot, G., Thouveny, N., Peyron, O., Andrieu-Ponel, V., Montade, V., Davtian, N., Reille, M., Bard, E., 2020. Early Holocene
756 Thermal Maximum recorded by branched tetraethers and pollen in Western Europe (Massif Central, France). *Quaternary Science*
757 *Reviews* 228, 106109.

758 Matsueda, M., 2011. Predictability of Euro-Russian blocking in summer of 2010. *Geophysical Research Letters* 38.

759 Mauri, A., Davis, B., Collins, P., Kaplan, J., 2015. The climate of Europe during the Holocene: a gridded pollen-based reconstruction and its
760 multi-proxy evaluation. *Quaternary Science Reviews* 112, 109–127.

761 Mayewski, P.A., Rohling, E.E., Curt Stager, J., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S.,
762 Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability.
763 *Quat. res.* 62, 243–255. <https://doi.org/10.1016/j.yqres.2004.07.001>

764 Moiseev, P., Bartysh, A., Nagimov, Z.Y., 2010. Climate changes and tree stand dynamics at the upper limit of their growth in the North Ural
765 Mountains. *Russian Journal of Ecology* 41, 486–497.

766 Naafs, B., Inglis, G., Zheng, Y., Amesbury, M., Biester, H., Bindler, R., Blewett, J., Burrows, M., Del Castillo Torres, D., Chambers, F.M.,
767 2017. Introducing global peat-specific temperature and pH calibrations based on brGDGT bacterial lipids. *Geochimica et Cosmochimica*
768 *Acta* 208, 285–301.

769 Naeher, S., Peterse, F., Smittenberg, R.H., Niemann, H., Zigah, P.K., Schubert, C.J., 2014. Sources of glycerol dialkyl glycerol tetraethers
770 (GDGTs) in catchment soils, water column and sediments of Lake Rotsee (Switzerland) – Implications for the application of GDGT-
771 based proxies for lakes. *Organic Geochemistry* 66, 164–173. <https://doi.org/10.1016/j.orggeochem.2013.10.017>

772 Naryshkin, A.G., 2003. Fire and sustainable use of northern conifer forest in Russia. Presented at the *Acta Horticulturae* 615, IV International
773 Conifer Conference 615, pp. 361–373.

774 Nazarova, L., Self, A.E., Brooks, S.J., van Hardenbroek, M., Herzschuh, U., Diekmann, B., 2015a. Northern Russian chironomid-based modern
775 summer temperature data set and inference models. *Global and Planetary Change* 134, 10–25.

776 Nazarova, L., Self, A.E., Brooks, S.J., van Hardenbroek, M., Herzschuh, U., Diekmann, B., 2015b. Northern Russian chironomid-based modern
777 summer temperature data set and inference models. *Global and Planetary Change* 134, 10–25.

778 Nedwell, D.B., 1999. Effect of low temperature on microbial growth: lowered affinity for substrates limits growth at low temperature. *FEMS*
779 *Microbiology Ecology* 30, 101–111. <https://doi.org/10.1111/j.1574-6941.1999.tb00639.x>

780 Novenko, E., Olchev, A., 2015. Early Holocene vegetation and climate dynamics in the central part of the East European Plain (Russia).
781 *Quaternary International* 388. <https://doi.org/10.1016/j.quaint.2015.01.027>

782 Pearson, E.J., Juggins, S., Talbot, H.M., Weckström, J., Rosén, P., Ryves, D.B., Roberts, S.J., Schmidt, R., 2011. A lacustrine GDGT-
783 temperature calibration from the Scandinavian Arctic to Antarctic: Renewed potential for the application of GDGT-paleothermometry in
784 lakes. *Geochimica et Cosmochimica Acta* 75, 6225–6238. <https://doi.org/10.1016/j.gca.2011.07.042>

785 Peterse, F., Nicol, G.W., Schouten, S., Damsté, J.S.S., 2010. Influence of soil pH on the abundance and distribution of core and intact polar
786 lipid-derived branched GDGTs in soil. *Organic Geochemistry* 41, 1171–1175.

787 Peterse, F., van der Meer, J., Schouten, S., Weijers, J.W., Fierer, N., Jackson, R.B., Kim, J.-H., Damsté, J.S.S., 2012. Revised calibration of the
788 MBT–CBT paleotemperature proxy based on branched tetraether membrane lipids in surface soils. *Geochimica et Cosmochimica Acta*
789 96, 215–229.

790 Peyron, O., Bégeot, C., Brewer, S., Heiri, O., Magny, M., Millet, L., Ruffaldi, P., Van Campo, E., Yu, G., 2005. Late-Glacial climatic changes
791 in Eastern France (Lake Lautrey) from pollen, lake-levels, and chironomids. *Quaternary Research* 64, 197–211.

792 Peyron, O., Bordon, A., Vignot, A., Damy, S., Combourieu-Nebout, N., Brewer, S., Tarasov, P., Barboni, D., 2008. A modern pollen–climate
793 database as a tool for quantitative climate and vegetation reconstructions, in: *12th International Palynological Congress IPC–XII*. Bonn,
794 Germany.

795 Peyron, O., Guiot, J., Cheddadi, R., Tarasov, P., Reille, M., de Beaulieu, J.-L., Bottema, S., Andrieu, V., 1998. Climatic reconstruction in
796 Europe for 18,000 yr BP from pollen data. *Quaternary research* 49, 183–196.

797 Peyron, O., Magny, M., Goring, S., Joannin, S., de Beaulieu, J.-L., Bruggiapaglia, E., Sadori, L., Garfi, G., Kouli, K., Ioakim, C., 2013.
798 Contrasting patterns of climatic changes during the Holocene across the Italian Peninsula reconstructed from pollen data.

799 Peyron, O., Simon, G., Isabelle, D., Ulrich, K., Jörg, P., Jacques-Louis, de B., Ruth, D.-S., Boris, V., Michel, M., 2011. Holocene seasonality
800 changes in the central Mediterranean region reconstructed from the pollen sequences of Lake Accessa (Italy) and Tenaghi Philippon
801 (Greece) [WWW Document]. URL <https://journals.sagepub.com/doi/10.1177/0959683610384162> (accessed 9.12.22).

802 Ponel, P., Guiter, F., Gandouin, E., Peyron, O., Beaulieu, J.-L. de, 2022. Late-Glacial palaeotemperatures and palaeoprecipitations in the
803 Aubrac Mountains (French Massif Central) reconstructed from multiproxy analyses (Coleoptera, chironomids and pollen). *Quaternary*
804 *International*. <https://doi.org/10.1016/j.quaint.2022.02.005>

805 Pörtner, H.O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R.A., Betts, R., Kerr, R.B., Biesbroek, R., 2022. Climate
806 change 2022: impacts, adaptation and vulnerability.

807 Prentice, C., Guiot, J., Huntley, B., Jolly, D., Cheddadi, R., 1996. Reconstructing biomes from palaeoecological data: a general method and its
808 application to European pollen data at 0 and 6 ka. *Climate Dynamics* 12, 185–194.

809 Ramos-Román, M.J., De Jonge, C., Magyari, E., Veres, D., Ilvonen, L., Develle, A.-L., Seppä, H., 2022. Lipid biomarker (brGDGT)- and
810 pollen-based reconstruction of temperature change during the Middle to Late Holocene transition in the Carpathians. *Global and
811 Planetary Change* 215, 103859. <https://doi.org/10.1016/j.gloplacha.2022.103859>

812 Raspopov, O., Lopatin, E., Kolström, T., Dergachev, V., Dmitriev, P., Kahle, H.-P., Spiecker, H., 2013. Spatial structure of periodicity in the
813 conifer tree radial increment in the Republic of Komi. *Izvestiya, Atmospheric and Oceanic Physics* 49, 799–811.

814 Remy, C.C., Hély, C., Blarquez, O., Magnan, G., Bergeron, Y., Lavoie, M., Ali, A.A., 2017. Different regional climatic drivers of Holocene
815 large wildfires in boreal forests of northeastern America. *Environmental Research Letters* 12, 035005.

816 Robles, M., Peyron, O., Brugiapaglia, E., Ménot, G., Dugerdil, L., Ollivier, V., Ansanay-Alex, S., Develle, A.-L., Tozalakyan, P., Meliksetian,
817 K., 2022. Impact of climate changes on vegetation and human societies during the Holocene in the South Caucasus (Vanevan,
818 Armenia): A multiproxy approach including pollen, NPPs and brGDGTs. *Quaternary Science Reviews* 277, 107297.

819 Ryzhkova, N., Kryshen, A., Niklasson, M., Pinto, G., Aleinikov, A., Kutuyavin, I., Bergeron, Y., Ali, A.A., Drobyshev, I., 2022. Climate drove
820 the fire cycle and humans influenced fire occurrence in the East European boreal forest. *Ecological Monographs* n/a, e1530.
821 <https://doi.org/10.1002/ecm.1530>

822 Salonen, J.S., Ilvonen, L., Seppä, H., Holmström, L., Telford, R.J., Gaidamavičius, A., Stančikaitė, M., Subetto, D., 2012. Comparing different
823 calibration methods (WA/WA-PLS regression and Bayesian modelling) and different-sized calibration sets in pollen-based quantitative
824 climate reconstruction. *The Holocene* 22, 413–424.

825 Salonen, J.S., Seppä, H., Väiliranta, M., Jones, V.J., Self, A., Heikkilä, M., Kultti, S., Yang, H., 2011. The Holocene thermal maximum and late-
826 Holocene cooling in the tundra of NE European Russia. *Quaternary Research* 75, 501–511.

827 Sannikov, S., Goldammer, J., 1996. Fire ecology of pine forests of northern Eurasia, in: *Fire in Ecosystems of Boreal Eurasia*. Springer, pp.
828 151–167.

829 Schostag, M., Stibal, M., Jacobsen, C.S., Bælum, J., Taş, N., Elberling, B., Jansson, J.K., Semenchuk, P., Priemé, A., 2015. Distinct summer
830 and winter bacterial communities in the active layer of Svalbard permafrost revealed by DNA- and RNA-based analyses. *Frontiers in
831 Microbiology* 6.

832 Schubert, S., Wang, H., Suarez, M., 2011. Warm season subseasonal variability and climate extremes in the Northern Hemisphere: The role of
833 stationary Rossby waves. *Journal of Climate* 24, 4773–4792.

834 Schubert, S.D., Wang, H., Koster, R.D., Suarez, M.J., Groisman, P.Y., 2014. Northern Eurasian heat waves and droughts. *Journal of Climate*
835 27, 3169–3207.

836 Schulze, E.-D., Wirth, C., Mollicone, D., Ziegler, W., 2005. Succession after stand replacing disturbances by fire, wind throw, and insects in the
837 dark Taiga of Central Siberia. *Oecologia* 146, 77–88.

838 Seppä, H., Bjune, A.E., Telford, R.J., Birks, H., Veski, S., 2009. Last nine-thousand years of temperature variability in Northern Europe.
839 *Climate of the Past* 5, 523–535.

840 Shorohova, E., Kuuluvainen, T., Kangur, A., Jõgiste, K., 2009. Natural stand structures, disturbance regimes and successional dynamics in the
841 Eurasian boreal forests: a review with special reference to Russian studies. *Annals of Forest Science* 66, 1–20.

842 Sinopoli, G., Peyron, O., Masi, A., Holtvoeth, J., Francke, A., Wagner, B., Sadori, L., 2019. Pollen-based temperature and precipitation changes
843 in the Ohrid Basin (western Balkans) between 160 and 70 ka. *Climate of the Past* 15, 53–71. [https://doi.org/10.5194/cp-15-53-
844 2019](https://doi.org/10.5194/cp-15-53-2019)

845 Solovieva, N., Tarasov, P.E., MacDonald, G., 2005. Quantitative reconstruction of Holocene climate from the Chuna Lake pollen record, Kola
846 Peninsula, northwest Russia. *The Holocene* 15, 141–148. <https://doi.org/10.1191/0959683605hl793rr>

847 Subetto, D.A., Nazarova, L.B., Pestryakova, L.A., Syrykh, L.S., Andronikov, A.V., Biskaborn, B., Diekmann, B., Kuznetsov, D.D., Sapelko,
848 T.V., Grekov, I.M., 2017. Paleolimnological studies in Russian northern Eurasia: A review. *Contemp. Probl. Ecol.* 10, 327–335.
849 <https://doi.org/10.1134/S1995425517040102>

850 Sun, Q., Chu, G., Liu, M., Xie, M., Li, S., Ling, Y., Wang, X., Shi, L., Jia, G., Lü, H., 2011. Distributions and temperature dependence of
851 branched glycerol dialkyl glycerol tetraethers in recent lacustrine sediments from China and Nepal. *Journal of Geophysical Research:
852 Biogeosciences* 116.

853 Tabatabai, M., Bailey, S., Bursac, Z., Tabatabai, H., Wilus, D., Singh, K.P., 2021. An introduction to new robust linear and monotonic
854 correlation coefficients. *BMC Bioinformatics* 22, 170. <https://doi.org/10.1186/s12859-021-04098-4>

855 Tarasov, P., Bezrukova, E., Karabanov, E., Nakagawa, T., Wagner, M., Kulagina, N., Letunova, P., Abzaeva, A., Granoszewski, W., Riedel, F.,
856 2007. Vegetation and climate dynamics during the Holocene and Eemian interglacials derived from Lake Baikal pollen records.
857 *Palaeogeography, Palaeoclimatology, Palaeoecology* 252, 440–457.

858 Tarasov, P.E., Bezrukova, E.V., Krivonogov, S.K., 2009. Late Glacial and Holocene changes in vegetation cover and climate in southern
859 Siberia derived from a 15 kyr long pollen record from Lake Kotokel. *Clim. Past* 11.

860 Tarasov, P.E., Guiot, J., Cheddadi, R., Andreev, A.A., Bezusko, L.G., Blyakharchuk, T.A., Dorofeyuk, N.I., Filimonova, L.V., Volkova, V.S.,
861 Zernitskaya, V.P., 1999. Climate in northern Eurasia 6000 years ago reconstructed from pollen data. *Earth and Planetary Science Letters*
862 171, 635–645. [https://doi.org/10.1016/S0012-821X\(99\)00171-5](https://doi.org/10.1016/S0012-821X(99)00171-5)

863 ter Braak, C.J., Juggins, S., 1993. Weighted averaging partial least squares regression (WA-PLS): an improved method for reconstructing
864 environmental variables from species assemblages. Presented at the Twelfth International Diatom Symposium, Springer, pp. 485–502.

865 Tierney, J.E., Russell, J.M., Eggermont, H., Hopmans, E., Verschuren, D., Damsté, J.S., 2010. Environmental controls on branched tetraether
866 lipid distributions in tropical East African lake sediments. *Geochimica et Cosmochimica Acta* 74, 4902–4918.

867 Tierney, J.E., Schouten, S., Pitcher, A., Hopmans, E.C., Damsté, J.S.S., 2012. Core and intact polar glycerol dialkyl glycerol tetraethers
868 (GDGTs) in Sand Pond, Warwick, Rhode Island (USA): Insights into the origin of lacustrine GDGTs. *Geochimica et Cosmochimica*
869 *Acta* 77, 561–581.

870 Tyler, J.J., Nederbragt, A.J., Jones, V.J., Thurow, J.W., 2010. Assessing past temperature and soil pH estimates from bacterial tetraether
871 membrane lipids: evidence from the recent lake sediments of Lochnagar, Scotland. *Journal of Geophysical Research: Biogeosciences*
872 115.

873 Ulrich, M., Wetterich, S., Rudaya, N., Frolova, L., Schmidt, J., Siegert, C., Fedorov, A.N., Zielhofer, C., 2017. Rapid thermokarst evolution
874 during the mid-Holocene in Central Yakutia, Russia. *The Holocene* 27, 1899–1913.

875 Velichko, A., Catto, N., Drenova, A., Klimanov, V., Kremenetski, K., Nechaev, V., 2002. Climate changes in East Europe and Siberia at the
876 Late glacial–holocene transition. *Quaternary International* 91, 75–99.

877 Walker, X.J., Baltzer, J.L., Cumming, S.G., Day, N.J., Ebert, C., Goetz, S., Johnstone, J.F., Potter, S., Rogers, B.M., Schuur, E.A.G., Turetsky,
878 M.R., Mack, M.C., 2019. Increasing wildfires threaten historic carbon sink of boreal forest soils. *Nature* 572, 520–523.
879 <https://doi.org/10.1038/s41586-019-1474-y>

880 Wang, H., Liu, W., Zhang, C.L., Wang, Z., Wang, J., Liu, Z., Dong, H., 2012. Distribution of glycerol dialkyl glycerol tetraethers in surface
881 sediments of Lake Qinghai and surrounding soil. *Organic Geochemistry* 47, 78–87.

882 Wang, L., Chen, W., Zhou, W., Chan, J.C., Barriopedro, D., Huang, R., 2010. Effect of the climate shift around mid 1970s on the relationship
883 between wintertime Ural blocking circulation and East Asian climate. *International Journal of Climatology: A Journal of the Royal*
884 *Meteorological Society* 30, 153–158.

885 Weijers, J., Wiesenberg, G.L., Bol, R., Hopmans, E., Pancost, R., 2010. Carbon isotopic composition of branched tetraether membrane lipids in
886 soils suggest a rapid turnover and a heterotrophic life style of their source organism (s). *Biogeosciences* 7, 2959–2973.

887 Weijers, J.W., Bernhardt, B., Peterse, F., Werne, J.P., Dungait, J.A., Schouten, S., Damsté, J.S.S., 2011. Absence of seasonal patterns in MBT–
888 CBT indices in mid-latitude soils. *Geochimica et Cosmochimica Acta* 75, 3179–3190.

889 Weijers, J.W., Schouten, S., Hopmans, E.C., Geenevasen, J.A., David, O.R., Coleman, J.M., Pancost, R.D., Sinninghe Damsté, J.S., 2006a.
890 Membrane lipids of mesophilic anaerobic bacteria thriving in peats have typical archaeal traits. *Environmental Microbiology* 8, 648–
891 657.

892 Weijers, J.W., Schouten, S., Sluijs, A., Brinkhuis, H., Damsté, J.S.S., 2007a. Warm arctic continents during the Palaeocene–Eocene thermal
893 maximum. *Earth and Planetary Science Letters* 261, 230–238.

894 Weijers, J.W., Schouten, S., Spaargaren, O.C., Damsté, J.S.S., 2006b. Occurrence and distribution of tetraether membrane lipids in soils:
895 Implications for the use of the TEX86 proxy and the BIT index. *Organic Geochemistry* 37, 1680–1693.

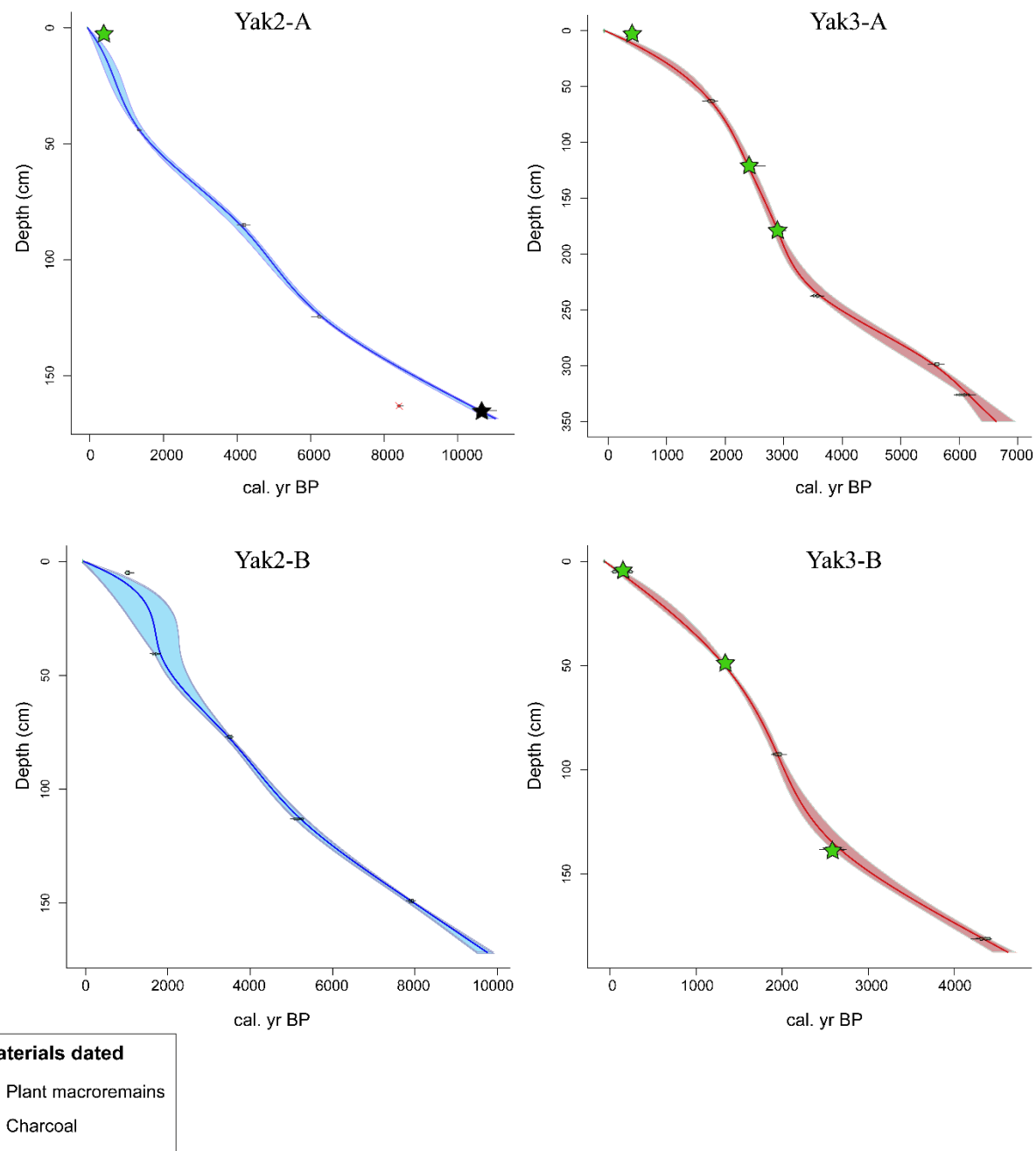
896 Weijers, J.W., Schouten, S., van den Donker, J.C., Hopmans, E.C., Damsté, J.S.S., 2007b. Environmental controls on bacterial tetraether
897 membrane lipid distribution in soils. *Geochimica et Cosmochimica Acta* 71, 703–713.

898 Weijers, J.W., Schouten, S., van der Linden, M., van Geel, B., Sinninghe Damsté, J.S., 2004. Water table related variations in the abundance of
899 intact archaeal membrane lipids in a Swedish peat bog. *FEMS Microbiology Letters* 239, 51–56.

900 Wohlfarth, B., Lacourse, T., Bennike, O., Subetto, D., Tarasov, P., Demidov, I., Filimonova, L., Sapelko, T., 2007. Climatic and environmental
901 changes in north-western Russia between 15,000 and 8000calyrBP: a review. *Quaternary Science Reviews* 26, 1871–1883.
902 <https://doi.org/10.1016/j.quascirev.2007.04.005>

- 903 Xiao, W., Wang, Y., Zhou, S., Hu, L., Yang, H., Xu, Y., 2016. Ubiquitous production of branched glycerol dialkyl glycerol tetraethers
904 (brGDGTs) in global marine environments: a new source indicator for brGDGTs. *Biogeosciences* 13, 5883–5894.
905 <https://doi.org/10.5194/bg-13-5883-2016>
- 906 Zaboeva, I.V., 1997. Soil ecology of Northern Taiga.
- 907 Zaretskaya, N.E., Panin, A.V., Golubeva, Y.V., Chernov, A.V., 2014. Sedimentation settings and the late pleistocene-holocene geochronology
908 in the Vychegda River valley. *Doklady Earth Sciences* 455, 223–228. <https://doi.org/10.1134/S1028334X14030118>
- 909 Zink, K.-G., Vandergoes, M.J., Mangelsdorf, K., Dieffenbacher-Krall, A.C., Schwark, L., 2010. Application of bacterial glycerol dialkyl
910 glycerol tetraethers (GDGTs) to develop modern and past temperature estimates from New Zealand lakes. *Organic Geochemistry* 41,
911 1060–1066.
- 912

913 **8. Supplementary Information**



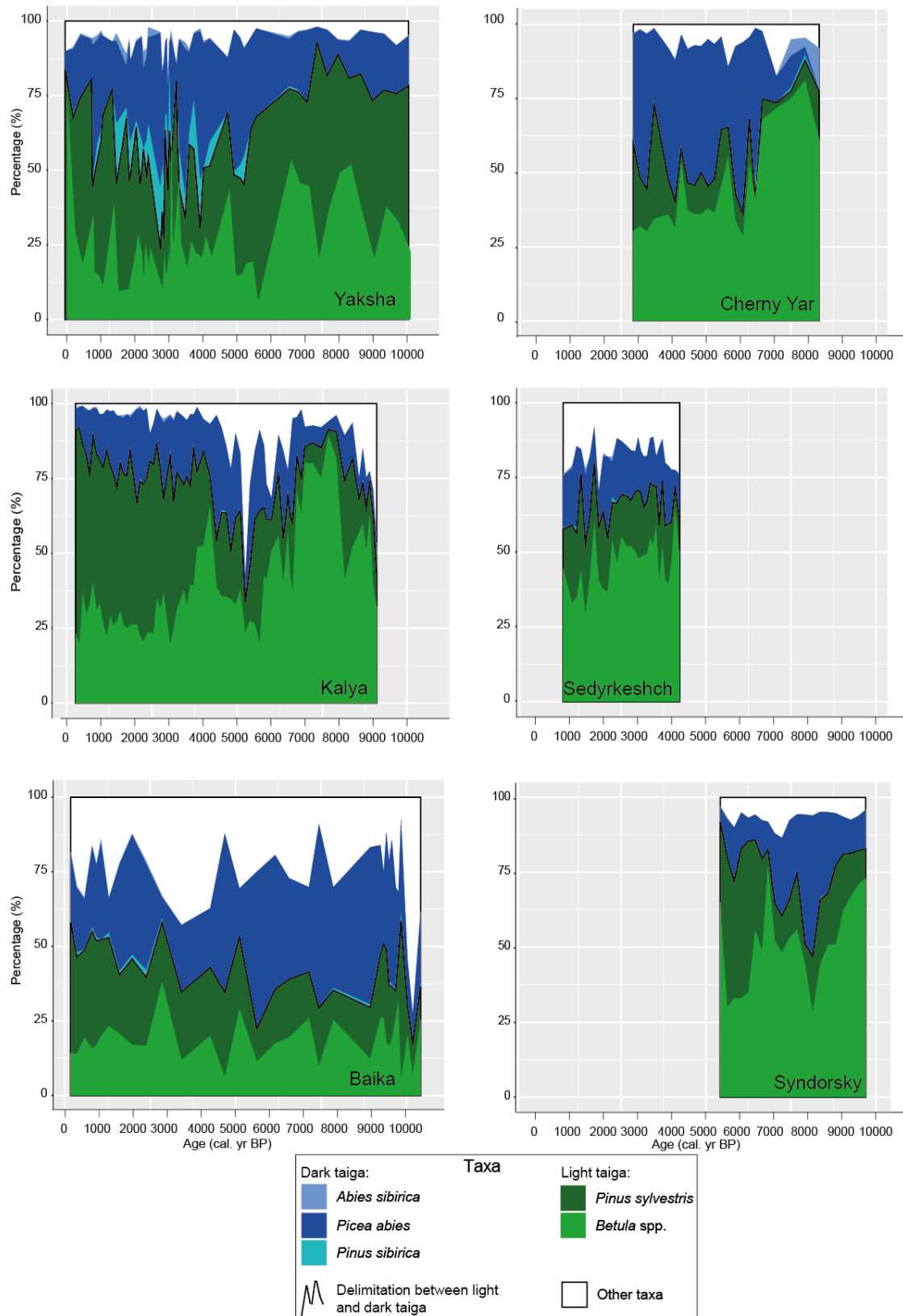
914

915 *SI 1: From Barhoumi et al. (2019): Age-depth model based on radiocarbon ages (see Table 2) from Yak2-A, Yak2-B, Yak3-A and Yak3-B cores.*
 916 *The materials dated by 14C are bulk (single black lines), plant macroremains (green stars), macrocharcoal (black star).*

917

918

919

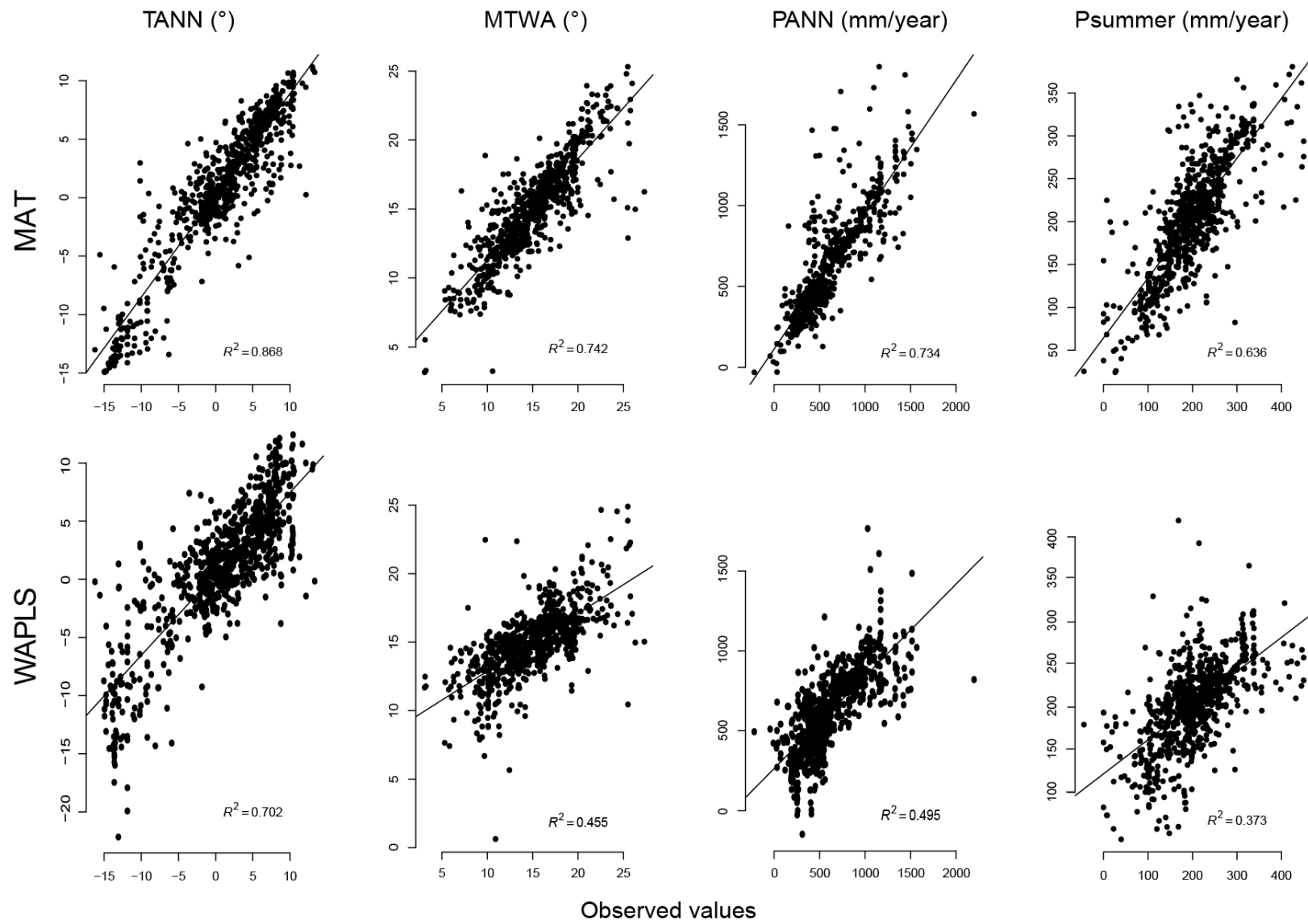


920

921 *SI 2: Cumulative pollen percentage diagram of principal taxa for each site: Yaksha, Baika, Kalya, Cherny Yar, Sedyrkeshch and Syndorsky.*

922 *The main taxa shown are Betula spp. and Pinus sylvestris for the light taiga and Pinus sibirica, Picea abies and Abies sibirica for the dark taiga.*

923



924

925 *SI 3: Correlations between the reconstructed values from the pollen transfer functions and the observed values of the randomly selected 40% of*
 926 *the database*

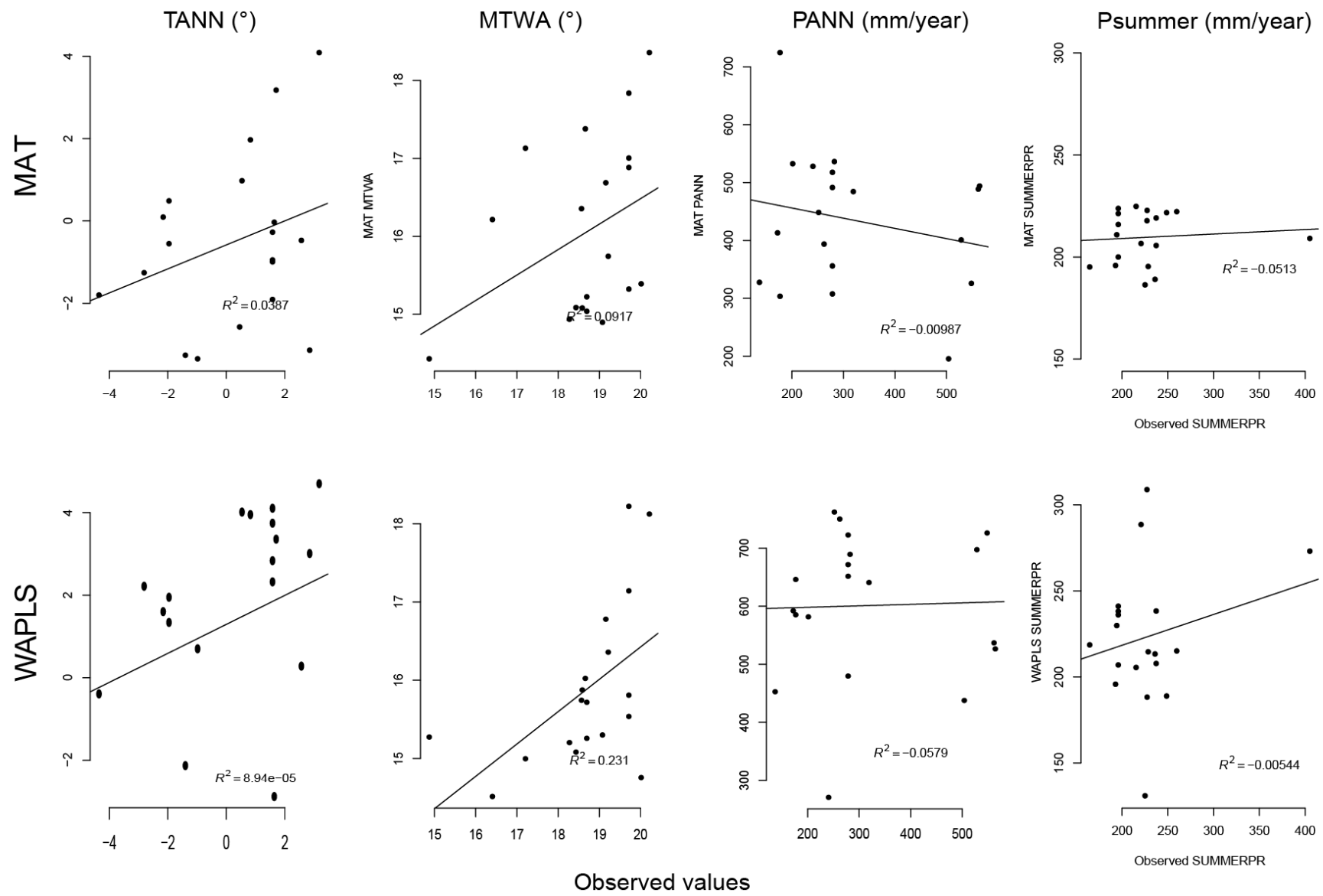
927

928

929

930

931



933 *SI 4: Correlations between the reconstructed values from the pollen transfer functions and the observed values of the 19 samples situated between*
 934 *40-50°N, 40-50°E of the database*

935

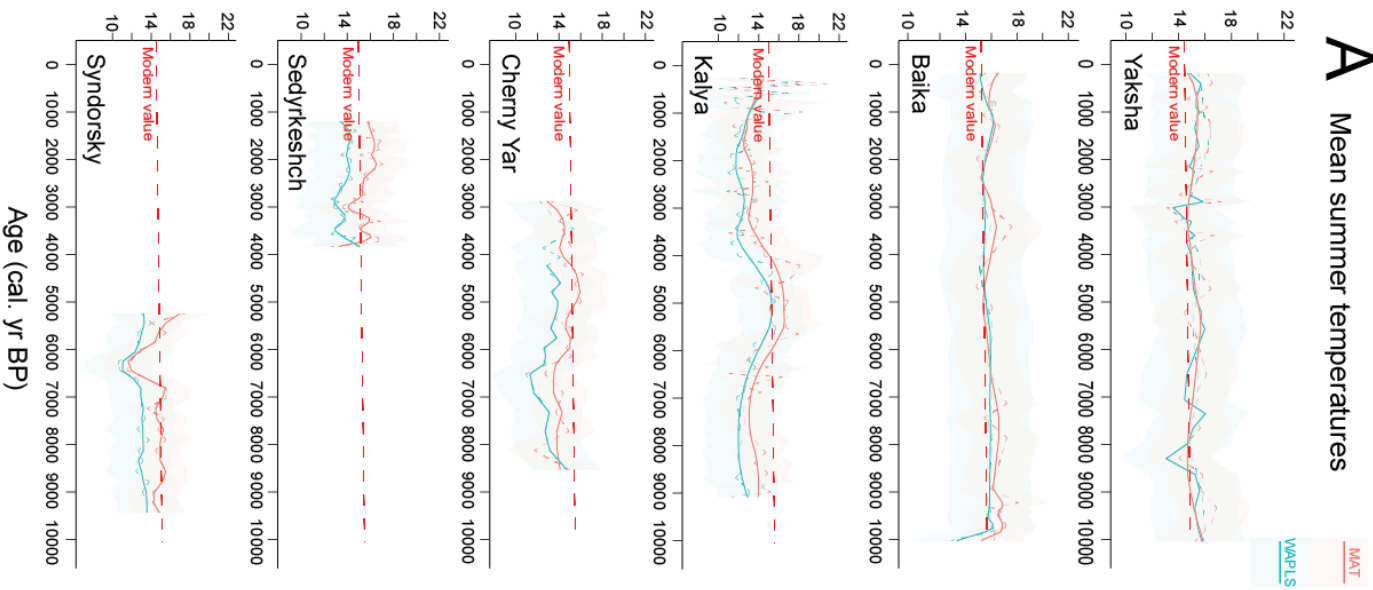
936

937

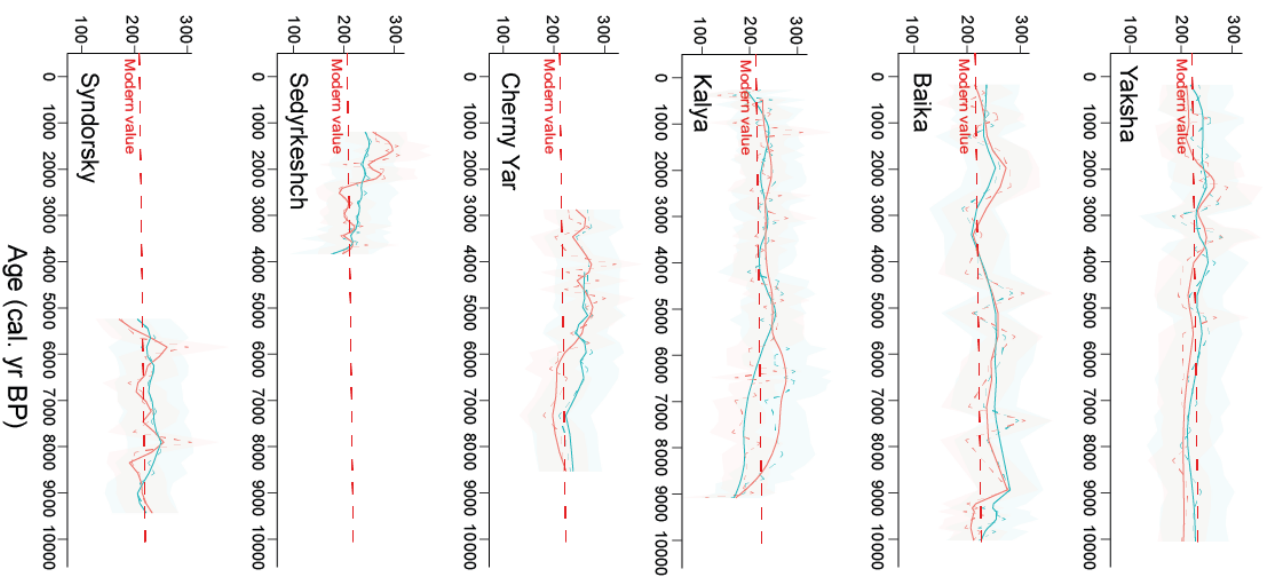
938

939

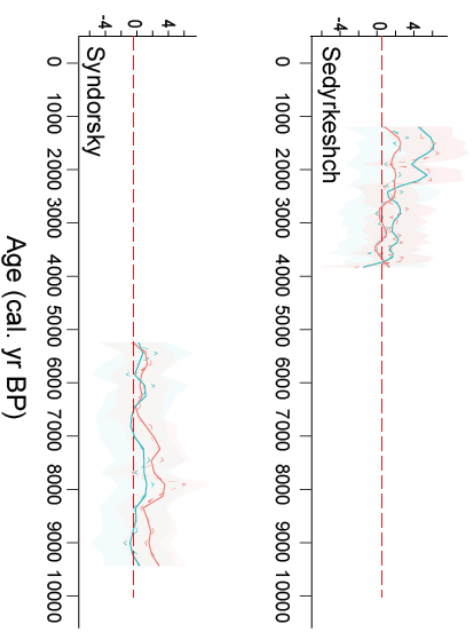
A Mean summer temperatures



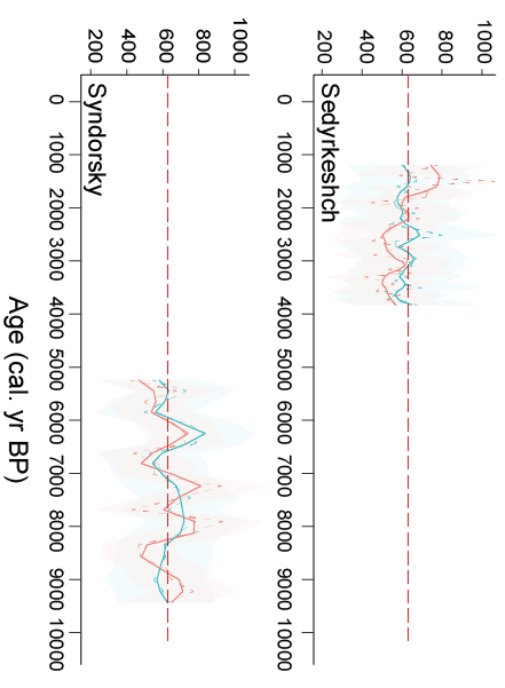
B Summer precipitation



C Mean annual temperatures



D Mean annual precipitation

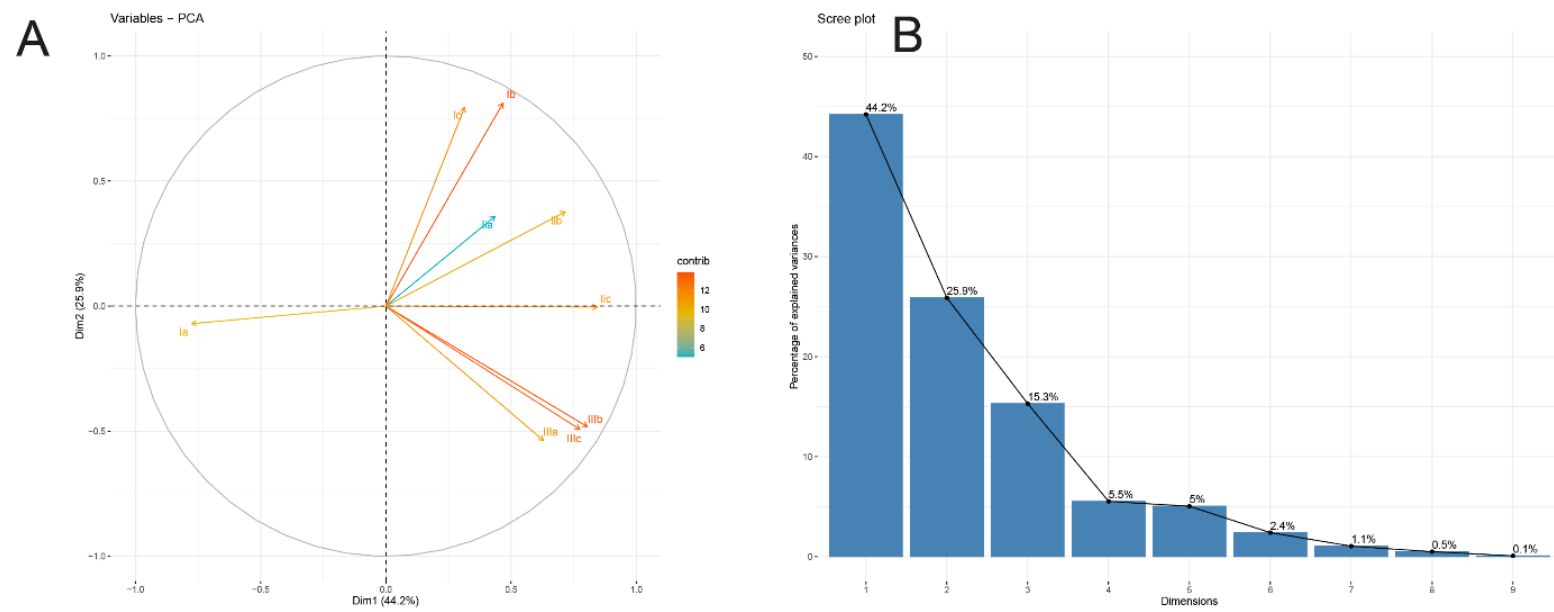


941 *SI 5: Regional climatic synthesis of the Republic of Komi of pollen-based climatic reconstructions. Mean summer temperature (A), summer*
 942 *precipitation (B) and mean annual temperatures and precipitations (C and D) were calculated using the modern analogue technique (MAT)*
 943 *and the weighted average partial Least squares regression (WA-PLS) and smoothed using Loess (span = 0.3, solid lines). Shaded areas are*
 944 *confidence intervals. Red dashed lines are modern values for each site.*

945

946

947



948 *SI 6: A: Yaksha brGDGTs PCA (axis 1 and axis 2). B: Yaksha brGDGTs PCA percentage of explained variances for each axis.*

949